APPENDIX E
Part 1 of 3

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ISSUE DATE: *September 20, 2005*

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Under Secretary of Commerce for Intellectual Property
and Director of the United States Patent and Trademark Office

T. WALLACE
Certifying Officer

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Chin et al.

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(45) **Date of Patent:** **Sep. 20, 2005**

(54) **OPEN-LOOP LASER DRIVER HAVING AN INTEGRATED DIGITAL CONTROLLER**

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(58) **Field of Search** 372/8, 29.01, 29.011, 372/29.014, 29.02, 38.1, 38.02, 38.08, 38.01, 43, 29.015, 34, 38.07

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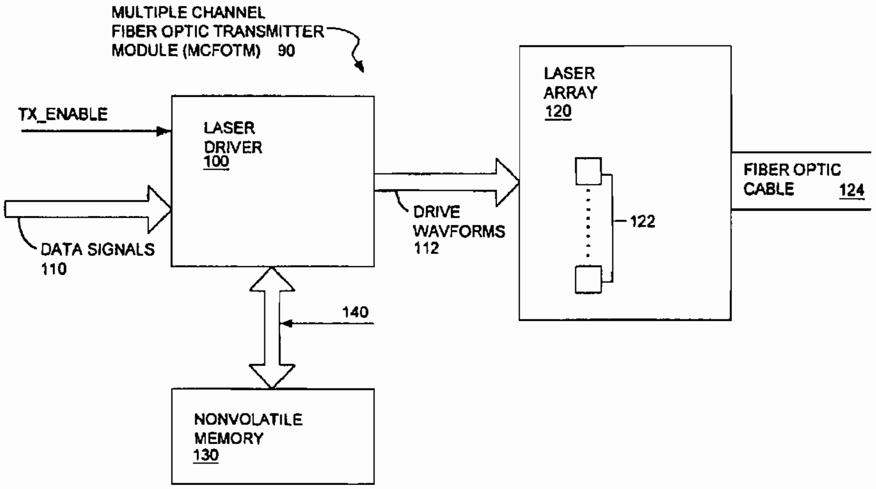
* cited by examiner

Primary Examiner—Minsun Oh Harvey
Assistant Examiner—Armando Rodriguez

(57) **ABSTRACT**

A laser driver for generating drive waveforms that are suitable for driving a single VCSEL or an array of VCSELs. A digital controller is integrated into the laser driver and is utilized to initially program and selectively adjust during the operation of the driver one or more of the following VCSEL drive waveform parameters: (1) bias current, (2) modulation current, (3) negative peaking depth, and (4) negative peaking duration. The laser driver has an aging compensation mechanism for monitoring the age of the laser and for selectively adjusting the dc and ac parameters of the VCSEL drive waveform to compensate for the aging of the laser. The laser driver also has a temperature compensation mechanism for monitoring the temperature of the driver IC and selectively adjusting the dc and ac parameters of the VCSEL drive waveform to compensate for the changes in temperature.

20 Claims, 7 Drawing Sheets



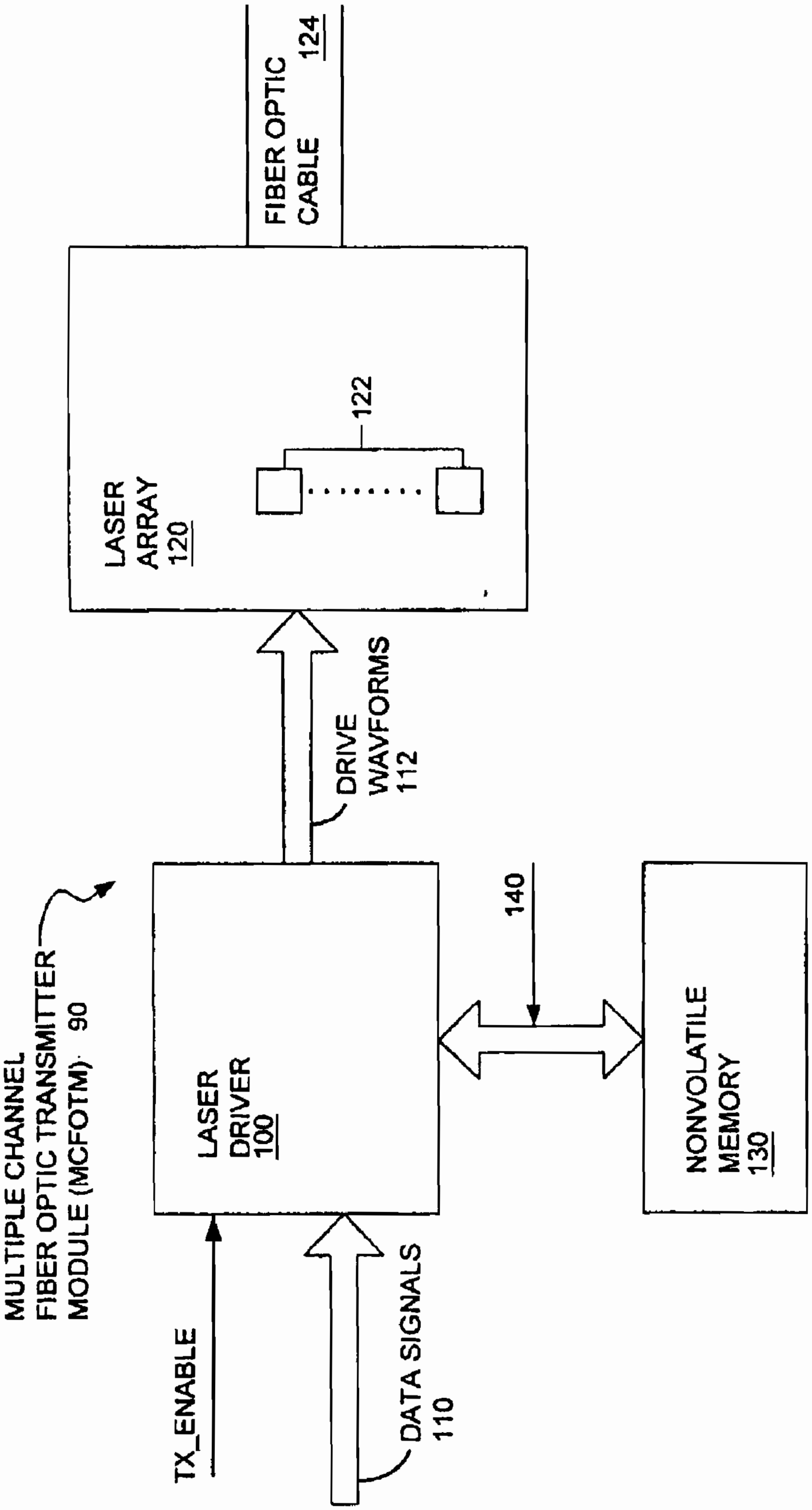

MULTIPLE CHANNEL
FIBER OPTIC TRANSMITTER
MODULE (MCFOTM) 90
TX_ENABLE
DATA SIGNALS
110
LASER
DRIVER
100
DRIVE
WAVFORMS
112
LASER
ARRAY
120
122
FIBER OPTIC
CABLE
124
140
NONVOLATILE
MEMORY
130

FIG. 1

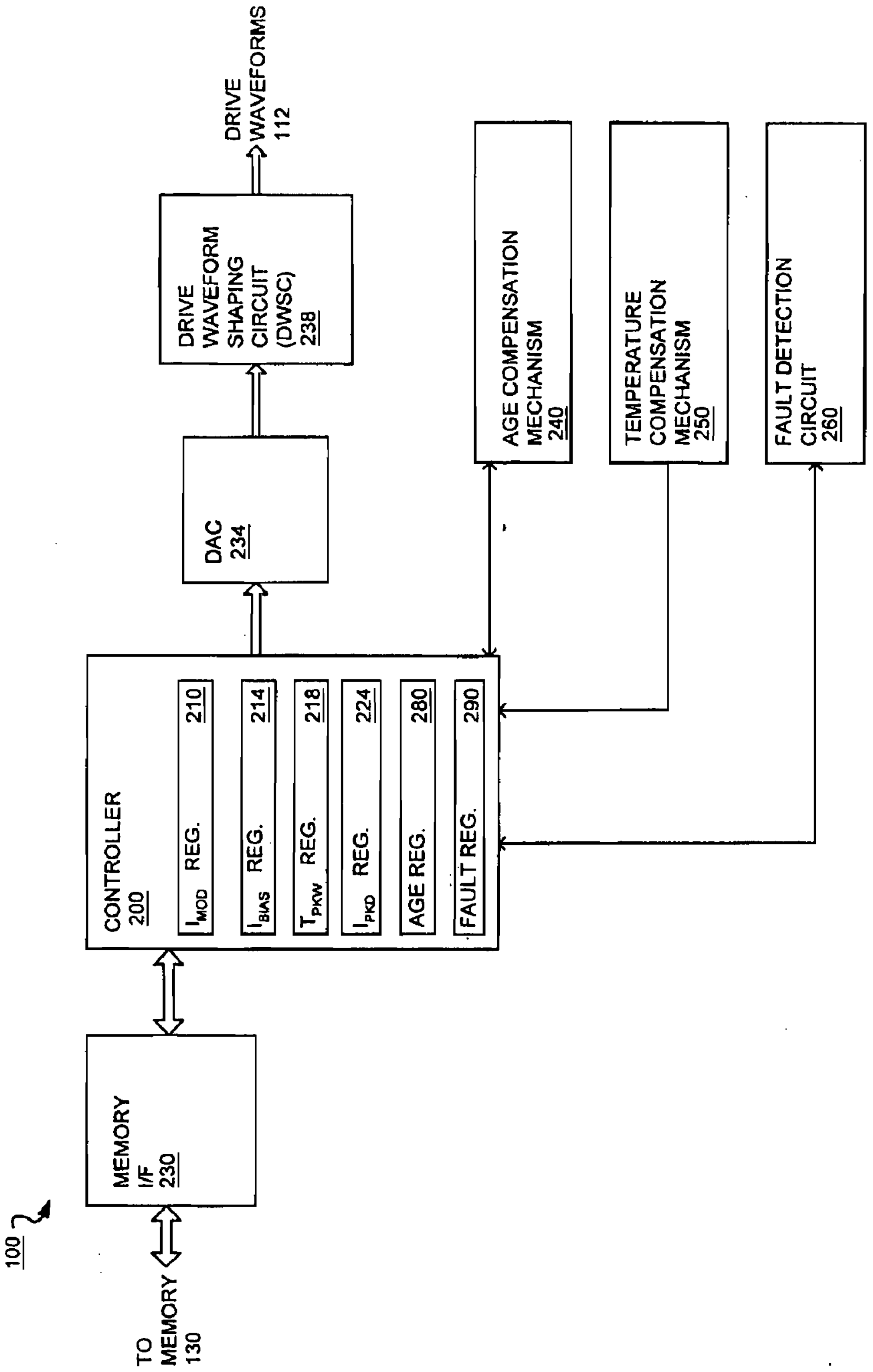

100
TO MEMORY 130
MEMORY I/F 230
CONTROLLER 200
I_{MOD} REG. 210
I_{BIAS} REG. 214
T_{PKW} REG. 218
I_{PKD} REG. 224
AGE REG. 280
FAULT REG. 290
DAC 234
DRIVE WAVEFORM SHAPING CIRCUIT (DWSC) 238
DRIVE WAVEFORMS 112
AGE COMPENSATION MECHANISM 240
TEMPERATURE COMPENSATION MECHANISM 250
FAULT DETECTION CIRCUIT 260

FIG. 2

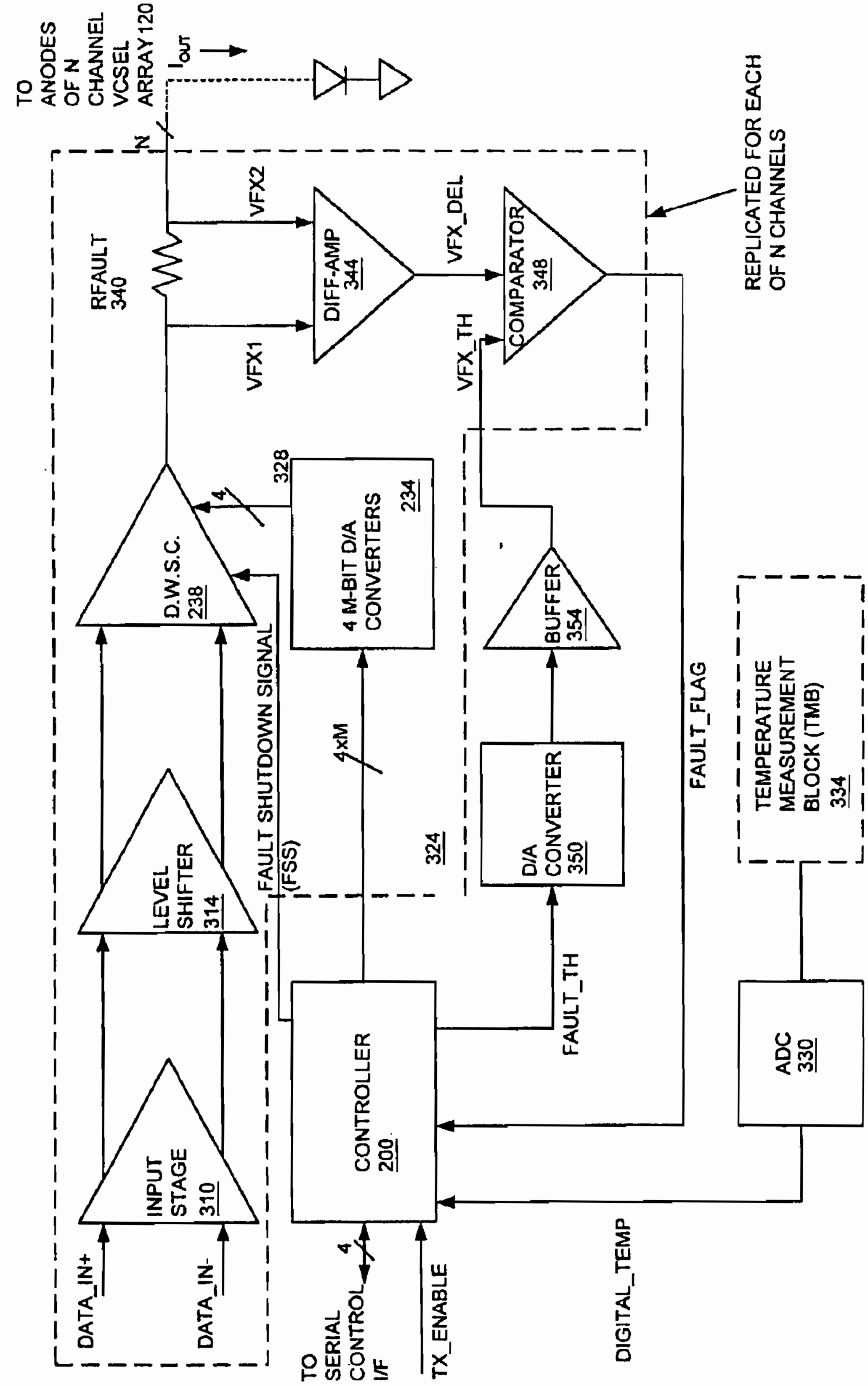

TO ANODES OF N CHANNEL VCSEL ARRAY 120
I_{OUT}
N
RFAULT 340
VFX2
VFX1
DIFF-AMP 344
VFX_DEL
VFX_TH
COMPARATOR 348
REPLICATED FOR EACH OF N CHANNELS
328
4
D.W.S.C. 238
4 M-BIT D/A CONVERTERS 234
BUFFER 354
FAULT SHUTDOWN SIGNAL (FSS)
4xM
324
LEVEL SHIFTER 314
D/A CONVERTER 350
FAULT_FLAG
TEMPERATURE MEASUREMENT BLOCK (TMB) 334
FAULT_TH
INPUT STAGE 310
CONTROLLER 200
ADC 330
DATA_IN+
DATA_IN-
TO SERIAL CONTROL I/F
4
TX_ENABLE
DIGITAL_TEMP

FIG. 3

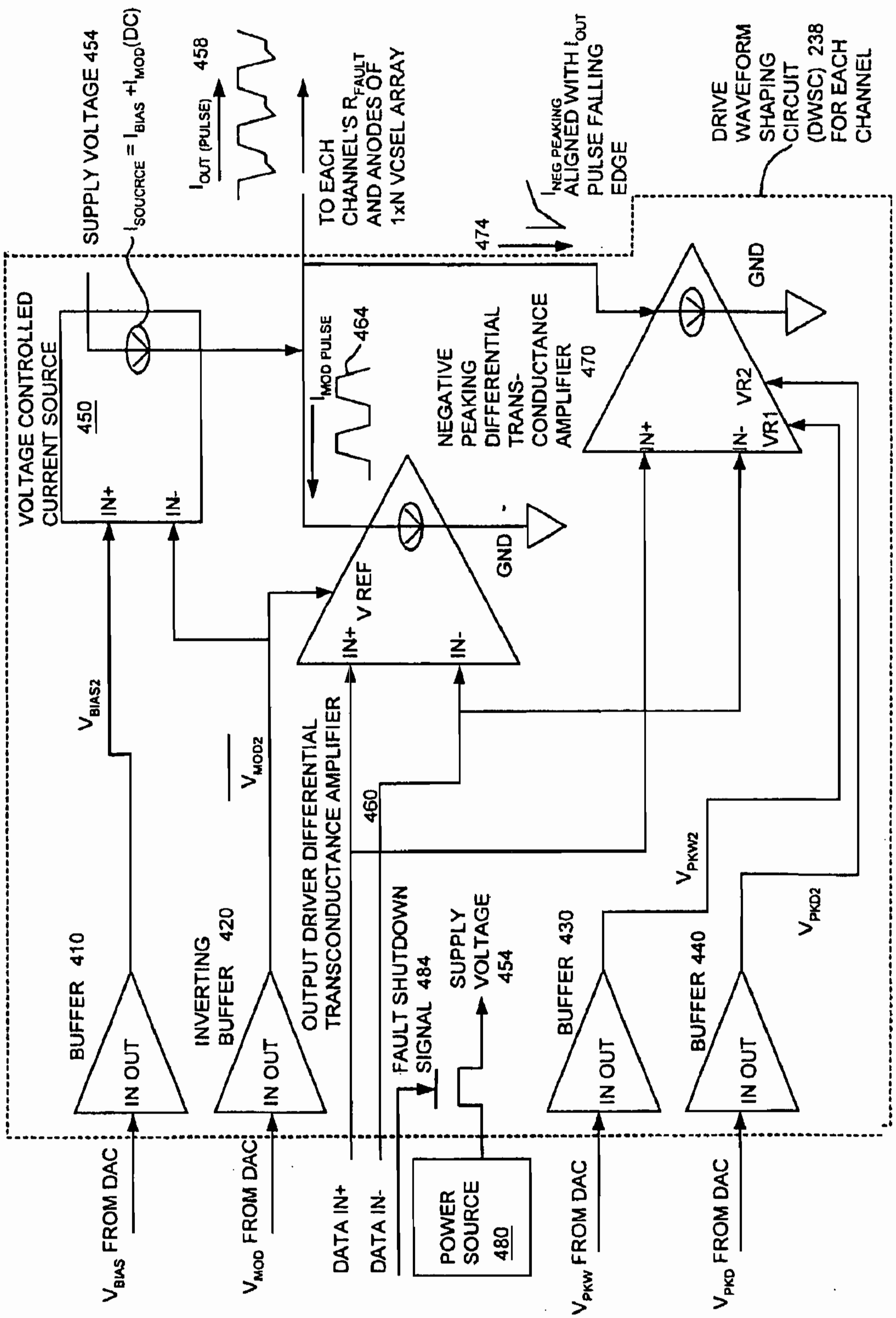

SUPPLY VOLTAGE 454
$I_{SOUCRCE} = I_{BIAS} + I_{MOD}(DC)$
$I_{OUT\ (PULSE)}$ 458
TO EACH CHANNEL'S R_{FAULT} AND ANODES OF 1xN VCSEL ARRAY
$I_{NEG\ PEAKING}$ ALIGNED WITH I_{OUT} PULSE FALLING EDGE
474
DRIVE WAVEFORM SHAPING CIRCUIT (DWSC) 238 FOR EACH CHANNEL
VOLTAGE CONTROLLED CURRENT SOURCE
450
IN+
IN-
$I_{MOD\ PULSE}$
464
NEGATIVE PEAKING DIFFERENTIAL TRANS-CONDUCTANCE AMPLIFIER 470
IN+
IN-
VR1
VR2
GND
V REF
IN+
IN-
GND
V_{BIAS2}
$\overline{V_{MOD2}}$
OUTPUT DRIVER DIFFERENTIAL TRANSCONDUCTANCE AMPLIFIER
460
V_{PKW2}
V_{PKD2}
BUFFER 410
INVERTING BUFFER 420
FAULT SHUTDOWN SIGNAL 484
SUPPLY VOLTAGE 454
BUFFER 430
BUFFER 440
IN OUT
IN OUT
IN OUT
IN OUT
V_{BIAS} FROM DAC
V_{MOD} FROM DAC
DATA IN+
DATA IN-
POWER SOURCE 480
V_{PKW} FROM DAC
V_{PKD} FROM DAC

FIG. 4

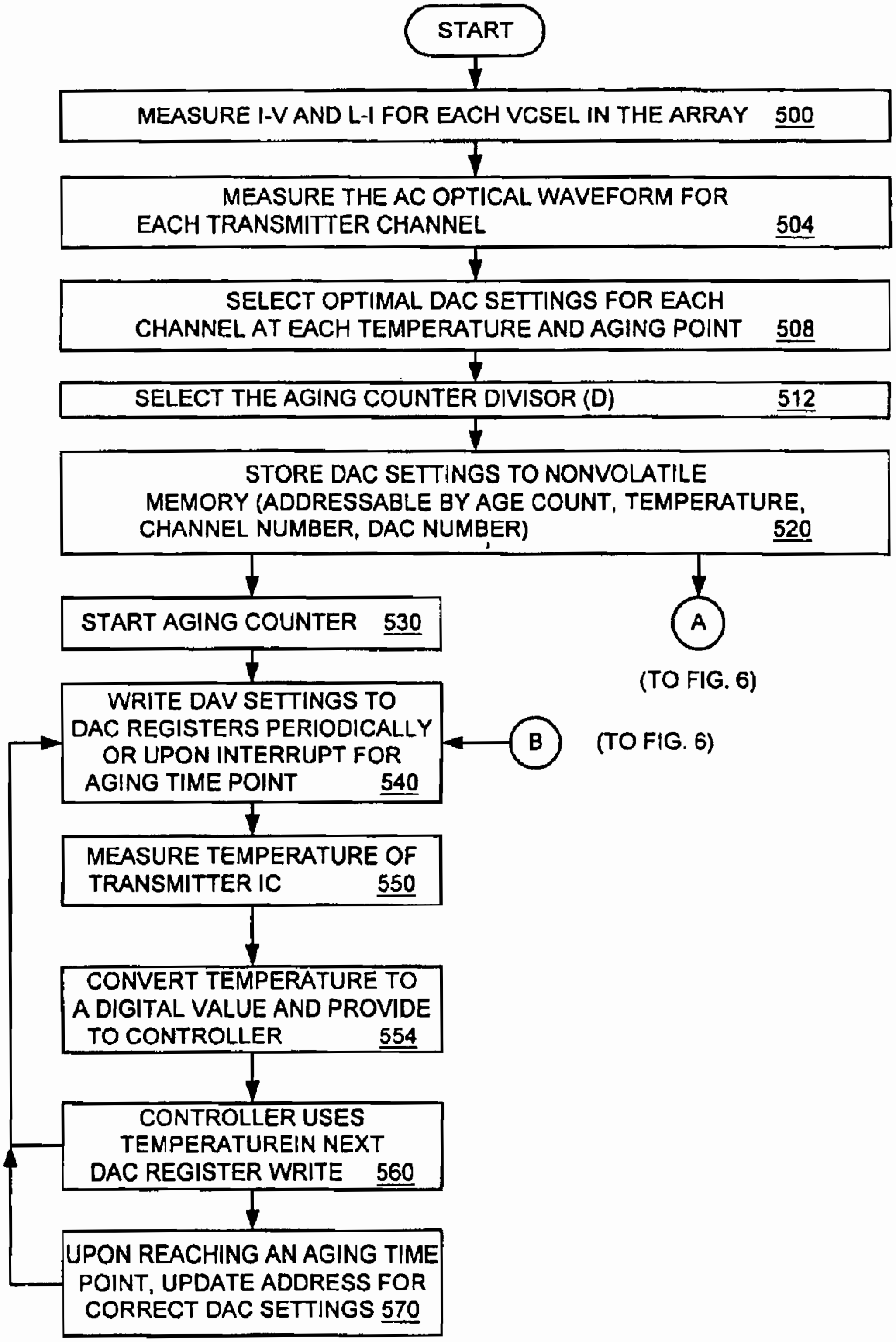

START
MEASURE I-V AND L-I FOR EACH VCSEL IN THE ARRAY 500
MEASURE THE AC OPTICAL WAVEFORM FOR EACH TRANSMITTER CHANNEL 504
SELECT OPTIMAL DAC SETTINGS FOR EACH CHANNEL AT EACH TEMPERATURE AND AGING POINT 508
SELECT THE AGING COUNTER DIVISOR (D) 512
STORE DAC SETTINGS TO NONVOLATILE MEMORY (ADDRESSABLE BY AGE COUNT, TEMPERATURE, CHANNEL NUMBER, DAC NUMBER) 520
START AGING COUNTER 530
A
(TO FIG. 6)
WRITE DAV SETTINGS TO DAC REGISTERS PERIODICALLY OR UPON INTERRUPT FOR AGING TIME POINT 540
B
(TO FIG. 6)
MEASURE TEMPERATURE OF TRANSMITTER IC 550
CONVERT TEMPERATURE TO A DIGITAL VALUE AND PROVIDE TO CONTROLLER 554
CONTROLLER USES TEMPERATUREIN NEXT DAC REGISTER WRITE 560
UPON REACHING AN AGING TIME POINT, UPDATE ADDRESS FOR CORRECT DAC SETTINGS 570

FIG. 5

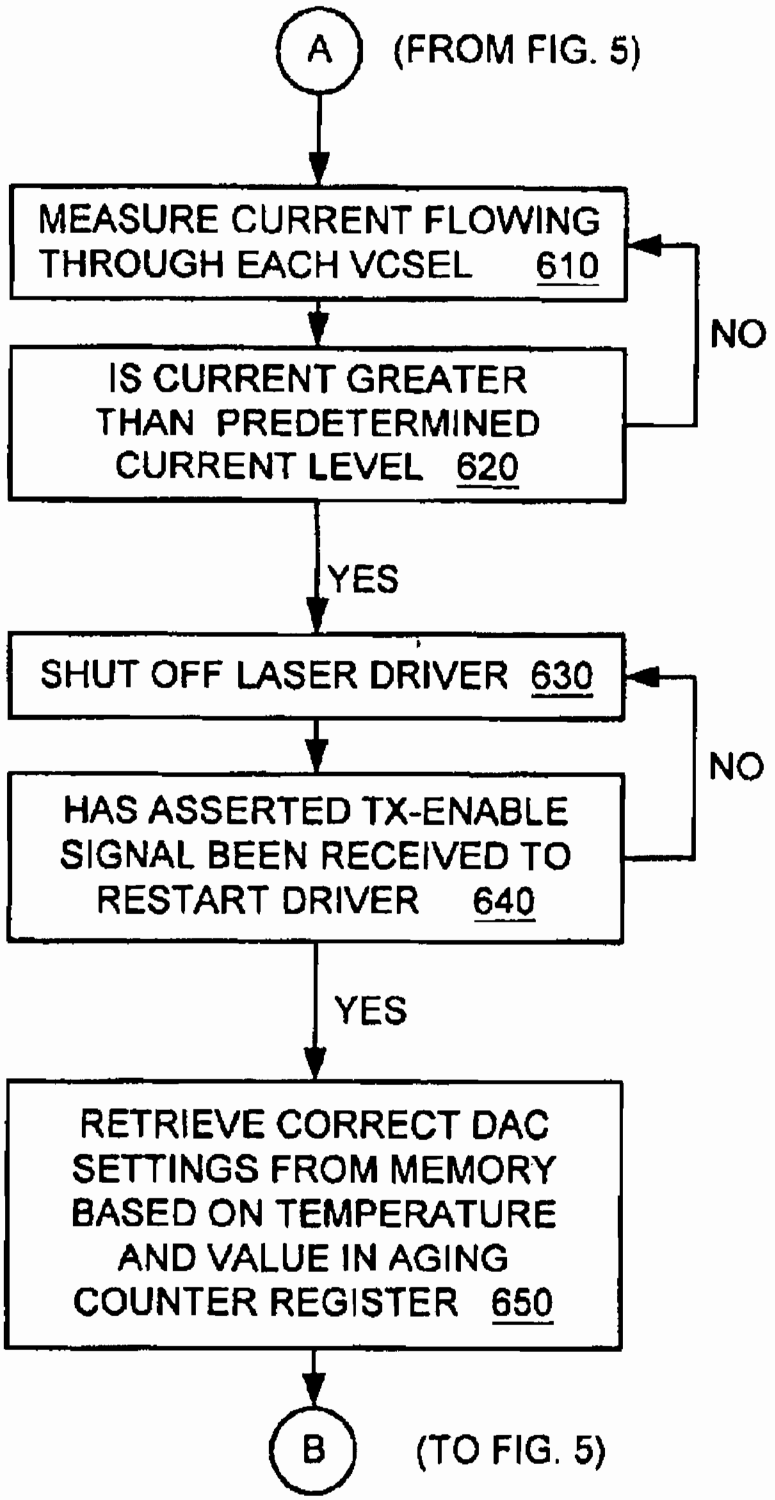

A
(FROM FIG. 5)
MEASURE CURRENT FLOWING THROUGH EACH VCSEL 610
IS CURRENT GREATER THAN PREDETERMINED CURRENT LEVEL 620
NO
YES
SHUT OFF LASER DRIVER 630
HAS ASSERTED TX-ENABLE SIGNAL BEEN RECEIVED TO RESTART DRIVER 640
NO
YES
RETRIEVE CORRECT DAC SETTINGS FROM MEMORY BASED ON TEMPERATURE AND VALUE IN AGING COUNTER REGISTER 650
B
(TO FIG. 5)

FIG. 6

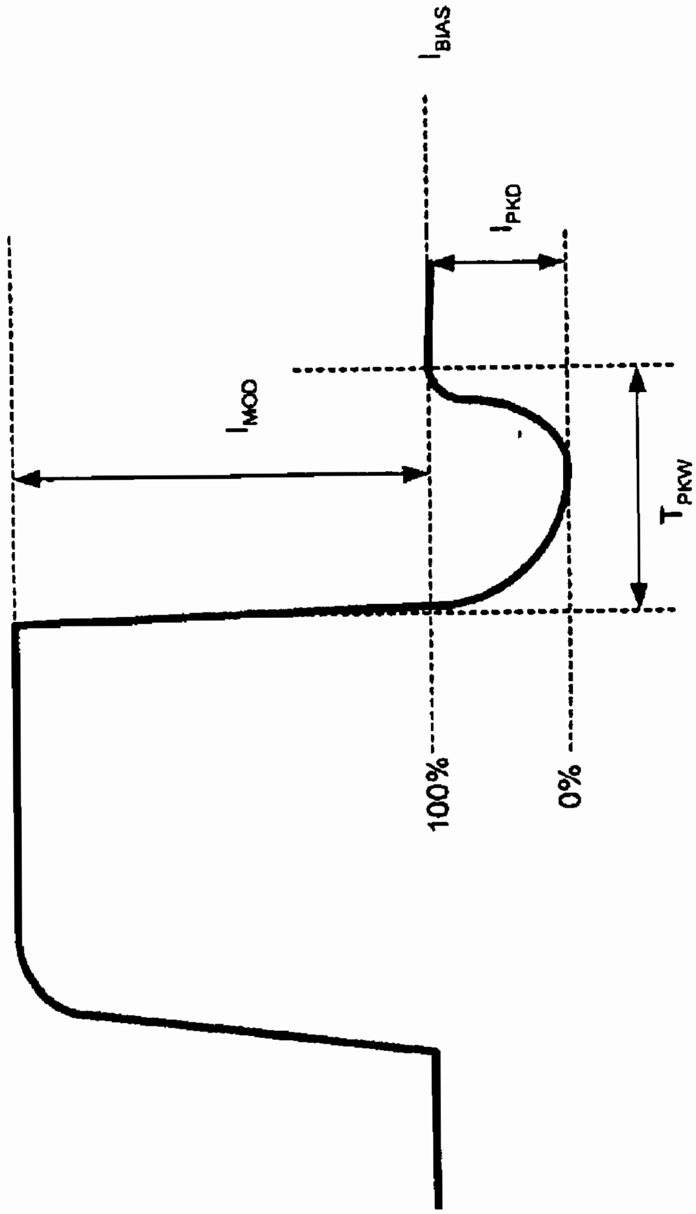


FIG. 7

OPEN-LOOP LASER DRIVER HAVING AN INTEGRATED DIGITAL CONTROLLER

FIELD OF THE INVENTION

The present invention relates generally to semiconductor lasers, and more particularly, to an open-loop laser driver having an integrated digital controller for providing drive waveforms to lasers.

BACKGROUND OF THE INVENTION

An optical transmitter module is an important component in networking systems. The purpose of an optical transmitter module is to convert data signals in electrical form into corresponding data signals in optical form. In this manner, the data can be communicated as light to another module (e.g., an optical receiver module) through a light-conducting medium, such as a fiber optic cable.

The optical transmitter module typically employs a laser to convert the electrical data signals into the light data signals. One commonly utilized semiconductor laser is the vertical cavity surface emitting laser (VCSEL). However, the VCSEL is configured to operate only with input signals (e.g., drive waveforms) that conform to particular predetermined electrical properties. The drive waveforms can have both dc operating parameters and ac operating parameters. For example, the dc operating parameters may include bias current to obtain either average or low state output power. The ac operating parameters may include modulation current, peaking current, and time constant parameters associated with pulsed waveforms. The data signals typically do not have these predetermined electrical characteristics (e.g., specific dc and ac operating parameters). Consequently, a circuit is needed for accepting the data signals, and responsive thereto, for generating corresponding VCSEL drive signals (e.g., a drive waveform) with the electrical characteristics that are suitable to drive the VCSEL. This circuit is commonly referred to as a VCSEL driver.

Furthermore, the VCSEL driver programs or sets the drive waveform with particular dc and ac parameters in order to optimize the bit error rate (BER) of the fiber optic link using the transmitter. The bit error rate is simply a measure of the number of bit errors caused by the transmitter module. A bit error is simply a data error when a data "1" is transmitted as a data "0" or when a data "0" is transmitted as a data "1".

There are two main approaches in the design of prior art laser drivers. The first approach employs a closed loop (i.e., uses optical feedback to adjust the light output power) to program the drive waveforms. The second approach employs an open loop (i.e., does not use optical feedback to adjust the light output power) to program the drive waveforms. These prior art approaches with their attendant disadvantages are described hereinafter.

Closed-Loop Approaches

U.S. Pat. No. 5,638,390 describes an exemplary closed-loop approach embodied in a laser output power stabilizing circuit. The laser output power stabilizing circuit uses a photodiode to monitor the laser's optical power. The photodiode output is compared to a reference voltage from a digital potentiometer, to obtain the correct dc bias current for the laser. At the time of the transmitter's manufacture, the digital potentiometer is set to optimize the laser's dc bias current. During operation of the transmitter, the laser's bias current is adjusted when any change in photodiode output occurs.

Unfortunately, these closed-loop approaches suffer from several disadvantages. First, the use of the photodiode increases the cost of the optical transmitter. Second, the requirement of the photodiode introduces packaging concerns related to the mounting of the photodiodes in such a manner as to be optimally aligned with the VCSEL. Third, the closed-loop approaches require complex feedback circuits that need to be replicated for each VCSEL, thereby further increasing costs and manufacturing complexity.

Open-Loop Approaches

The data sheet for the AMCC S7011 transmitter integrated circuit (IC) that is available from Applied Micro Circuits Corporation (AMCC) describes an exemplary open-loop approach. The S7011 IC appears to be capable of adjusting the laser drive waveform parameters Imod and Ibias, given input from an external source (e.g., a microprocessor), or input from external resistors and voltage references. Unfortunately, the prior art open-loop approaches, including the AMCC approach, fail to provide or provide very limited mechanisms to adjust the drive waveform based on changes in age and temperature of the laser. These prior art open-loop approaches also fail to allow programming of the transitional aspects of the VCSEL drive waveform (e.g. negative peaking).

VCSEL Arrays

Recently, there has been interest in moving from a single VCSEL to an array of VCSELs, which for example, can be a plurality of VCSELs that are arranged in a row. As can be appreciated, an array of VCSELs can be employed to transmit more data through multi-channel fiber optic cable than a single VCSEL can transmit through a fiber optic cable having a single channel. Unfortunately, one of the engineering challenges for implementing the array of VCSELS is that optical waveform uniformity across the VCSEL array needs to be maintained in order to optimize the BER of the fiber optic link.

Consequently, correct settings for the dc and ac parameters of the drive waveforms are particularly critical for fiber optic transmitters using an array of VCSELs. The parameters must be set to maintain optical waveform uniformity across the VCSEL array. The setting of these properties needs to occur at the beginning of operation and also at periodic intervals during the product's lifetime.

Semiconductor electrical to optical transmitters often require a scheme to program the optical de and ac operating characteristics of the light-emitting device. Preferably, the programming is performed at the beginning of product use, and periodically programmed throughout the lifetime of the transmitter. Unfortunately, the prior art approaches that do periodically program the waveforms during the lifetime of the transmitter are costly, complex to implement, and limited to dc parameters. Those prior art approaches that address some of the ac issues, such as modulation current, are limited to programming only at the beginning of product use. Consequently, if the product requires programming during the operating life of the driver, these prior art approaches are unable to perform this type of programming.

Age Dependence of Light Output

Ideally, the laser's performance in terms of light output remains constant throughout the operating life of the laser. If this were the case, the drive waveforms can be programmed once by the laser driver and would require no further changes or re-programming. Unfortunately, in reality, VCSEL light output tends to degrade over the operating life of the laser. Consequently, it would be desirable to have a mechanism in the VCSEL driver for periodically adjusting the VCSEL drive waveform parameters to compensate for the degradation. Regrettably, the prior art approaches that employ an open-loop approach, such as the AMCC approach, are limited to programming the waveform parameters at the beginning of the product life and do not have a mechanism for periodically adjusting the VCSEL drive waveform parameters to compensate for the degradation.

Temperature Dependence of Light Output

Moreover, in an ideal situation, the laser's light output would be independent of operating temperature. If this were the case, the drive waveform would not require adjustment as the operating temperature changes. Unfortunately, in reality, the laser's light output is dependent on operating temperature. Accordingly, it would be desirable to have a mechanism that adjusts the drive waveforms as the operating temperature changes. By so doing, optimum VCSEL optical waveform characteristics can be maintained. Regrettably, the prior art approaches do not offer any mechanism for periodically adjusting the VCSEL drive waveform parameters to compensate for changing operating temperatures.

Based on the foregoing, there remains a need for a digital control method and apparatus for semiconductor lasers that overcomes the disadvantages set forth previously.

SUMMARY OF THE INVENTION

According to one embodiment, the laser driver of the present invention includes an integrated digital controller for programming the dc and ac parameters of the drive waveform that drives a single VCSEL or an array of VCSELs for use in a fiber optic transmitter. The digital controller is integrated into the driver IC and is utilized to program one or more of the following VCSEL drive waveform parameters: (1) bias current, (2) modulation current, (3) negative peaking depth, and (4) negative peaking duration.

In one embodiment, the laser driver includes an aging compensation mechanism for monitoring the age of the laser and for selectively adjusting the dc and ac parameters of the VCSEL drive waveform to compensate for the aging of the laser. Preferably, a timer is employed to monitor the age of the laser.

In another embodiment, the laser driver includes a temperature compensation mechanism for monitoring the temperature of the driver IC and selectively adjusting the dc and ac parameters of the VCSEL drive waveform to compensate for the changes in temperature. Preferably, a temperature sensor is employed to monitor the temperature of the driver IC.

As described previously, the optimization of VCSEL optical waveform characteristics in a multi-channel fiber optic transmitter can pose a difficult challenge. The laser driver of the present invention separately programs each channel's VCSEL drive waveform parameters initially and during operation of the transmitter in order to maintain optimum optical waveforms for each channel. By updating of VCSEL drive parameters during transmitter operation, the laser driver of the present invention compensates for aging of the laser and temperature changes.

According to another embodiment of the present invention, a design methodology for the programming of the VCSEL drive waveform is provided.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings and in which like reference numerals refer to similar elements.

FIG. **1** is a block diagram of an exemplary multiple channel fiber optic transmitter module in which the laser driver of the present invention can be implemented.

FIG. **2** illustrates in greater detail the laser driver of FIG. **1** according to one embodiment of the present invention.

FIG. **3** is a block diagram illustrates in greater detail the laser driver of FIG. **1** according to one embodiment of the present invention.

FIG. **4** illustrates in greater detail the drive waveform shaping circuit of FIG. **3** according to one embodiment of the present invention.

FIG. **5** is a flowchart illustrating the steps performed by the controller of FIG. **2**. according to one embodiment of the present invention.

FIG. **6** is a flowchart illustrating the steps performed by the controller of FIG. **2**. according to one embodiment of the present invention.

FIG. **7** illustrates an exemplary drive waveform that is generated by the laser driver of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

An open-loop laser driver having an integrated digital controller and programming method are described. In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one skilled in the art that the present invention may be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form in order to avoid unnecessarily obscuring the present invention.

The laser driver of the present invention integrates a digital controller, data storage/retrieval facilities, and the needed mechanisms to initially set and periodically adjust the parameters of the VCSEL drive waveform for each channel to effectively compensate for aging and operating temperature changes.

Multiple Channel Fiber Optic Transmitter Module **90**

FIG. **1** is a block diagram of an exemplary multiple channel fiber optic transmitter module (MCFOTM) **90** in which the laser driver of the present invention can be implemented. For example, the multiple channel fiber optic transmitter module (MCFOTM) **90** can be a 12-channel transmitter module. The multiple channel fiber optic transmitter module **90** includes a laser driver **100** for receiving data signals **110** and responsive thereto for generating drive waveforms **112**, a laser array **120** that has a plurality of lasers **122** (e.g., VCSELs), and a nonvolatile memory **130** for storing drive waveform parameters. A fiber optic cable **124** is coupled to the laser array **120** in order to receive light launched therein by the lasers **122**.

The drive current waveform associated with each channel's VCSEL diode is programmed by the laser driver **100** and the non-volatile memory **130**. In one embodiment, the MCFOTM **90** includes a VCSEL driver, a 1×N VCSEL array, and an EEPROM. As described in greater detail hereinafter, the laser driver **100** includes a digital controller for programming and data retrieval.

In one embodiment, there are 2*N signal lines interposed between the laser driver **100** and the VCSEL array **120**, where N signal lines are coupled to the anodes of the VCSELs, and N lines that are coupled to either a ground plane or to the cathodes of the VCSELs depending on the type of VCSEL and configuration of the laser driver **100**. It is noted that N is the number of channels incorporated into the multiple channel fiber optic transmitter module **90**.

An access point **140** is provided for reading and writing data into the memory **130** and the laser driver **100**. As will be described in greater detail hereinafter, the access point **140** can be used to communicate test signals and data to the laser driver **100** and the memory **130**.

Laser Driver **100**

FIG. **2** illustrates in greater detail the laser driver **100** of FIG. **1** according to one embodiment of the present invention. The laser driver **100** includes a controller **200**, a plurality of drive parameter registers (**210, 214, 218, 224**) for storing drive parameters, an age compensation mechanism **240**, a temperature compensation mechanism **250**, a fault determination circuit **260**, a plurality of digital-to-analog converters (DACs) **234**, a drive waveform shaping circuit **238**, an age register **280** for storing an age value, and a fault register **290** for storing a predetermined fault value.

Integrated Digital Controller **200** in the VCSEL Driver IC

One aspect of the present invention is the integration of a digital controller **200** in the laser driver **100**. The laser driver **100** of the present invention employs the controller **200** to digitally program the dc and ac properties of the VCSEL drive waveform for a single laser die or for a 1×N array of laser die.

The laser driver **100** of the present invention provides a mechanism for individually programming the parameters (e.g., dc and ac parameters) for each laser die in an array in order to obtain uniformity in the optical waveforms across the array.

Programming the Driver Waveform Parameters

For example, the laser driver **100** can digitally program the VCSEL bias for an optical logic zero by using the integrated controller **200** and the digital-to-analog converters (DACs) **234**. Furthermore, the laser driver **100** can digitally program the VCSEL drive waveform for modulating an optical zero to one transition by using the integrated controller **200** and the DACs **234**.

One feature of the laser driver of the present invention is the programmability of the ac characteristics, such as negative peaking depth and duration, of the VCSEL drive waveform. Negative peaking refers to peaking of the VCSEL drive waveform during the logic one to logic zero falling transition. I_{pkd} is the negative peaking depth. T_{pkw} is the negative peaking duration.

The laser driver **100** can digitally program a negative peaking depth on the VCSEL drive waveform for use during an optical one to zero transition. The negative peaking is used to decrease the optical fall time during a one to zero transition. Also, the laser driver **100** can digitally program a negative peaking duration on the VCSEL drive waveform for use during an optical one to zero transition.

As described in greater detail hereinafter, the laser driver **100** of the present invention can also use the digital controller **200** to implement a timer function for periodically adjusting the VCSEL drive waveform to compensate for aging.

Furthermore, as described in greater detail hereinafter, the laser driver **100** of the present invention can use an integrated digital control loop to monitor die temperature and adjust the dc and ac parameters of the VCSEL drive waveforms to compensate for changes in temperature.

Age Compensation Mechanism **240**

As described previously, the VCSEL light output tends to degrade over the operating life of the laser. In this regard, the VCSEL drive waveform parameters need to be adjusted periodically to compensate for the degradation. In one embodiment, the laser driver of the present invention includes a programmable timer that in cooperation with in the digital controller periodically adjusts each VCSEL's drive waveform parameters to compensate for aging.

A further aspect of the laser driver of the present invention is the integration of a timer function into the digital controller to enable the compensation of light output due to VCSEL aging. The timer allows periodic adjustment of the VCSEL drive waveform dc and ac parameters to compensate for aging.

In one embodiment, the age compensation mechanism **240** can be implemented by using an on-chip 10 Mhz clock, a programmable divisor (D) for the clock, a 31 bit counter (herein referred to as a low order aging counter) in the controller **200**, and a 16 bit counter (herein referred to as a high order aging counter in the non-volatile memory **130**. The clock divisor D combined with the 10 MHz clock period determine how often (in seconds or minutes) the high order aging counter is incremented. The controller **200** updates the DAC settings when the four MSB of the high order aging counter are incremented. For example, when D is equal to 32, and 10 Mhz clock period is equal to 100 ns, then the low order aging counter be incremented every 114.5 minutes, and the high order aging counter's 4 MSB is be incremented every 325 days.

If power to the transmitter is interrupted, the EEPROM stores the last counter setting in multiple registers (e.g., three registers). Once power resumes, the counter setting in each of the registers is compared with the counter values in the other two registers for accuracy. The counter setting found in at least two registers is chosen as the correct setting.

Temperature Compensation Mechanism **250**

As described previously, as the operating temperature of the transmitter module changes, the VCSEL drive waveform parameters require adjustment in order to maintain optimum VCSEL optical waveform characteristics. In one embodiment, the laser driver of the present invention includes an integrated temperature monitor and feedback system for adjusting the VCSEL drive waveform parameters after a temperature change.

Another aspect of the laser driver of the present invention is the integration of a temperature sensing and feedback circuitry onto the driver IC.

The laser driver **100** also includes a non-volatile memory interface **230** for communicating with the nonvolatile memory **130**. The nonvolatile memory **130** stores the DAC settings for I_{mod}, I_{bias}, T_{pkw}, and I_{pkd} in a lookup table format. Each DAC setting can be referenced (e.g., accessed by a read operation) by employing an address that has the following format: AAAATTTTTCCCCXX. The "A"s represent the four most significant bits (MSB) of the aging counter. The "T"s represent five bits that represent the temperature of the laser driver **100**. The "C"s represent the channel number, and the "X"s represent the DAC number. It is noted that the DACs for the I_{mod}, I_{bias}, T_{pkw}, I_{pkd} parameters each has a different number associated therewith.

FIG. **3** illustrates an exemplary implementation of the temperature compensation mechanism **250** and the fault determination circuit **260** of FIG. **2**. For each channel, differential input data flows from Data_in+ and Data_in− through the input stage **310** and level shift stage **314** to the drive waveform shaping circuit **238**. The drive waveform shaping circuit **238** generates a current pulse (i.e., a drive waveform) for each data pulse to drive a laser **122** in the laser array **120**.

The VCSEL current pulse shape is optimized by the drive waveform shaping circuit **238** in terms of I_{mod}, I_{bias}, T_{pkw}, and I_{pkd} as shown in FIG. **7**. Each channel's output current I_{out} is sent to one of the lasers **122** in the VCSEL array **120**. An exemplary embodiment of the drive waveform shaping circuit **238** is described in greater detail hereinafter with reference to FIG. **4**.

Temperature Measurement Block 334

As the VCSEL operating parameters need to change over time or temperature, the controller **200** updates the drive parameters in real time. For example, adjustments for temperature can occur periodically (e.g., in intervals of 30 milliseconds). In one embodiment, the temperature compensation mechanism **250** can be implemented in part by a temperature measurement block (TMB) **334** and an analog to digital converter **330**. The temperature measurement block (TMB) **334** is a sensor that measures the die substrate temperature. The measured data is then converted to a digital format by the analog-to-digital converter (ADC) **330** and then provided to the controller **200** as the digital temp_ signal. The controller **200** then retrieves (from the EEPROM **130**) new DAC settings for I_{mod}, I_{bias}, T_{pkw}, I_{pkd} based upon the temperature. The new DAC settings are stored in registers (e.g., I_{mod} register **210**, I_{bias} register **214**, T_{pkw} register **218**, I_{pkd} register **224**). Preferably, the registers (herein referred to also as DAC registers) are disposed inside the DACs **234**. The DACs **234** use the current DAC values in these registers (**210**, **214**, **218**, **224**) to set the VCSEL drive waveform parameters.

Similarly, when an aging time point is reached as determined by the aging counter (e.g., the low order aging counter and the high order aging counter), the new DAC settings for I_{mod}, I_{bias}, T_{pkw}, and I_{pkd} are retrieved from the EEPROM, and written to the DAC registers. The VCSEL drive waveform parameters are then adjusted.

Fault Detection Circuit 260

According to one embodiment, the fault detection circuit **260** includes a resistor (Rfault) **340**, a differential amplifier **344**, a comparator **348**, a DAC **350**, and a buffer **354**. The fault detection circuit **260** determines when the average amount of current flowing through each VCSEL is above a predetermined safety limit. The amount of average VCSEL current is determined by measuring the voltage difference (vfx_del) across the Rfault resistor **340**. The voltage difference across the Rfault resistor **340** is then compared to a predetermined fault threshold vfx_th. The fault threshold vfx_th is programmable by the user and may be stored in the EEPROM **130** and a fault register **290** in the controller **200** as fault_th.

If vfx_del is higher than vfx_th, the comparator **348** changes the state of the fault_flag. A change in state of the fault_flag signal for any channel interrupts the controller **200**. The controller **200** then sets the DAC values for I_{mod}, I_{bias}, T_{pkw}, and I_{pkd} for all N channels, to all zeroes, which in turn changes each channel's VCSEL current to zero milliamperes.

The state of the tx_enable line is toggled for the laser driver **100** to resume operation. Once operation is resumed, the controller **200** retrieves the correct DAC settings based upon temperature and the value in the aging counter. As described previously, the age value may be stored in multiple registers (e.g., age register **280**) in the controller **200**.

Data Waveform Shaping Circuit 238

FIG. **4** illustrates in greater detail the drive waveform shaping circuit (DWSC) **238** of FIG. **3** according to one embodiment of the present invention. For the sake of brevity, the drive waveform shaping circuit **238** for a single channel is illustrated in FIG. **4** and described hereinafter. It is noted that the drive waveform shaping circuit **238** can be replicated to match the specific number of channels in a particular application.

In this embodiment, the drive waveform shaping circuit **238** includes inputs for receiving differential data signals (DataIn+and DataIn−) and inputs for receiving the output voltage signals from the DAC **234**. Specifically, the drive waveform shaping circuit **238** further includes an input for receiving V_{bias} from the DAC **234**, an input for receiving V_{mod} from the DAC **234**, an input for receiving V_{pkw} from the DAC **234**, and an input for receiving V_{pkd} from the DAC **234**. As described previously, the output voltage signals of the DAC **234** are generated based on drive waveform dc and ac parameters associated with the current age and temperature conditions. Based on these inputs, the drive waveform shaping circuit **238** generates a drive waveform (e.g., the I_{out}) that is provided to an anode of a laser (e.g., an anode of the VCSEL **122**). An example of this drive waveform that has a negative peaking portion is shown in FIG. **7**.

The DWSC **238** includes a plurality of input buffers (**410**, **420**, **430**, and **440**) for buffering the output voltage signals received from the DAC **234** before providing the voltage signals to the other blocks of the DWSC **238**. It is noted that buffer **420** is an inverting buffer that receives V_{mod} and generates an inverted V_{mod} signal.

The DWSC **238** further includes a voltage controlled current source (VCCS) **450**, an output driver differential transconductance amplifier (ODDTA) **460** that is coupled to the voltage controlled current source **450**, and a negative peaking differential transconductance amplifier (NPDTA) **470** that is also coupled to the voltage controlled current source **450**. The VCCS **450**, ODDTA **460**, and NPDTA **470** selectively shape the drive waveform (I_{out}) based on the input data signals and input voltage signals.

The voltage controlled current source (VCCS) **450** includes an input for receiving the V_{bias2} signal, an input for receiving the inverted V_{mod2} signal, and an input coupled to a supply voltage **454**. Based on these inputs, the VCCS **450** generates I_{source}, which is a dc current sum of I_{bias} and I_{mod}. The logic 1 level of the drive waveform (I_{out}) is equal to I_{source}. A data pulse into the ODDTA **460** causes $I_{modpulse}$ to be subtracted from I_{source} to leave $I_{out}=I_{bias}$ for logic 0 data bits and $I_{out}=I_{bias}+I_{mod}$ for logic 1 data bits.

A power source **480** is coupled to the VCCS **450** through a switch **484** (e.g., a FET switch). The switch **484** selectively opens and closes in response to the fault shutdown signal. When the switch **484** is closed, the supply voltage signal **454** is provided to the VCCS **450**.

The ODDTA **460** includes inputs for receiving the differential data signals (DataIn+and DataIn−) and an input for receiving the inverted V_{mod2} signal. Based on these inputs, the ODDTA **460** produces a current pulse **464** (i.e., $I_{modpulse}$) for every input data pulse. The amplitude of $I_{modpulse}$ is set by a reference voltage provided to the V_{ref} input. Since the reference voltage in this case is equal to the inverted V_{mod2} signal, the amplitude of the current pulses is equal to the amplitude of the I_{mod} signal.

The NPDTA **470** includes inputs for receiving the differential data signals (DataIn+and DataIn−), an input for receiving the V_{pkw2} signal, and an input for receiving the V_{pkd2} signal. Based on these inputs, the NPDTA **470** generates a negative peaking current transient **474** ($I_{negpeaking}$ or I_{np}) for every logic 1 to logic 0 transition observed on the DataIn pulses It is noted that the negative peaking current $I_{negpeaking}$ is aligned with the falling edge of the I_{out} pulse. The negative peaking current transients ($I_{negpeaking}$) are also denoted herein as I_{np}. The negative peaking transient ($I_{negpeaking}$) has current amplitude (depth) and decay time (width) equal to I_{pkd} and T_{pkw}, respectively. The NPDTA **470** employs the V_{pkw2} signal to set the decay time for the negative peaking transient, and the V_{pkd2} signal to set the current amplitude for the negative peaking transient.

In summary, the current sunk by ODDTA **460** is denoted as $I_{modpulse}$, and the current sunk by NPDTA **470** is denoted as $I_{negpeaking}$ or I_{np}. The following expression provides the value of the output current:

$$I_{out}=I_{source}-I_{modpulse}-I_{np}.$$

A data pulse causes $I_{modpulse}$ to subtract I_{mod} from I_{source} to leave $I_{out}=I_{bias}$ for logic 0 data bits, and leave $I_{out}=I_{bias}+I_{mod}$ for logic 1 data bits. A 1 to 0 transition causes an I_{np} transient to be subtracted from I_{source} in phase with the 1 to 0 transition.

Methodology

FIG. **5** is a flowchart illustrating the steps performed by the laser driver **100** of FIG. **1** to set and control the VCSEL drive parameters according to one embodiment of the present invention. Each VCSEL **122** in the VCSEL array **120** is characterized and the resulting data is saved. The lasers are then assembled into the MCFOTM **90**. Each transmit channel in the assembled unit is characterized over temperature, and the resulting data is also saved. Then, the saved data is downloaded into the non-volatile memory **130**. Each VCSEL is then independently programmed using the stored parameters. The programming is performed initially upon "power-up" (e.g., when the module is initially installed into a network device, such as a router or switch) and also periodically during operation as described hereinafter.

In step **500**, the voltage versus current (V-I) and VCSEL light output versus current (L-I) are measured for each laser (e.g., VCSEL) **122** in the array **120**. Preferably, these measurements are performed prior to assembly. Test equipment, such as Agilent 4145 Semiconductor Parameter Analyzer and Agilent 8153A Lightwave Multimeter, that are available from Agilent Technologies, Inc. can be employed to make the measurements.

TABLE I sets forth exemplary VCSEL V-I data and L-I data. This data is used by a production test system to determine the DAC settings to use during I_{bias}, I_{mod}, I_{pkd}, and T_{pkw} optimization. The V-I data shows the maximum current range for a given VCSEL so as not to exceed a maximum VCSEL voltage allowed for correct circuit operation. Once the VCSEL current maximum is known, the L-I data is used to calculate the minimum VCSEL current for light output and the VCSEL slope efficiency (i.e., the change in light output with respect to a change in current). The allowable VCSEL current range and VCSEL slope efficiency, determined previously, are then used to calculate starting points for I_{bias}, I_{mod}, I_{pkd}, and T_{pkw} during optimization.

TABLE I

VCSEL Voltage (V)	VCSEL Current (mA)	VCSEL Light Output (mW)
1.49	1.0	0.012
1.67	5.0	1.59
1.80	10.0	4.32
1.92	15.0	6.84

In step **504**, the AC optical waveform for each transmitter channel is measured. Preferably, during production test, the AC optical waveform of each channel is measured and optimized for performance factors by a tester. These performance factors can include, but is not limited to, extinction ratio (i.e., the ratio of logic 1 optical power to logic 0 optical power), rise/fall times, overshoot, jitter, and mask margin. Optimization of the AC optical waveform utilizes the previously recorded VCSEL optical parameters.

AC optical waveform properties are measured for each VCSEL in the transmitter. The I_{bias}, I_{mod}, I_{pkd}, and T_{pkw} DAC settings are varied around the starting points until the AC optical waveform properties are optimized. Preferably, the optimization is performed at a few temperatures. The AC optical waveform properties can include, but is not limited to, extinction ratio (ER), which is the optical power ratio of a logic 1 bit to a logic 0 bit, rise time, fall time, overshoot, and jitter.

The optimum DAC settings for I_{bias}, I_{mod}, I_{pkd}, and T_{pkw} are, then calculated for each allowed temperature and aging time point and written to the nonvolatile memory **130**. The nonvolatile memory (e.g., an EEPROM) **130** stores all of the DAC settings for I_{bias}, I_{mod}, I_{pkd}, and T_{pkw}, referenced by temperature and aging time point. These addressable DAC settings are then used to program each VCSEL's current drive waveform during operation. For example, the I_{bias} DAC register stores a number from 0 to 2^M (for an M bit DAC), which is used to generate a voltage V_{bias} on the DAC output. V_{bias} is used by the drive waveform shaping circuit **238** to set the I_{bias} parameter of the VCSEL drive current waveform. Similarly, V_{mod}, V_{pkw}, and V_{pkd} are generated by the other DACs.

In step **508**, DAC settings for each channel are optimized at each temperature and aging point. The DACs **234** are used to convert the drive parameters into an analog signals that are utilized by the drive waveform shaping circuit (DWSC) **238** to generate the drive waveforms.

In one embodiment, the DACs **234** are integrated into the laser driver **100** and are M bits wide. The number of bits M is chosen to provide adequate resolution for each of the parameters. For example, M may be chosen to be 6 bits for typical implementations.

In step **512**, an aging counter divisor (D) is selected. In step **520**, the DAC settings (i.e., drive parameters) are downloaded into the non-volatile memory from a test system, for example. The DAC settings are stored in such a manner as to allow the retrieval of the DAC settings by aging count, temperature, channel number, and DAC number (i.e., the DAC settings in the non-volatile memory are addressable by aging count, temperature, channel number, and DAC number).

In step **530**, the aging counter is started. In step **540**, drive parameters are loaded into the drive registers (**210**, **214**, **218**, and **224**) from the non-volatile memory **130** upon a predetermined condition. The predetermined condition can be, but is not limited to, the passage of time (e.g., every 30 milliseconds) or an interrupt for an aging time point. It is noted that step **540** occurs during the operation of the transmitter module **90**.

In step **550**, the temperature of the laser driver integrated circuit is measured by the temperature measurement block

(TMB) **334**. In step **554**, the measured temperature is converted into a digital form (e.g., a digital_temp signal) and provided to the controller **200**. In step **560**, the controller **200** employs the measured temperature as one of the input parameters in a subsequent DAC register write cycle for updating the drive parameter registers (**210**, **214**, **218**, and **224**).

In step **570**, the controller **200** updates a read address for retrieving values for the drive parameters. Processing then proceeds to step **540** where the drive parameter registers are written with values read from the non-volatile memory **130** at the address that may be modified in step **570**.

Handling Unsafe Current Conditions

FIG. **6** is a flowchart illustrating the steps performed by the laser driver **100** of FIG. **1** to detect and manage unsafe current conditions according to one embodiment of the present invention. After step **520** of FIG. **5**, the steps, described below for detecting and managing unsafe current conditions are performed. In step **610**, the current flowing through each VCSEL is measured. In decision block **620**, a determination is made whether the measured current is greater than a predetermined safe current. When the measured current is greater than a predetermined safe current, the output current of the laser driver **100** is maintained at a constant minimum current equal to a minimum I_{bias} plus a minimum I_{mod}. Otherwise, when the measured current is not greater than a predetermined safe current, processing loops back to step **610**.

In decision block **640**, a determination is made whether a valid restart signal (e.g., a tx_enable signal) has been received by the laser driver **100**. When a valid restart signal (e.g., a tx_enable signal) has been received by the laser driver **100**, the processing proceeds to step **650**. In step **650**, the TMB **334** and the age register **280** are employed to generate an address based on a temperature value and age value. As noted previously, the nonvolatile memory **130** is addressable by aging count, temperature, channel number, and DAC number. Processing then proceeds to step **540** of FIG. **5**, where the drive parameter registers are loaded with the values read from the non-volatile memory **130**.

Otherwise, when a valid restart signal (e.g., a Tx_enable signal) has not been received by the laser driver **100**, the processing proceeds to step **630** where the laser driver **100** remains in the minimum output current state.

The digital control method and apparatus for driving semiconductor lasers of the present invention has been described in connection with a VCSEL array. However, it is noted that the digital control method and apparatus for driving semiconductor lasers is useful for other applications whenever drive current is needed for driving any type of semi-conductor laser. The digital control method and apparatus for semiconductor lasers of the present invention are especially useful for applications that have temperature fluctuations across array elements, and yet require an even performance across elements in the array. The digital control method and apparatus for semiconductor lasers of the present invention are also useful for applications whose light output tends to degrade over its operating life. The digital control method and apparatus for semiconductor lasers of the present invention are especially useful for applications that can benefit from programming of AC parameters.

In the foregoing specification, the invention has been described with reference to specific embodiments thereof. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader scope of the invention. The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense.

What is claimed is:

1. An optical transmitter comprising:

an array having at least one semiconductor laser;

a memory for storing a plurality of drive waveform parameters;

a driver circuit, coupled to the memory and the array, for receiving data signals and at least one drive waveform parameter, and responsive thereto, for generating at least one drive waveform to drive the semiconductor laser; wherein the drive waveform includes a negative peak portion;

wherein the drive waveform parameters includes at least one parameter for affecting the negative peak portion of the drive waveform.

2. The optical transmitter of claim **1** wherein the array includes a plurality of semiconductor lasers, each of the plurality of semiconductors lasers associated with its own set of drive waveform parameters;

wherein the driver circuit generates an individual drive waveform for each semiconductor laser based on the set of drive waveform parameters associated with that semiconductor laser increasing the uniformity in the resulting optical waveforms of the semiconductor lasers; and

wherein the driver circuit updates at least one drive waveform parameter during the operation of the transmitter based on one of an aging factor of the array and a temperature factor of the array and generates an updated drive waveform based on the updated drive waveform parameter.

3. The optical transmitter of claim **1** wherein the memory stores the dc properties and the ac properties for each semiconductor laser in the array for different age factors and temperature factors; and wherein the driver circuit generates a drive waveform for each semiconductor laser based on the dc properties and ac properties for that semiconductor laser.

4. The optical transmitter of claim **1** wherein the driver circuit includes an integrated digital controller and a temperature sensor for sensing the temperature of the driver circuit; and wherein the integrated digital controller selectively updates the drive waveform parameters based on the temperature of the driver circuit.

5. The optical transmitter of claim **1** wherein the driver circuit includes and integrated digital controller having a timer function for periodically adjusting at least one drive waveform parameter to compensate for aging of the semiconductor laser.

6. The optical transmitter of claim **1** wherein the array includes a 1xN array semiconductor lasers.

7. The optical transmitter of claim **6** wherein the semiconductor laser is a vertical cavity emitting laser (VCSEL).

8. A laser driver for generating drive waveforms that drives an array having at least one semiconductor laser comprising:

a storage for storing a plurality of drive waveform parameters;

a digital controller coupled to the storage for initially accessing a first set of drive waveform parameters that correspond to a first semiconductor laser and subsequently accessing the storage for other sets of drive waveform parameters corresponding to the first semiconductor laser based on one of an age factor and a temperature factor; and

a waveform shaping circuit coupled to the digital controller for receiving the set of drive waveform parameters and responsive thereto for generating a drive waveform that is dependent on the set of drive waveform parameters; wherein the waveform includes a negative peaking portion; and wherein the drive waveform parameters includes at least one parameter for affecting the negative peaking portion of the drive waveform.

9. The laser driver of claim **8** further comprising:

an aging compensation mechanism for monitoring the age of the laser and for providing an age factor for use in selecting a set of drive waveform parameters from the storage to be utilized in generating a drive waveform that compensates for the aging of the laser.

10. The laser driver of claim **8** further comprising:

a temperature compensation mechanism for monitoring the temperature of the driver and for providing a temperature factor for use in selecting a set of drive waveform parameters from the storage to be utilized in generating a drive waveform that compensates for the changes in temperature of the laser.

11. The laser driver of claim **8** wherein the drive waveform parameters includes

at least one dc parameter and at least one ac parameter.

12. The laser driver of claim **8** wherein the drive waveform parameters associated with the drive waveform include one of

bias current, modulation current, negative peaking depth, and negative peaking duration.

13. The laser driver of claim **8** further comprising:

a digital to analog converter for receiving the drive waveform parameters in digital form and responsive thereto for generating corresponding drive waveform parameters in analog form; and

wherein the drive waveform parameters in analog form are provided to the waveform shaping circuit.

14. The laser driver of claim **8** wherein the laser driver is suitable for driving a single vertical cavity surface emitting laser (VCSEL) or an array of vertical cavity surface emitting lasers (VCSELs).

15. A method for providing a drive waveform that includes ac characteristics for at least one semiconductor laser in a laser driver, the laser driver including an integrated digital controller and a storage for storing a plurality of drive waveform parameters, the method comprising the steps of:

employing the digital controller to access from the storage a first set of drive waveform parameters for a first laser; and

generating a drive waveform for driving the first laser based on the first set of waveform parameters;

employing the digital controller to access from the storage a second set of drive waveform parameters during the operation of the laser driver based on one of a temperature factor and an aging factor; and

generating an updated drive waveform for driving the first laser based on the second set of drive waveform parameters;

wherein the waveform includes a negative peaking portion; and

wherein the drive waveform parameters includes at least one parameter for affecting the negative peaking portion of the drive waveform.

16. The method of claim **15** wherein the drive waveform parameters in the storage are organized by laser, temperature factor, and age factor; and wherein adjusting the parameter during the operation of the laser driver includes retrieving at least one updated drive waveform parameter from the storage based on the operating temperature of the semiconductor laser.

17. The method of claim **15** wherein the drive waveform parameters in the storage are organized by laser, temperature factor, and age factor; and wherein adjusting the parameter during the operation of the laser driver includes periodically retrieving at least one updated drive waveform parameter from the storage based on the age of the semiconductor laser.

18. The method of claim **15** wherein employing the digital controller to access from the storage a first set drive waveform parameters for a first laser includes one of:

prior to operation of the first laser,

digital programming of a bias current parameter;

digital programming of a modulation current parameter;

digital programming of a negative peaking depth parameter during an optical one to optical zero transition; and

digital programming of a negative peaking duration parameter during an optical one to optical zero transition.

19. The method of claim **15** wherein employing the digital controller to access from the storage a second set of drive waveform parameters during the operation of the laser driver based on one of a temperature factor and an aging factor includes one of:

digital programming of an updated bias current parameter;

digital programming of an updated modulation current parameter;

digital programming of an updated negative peaking depth parameter during an optical one to optical zero transition; and

digital programming of an updated negative peaking duration parameter during an optical one to optical zero transition.

20. The optical transmitter of claim **1** wherein the drive waveform parameters include a bias current parameter, a modulation current paramerer, a negative peaking depth paramerer, and a negative peaking duration parameter for each semiconductor laser in the array.

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(12) EX PARTE REEXAMINATION CERTIFICATE (8966th)

United States Patent

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(45) **Certificate Issued:** **Apr. 17, 2012**

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(54) **OPEN-LOOP LASER DRIVER HAVING AN INTEGRATED DIGITAL CONTROLLER**

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(52) **U.S. Cl.** **372/38.02**; 372/8

(58) **Field of Classification Search** 372/38
See application file for complete search history.

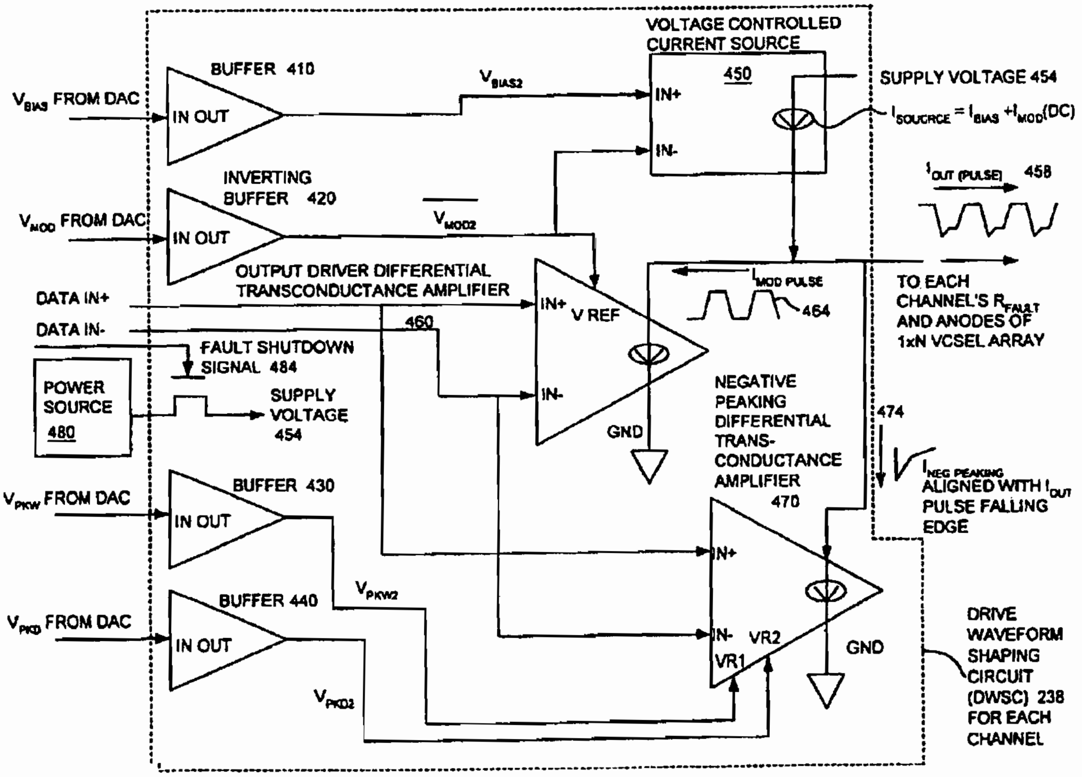
(56) **References Cited**

To view the complete listing of prior art documents cited during the proceeding for Reexamination Control Number 90/011,519, please refer to the USPTO's public Patent Application Information Retrieval (PAIR) system under the Display References tab.

Primary Examiner—John S. Heyman

(57) **ABSTRACT**

A laser driver for generating drive waveforms that are suitable for driving a single VCSEL or an array of VCSELs. A digital controller is integrated into the laser driver and is utilized to initially program and selectively adjust during the operation of the driver one or more of the following VCSEL drive waveform parameters: (1) bias current, (2) modulation current, (3) negative peaking depth, and (4) negative peaking duration. The laser driver has an aging compensation mechanism for monitoring the age of the laser and for selectively adjusting the dc and ac parameters of the VCSEL drive waveform to compensate for the aging of the laser. The laser driver also has a temperature compensation mechanism for monitoring the temperature of the driver IC and selectively adjusting the dc and ac parameters of the VCSEL drive waveform to compensate for the changes in temperature.



EX PARTE REEXAMINATION CERTIFICATE ISSUED UNDER 35 U.S.C. 307

THE PATENT IS HEREBY AMENDED AS INDICATED BELOW.

Matter enclosed in heavy brackets [ ] appeared in the patent, but has been deleted and is no longer a part of the patent; matter printed in italics indicates additions made to the patent.

AS A RESULT OF REEXAMINATION, IT HAS BEEN DETERMINED THAT:

Claims **1**, **5**, **6**, **8**, **11**, **15**, **18** and **20** are determined to be patentable as amended.

Claims **2**-**4**, **7**, **9**-**10**, **12**-**14**, **16**-**17** and **19**, dependent on an amended claim, are determined to be patentable.

New claims **21**, **22**, **23** and **24** are added and determined to be patentable.

1. An optical transmitter comprising:

an array having at least one semiconductor laser;

a memory for storing a plurality of drive waveform parameters;

a driver circuit, coupled to the memory and the array, for receiving data signals and at least one drive waveform parameter, and responsive thereto, for generating at least one drive waveform to drive the semiconductor laser;

wherein the drive waveform includes a negative peak portion;

wherein the drive waveform parameters [includes] *include* at least one parameter for affecting the negative peak portion of the drive waveform.

5. The optical transmitter of claim **1** wherein the driver circuit includes [and] *an* integrated digital controller having a timer function for periodically adjusting at least one drive waveform parameter to compensate for aging of the semiconductor laser.

6. The optical transmitter of claim **1** wherein the array includes a 1×N array *of* semiconductor lasers.

8. A laser driver for generating drive waveforms that drives an array having at least one semiconductor laser comprising:

a storage for storing a plurality of drive waveform parameters;

a digital controller coupled to the storage for initially accessing a first set of drive waveform parameters that correspond to a first semiconductor laser and subsequently accessing the storage for other sets of drive waveform parameters corresponding to the first semiconductor laser based on one of an age factor and a temperature factor; and

a waveform shaping circuit coupled to the digital controller for receiving the set of drive waveform parameters and responsive thereto for generating a drive waveform that is dependent on the set drive waveform parameters;

wherein the waveform includes a negative peaking portion; and

wherein the drive waveform parameters [includes] *include* at least one parameter for affecting the negative peaking portion of the drive waveform.

11. The laser driver of claim **8** wherein the drive waveform parameters [includes] *include* at least one dc parameter and at least one ac parameter.

15. A method for providing drive waveform that includes ac characteristics for at least one semiconductor laser in a laser driver, the driver including an integrated digital controller and a storage for storing a plurality of drive waveform parameters, the method comprising the steps of:

employing the digital controller to access from the storage a first set of drive waveform parameters for a first laser; [and]

generating a drive waveform for driving the first laser based on the first set of waveform parameters;

employing the digital controller to access from the storage a second set of drive waveform parameters during the operation of the laser driver based on one of a temperature factor and an aging factor; and

generating an updated drive waveform for driving the first laser based on the second set of drive waveform parameters;

wherein the waveform includes a negative peaking portion; and

wherein the drive waveform parameters [includes] *include* at least one parameter for affecting the negative peaking portion of the drive waveform.

18. The method of claim **16** wherein employing the digital controller to access from the storage a first set *of* drive waveform parameters for the first laser includes one of:

prior to operation of the first laser, digital programming of a bias current parameter;

digital programming of a modulation current parameter;

digital programming of a negative peaking depth parameter during an optical one to optical zero transition; and

digital programming of a negative peaking duration parameter during an optical one to optical zero transition.

20. The optical transmitter of claim **1** wherein the drive waveform parameters include a bias current parameter, a modulation current [paramerer] *parameter*, a negative peaking depth [paramerer] *parameter*, and a negative peaking duration parameter for each semiconductor laser in the array.

21. An optical transmitter comprising:

an array having at least one semiconductor laser;

a memory for storing a plurality of drive waveform parameters;

a driver circuit, coupled to the memory and the array, for receiving a data signal and at least one drive waveform parameter, and responsive thereto, for generating at least one drive waveform to drive the semiconductor laser;

wherein the drive waveform includes a negative peak portion generated by applying a negative peaking current transient to the data signal during a falling edge of a transition from logic one to logic zero in the data signal, such that the negative peak portion has a duration that is shorter than the duration of its associated data bit;

wherein the drive waveform parameters include at least one parameter for affecting the negative peak portion of the drive waveform.

22. The optical transmitter of claim 21 wherein the driver circuit generates the negative peaking current transient.

23. The optical transmitter of claim 22 wherein the driver circuit generates the negative peaking current transient *based on the at least one parameter affecting the negative peaking portion of the drive waveform.*

24. The optical transmitter of claim 23 wherein the at least one parameter affecting the negative peaking portion of the drive waveform includes a negative peaking duration parameter and a negative peaking depth parameter.

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(58) **Field of Classification Search** 372/38
See application file for complete search history.

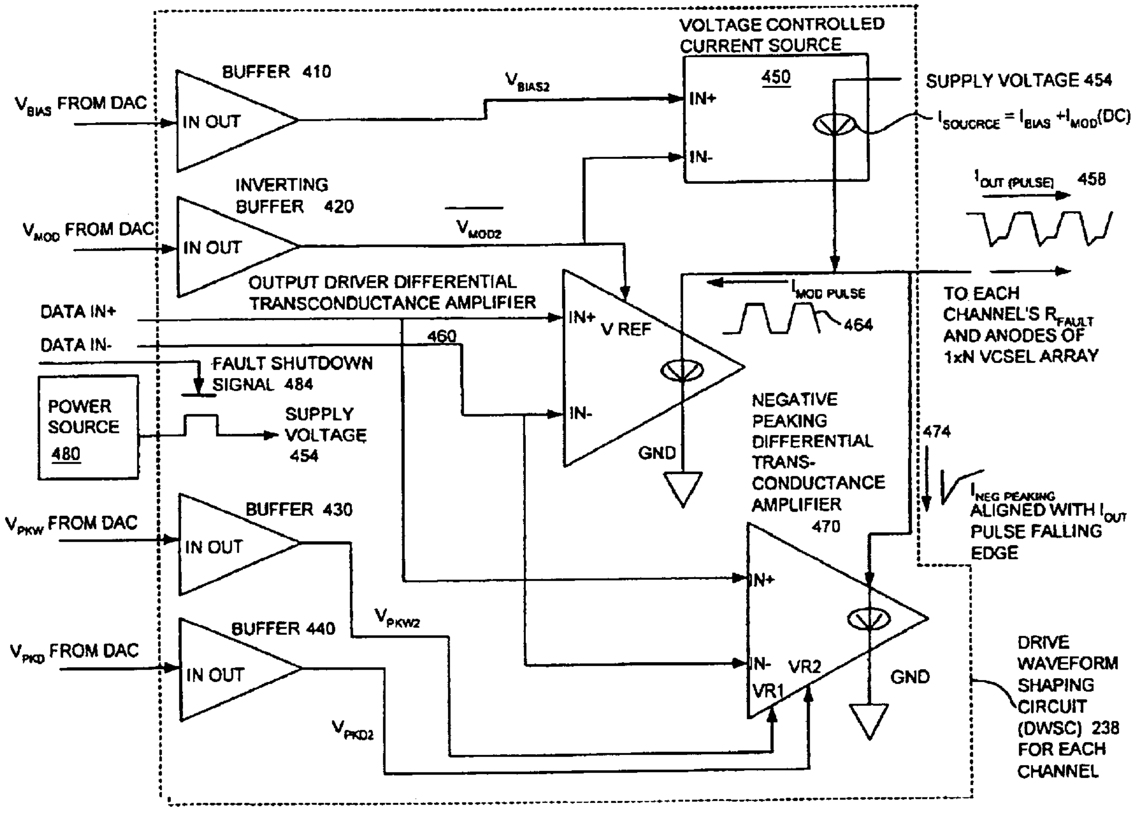
(56) **References Cited**

To view the complete listing of prior art documents cited during the proceeding for Reexamination Control Number 90/011,519, please refer to the USPTO's public Patent Application Information Retrieval (PAIR) system under the Display References tab.

Primary Examiner—John S. Heyman

(57) **ABSTRACT**

A laser driver for generating drive waveforms that are suitable for driving a single VCSEL or an array of VCSELs. A digital controller is integrated into the laser driver and is utilized to initially program and selectively adjust during the operation of the driver one or more of the following VCSEL drive waveform parameters: (1) bias current, (2) modulation current, (3) negative peaking depth, and (4) negative peaking duration. The laser driver has an aging compensation mechanism for monitoring the age of the laser and for selectively adjusting the dc and ac parameters of the VCSEL drive waveform to compensate for the aging of the laser. The laser driver also has a temperature compensation mechanism for monitoring the temperature of the driver IC and selectively adjusting the dc and ac parameters of the VCSEL drive waveform to compensate for the changes in temperature.



EX PARTE REEXAMINATION CERTIFICATE ISSUED UNDER 35 U.S.C. 307

THE PATENT IS HEREBY AMENDED AS INDICATED BELOW.

Matter enclosed in heavy brackets [ ] appeared in the patent, but has been deleted and is no longer a part of the patent; matter printed in italics indicates additions made to the patent.

AS A RESULT OF REEXAMINATION, IT HAS BEEN DETERMINED THAT:

Claims **1**, **5**, **6**, **8**, **11**, **15**, **18** and **20** are determined to be patentable as amended.

Claims **2-4**, **7**, **9-10**, **12-14**, **16-17** and **19**, dependent on an amended claim, are determined to be patentable.

New claims **21**, **22**, **23** and **24** are added and determined to be patentable.

1. An optical transmitter comprising:

an array having at least one semiconductor laser;

a memory for storing a plurality of drive waveform parameters;

a driver circuit, coupled to the memory and the array, for receiving data signals and at least one drive waveform parameter, and responsive thereto, for generating at least one drive waveform to drive the semiconductor laser;

wherein the drive waveform includes a negative peak portion;

wherein the drive waveform parameters [includes] *include* at least one parameter for affecting the negative peak portion of the drive waveform.

5. The optical transmitter of claim **1** wherein the driver circuit includes [and] *an* integrated digital controller having a timer function for periodically adjusting at least one drive waveform parameter to compensate for aging of the semiconductor laser.

6. The optical transmitter of claim **1** wherein the array includes a 1×N array *of* semiconductor lasers.

8. A laser driver for generating drive waveforms that drives an array having at least one semiconductor laser comprising:

a storage for storing a plurality of drive waveform parameters;

a digital controller coupled to the storage for initially accessing a first set of drive waveform parameters that correspond to a first semiconductor laser and subsequently accessing the storage for other sets of drive waveform parameters corresponding to the first semiconductor laser based on one of an age factor and a temperature factor; and

a waveform shaping circuit coupled to the digital controller for receiving the set of drive waveform parameters and responsive thereto for generating a drive waveform that is dependent on the set drive waveform parameters;

wherein the waveform includes a negative peaking portion; and

wherein the drive waveform parameters [includes] *include* at least one parameter for affecting the negative peaking portion of the drive waveform.

11. The laser driver of claim **8** wherein the drive waveform parameters [includes] *include* at least one dc parameter and at least one ac parameter.

15. A method for providing drive waveform that includes ac characteristics for at least one semiconductor laser in a laser driver, the driver including an integrated digital controller and a storage for storing a plurality of drive waveform parameters, the method comprising the steps of:

employing the digital controller to access from the storage a first set of drive waveform parameters for a first laser; [and]

generating a drive waveform for driving the first laser based on the first set of waveform parameters;

employing the digital controller to access from the storage a second set of drive waveform parameters during the operation of the laser driver based on one of a temperature factor and an aging factor; and

generating an updated drive waveform for driving the first laser based on the second set of drive waveform parameters;

wherein the waveform includes a negative peaking portion; and

wherein the drive waveform parameters [includes] *include* at least one parameter for affecting the negative peaking portion of the drive waveform.

18. The method of claim **16** wherein employing the digital controller to access from the storage a first set *of* drive waveform parameters for the first laser includes one of:

prior to operation of the first laser, digital programming of a bias current parameter;

digital programming of a modulation current parameter;

digital programming of a negative peaking depth parameter during an optical one to optical zero transition; and

digital programming of a negative peaking duration parameter during an optical one to optical zero transition.

20. The optical transmitter of claim **1** wherein the drive waveform parameters include a bias current parameter, a modulation current [paramerer] *parameter*, a negative peaking depth [paramerer] *parameter*, and a negative peaking duration parameter for each semiconductor laser in the array.

21. An optical transmitter comprising:

an array having at least one semiconductor laser;

a memory for storing a plurality of drive waveform parameters;

a driver circuit, coupled to the memory and the array, for receiving a data signal and at least one drive waveform parameter, and responsive thereto, for generating at least one drive waveform to drive the semiconductor laser;

wherein the drive waveform includes a negative peak portion generated by applying a negative peaking current transient to the data signal during a falling edge of a transition from logic one to logic zero in the data signal, such that the negative peak portion has a duration that is shorter than the duration of its associated data bit;

wherein the drive waveform parameters include at least one parameter for affecting the negative peak portion of the drive waveform.

22. The optical transmitter of claim 21 wherein the driver circuit generates the negative peaking current transient.

23. The optical transmitter of claim 22 wherein the driver circuit generates the negative peaking current transient *based on the at least one parameter affecting the negative peaking portion of the drive waveform.*

24. The optical transmitter of claim 23 wherein the at least one parameter affecting the negative peaking portion of the drive waveform includes a negative peaking duration parameter and a negative peaking depth parameter.

* * * * *

Data sheet entitled ‘S7011 1.0/1.25 Gbps VCSEL Driver’, Revision 3, Jun. 7, 1999, by Applied Micro Circuits Corporation (AMCC) of San Diego, California.

The certified file history of U.S. Patent No. 6,947,456 does not contain this cited reference, and Complainants have been unable to locate it after a diligent search.

US 20020064193A1

(19) **United States**

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Diaz et al. (43) **Pub. Date: May 30, 2002**

(54) HIGH-SPEED LASER ARRAY DRIVER

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(21) Appl. No.: **09/990,771**

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Related U.S. Application Data

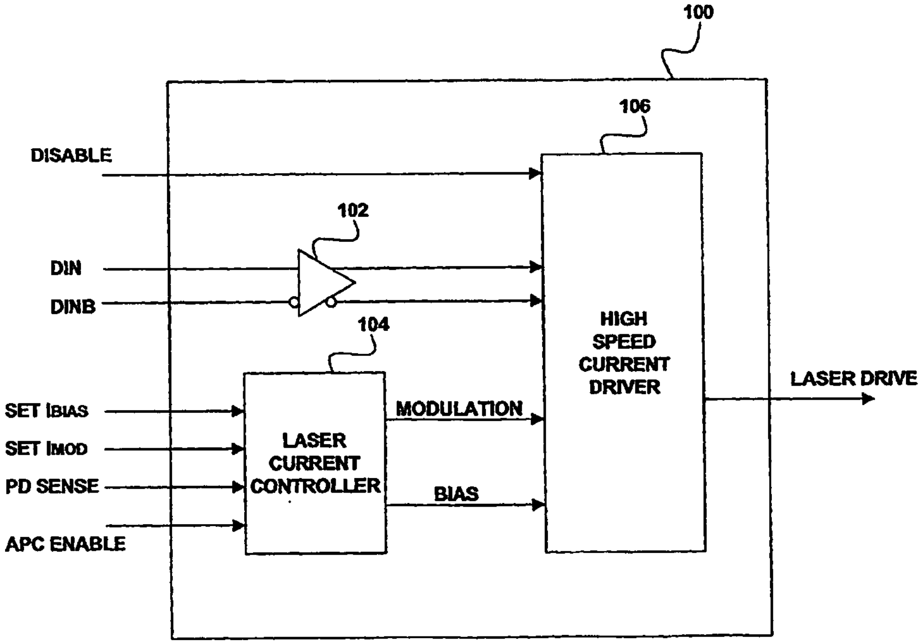
(63) Non-provisional of provisional application No. 60/252,838, filed on Nov. 22, 2000.

Publication Classification

(51) **Int. Cl.^{7}** **H01S 3/10**
(52) **U.S. Cl.** **372/26**

(57) ABSTRACT

A method and apparatus for driving lasers. An example laser driving system includes a laser current controller for providing a modulation signal and a bias signal. The modulation signal and bias signal is used by a plurality of high-speed current drivers that accept the modulation signal and the bias signal and produce a plurality of laser drive signals. The example system also has a disable input that disconnects power from a high-speed current driver when the high-speed current driver is not in use. The exemplary system develops the modulation and bias signals by feeding back a signal developed from detection of laser light from one of the lasers driven by the system. The laser may be a data laser or a control laser that is modulated by a signal having a lower frequency than the data lasers. If a control laser is used then the photodetector circuit used for feedback can have a lower frequency response because of the lower frequency of the control laser signal. The photodetector system may also employ a peak detector capacitor discharge circuit where a large capacitance is simulated by having the capacitor discharge through the base of a transistor have a current source in the emitter circuit.



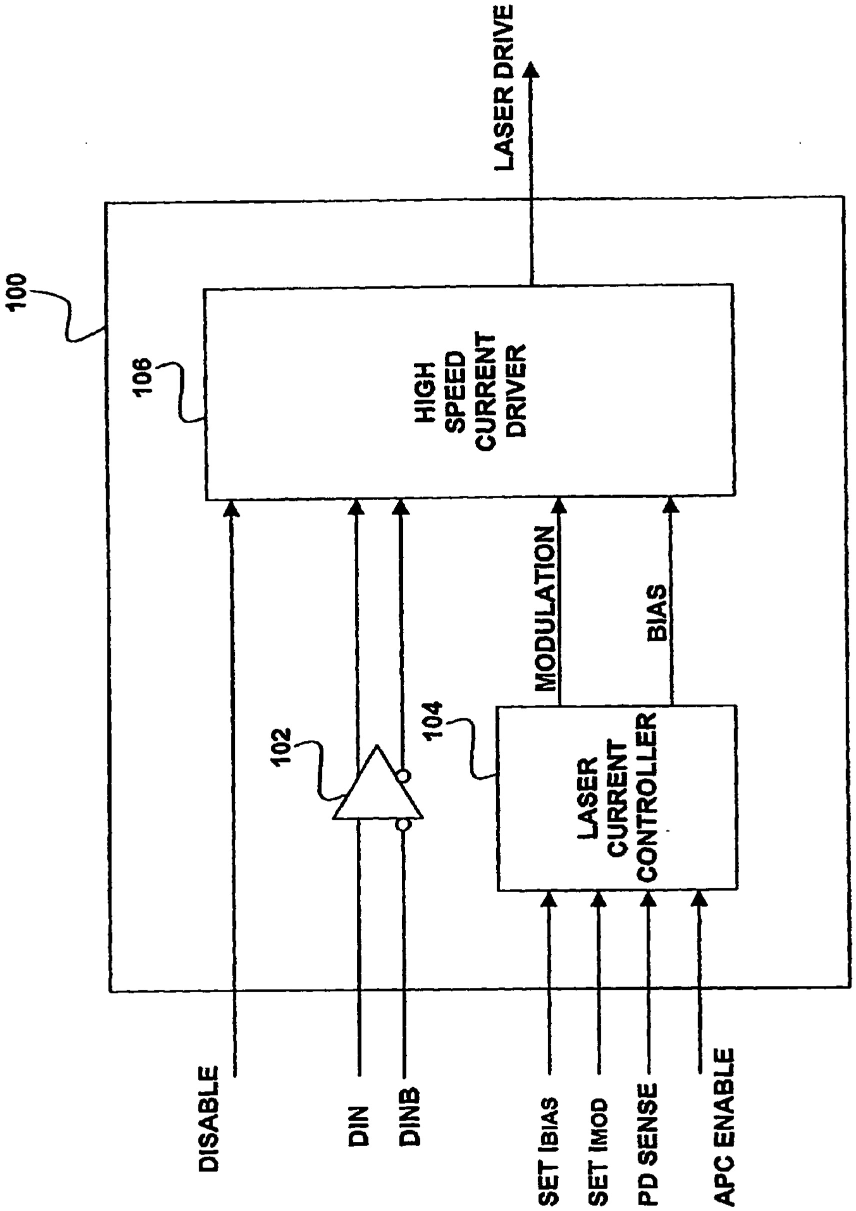

100
106
HIGH SPEED CURRENT DRIVER
LASER DRIVE
DISABLE
DIN
DINB
102
104
LASER CURRENT CONTROLLER
MODULATION
BIAS
SET IBIAS
SET IMOD
PD SENSE
APC ENABLE

FIG. 1

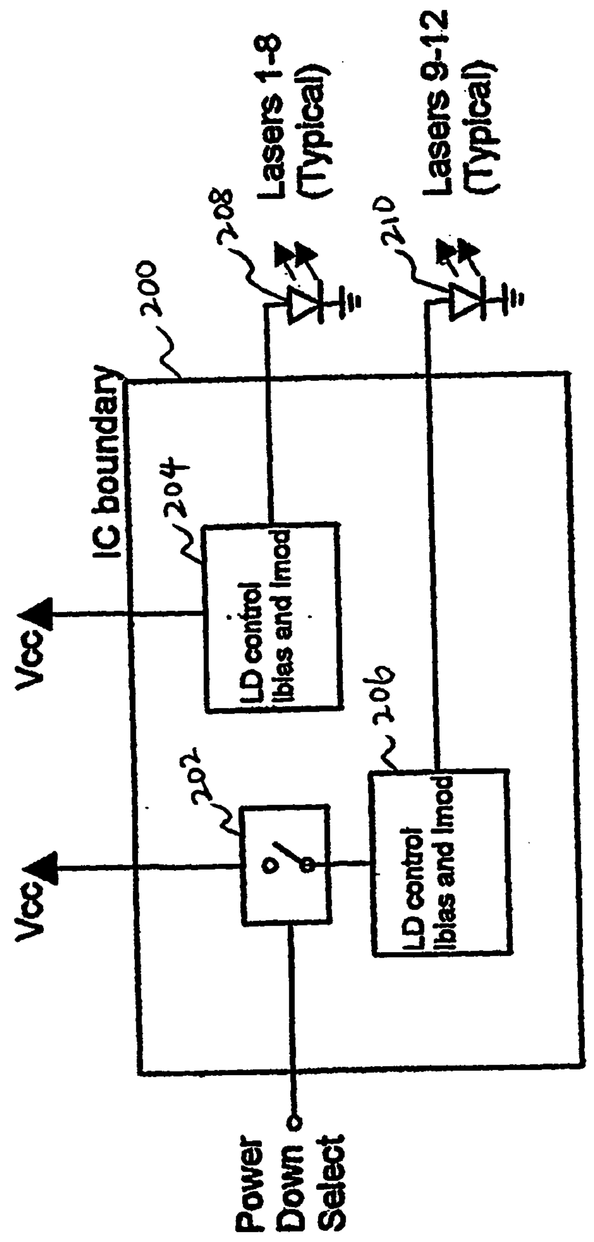

Vcc
Vcc
IC boundary
200
202
204
206
208
210
LD control Ibias and Imod
LD control Ibias and Imod
Lasers 1-8 (Typical)
Lasers 9-12 (Typical)
Power Down Select

FIG. 2

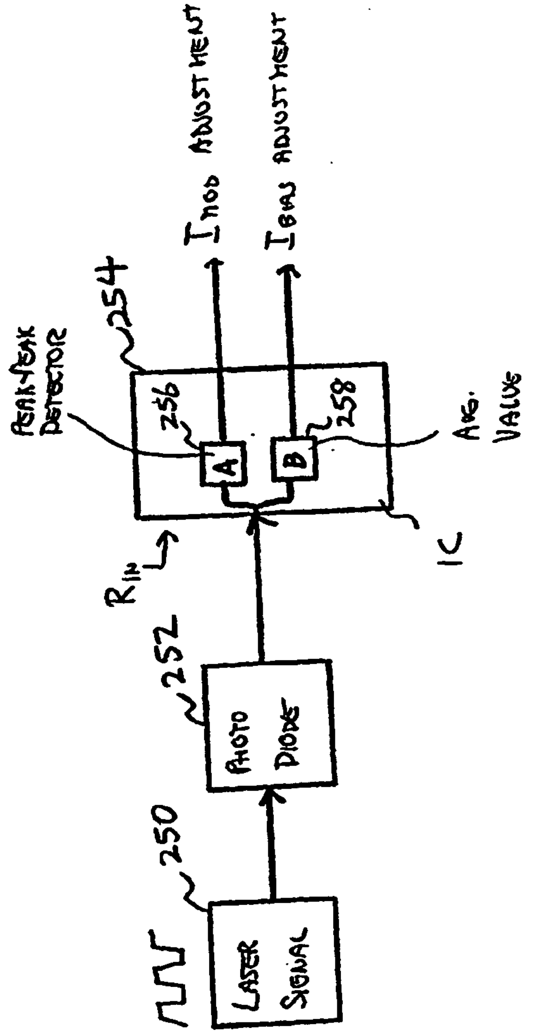

Laser Signal
250
Photo Diode
252
R_{IN}
254
Peak-Peak Detector
256
A
B
258
Avg. Value
IC
I_{MOD} Adjustment
I_{BIAS} Adjustment

FIG. 3

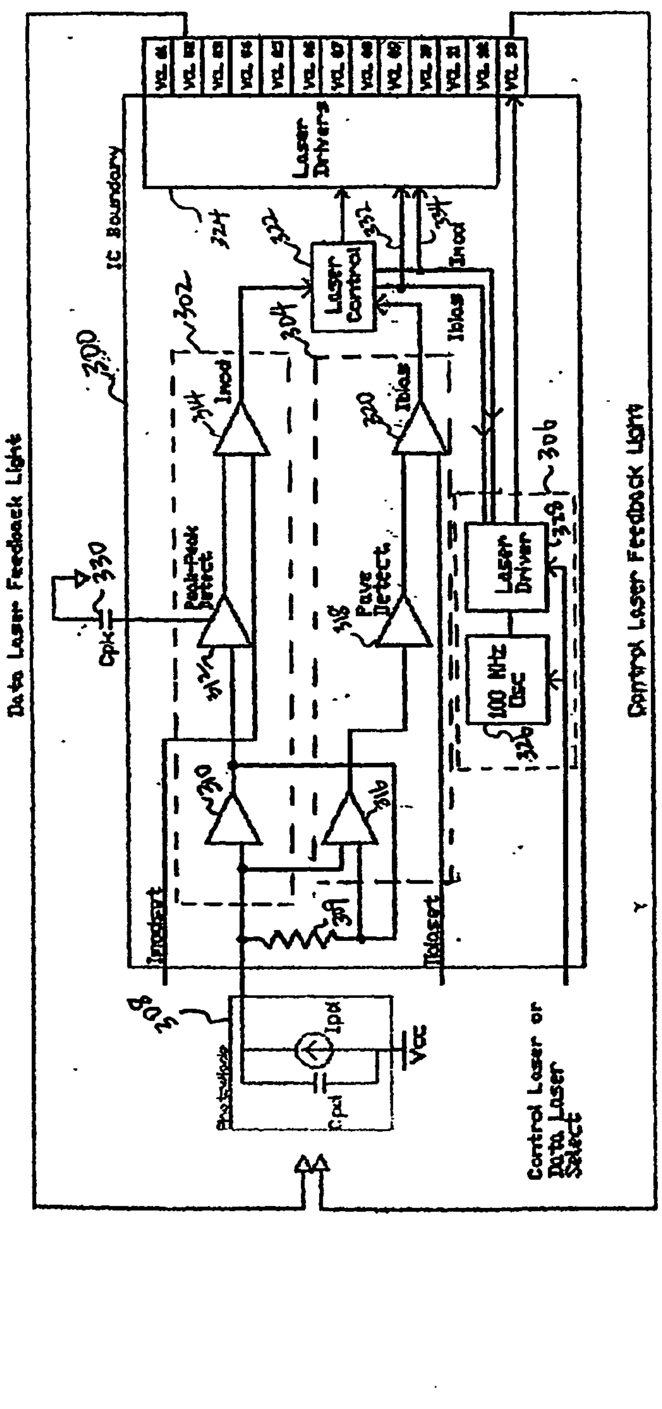

Data Laser Feedback Light
VCL 01
VCL 02
VCL 03
VCL 04
VCL 05
VCL 06
VCL 07
VCL 08
VCL 09
VCL 10
VCL 11
VCL 12
Laser Drivers
IC Boundary
324
322
332
334
Laser Control
Imod
Ibias
302
304
300
314
320
Peak-Peak Detect
Pave Detect
312
318
Cpk
330
306
328
Laser Driver
100 MHz Osc
326
310
316
309
Imodset
Ibiasset
308
Photodiode
Ipd
Cpd
Vcc
Control Laser or Data Laser Select
Control Laser Feedback Light

FIG. 4

Option 1: Extra Laser, use of control laser for Feedback.

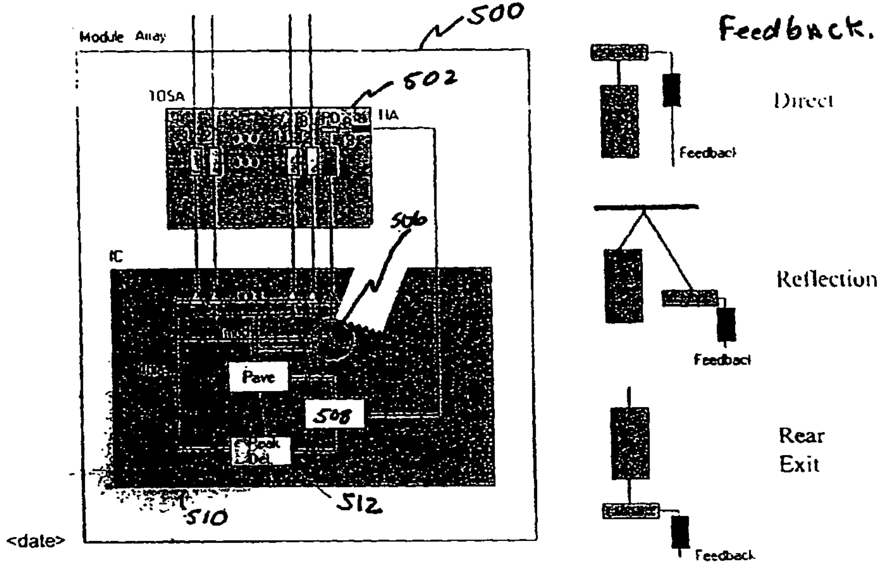
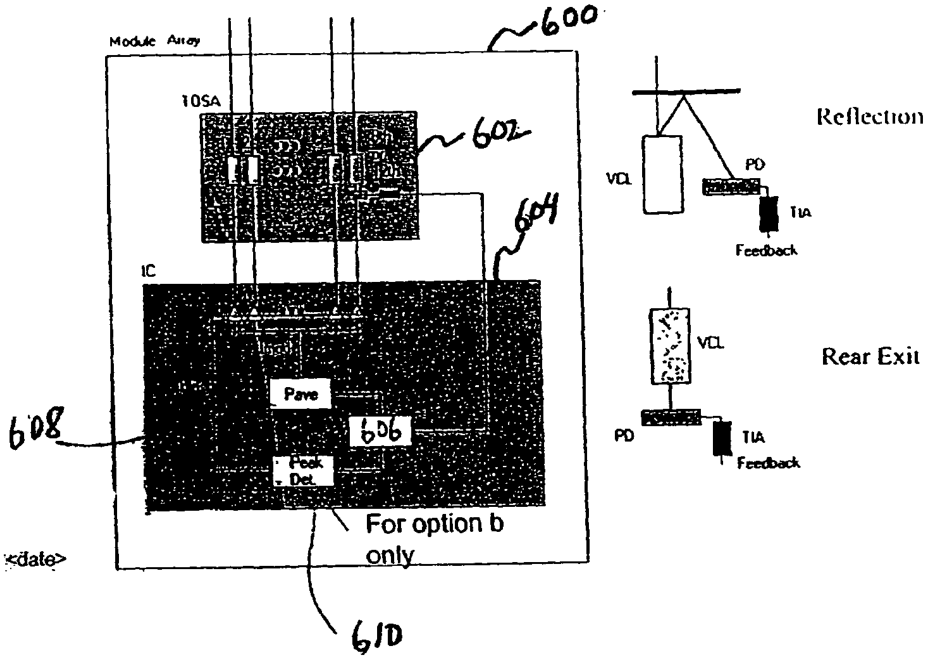


FIGURE 5

Option 2 a & b : Use of Data Laser for Feedback



For option b only

Figure 6

FIG. 7A

GENERAL CASE

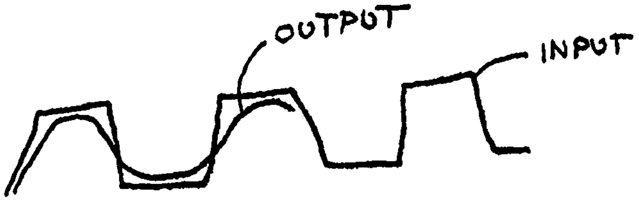


FIG. 7B

HIGH BW, LOW CAPACITANCE PHOTODIODE

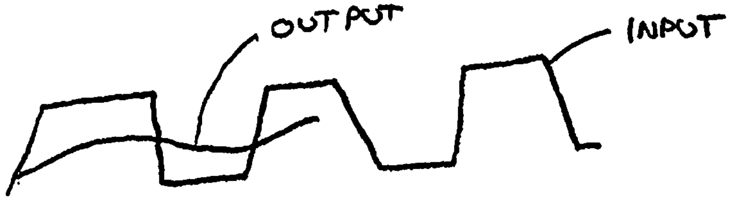


FIG. 7C

LOW BW, HIGH CAPACITANCE PHOTODIODE

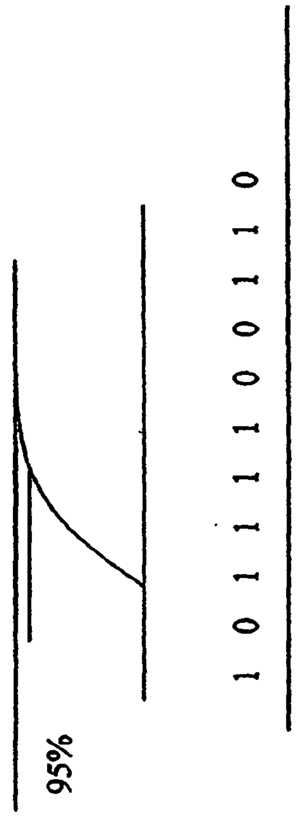
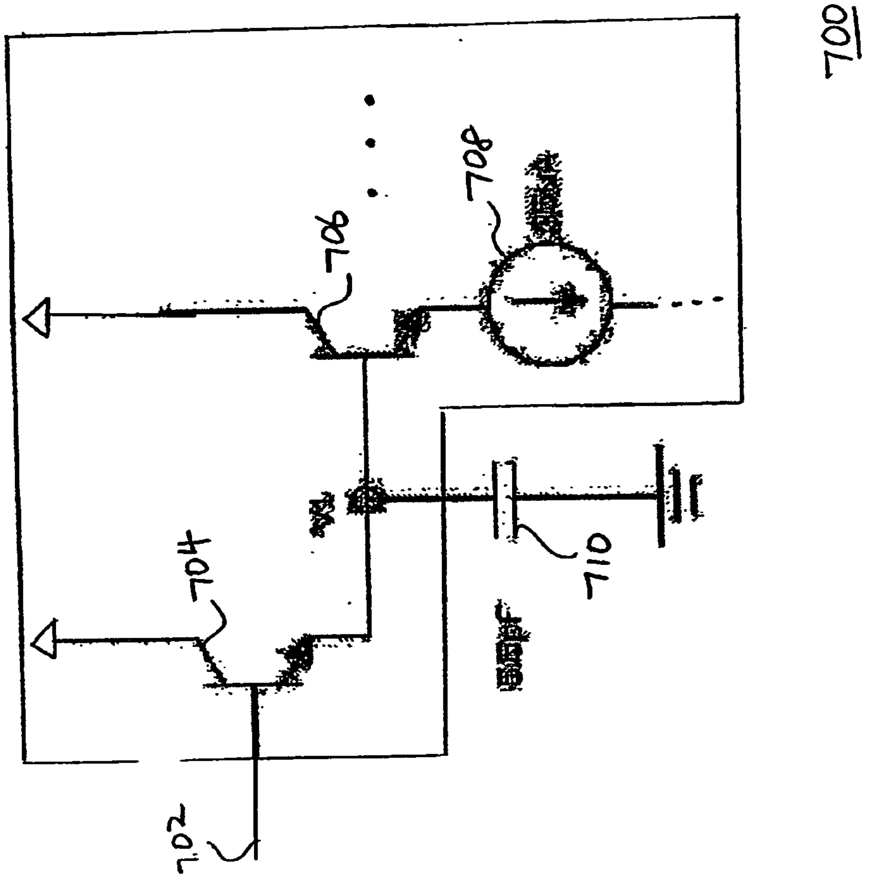


FIG. 8

FIG. 9



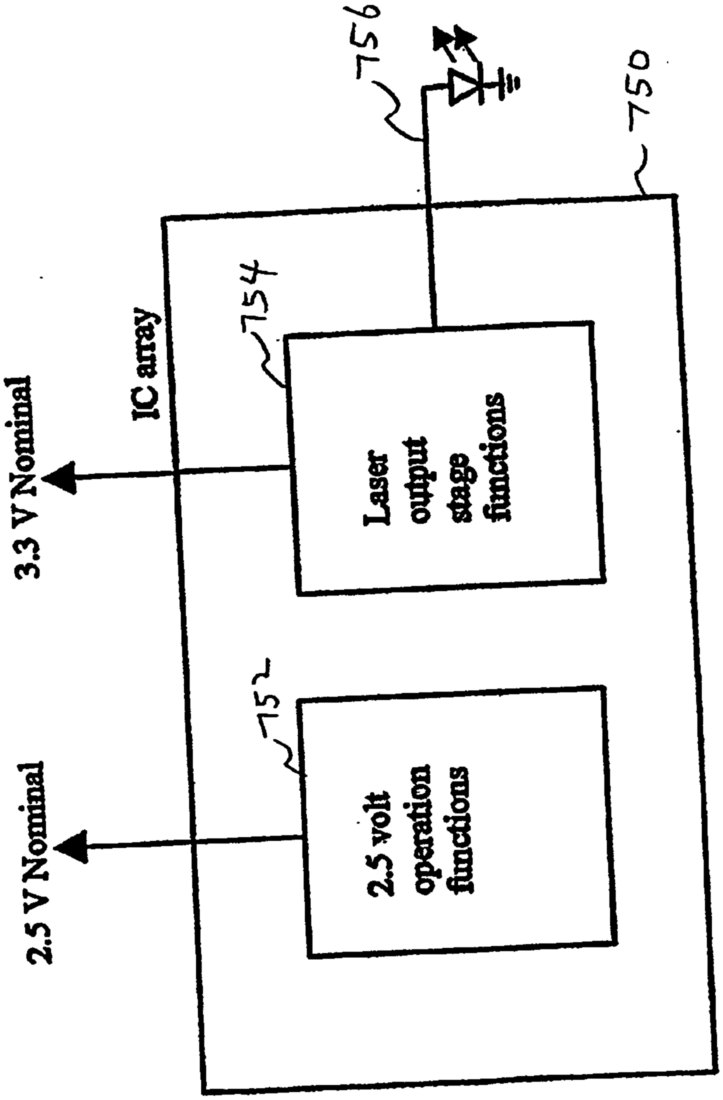

756
750
754
IC array
3.3 V Nominal
Laser output stage functions
752
2.5 V Nominal
2.5 volt operation functions

FIG. 10

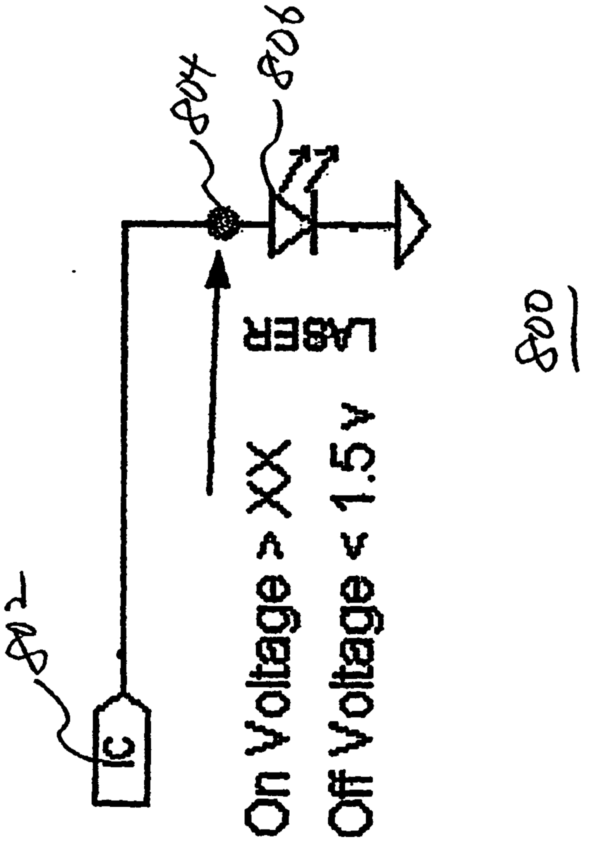


FIG. 11

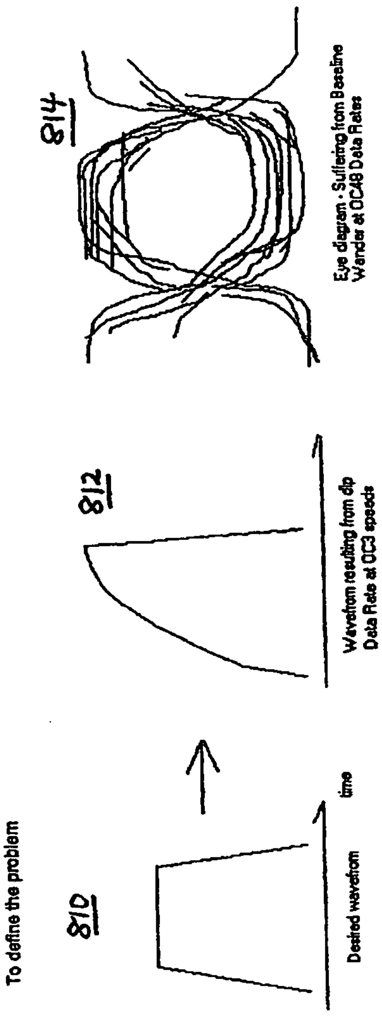


FIG. 12A

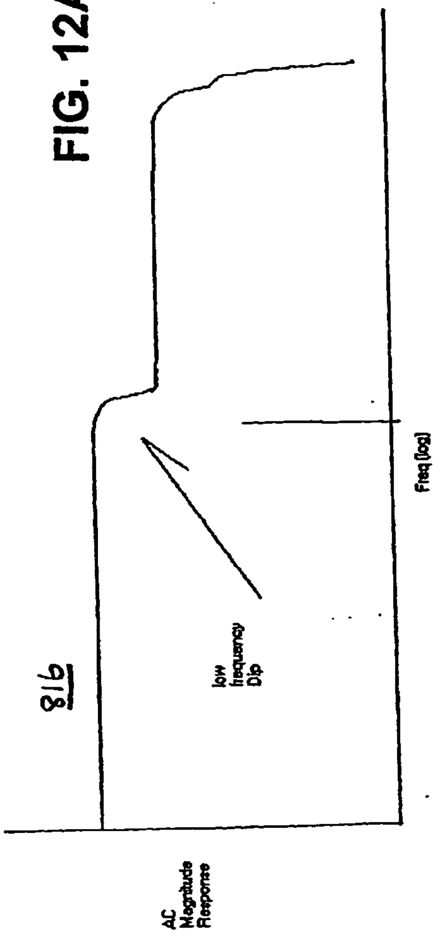


FIG. 12B

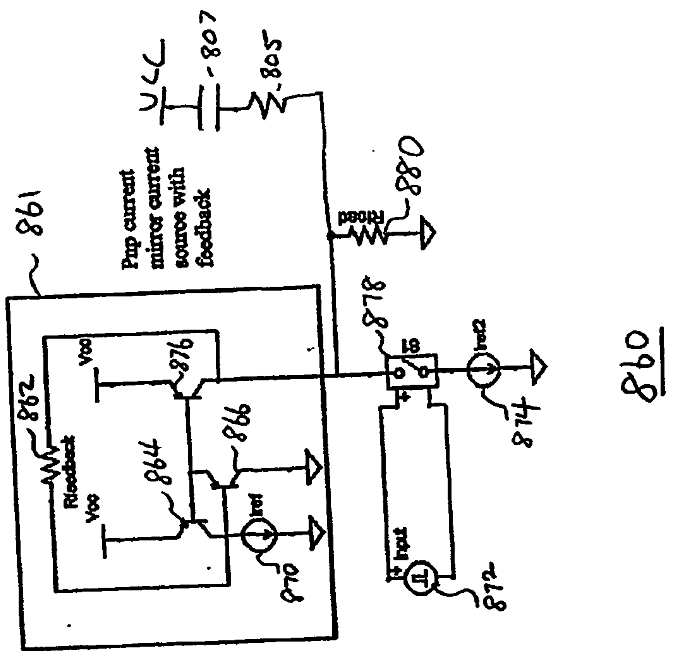


FIG. 13B

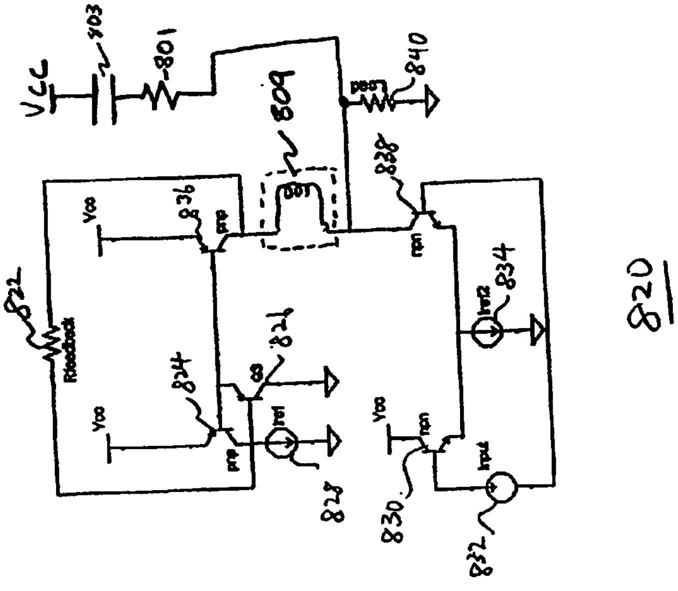


FIG. 13A

HIGH-SPEED LASER ARRAY DRIVER

CROSS-REFERENCE TO RELATED APPLICATION(S)

[0001] The present application claims the priority of U.S. Provisional Application No. 60/252,838 entitled "High-speed Laser Array Driver," filed Nov. 22, 2000, the contents of which are fully incorporated by reference herein.

FIELD OF THE INVENTION

[0002] The present invention relates most generally to the field of optical transmission of information. More particularly, the present invention relates to an integrated circuit apparatus and method for driving lasers to maintain desired optical of lasers while reducing power consumption.

BACKGROUND OF THE DISCLOSURE

[0003] In the field of telecommunications, lasers such as vertical cavity surface emitting lasers (VCSELs) and other opto-electronic devices are commonly used for the transmission of information along optical fibers and the like. VCSELs, in particular are especially desirable in today's optical communication systems because they are efficient, small in size, readily assembled into arrays, and easy to manufacture.

[0004] Within optical communication systems utilizing VCSELs or other lasers, it is often desirable to control the parameters of the optical data signal being transmitted. For example, it is often desirable to control average power and amplitude of the signal. If the average power P_{ave} is maintained properly, the laser may be modulated about the average power bias point at a modulation level necessary to achieve desired high and low light output power levels, P_{high} and P_{low}.

[0005] An optical modulation amplitude (OMA) and an extinction ratio (ER) of the laser, defined as $P_{high}-P_{low}$ and P_{high}/P_{low}, respectively, is commonly maintained within predetermined limiting values to maintain desired optical signal integrity. The limit values commonly are per specification such as the Synchronous Optical NETwork (SONET) or Gigabit Ethernet specification, or any other specification that the system is designed to meet.

[0006] Therefore, in order to obtain reliable and repeatable results in many fiber optic transmission applications, it is desirable to maintain both the average signal power and the OMA (or ER) within predetermined limit values. Unfortunately, laser characteristics change during the operation of the laser. In particular, as a laser such as a VCSEL is used to transmit optical data, the temperature of the operating laser and the environment which contains it, typically tends to increase, which may degrade laser performance. The OMA also changes as the temperature of the operating environment changes, and the change of the OMA with temperature is typically dependent on the particular laser used and the age of the particular laser. For example slope efficiency, a measure of optical output per current used to drive the laser, of the lasers may change due to temperature and age of the lasers. Automatic power control may be used to ameliorate these problems. Automatic power control is also used to account for laser threshold changes.

[0007] Similar to many other electronic systems, it is desirable to limit the power used by the laser drivers to drive the lasers. The limiting of the power used by the laser drivers to drive lasers result in reduction to power requirements and also reduces heat dissipation. Due to the reduced heat dissipation, the reduction in power requirements may also result in improvement of the laser performance due to reduced increase in temperature.

SUMMARY OF EMBODIMENTS OF THE INVENTION

[0008] In one embodiment of the present invention, a power down feature is provided to disable one or more unused lasers so as to reduce power dissipation.

[0009] In another embodiment, a dual feedback system is used to provide feedback signals for the adjustment of modulation and bias currents delivered to a single laser or each laser in a laser array through the respective laser drivers. In this manner, the dual feedback system may be used to maintain average optical power and Optical Modulation Amplitude (OMA) within predetermined limit values. The feedback signals may be provided by one of the data lasers or by an additional control laser that operates at a lower frequency than the data lasers.

[0010] In yet another embodiment of the present invention, a transistor base leakage is used to emulate a large resistance element to result in a long time constant without the use of a large capacitor or large resistance.

[0011] In yet another embodiment of the present invention, a split power supply is provided to provide a lower supply voltage to a portion of a circuit, thus reducing power consumption of the overall circuit.

[0012] In yet another embodiment of the present invention, a low off-voltage is selected for a laser driver for driving longwave VCSELs.

[0013] In yet another embodiment of the present invention, feedback is used to reduce baseline wander and Inter Symbol Interference (ISI) that are produced by a low frequency dip appearing in the frequency response observed when using a PNP current source in conjunction with an NPN differential stage to drive a laser. A feedback resistor is employed in the PNP current mirror to substantially flatten the dip present in the frequency response.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The present invention will be better understood from the following detailed description, when read in conjunction with the accompanying drawings. It is emphasized that, according to common practice, the various features of the drawings are not to-scale. On the contrary, the dimensions of the various features are arbitrarily expanded or reduced for clarity. Included in the drawings are the following figures:

[0015] **FIG. 1** is a generalized schematic laser driver array block diagram;

[0016] **FIG. 2** is a generalized schematic block diagram showing an integrated circuit with laser power down feature;

[0017] **FIG. 3** is a generalized schematic block diagram showing I_{mod} and I_{bias} adjustment currents generated using a photodiode, peak detector and a average power circuit;

[0018] **FIG. 4** is a combination circuit and block diagram showing the dual feedback loop in an embodiment of the present invention;

[0019] **FIG. 5** is a block diagram illustrating another laser feedback loop embodiment of the present invention;

[0020] **FIG. 6** is a block diagram illustrating yet another laser feedback loop according to an embodiment of the present invention;

[0021] **FIGS. 7A, 7B** and **7C** are graphical diagrams illustrating the effect of photodiode capacitance on a received optical signal;

[0022] **FIG. 8** is a graphical illustration of the accumulation of charge in an optical detector with respect to the data pattern received;

[0023] **FIG. 9** is a generalized schematic block diagram of input circuitry of a peak-to-peak detector, which includes transistors configured to result in a sufficiently long discharge time;

[0024] **FIG. 10** is a generalized schematic block diagram showing a dual power supply according an embodiment of the present invention;

[0025] **FIG. 11** is a simplified circuit diagram of a low off-voltage laser driver for longwave VCSELs according to an embodiment of the invention;

[0026] **FIGS. 12A and 12B** are graphical illustrations of pulse shaping and baseline wander problems as may be caused by a low frequency dip.

[0027] **FIGS. 13A and 13B** are schematic diagrams illustrating the use of feedback in a PNP current mirror source to reduce baseline wander and ISI according to one embodiment of the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

[0028] I. Overview

[0029] One embodiment of the present invention provides an apparatus and method to control both the average power and optical modulation amplitude (OMA) of laser signals driven by an array of laser drivers. The apparatus and method may be used to drive a single laser using a single laser driver or an array of lasers. The laser drivers in such a driver array may be integrated on a single integrated circuit. Other embodiments of the present invention are directed to providing power savings to the laser driver (or the laser driver array in case of driving multiple lasers) and to maintaining desired parameters of the optical output signals. Embodiments of the present invention may be particularly useful in high-speed applications, such as, for example, ones having 2.5 GBPS (Giga Bits Per Second) data rates. Embodiments of the present invention may also support systems having lower or higher data rates than 2.5 GBPS. In an exemplary embodiment, the lasers may be shortwave or longwave VCSELs but it should be understood that embodiments of the present invention also apply to other lasers, such as, for example, edge emitting lasers.

[0030] **FIG. 1** is a block diagram of a laser driver **100**, which may include one or more embodiments of the present invention. The laser driver **100** may be implemented on a single integrated circuit chip, but may also be implemented in two or more separate integrated circuit chips. The laser driver **100** typically has an operating temperature range of 0-85 C., but it may operate at other temperatures as well. The laser driver **100** may include one or more of the following features which are described in detail below: 1) Laser Power Down Feature; 2) Dual Feedback Laser Driver Implementation for Use with Low Bandwidth Photodetectors, using either a control laser or a data laser for feedback; 3) Slow Discharge Implementation by Use of Transistor Base Leakage; 4) Laser Driver Split Power Supply 2.5/3.3 Volt Feature; 5) Low Off-Voltage Laser Driver for Longwave VCSELs; and 6) Feedback to Reduce Baseline Wander and Inter Symbol Interference (ISI) for Low Bandwidth PNP source.

[0031] As shown, the laser driver **100** includes a differential data driver **102**, a laser current controller **104** and a high-speed current driver **106**. It should be understood, however, that the laser driver **100** as illustrated is exemplary only, and the laser driver **100** may include one or more other components to perform laser driving functions in conjunction with the components illustrated in **FIG. 1**. For example, the laser driver **100** may be used to drive a single laser or multiple lasers, which may be organized into a laser array. When the laser driver **100** is used to drive multiple lasers, for example, the laser driver **100** may include multiple high-speed current drivers, one for each of the multiple lasers. However, even when multiple high-speed current drivers are used, only one laser current controller need be used to provide modulation and bias currents to the multiple high-speed current drivers. By avoiding duplication of the circuitry for overhead functions that may be implemented in a single circuit, e.g., the laser current controller, additional power savings may be realized.

[0032] To provide the modulation and bias currents to the high-speed current driver **106**, the laser current controller **104** receives a set bias current (Set I_{bias}) signal and a set modulation current (Set I_{mod}) signal. The laser driver **100** may work in an open loop mode where the set bias current signal and the set modulation current signal are used to set bias and modulation currents, respectively. The set bias current signal may be used to set the bias current, for example, to 4 mA or 6 mA. The set modulation current signal may be used to set the modulation current.

[0033] In one embodiment of the present invention, the laser driver array may also work in a feedback loop mode, which may also be referred to as an automatic power control (APC) mode, to adjust the modulation and bias currents. Upon assertion of an APC enable signal received by the laser current controller **104**, the laser driver **100** may operate in the feedback mode in which the modulation and bias currents are adjusted based on one or more feedback signals (not shown).

[0034] The high-speed current driver **106** receives differential data signals, DIN and DINB from the differential data driver **102**, and converts them into an appropriate current signal, using the bias and modulation currents, to drive the corresponding laser. A single-ended driver may be used instead of the differential driver in some embodiments. When multiple high-speed current drivers are used to drive multiple lasers, multiple differential data drivers provide differential data signals to the multiple high-speed current drivers.

[0035] The laser driver **100** may further includes a disable feature using a disable signal to disable the laser when the laser is not used, further reducing power consumption. The disable signal may be provided to the high-speed current driver **106**. When the laser driver includes a laser driver array implemented on a single integrated circuit chip to drive multiple lasers, the disable feature allows the laser driver to selectively drive lasers, in an array of lasers, separately. If the integrated circuit is designed to drive 12 VCSELs, for example, a quad disable signal may be used to turn off four of the laser drivers, allowing the integrated circuit to drive an array of 8 VCSELs. The capability to turn off one or more laser drivers may be referred to as an IC laser power down feature, or as a laser power down feature.

[0036] II. Laser Power Down Feature

[0037] One embodiment the present invention includes a laser driver array for driving a laser array in the present includes a power down feature as illustrated in **FIG. 2**. The power down feature is typically implemented in an integrated circuit that includes a laser driver array. The laser driver array **200** includes a first laser driver control circuit **204** and a second laser driver control circuit **206**. The laser driver array **200** also includes a power down select switch **202**. The first laser driver control circuit drives, by providing I_{bias} and I_{mod} currents, lasers **1-8** represented by a laser **208**. Similarly the second laser driver control circuit drives, by providing I_{bias} and I_{mod} currents, lasers **9-12** represented by a laser **210**.

[0038] The first laser driver control circuit **204** is coupled directly to a power supply voltage Vcc. However, the second laser driver control circuit **206** is coupled to the power supply voltage Vcc via a power down select switch **202**. A power down select signal is provided to the power down select switch to open and close the switch **202**. When the switch is closed, the power supply voltage Vcc is provided to the second laser driver control circuit, allowing it to drive four lasers, lasers **9-12**, in addition to the lasers **1-8**. When the switch is open, however, the second laser driver control circuit is not powered. With this option for controlling power to one or more laser drivers, power may be saved while less than all the laser drivers in the laser driver array are needed to meet laser driving needs for low power dissipation applications. At the same time, availability of the additional laser driving capability allows for a flexible design so that a single IC design may be used for multiple applications.

[0039] In the laser driver array **200**, there are total of twelve laser drivers, four of which may be turned off and on with the power down select switch. In other embodiments, there may be more or less than twelve laser drivers in the laser driver array. In addition, the number of lasers that may be switched off and on may be different. For example, the laser driver array may include eight, twelve or any other suitable number of laser drivers. Further, other embodiments may include more than one power down select switch to switch more than one group of laser drivers on and off.

[0040] The laser power down feature may be applied to various different types of laser drivers including but not limited to longwave VCL (vertical cavity laser) array drivers, shortwave VCL array drivers and edge emitting laser array drivers. In many system applications, use of a single part rather than multiple different parts having different number of laser drivers in the laser driver array may result in cost reduction and reduction of manufacturing process needs due to production of greater volume for a single part.

[0041] III. Dual Feedback Laser Driver Implementation for Use with Low Bandwidth Photodetectors

[0042] Bias and modulation currents I_{bias} and I_{mod} are typically fed to a single laser driver to drive a single laser or to multiple laser drivers to drive multiple lasers. The bias current I_{bias} given a constant modulation current, will affect the average power, P_{ave}, of the optical signal emitted by the laser. The modulation current I_{mod} typically modulates the optical power signal above and below the average power level to provide peak-to-peak amplitude. It is often desirable to maintain an average power P_{ave} as well as optical modulation amplitude (OMA), typically defined as P_{high}-P_{low}, or extinction ratio (ER) of the laser, typically defined as P_{high}/P_{low}, within predetermined limit values in order to insure proper operating parameters. It should be understood that when OMA falls within the predefined range, in accordance with relevant specifications, for example, ER commonly also falls within an acceptable range, since the OMA and ER are related to one another.

[0043] As the operating temperature of the laser increases, the slope efficiency, typically defined as the laser current-to-optical power ratio, commonly decreases. As the temperature of the environment including the laser increases, the bias current needed to produce a given average optical power typically also changes. Specifically, the slope of the laser current-to-optical power ratio decreases, and more current is typically used to produce a given change in optical power. Furthermore, the change in slope as a function of temperature varies from laser to laser, and the slope for a given laser varies with the age of the laser.

[0044] In one embodiment of the present invention, I_{bias} and I_{mod} currents are adjusted using dual feedback loops, one for each of the I_{bias} and I_{mod} currents, to maintain laser power within predetermined limit values to compensate for changes to laser characteristics due to such factors as the operating temperature and the age of the laser. **FIG. 3** is a generalized schematic block diagram showing a laser signal **250** sensed by a photodetector **252** which may be a photodiode. The terms photodiode and photodetector may generally be used interchangeably. **FIG. 3** illustrates the general principle used for adjustment of the I_{bias} and I_{mod} currents using the feedback loops.

[0045] The signal from the photodetector is fed to a circuit **254**, which includes a peak-to-peak detector **256**, and an average power detector **258**. The peak-to-peak detector and the average power detector are used in their respective feedback loop to adjust the modulation current I_{mod} and the bias current I_{bias}, respectively. In this scheme, the laser signal **250** is the output of the laser that is being adjusted by the adjustments to the I_{bias} and I_{mod} currents. Therefore, the laser signal in this circuit is fed back into the circuit to make the laser output power adjustment. In embodiments of the present invention, use of the dual feedback loops to adjust the laser output power may also be referred to as an Automatic Power Control (APC) and Automatic Modulation Control (AMC).

[0046] **FIG. 4** is a circuit/block diagram showing a dual feedback loop in one embodiment of the present invention. In the embodiment shown in **FIG. 4**, a laser driver array **300** is implemented on a single integrated circuit (IC). In other embodiments, more than one integrated circuit may be used to implement the laser driver array. In still other embodiments, the dual feedback loop may be used with only a single laser driver for driving a single laser.

[0047] The laser driver array **300** includes laser drivers **324**. The laser drivers **324** include twelve laser drivers for VCSEL **01** through VCSEL **12**. The twelve laser drivers in the laser driver array **324** may be referred to as data laser drivers for VCSEL **01** through VCSEL **12**. The laser driver array also includes a 13th laser driver **328**, which is used as a control laser driver for VCSEL **13**. VCSEL **13** is referred to as a control VCSEL or as an extra VCSEL.

[0048] In the laser drivers **324** of **FIG. 4**, the 13th laser driver **328** is a control laser driver, however, in practice, any one of the twelve laser drivers in the laser drivers **324** may be used as a control laser driver. The lasers, which may be driven, are not limited to VCSELs, and in other embodiments, other lasers such as edge emitting lasers may be used. In still other embodiments, some or all of the laser drivers may be external to the integrated circuit. Furthermore, the thirteen VCSELs illustrated are intended to be exemplary only and other numbers of data and total VCSELs may be included in alternative embodiments. In some embodiments data lasers may be used to provide feedback, thus eliminating the need for a control laser and a control laser driver.

[0049] The laser driver array **300** provides for Automatic Power Control (APC) feedback or open loop operation and the ability to switch between the two modes. The second feedback mechanism is an automatic modulation control (AMC). The dual feedback control system is used to provide an adjustment to both the bias current and the modulation current fed to the laser drivers. The laser driver array **300** includes a bias feedback loop for adjusting the bias current based on average optical power detection. The bias feedback loop includes a bias feedback path **304**. The laser driver array **300** also includes a modulation feedback loop for adjusting the modulation current based on peak-to-peak detection. The modulation feedback loop includes a modulation feedback path **302**. A signal accumulation capacitor C_{pk} may be used to set the discharge time constant for the peak-to-peak detector. The signal accumulation capacitor C_{pk} may be integrated with the integrated circuit **300**, or it may be implemented as an external capacitor.

[0050] Light emitted from either the control laser or one of the data lasers is monitored using the photodetector **308** and a transimpedence amplifier (TIA) **310**. The TIA **310** is used in the modulation current feedback path to adjust the modulation current I_{mod}, while the amplifier **316** is used in the bias feedback path to adjust the bias current I_{bias}. According to one exemplary embodiment, the laser driver for each of the lasers within the array is included within an integrated circuit. According to another exemplary embodiment, the laser drivers may be external to the integrated circuit.

[0051] The bias and modulation currents, I_{bias} and I_{mod}, respectively, are used to set the lasers at room temperature and are programmed from a temperature stabilized voltage reference. The I_{bias} and I_{mod} currents may be adjusted through the selection of one set resistor for all lasers in the array. From the laser control, an adjusted bias current **332** and an adjusted modulation current **334** are generated, and each is fed to each laser driver of the array of laser drivers **324** as well as the control laser driver **328**. The photodetector **308** may be disposed in proximity to one of the data lasers VCSEL **01** through VCSEL **12** or the control laser (VCSEL **13**) depending on the exemplary embodiment used. More particularly, the photodetector **308** may be configured to absorb light emitted from the VCSEL that is situated proximately to the photodetector. **FIG. 4** shows that the singular detected bias and modulation currents are used to adjust the I_{bias} and I_{mod} signals **332** and **334** respectively, provided to each of the VCSELs **01-13**.

[0052] The laser driver array **300** of **FIG. 4** is illustrated as receiving two feedback lights, a data laser feedback light and a control laser feedback light. Generally, only one of the feedback lights may be implemented and used. For example, one embodiment may use only the control laser feedback while another embodiment may use only the data laser feedback.

[0053] A. Use of Control Laser Feedback Loop

[0054] Conventional photodetectors used in feedback systems for optical communication systems typically have capacitance that tends to slow down data detection, so that P_{high} and P_{low} may not be detected properly on a real-time basis for high-speed optical communication systems. Thus, laser drivers that use feedback for adjusting output optical modulation amplitude generally use high-speed photodetectors which are typically difficult to assemble and costly to manufacture. If a laser that is driven at a slower speed may be used to provide feedback signal, slower photodetectors may be used. The slower speed photodetectors are typically easier to assembly and less costly to manufacture.

[0055] In this embodiment of the present invention, an extra laser is used as a control laser to provide average optical power and peak-to-peak information and to provide for the adjustment of the modulation current and the bias current delivered to each of the data laser drivers of the laser driver array **324** to control the average optical power and optical modulation amplitude (OMA).

[0056] As illustrated in **FIG. 4**, a control laser driver circuit **306** is used to drive the control laser, VCSEL **13**. The VCSEL **13** may have substantially the same operating characteristics as those of the other VCSELs of the array, such as VCSELs formed on the same substrate. The control laser driver circuit **306** includes a 100 MHz oscillator **326** and the laser driver **328**. The 100 MHz oscillator may provide the modulation to the laser driver **328** to drive the control laser. In other embodiments, the oscillation frequency of the oscillator may be more or less than 100 MHz. Since the oscillation frequency of 100 MHz is generally much lower than the data rate commonly used in optical communication systems, such as, for example, 2.5 GBPS (Gigabits per second). Since the control laser operates at a lower frequency photodetectors having lower frequency responses may be used.

[0057] **FIG. 5** is a block diagram **500** illustrating an arrangement of data lasers and a control laser in an exemplary laser array **502**. In other embodiments, the control laser may be used with varying numbers of data lasers, including a single laser. The control laser in **FIG. 5** is illustrated as the 13th laser, however the distinction is arbitrary and any laser may be used as the control laser. The same I_{bias} and I_{mod} currents, used to drive the data lasers within the array, also drive the control laser.

[0058] Depending on the laser used, any of a direct, reflection, or rear exit feedback configuration may be used for the photodetector and TIA arrangement to provide feedback as to the laser output power. For the case of the rear exit feedback configuration, the optical power feedback is commonly proportional to the light from the primary emission. For example, when edge emitting lasers or long wavelength VCSELs emitting at 1.3 microns are used, the rear exit configuration may be used since light is transmitted out of each of the opposing ends of the laser. The other feedback configurations illustrated may be used as well. For another example, for a non-long wavelength VCSEL, a direct or reflection configuration may be used depending on the environment within which the control laser is formed.

[0059] As shown in each of **FIGS. 4 and 5**, an oscillator (100 MHz oscillator **326** or the oscillator **506**) is used to provide a signal to the control laser. The signal has a significantly lower frequency than the data signal delivered to the data lasers. For example, in a 2.5 GBPS system, the signal provided to the control laser may be on the order of 50 MHz-150 MHz. This signal may include substantially the same amplitude and power but is transmitted at a lower speed.

[0060] According to this exemplary embodiment, the capacitance of the photodetector, which is typically a limiting factor in high-speed applications because it does not allow the photodetector to charge and discharge quickly enough for the peak-to-peak amplitude to be detected. By using a lower frequency signal, such as the 50 MHz-150 MHz signal of the present embodiment a lower frequency response photodetector may be used. It is typically advantageous to use the lower frequency photodetector because they are generally easier to build than high-speed photodetectors, which commonly must be built smaller to limit their capacitance. Further, for the high-speed photodetector to operate successfully, the TIA typically may need to be placed in proximity to the photodetector itself, and not integrated into the IC.

[0061] Since the control laser operates at a significantly lower frequency, the average optical power and the peak-to-peak optical power may be determined for the control laser on a real time basis, instead of having to wait for a suitable data pattern so that these parameters may be detected. The average optical power and the peak-to-peak optical power may then be provided in a timely fashion to the feedback loops which adjust the modulation and bias currents.

[0062] The control laser is useful in high-speed application such as Gigabit Ethernet applications or other applications where repeated bit streams are limited in number such that low speed photodetectors are not practical to detect average and peak to peak values for feedback purposes. The capability to use slower photodetector diodes may result in simplified assembly and manufacture, which in turn may lead to reduction in cost. The lower frequency parameter detection also requires reduced high-speed considerations such as impedance matching, transmission lines, and issues associated with parasitic capacitance, inductance, etc. Further, the capability to operate at low frequency may simplify the use of the TIA, allowing it to be located further away from its photodiode and placed in an IC with less power dissipation than would otherwise have been required.

[0063] The laser driver array may support various different signaling formats including but not limited to SONET (Synchronous Optical NETwork) that uses pseudo random signal formats as well as Gigabit Ethernet and other applications that do not use pseudo random signal formats. The embodiment using the control laser supports applications that do not use pseudo random signal formats as well as those that do. However, for applications that use pseudo random signal formats, a data laser may be used instead of the control laser to provide feedback signals to adjust I_{mod} and I_{bias}. Use of the data laser instead of the control laser eliminates the need to supply power to the control laser, and thus results in reduced overall power requirements.

[0064] B. Use of Data Laser for Feedback

[0065] One of the data lasers may be used to provide feedback in one embodiment of the present invention when the application is for a system with pseudo random signal formats, such as, for example, SONET, a commonly used network used in optical communication equipment. In this embodiment, the control laser may be disabled to reduce power dissipation by using a control laser select signal provided to the control laser driver circuit **306**. This embodiment may be used with other data formats other than SONET. It may work with any system for dealing with pseudo random data, anything that allows for a long string of 1's sufficient to allow a photodetector used with the system to reach substantially a peak value of the signal. The data is not required to be pseudo random if a sufficient number of successive 1's are periodically present. If a sufficient number of successive 1's are periodically present a photodetector may reach substantially the peak value (and a sufficient number of successive 0's are present to allow the photodectector to discharge to the level corresponding to a logical zero light intensity). Statistically a sufficient number of repeated bits are necessary to allow the photodector to charge or discharge to levels representative of limit values. The present embodiment, however, will be described in detail primarily in reference to a SONET system for illustrative purposes.

[0066] SONET specifications are commonly prescribed and used in optical communication systems. A SONET data signal is a pseudo random signal which provides a high statistical probability that a sufficient number of consecutive bits will be present and therefore may be received and accumulated within a parasitic capacitance of the photodetector to allow the photodetector to charge to a maximum (and discharge to a minimum) value even for very high-speed applications. A bit may be a "1" or a "0". Although the following discussion will refer to bits as "1's" and will discuss the accumulated charge associated with having a sufficient number of repeating "1s" (high power level) in a data sequence, it should be understood that the same applies to repeating "0s" (low power level) in a data sequence. In other words though a sequence of "1s" will be used to illustrate the photodetector charging to a maximum value, a sequence of "0s" is equivalently necessary to discharge the photo detector to a minimum value.

[0067] **FIG. 6** shows an exemplary arrangement for the embodiment in which one of the data lasers is used to provide the feedback signal. It can be seen that the photodetector (PD) arrangement may be a reflection arrangement or a rear exit arrangement, which have been discussed above in reference to **FIG. 5**. The use of the data laser to provide feedback typically does not provide for direct monitoring of the optical signal from the data laser because the optical signal is transmitted to an optical medium and any direct monitoring would necessarily attenuate or otherwise compromise the transmitted signal. Therefore, one of reflection and rear exit arrangements commonly are used. The TIA used may be a low power TIA.

[0068] FIGS. 7A-C illustrate the effect that the photodetector capacitance may have upon a propagated optical signal. **FIG. 7A** shows a general case in which a photodetector is modeled as a low pass filter (LPF) receiving a waveform representing a laser signal. It can be seen that the rise and fall times of the peak-to-peak signal have been increased, as the high frequency components of the signal are attenuated. **FIG. 7B** shows the effect of low capacitance, high bandwidth photodetectors and shows that the peak-to-peak amplitude is approximated, even though the limited bandwidth still results in somewhat slower rise and fall times than the original signal. Such high frequency response photodetectors are difficult and expensive to make and are not therefore commercially practical. **FIG. 7C** shows the effect on a laser signal of a low bandwidth, high capacitance photodetector. It can be seen that the peak-to-peak information regarding the signal is generally lost, as the photodetector does not have the high frequency response necessary to produce a good approximation of the original signal.

[0069] In SONET and other pseudo random signal generation applications, it is assumed that the pseudo random data signal provides a statistical probability that a sufficient number of repeating "1's" in a data sequence will be provided to allow a capacitance of a photodetector to charge sufficiently to approximate the peak value of the signal. An example of a sufficient number of consecutive "1s" being received to allow a photodetector to charge to essentially a maximum value is shown in **FIG. 8**. If a sufficient number of consecutive 1's are received to charge a capacitor to approximately the peak value, a representation of that peak can be obtained using a photodetector operating at a lower speed than the transmit data rate.

[0070] The data sequence shown in **FIG. 8** is intended to be exemplary only, and various other data sequences can be obtained in SONET and other pseudo random signal generation applications. It should be understood that SONET and other pseudo random signal generation applications may insure statistically that a sufficient number of "1's" in a data sequence will be provided to accumulate and provide an approximation of the peak amplitude. Accordingly an integrated circuit may be designed to provide for fast charging and slow discharging to assure that the statistical probability of repeating "1's" will allow sufficient charge accumulation to produce a signal of approximately the maximum amplitude, thus assuring accurate peak value detection.

[0071] For example, in order for an approximation of a full amplitude signal to be detected, the time constant for the discharge time should be controlled. Configuring the discharge time at a sufficiently large value by providing a high resistance and/or high capacitance, in the discharge circuitry, increases the discharge time constant of the circuit. A peak-to-peak detection circuit with a long discharge is illustrated at **312** in the laser driver array **300** of **FIG. 4**. In one embodiment, the capacitance of the signal accumulation capacitor C_{pk} **330** in **FIG. 4** may be maintained at a sufficiently high value. As discussed above however a high capacitance will limit the high frequency response and so it is preferable to produce a long time constant by increasing resistance rather than capacitance. Additionally higher capacitance tends to require increased integrated circuit real estate.

[0072] Thus, one of the data lasers operating at high-speed, e.g., 2.5 GBPS, may be used for feedback when single or array lasers, including but not limited to shortwave and longwave VCSELs for SONET or other signal formats using pseudo random data transfer, or signal formats with sufficient number of repeating data bits, are used. The capability to use slower photodetector diodes may result in simplified assembly and manufacture, which in turn may lead to reduction in cost. The operations at lower frequency also typically reduces the need to resolve issues related to impedance matching, transmission lines, and issues associated with parasitic capacitance, inductance, and the like.

[0073] Further, the capability to operate at low frequency may allow for the use of simplified TIA located further away from photodiode. Such a TIA may be placed in IC and dissipate less power than otherwise would be required. In addition, through the use of the slow discharge implementation, SONET or other applications using pseudo random signal formats may be supported without the added power dissipation required by an additional control laser.

[0074] IV. Slow Discharge Implementation by Use of Transistor Base Leakage

[0075] The slow discharging may also be realized through use of high resistance in the peak-to-peak detector. Returning now to **FIG. 4**, when a resistor is used in the peak-to-peak detector **312** to form a RC-circuit with the C_{pk} **330**, longer discharge times may be realized by using higher value resistors. Therefore, increasing the resistance of the resistor coupled to the signal accumulation capacitor Cpk may also increase the discharge time. However, it is often undesirable or impractical to implement a high value resistor in an integrated circuit due to space and other limitations. Additionally high resistances may be difficult to control accurately in fabrication.

[0076] Therefore, in one embodiment of the present invention, the high resistance of the resistor is simulated by using transistor base current, which may be provided in accordance with the circuitry of a peak-to-peak detector **700** shown in **FIG. 9**. Of course, a peak-to-peak detector may include other components, and the input circuitry shown in **FIG. 9** is for illustrative purposes only. The peak-to-peak detector **700** includes an input **702** via which the peak-to-peak detector receives an output of the feedback photodetector via a TIA. The input **702** is provided to a base of an illustrative NPN input transistor **704**. An emitter of the input transistor provides output voltage **V1** at a base of a discharge time control transistor **706**. The output voltage V1 depends on the photodetector voltage, which is provided as an input **702** via a TIA.

[0077] An emitter of the input transistor **704** provides the current to charge the capacitor **710**. The base of the discharge time control transistor **706** provides the discharge path for capacitor C_{pk} **710**. The input transistor **704** serves as a rectifier/diode of the electrical signal received from the photodetector. Since transistor **706** is limited to an emitter current of (illustratively) 35 μAmps the base leakage current of transistor **706** is limited to a value equal to the emitter current divided by β, the current amplification of transistor **706**. Accordingly the base current of transistor **706** is limited to 35 μAmps/β, that is a small value that generally results in a relatively long discharge time, thus providing a similar effect as adding a large resistor.

[0078] The signal accumulation capacitor C_{pk} **710** controls discharge time according to the equation $I=C_{pk}dv/dt$. C_{pk} may be on the order of 5.5 pf but other capacitance values may be used alternatively. The current source **708** that provides the discharge current may supply 35 μA or any other suitable current. In summary, the use of the capacitance and the discharge current that controls the charge and discharge time constants allows for the accumulation of a sufficient number of consecutive "1's" provided by SONET or other pseudo random signal formats to enable the peak and peak-to-peak values to be detected and provided to the dual feedback loops.

[0079] Use of fixed base current to simulate high resistance is described in reference to the specific circuit, however, it should be noted that it is applicable to any circuit where it is desirable to create a sufficiently long discharge time, especially when addition of a high value resistor to the circuit or large capacitance is undesirable.

[0080] V. Laser Driver Split Power Supply 2.5/3.3 Volt Feature

[0081] To further reduce power consumption, a dual power supply **750** may be used in one embodiment of the present invention, such as shown schematically in **FIG. 10**. Two power supplies, a 2.5 V power supply and a 3.3 V power supply, may be used to power various parts of the laser driver array, which may be implemented on an integrated circuit (IC). A power supply set at a nominal value of 3.3 volts, for example, is used to power laser output stage functions **754** to drive lasers **756**, and a second power supply set at a lower voltage, for example 2.5 volts, is used to power other components **752** of the integrated circuit. The use of the 2.5 volt power supply in parts of the integrated circuit may reduce the overall power consumption of the integrated circuit.

[0082] Thus, use of the split power supply reduces power consumption by powering selected functions in the laser output stage with a 3.3 Volt supply voltage and remaining function with a 2.5 Volt supply. In other embodiments, an option to use either a single 3.3 Volt supply or a split power supply of 2.5/3.3 Volt may be allowed to a laser driver array integrated on a single IC. The power consumption is reduced when two supplies are used. The split power supply may be used in the laser driver array to reduce power consumption. The split power supply may also be used in any other circuit that may benefit from reduced power consumption due to such split power system.

[0083] VI. Low Off-Voltage Laser Driver for Longwave VCSELs

[0084] Longwave VCSELs may or may not have an off voltage, also referred to as a low voltage, that differs from those of typical shortwave VCSELs.

[0085] **FIG. 11** is a simplified circuit diagram of a circuit **800** for driving a laser **806**. The laser **806** may be a single VCSEL or it may represent an array of VCSELs. In the IC **802**, power consumption may be altered by operating at voltage levels at the driving point **804** that are appropriate for the longwave VCSEL in question. Exemplary longwave VCSEL **806** has a low voltage, e.g., 1.5V or less, which is lower than the typical low voltage for an exemplary shortwave VCSEL. The circuit **800** allows direct current coupling with no AC coupling capacitor required, thus reducing PCB (printed circuit board) space requirements. The elimination of AC coupling reduces power consumption by eliminating losses in the capacitor. Those of ordinary skill in the art will appreciate that the low voltage of a particular longwave VCSEL may in fact be less than, comparable to or greater than that of a typical shortwave VCSEL, and that the circuits described herein may be used or modified in accordance with the voltages of the VCSEL in question.

[0086] VII. Feedback to Reduce Baseline Wander and ISI (Inter Symbol Interference) for Low Bandwidth PNP Source

[0087] One of the considerations that may be addressed in designing any data communication system is the shape of the waveform transmitted. A distorted waveform may not be detected correctly at the receiving end, thus resulting in error. **FIG. 12A**, for example, illustrates a desired waveform **810** for a data communication system, such as, for example, the optical communication system embodiment of the present invention.

[0088] When a PNP current mirror circuit having an NPN sink, such as the one that may be implemented with PNP transistors **824**, **836** and NPN transistors **830**, **838** of **FIG. 13A**, is used as a current source to drive the laser (e.g. **840**) an undesirable low frequency dip may occur in an AC magnitude response. Such a frequency dip is illustrated in frequency response plot **816** of **FIG. 12B**. The low frequency dip may distort the waveforms. A waveform **812** of **FIG. 12A** illustrates such distorted waveform, for example, at an OC-3 data rate (155 Mbps). An eye diagram **814** of **FIG. 12A** suffers from baseline wander, for example, at an OC-48 data rate (2.5 Gbps) due to the low frequency dip.

[0089] The low frequency dip, such as the one in the frequency response plot **816**, may be substantially flattened by adding a feedback resistor **862** to a PNP current mirror of the laser driver circuit, such as a laser driver circuit **860** of **FIG. 13B**. The resistance of the feedback resistor may be adjusted until a desired frequency response is achieved. The circuit may be applied to laser drivers including VCSELs. The feedback resistor may also be added to any driver, which uses a PNP current mirror source to drive a digital load, to substantially flatten the low frequency dip.

[0090] Additionally adding a series resistor-capacitor circuit as illustrated at **801** and **803** or **805** and **807** can lessen any deterministic jitter at the load **840** or **880**. The resistor-capacitor circuit may have different values, which will vary depending on the circuit parameters. Typical values for resistor **801** Or **805** are between 100 and 300 ohms and typical values for capacitor **803** or **807** are between 0.5 to 3.0 picofarads. The values may be adjusted depending on implementation and circuit details. The deterministic jitter and need for the feedback resistor **822** may also be diminished by the placement of an inductor **809** between the collector of PNP transistor **836** and the junction of transistor **838** and the load **840**.

[0091] It should be emphasized that the above-described embodiments are intended to be exemplary only. For example, the terms "laser" and "VCSEL" are used interchangeably to emphasize that the embodiments of the present invention may find application in optical systems using both VCSELs and other lasers. The laser array may include copy of various numbers of data lasers. Furthermore, the specific arrangement of the components of the integrated circuit and the details of the method generally covered by the integrated circuit, are exemplary only. The integrated circuit including the laser driver array of the present invention may be integrated into larger integrated circuits including other features, without departing from the scope and spirit of the inventive concepts disclosed herein. Further, the embodiments described herein may be useful for individual lasers as well as arrays.

What is claimed is:

1. An apparatus for driving lasers, the apparatus comprising:

a laser current controller for providing a modulation signal and a bias signal;

a plurality of high-speed current drivers that accept the modulation signal and the bias signal and produce a plurality of laser drive signals; and

a disable input that selectively disables power to at least one high-speed current driver when the high-speed current driver is not in use.

2. The apparatus of claim 1 wherein the apparatus is integrated on an integrated circuit.

3. The apparatus of claim 2 further comprising an integrated array of lasers coupled to the plurality of high-speed current drivers for receiving the plurality of laser drive signals.

4. The apparatus of claim 1 wherein the laser current controller comprises:

an automatic power control (APC) input that accepts a digital APC signal; and

circuitry that adjusts the modulation signal and bias signal to the high-speed current drivers.

5. The apparatus of claim 1 further comprising

a high-speed current driver that drives a feedback laser; and

a feedback circuit that accepts a signal from the feedback laser and generates a modulation feedback signal and a bias feedback signal and provides them to the laser current controller.

6. The apparatus of claim 5 wherein the feedback circuit comprises:

a peak to peak detector that generates the modulation feedback signal; and

an average value detector that generates the bias feedback signal.

7. The apparatus of claim 1 further comprising at least one high-speed current driver, which does not have a disable input.

8. The apparatus of claim 6 further comprising a photo detector that detects laser light produced by a laser driven by one of the high-speed current drivers of the integrated driver and provides it to the peak detector and the average value detector.

9. The apparatus of claim 8 wherein the laser, which provides light to the photodetector, is a control laser, which is modulated by a signal of substantially lower frequency than a maximum frequency of the data lasers.

10. The apparatus of claim 8 wherein the modulating frequency is approximately 100 MHZ.

11. The apparatus of claim 9 wherein the frequency response of the photodetector is less than a maximum frequency of the data lasers and equal to or greater than the modulating frequency.

12. The apparatus of claim 8 wherein the peak detector comprises:

an input that accepts an output of the photo detector;

a capacitance that accepts the output of the photodetector from the peak detector input and holds the output of the peak detector; and

means for producing a slow discharge of the capacitance.

13. The apparatus of claim 12 wherein the means for producing a slow discharge of the capacitance comprises:

a transistor, having a base collector and emitter, wherein the base of the transistor provides a discharge path for the capacitance; and

a constant current source coupled to the emitter circuit of the transistor.

14. The apparatus of claim 2 wherein the plurality of high-speed current drivers receive power from a first power supply, and the remainder of the integrated circuit receives its power from a second power supply thereby reducing the overall power consumed.

15. The apparatus of claim 10 further comprising a modulator that modulates the control laser with a signal having a lower frequency than a maximum frequency of any of the data lasers.

16. The apparatus of claim 15 wherein the maximum frequency response of the photo detector is lower than a maximum frequency of any of the data lasers.

17. An apparatus for driving lasers, the apparatus comprising:

a laser current controller for providing a modulation signal and a bias signal;

a plurality of high-speed current drivers that accept the modulation signal and the bias signal and produce a plurality of laser drive signals; and

a feedback circuit that detects laser light produced by a laser driven by one of the high-speed current drivers to produce a modulation feedback signal and a bias feedback signal for provision to the laser current controller.

18. An apparatus as in claim 17 wherein the laser current controller and the plurality of high-speed current drivers are integrated on an integrated circuit.

19. The apparatus of claim 18 further comprising a laser array integrated on the integrated circuit.

20. The apparatus of claim 17 wherein the feedback circuit further comprises a photo detector having lower frequency response than a maximum frequency of any of the data lasers.

21. An apparatus as in claim 17 further comprising a signal generator that generates a modulating signal that modulates the laser producing the laser light detected by the

photo detector, said modulation signal being of substantially lower frequency than a maximum frequency of any of the data lasers.

22. An apparatus as in 17 wherein the feedback circuit comprises:

a photodetector that accepts the laser light and produces a proportional voltage;

a peak detector that accepts an output of the photo detector;

a capacitance that holds the output of the peak detector; and

means for producing a slow discharge of the capacitance.

23. An apparatus as in claim 22 wherein the means for producing a slow discharge of the capacitance comprises:

a transistor, wherein the base of the transistor provides a discharge path for the capacitance; and

a constant current source within the emitter circuit of the transistor.

24. The apparatus of claim 18 wherein the plurality of high-speed current drivers receive power from a first power supply, and the remainder of the integrated circuit receives its power from a second power supply thereby reducing the overall power consumed.

25. An apparatus for driving lasers, the apparatus comprising:

a laser current controller for providing a modulation signal and a bias signal;

a plurality of high-speed current drivers that accept the modulation signal and the bias signal and produce a plurality of laser drive signals;

a disable input that disconnects power from a high-speed current driver when the high-speed current driver is not in use;

a feedback laser that is driven from one of the plurality of high-speed current drivers; and

a feedback circuit, including a photodetector that accepts light from the feedback laser and produces a modulation feedback signal and a bias feedback signal, said photodetector having a cutoff frequency lower than the maximum frequency of the high-speed current drivers.

26. The apparatus as in claim 25 further comprising a signal generator that modulates the feedback laser with a signal having a lower frequency than the maximum frequency of the high-speed current drivers.

27. An apparatus as in claim 25 wherein the feedback circuit further comprises:

a peak detector that accepts an output of the photo detector;

a capacitance that holds the output of the peak detector; and

means for producing a slow discharge of the capacitance.

28. An apparatus as in claim 27 wherein the means for producing a slow discharge of the capacitance comprises:

a transistor having a collector, emitter and base, wherein the base of the transistor provides a discharge path for the capacitance; and

a constant current source within the emitter circuit of the transistor.

29. The apparatus of claim 28 wherein the high-speed current driver and the laser current controller are integrated on the same integrated circuit.

30. The apparatus of claim 29 wherein the plurality of high-speed current drivers receive power from a first power supply, and the remainder of the integrated circuit receives its power from a second power supply thereby reducing the overall power consumed.

31. A method for controlling a laser the method comprising:

providing an integrated high-speed current driver in an integrated circuit;

driving an array of lasers from the integrated high-speed current driver;

accepting laser light from one of the array of lasers in a photodetector;

determining a maximum and a minimum level of light received from the laser that is providing light for the photodetector;

using the maximum and the minimum level of light received from the laser to produce a modulation feedback signal and a bias feedback signal;

using the modulation feedback signal and the bias feedback signal to produce a modulation and a bias signal; and

using the modulation signal and the bias signal to set the modulation and bias in the integrated high-speed current driver.

32. A method as in claim 31 wherein accepting laser light from one of the array of lasers in a photodetector comprises accepting laser light from a laser being modulated at a frequency less than the maximum frequency of the high-speed current driver.

33. A method as in claim 31 wherein accepting laser light from one of the array of lasers in a photocell comprises accepting laser light from a laser being modulated at a frequency of approximately 100 MHZ.

34. A method as in claim 31 wherein determining a maximum and a minimum level of light received from the laser that is providing light for the photocell comprises;

accepting a signal representative of the intensity of the laser light into a peak detector circuit; and

discharging the peak detector circuit by coupling a sampling capacitor, which holds peak detector voltage, to the base of an transistor and controlling the current of the transistor using a constant current supply.

35. An apparatus for driving a laser the apparatus comprising:

a current sink;

a differential pair of PNP transistors, each transistor having a base, emitter and collector the bases being coupled together, and the emitters being coupled to a supply voltage Vcc,

a differential pair of NPN transistors, each transistor having a base, emitter and collector the emitters being joined at a junction with the current sink, the bases providing the input across which and input signal is developed, and

a load junction of the collector of one of the PNP transistors and one of the collectors of one of the NPN transistors that is coupled to a laser load.

36. An apparatus as in claim 35 wherein the load junction is coupled to the base junction of the PNP transistors by a feedback resistor.

37. An apparatus as in 36 wherein the feedback resistor is coupled between the load junction and the base of a PNP feedback transistor; and

the emitter of the PNP feedback transistor is coupled to the base junction of the PNP differential transistor pair.

38. An apparatus as in claim 35 wherein the load junction is further coupled to a first end of a series resistor-capacitor circuit and the second end of the series resistor-capacitor circuit is coupled to ground.

39. An apparatus as in claim 35 wherein the load junction is further coupled to a first end of a series resistor-capacitor circuit and the second end of the series resistor-capacitor circuit is coupled to a power supply.

40. An apparatus as in claim 35 further comprising an inductor disposed between the load junction and the load.

41. A laser driver for driving a laser, the laser driver comprising:

a first control circuit for receiving power from a power supply and for providing current to drive a first laser; and

a switch located between the power supply and the control circuit,

wherein the switch is used to control the current provided to the laser.

42. The laser driver for driving a laser of claim 41, the laser driver further comprising:

a second control circuit for receiving power from the power supply and for providing current to drive a second laser, wherein the second control circuit is coupled to the power

supply with no switch between the second control circuit and the power supply.

43. The laser driver for driving a laser of claim 42 wherein the switch deactivates the first control circuit upon assertion of a power down select signal, while the second control circuit is not affected by the power down select signal.

44. A laser driver for driving a laser comprising:

a first feedback loop for adjusting a modulation current provided to the laser; and

a second feedback loop for adjusting a bias current provided to the laser.

45. The laser driver for driving a laser of claim 44 wherein the modulation current and the bias current are used to drive an array of lasers.

46. The laser driver for driving a laser of claim 44 wherein the modulation current is adjusted to control a peak-to-peak amplitude of a laser output.

47. The laser driver for driving a laser of claim 44 wherein the bias current is adjusted to control an average optical power of a laser output.

48. The laser driver for driving a laser of claim 44 further comprising an array of laser drivers, each laser driver for driving a corresponding laser, wherein the first feedback loop and the second feedback loop are used to adjust the modulation and bias currents for the array of laser drivers.

49. The laser driver for driving a laser of claim 44 wherein the first feedback loop includes a transimpedence amplifier (TIA) for converting a current generated by a feedback light into a feedback voltage used to adjust the modulation current.

50. The laser driver for driving a laser of claim 44 wherein the second feedback loop includes an amplifier for generating a feedback voltage used to adjust the bias current.

51. The laser driver for driving a laser of claim 48 wherein a particular laser corresponding to a particular laser driver is used to provide a feedback light to both the first and second feedback loops.

52. The laser driver for driving a laser of claim 48 wherein data transmitted using the laser has a pseudo random signal format or a format in which the data has a high statistical probability of having a sufficient number of consecutive "1's" so as to sufficiently charge a charge accumulation capacitor to enable detection of a value that is close to a peak value of a laser output.

53. The laser driver for driving a laser of claim 48 further comprising a control laser driver for driving a control laser, wherein the control laser is used to provide a feedback light to both the first and second feedback loops, and an oscillation frequency of a signal that drives the control laser driver is significantly lower than a frequency of a data signal provided to the array of laser drivers.

54. The laser driver for driving a laser of claim 52 wherein capacitance of the charge accumulation capacitor is adjusted to control a discharge time of the charge accumulation capacitor.

55. The laser driver for driving a laser of claim 52 wherein a base leakage current of a transistor is used to discharge the charge accumulation capacitor so as to lengthen a discharge time of the charge accumulation capacitor.

56. A laser driver for driving a laser comprising:

first circuitry for receiving approximately 2.5V power to perform various laser driver functions; and

second circuitry for receiving approximately 3.3V power to perform laser output stage functions.

57. A laser driver for driving a longwave VCSEL comprising:

control circuitry; and

laser output circuitry,

wherein a voltage lower than a typical low voltage for shortwave VCSEL is used to power the laser driver.

58. The laser driver for driving a longwave VCSEL of claim 57 wherein the voltage lower than the typical low voltage for shortwave VCSEL is less than or equal to approximately 1.5V.

59. The laser driver for driving a longwave VCSEL of claim 18 wherein a direct coupling is used to provide power to the laser driver so as to reduce power consumption associated with ac coupling.

60. A laser driver for driving a laser comprising:

A PNP current mirror to supply current for driving the laser, wherein the PNP current mirror includes a feedback resistor that can be adjusted to flatten a low frequency dip in an ac magnitude response of a laser output.

61. An integrated circuit comprising:

means for setting a bias current and a modulation current and for delivering each of said bias current and said modulation current to each laser driver of an array of laser drivers, each laser driver driving a laser of a corresponding array of lasers;

means for accepting P_{avg} information regarding an average optical output power of said lasers of said array of lasers;

means for accepting $P_{peak-peak}$ information regarding peak-peak power amplitude of said optical output of said lasers of said array of lasers;

means for adjusting said bias current based upon said P_{avg} information; and

means for adjusting said modulation current based upon said $P_{peak-peak}$ information.

62. The integrated circuit as in claim 61, further comprising a photodetector and associated circuitry capable of developing said P_{avg} information and said $P_{peak-peak}$ information.

63. The integrated circuit as in claim 61, wherein said lasers comprise VCSELs.

64. The integrated circuit as in claim 61, further comprising:

a further laser;

means for providing a pilot signal having a first frequency to said further laser; and

means for delivering a data signal to each laser of said array of lasers, each data signal having a second frequency being greater than said first frequency,

wherein said P_{avg} information and $P_{peak-peak}$ information are obtained from light emitted from said further laser.

65. A method for driving a VCSEL comprising:

providing a VCSEL and a corresponding VCSEL driver;

providing a bias current and a modulation current to said VCSEL driver to effectuate said VCSEL emitting a light signal including a first average power level and a first peak-to-peak power amplitude;

providing a data signal having a first data rate to said VCSEL driver;

detecting a second average power level and a second peak-to-peak power amplitude of a light signal emitted from a further VCSEL responsive to a further data signal having a further data rate being less than said first data rate; and

adjusting each of said bias current and said modulation current to maintain said VCSEL emitting light at said first average power level and said first peak-to-peak power amplitude based on said detecting.

66. A method for driving a VCSEL, comprising:

(a) providing a VCSEL and a corresponding VCSEL driver;

(b) providing each of a bias current and a modulation current to said VCSEL driver;

(c) providing a data signal having a first data rate being greater than 2.0 GBPS to said VCSEL driver;

(d) detecting an average power and a peak-to-peak power amplitude of an optical signal emitted by said VCSEL using a photodetector operating at a data rate being less than said first data rate; and

(e) adjusting each of said bias current and said modulation current to urge said VCSEL to emit a light signal having a desired average power and a desired peak-to-peak power amplitude.

* * * * *

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(54) **METHOD OF CONTROLLING THE TURN OFF CHARACTERISTICS OF A VCSEL DIODE**

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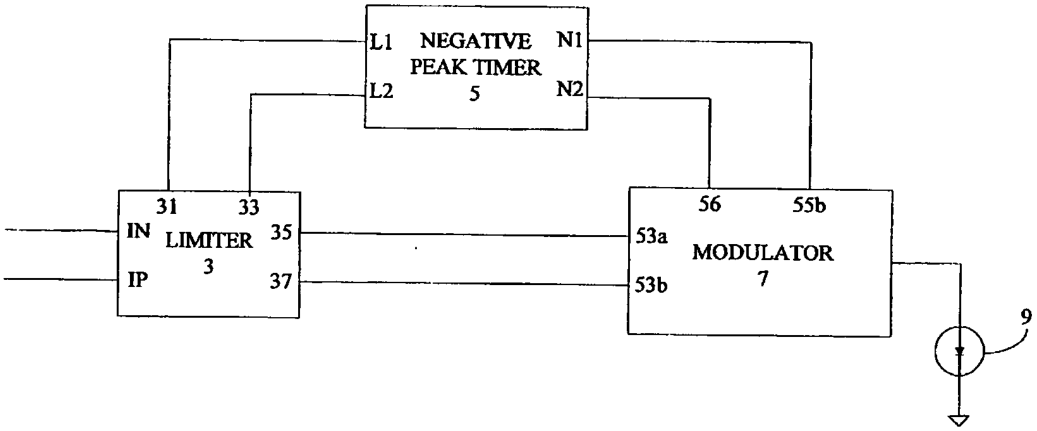
Publication Classification

(51) **Int. Cl.**^{7} **H01S 5/00**

(52) **U.S. Cl.** **372/38.02**; 372/43

(57) **ABSTRACT**

A drive circuitry that drives a vertical cavity surface emitting laser is provided. The drive circuitry includes a modulator, a negative peak timer and a limiter. The negative peak timer causes the modulator to rapidly decrease the magnitude of the output signal of the modulator to dissipate charge stored on the laser. Thus, the vertical cavity surface emitting laser quickly turns off.



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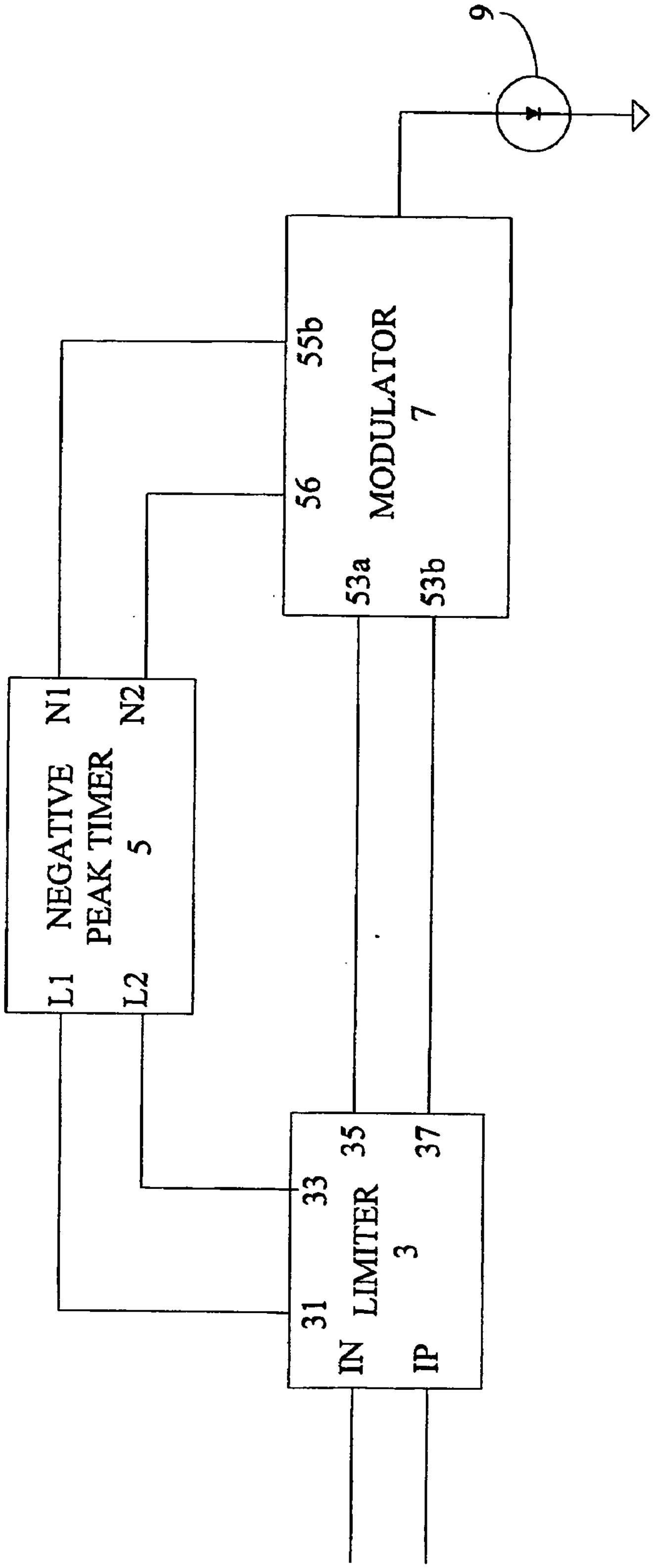
706.02(f)(1)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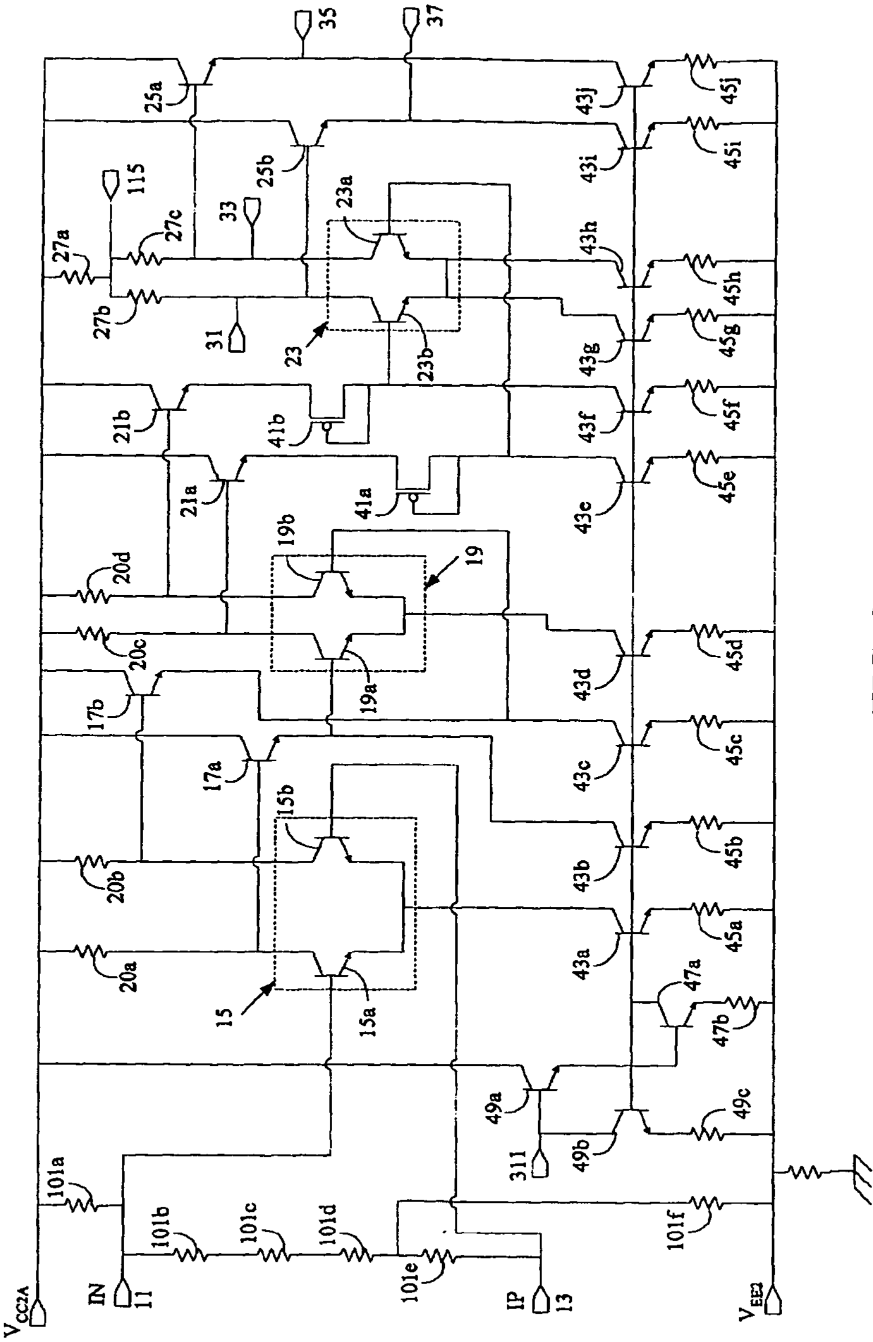
MODULATOR
7
55b
56
53a
53b
NEGATIVE
PEAK TIMER
5
N1
N2
L1
L2
LIMITER
3
31
33
35
37
IN
IP

FIG. 1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45h
43g
45g
21b
41b
43f
45f
21a
41a
43e
45e
19b
19
20d
20c
19a
43d
45d
17b
17a
43c
45c
15b
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43b
45b
43a
45a
20a
15
15a
47a
47b
49a
311
49b
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101d
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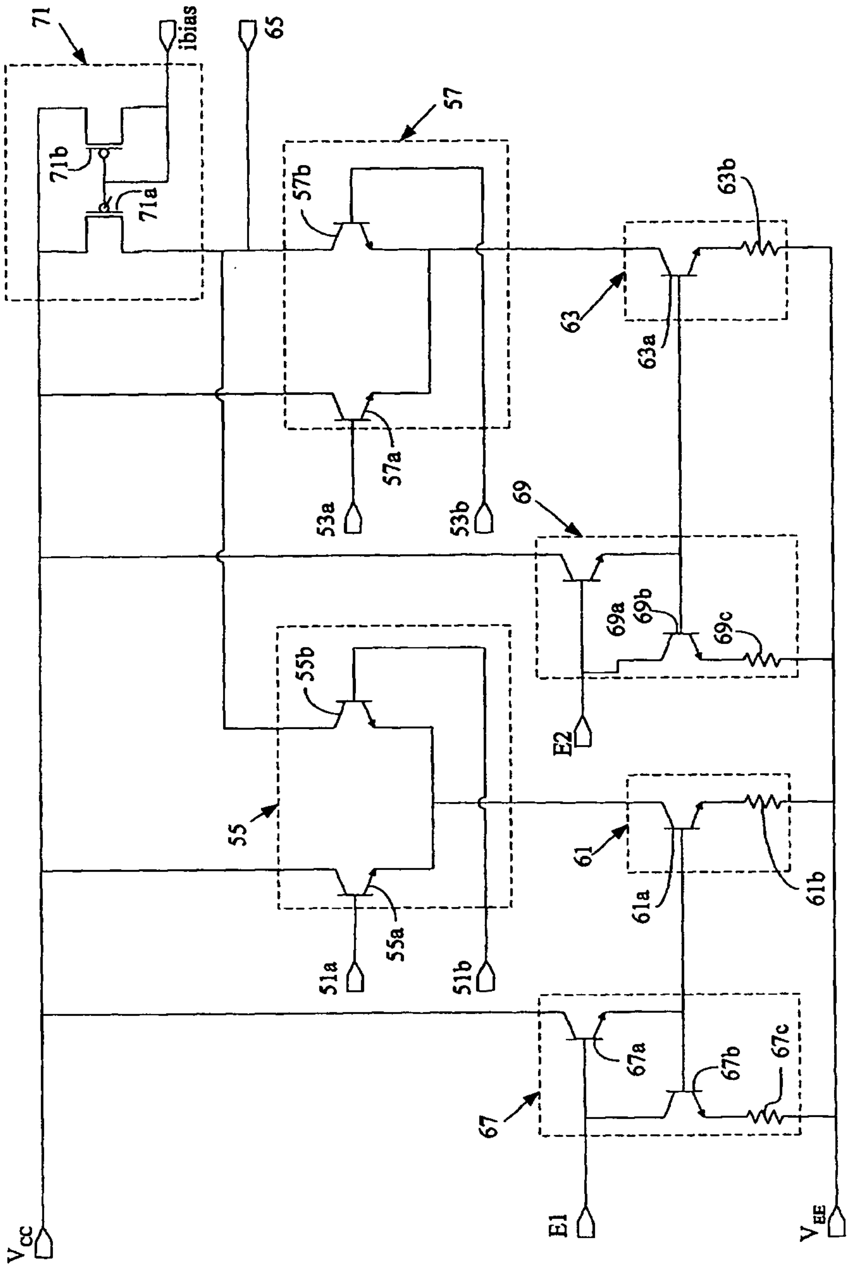
101f
V_CC2A
IN
11
IP
13
V_EE2

FIG. 2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69b
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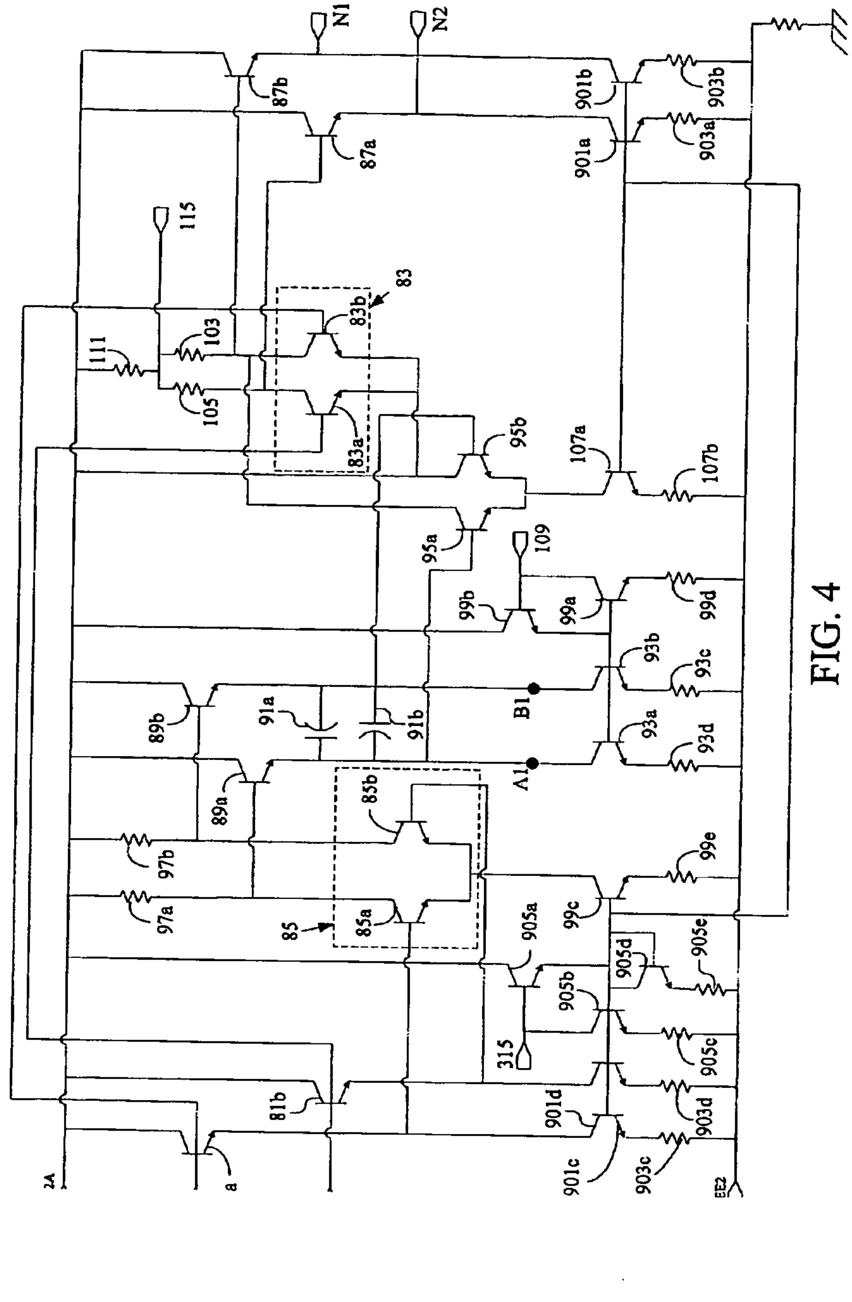
55b
55
61
61a
61b
55a
51a
51b
67
67a
67b
67c
E2
E1
V_{CC}
V_{EE}

FIG. 3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N2
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87a
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901a
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903a
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83a
111
103
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107b
109
99b
99a
99d
93b
93c
89b
91a
91b
B1
A1
93a
93d
89a
85b
97b
97a
85
85a
99e
99c
905a
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903c
a
2A
EE2

FIG. 4

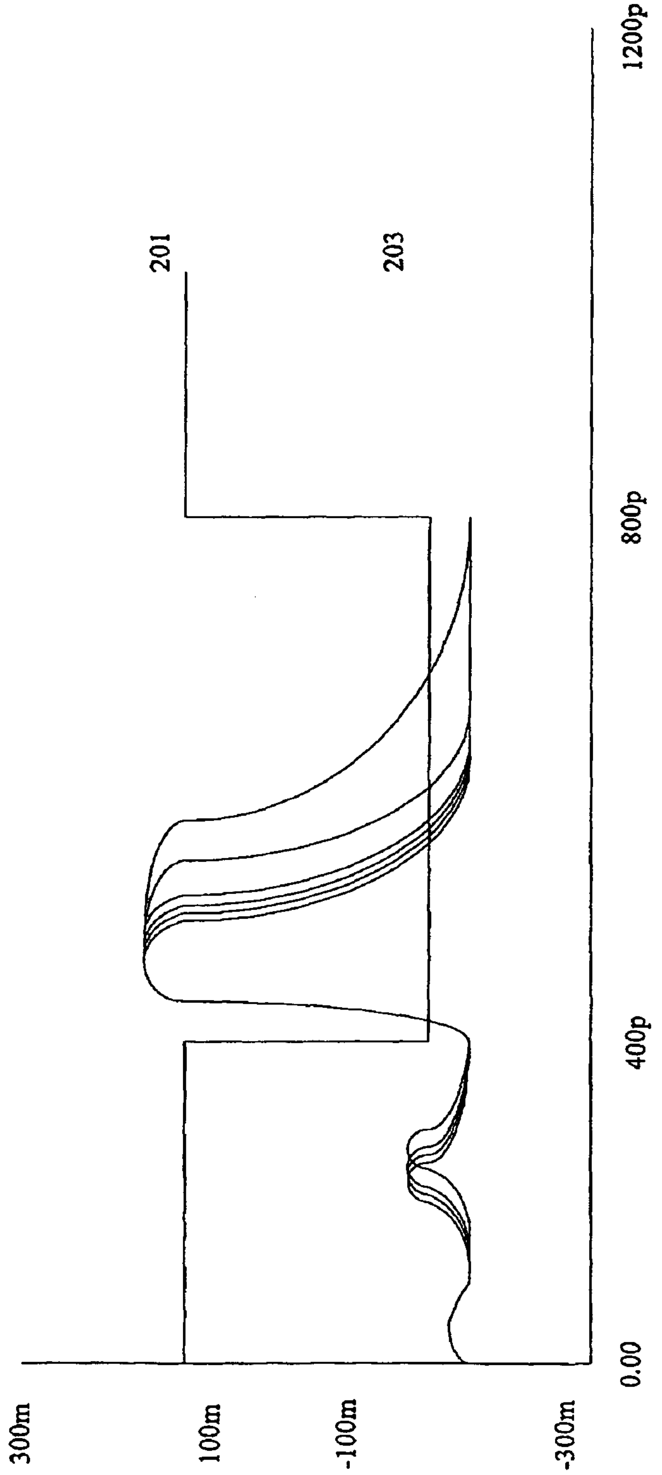

FIG. 5A

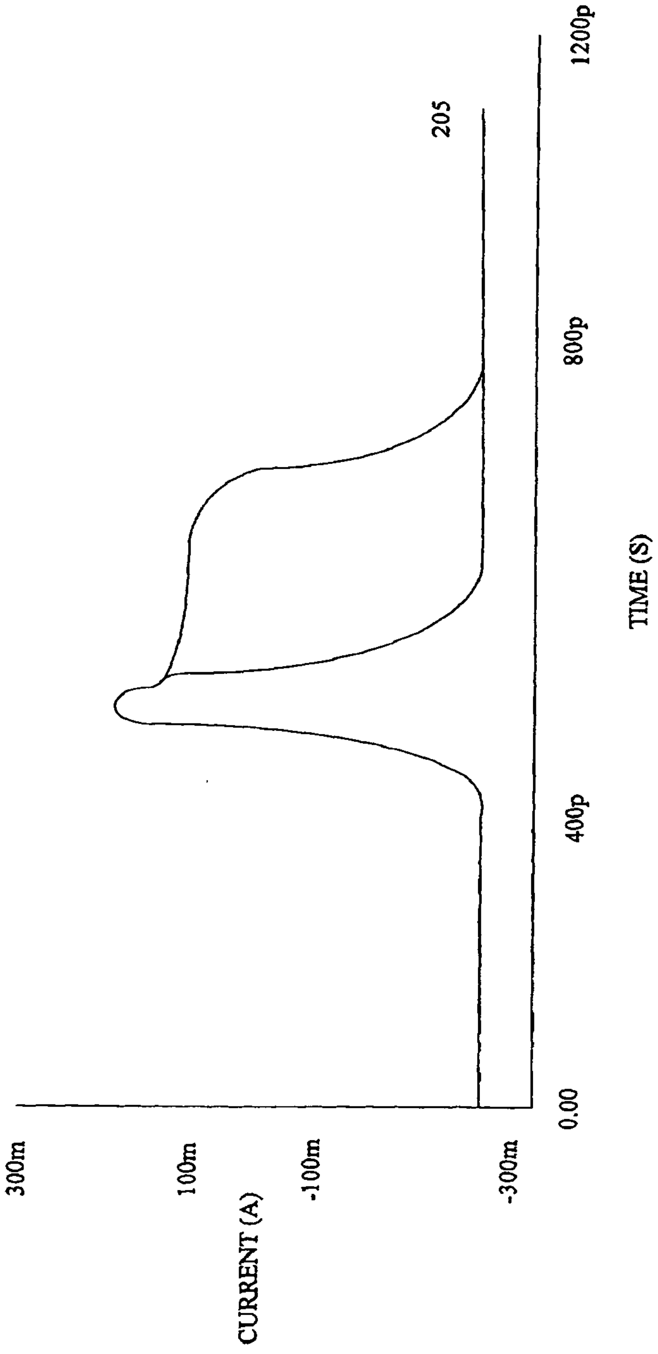

FIG. 5B

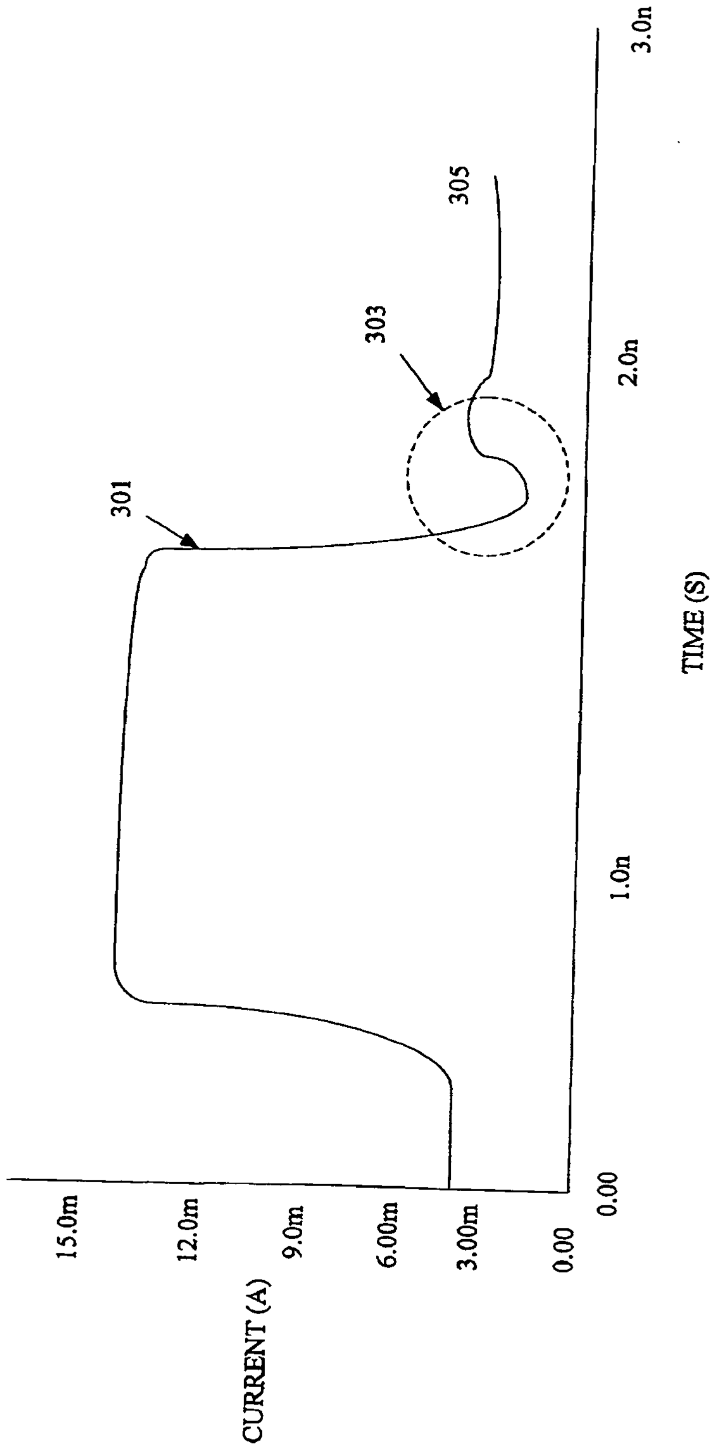
CURRENT (A)
15.0m
12.0m
9.0m
6.00m
3.00m
0.00
0.00
1.0n
2.0n
3.0n
TIME (S)
301
303
305

FIG. 6

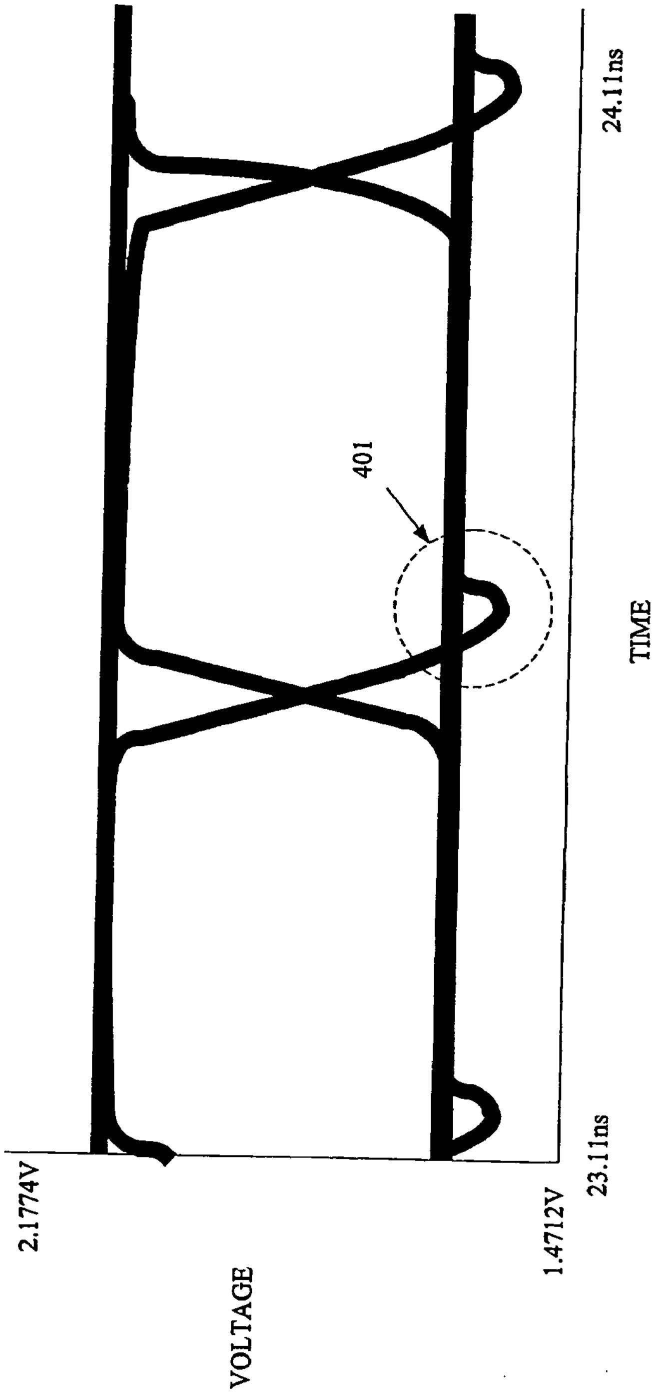

FIG. 7

METHOD OF CONTROLLING THE TURN OFF CHARACTERISTICS OF A VCSEL DIODE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuing application of U.S. patent application Ser. No. 10/012,776 filed Nov. 6, 2001 which claims the benefit of U.S. provisional applications No. 06/246,301 filed Nov. 6, 2000, No. 06/246,325 filed Nov. 6, 2000 and No. 06/246,407 filed Nov. 6, 2000, which are hereby incorporated by reference as if set forth in full herein.

BACKGROUND

[0002] The present invention relates generally to semiconductor lasers, and, in particular, to methods and circuits to decrease the turn off time for a vertical cavity surface emitting laser.

[0003] Semiconductor lasers are widely used in high speed data communications. Modulated light from the lasers are used to carry information through fiber optic lines. For some data formats, generally, when a laser emits light the data value is considered a logical one and when the laser is largely off the data value is considered a zero.

[0004] Vertical cavity surface emitting lasers (VCSELs) are one type of laser used in data communication networks. VCSELs are generally relatively easy to manufacture using semiconductor processes. Drive circuitry for VCSELs provide a VCSEL with sufficient current to turn "on", i.e., causing the VCSEL to emit light. Likewise, the drive circuitry removes or prevents current from flowing to the VCSEL to turn the VCSEL to turn "off", i.e., causing the VCSEL to largely not emit light. However, when VCSELs turn on, electrical charge is stored on the anode of the VCSEL. Removing this electrical charge decreases the turn-off time of the VCSEL, and thereby increases the maximum data rate the VCSEL can support. Furthermore, removing the excess charge can be difficult as it is often desirable to maintain a low bias current when the VCSEL is in the "off" state. The bias current allows the VCSEL to be turned on faster. Thus, although the extra electrical charge is removed from the VCSEL to turn off the VCSEL, bias current to the VCSEL still should be maintained.

SUMMARY OF THE INVENTION

[0005] The present invention provides methods and systems for driving semiconductor lasers such that turn-off time of a laser is decreased. In one embodiment, a drive circuitry that drives a semiconductor laser is provided. The drive circuitry includes a modulator coupled to the semiconductor laser and generates an output signal to control the semiconductor laser. A negative peak timer is coupled to the modulator and a limiter is coupled to the negative peak timer and the modulator. The negative peak timer causes the modulator to rapidly decrease magnitude of the output signal of the modulator to turn off the semiconductor laser.

[0006] In another embodiment, a drive circuitry is provided that drives a semiconductor laser. The drive circuitry includes a limiter which receives a differential input and is configured to generate first differential output signals and second differential output signals. A negative peak timer is coupled to the limiter and receives the first differential signals from the limiter. The negative peak timer is also configured to generate third differential output signals. A modulator is also coupled to the limiter and the negative peak timer and receives the second differential output signals from the limiter and the third differential output signals from the negative peak timer. The modulator is also configured to generate an output pulse. A vertical cavity surface emitting laser is coupled to the modulator and receives the output pulse from the modulator to turn the laser on and off. The modulator is also configured to remove excess charge stored when the vertical cavity surface emitting laser is turned off. In one aspect of the invention, the output pulse is a voltage pulse that has an adjustable undershoot. The adjustable undershoot is determined by a negative peaking pulse from the negative peak timer.

[0007] In another embodiment, a method of driving a semiconductor laser is provided. An output signal is generated from a modulator to control the semiconductor laser. The modulator causes a rapid decrease in magnitude of the output signal of the modulator to turn off the semiconductor laser.

[0008] Many of the attendant features of this invention will be more readily appreciated as the same becomes better understood by reference to the following detailed description and considered in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] **FIG. 1** illustrates a block diagram of drive circuitry for a semiconductor laser;

[0010] **FIG. 2** illustrates a circuit diagram of one embodiment of the limiter of **FIG. 1**;

[0011] **FIG. 3** illustrates a circuit diagram of one embodiment of the modulator of **FIG. 1**;

[0012] **FIG. 4** illustrates a circuit diagram of one embodiment of the negative peak timer of **FIG. 1**;

[0013] **FIG. 5*a*** illustrates a timing diagram of the output pulse generated by the negative peak timer of **FIG. 4**;

[0014] **FIG. 5*b*** illustrates a graphical representation of the collector current of transistor **55*b*** of **FIG. 3**;

[0015] **FIG. 6** illustrates a graphical representation of the output current from the modulator of **FIG. 3** that is supplied to a semiconductor laser; and

[0016] **FIG. 7** illustrates a graphical representation of an eye diagram of the output voltage of the drive circuitry of **FIG. 1**.

DETAILED DESCRIPTION

[0017] **FIG. 1** illustrates a block diagram of drive circuitry for a semiconductor laser. The drive circuitry includes a limiter **3**, a negative peak timer **5**, and a modulator **7**. The drive circuitry provides a signal to a vertical cavity service emitting laser (VCSEL) **9**. The limiter **3** receives an input signal, a differential input signal as illustrated in **FIG. 1**, and generates two differential output signals. One of the differential output signals is supplied to the negative peak timer. The other differential output signal is supplied to the modulator. The negative peak timer generates an output pulse having an adjustable pulse width which is supplied to the modulator. Based on the output pulse from the negative peak timer and the differential output signal from the limiter, the modulator generates current to drive the VCSEL.

[0018] **FIG. 2** illustrates a circuit diagram of one embodiment of the limiter of **FIG. 1**. The limiter receives a differential input at inputs IN **11** and IP **13** which are supplied to bases of transistors **15*a*** and **15*b***. The resistors **101*a-f*** are coupled to inputs **11** and **13** and the potentials V_{CC2A} and V_{EE2}, and form voltage dividers that provides sufficient biasing for transistors **15*a*** and **15*b***. The resistors also provide impedance matching to improve the quality of signals received at IN and IP.

[0019] As transistors **15*a*** and **15*b*** receive a differential signal, the transistors **15*a*** and **15*b*** turn on and off at different times. In other words, transistors **15*a*** and **15*b*** form a differential pair **15**. The collector of transistor **15*a*** is coupled to the base of emitter follower transistor **17*a***. Similarly, the collector of transistor **15*b*** is coupled to the base of emitter follower transistor **17*b***. Accordingly, voltage is provided by the respective transistors **15*a*** and **15*b*** to the transistors **17*a*** and **17*b***. The voltage level of the provided voltage is based on transistor **43*a*** and resistor **45*a*** acting as a current source and resistors **20*a*** and **20*b*** coupled to voltage potential V_{CC2A}.

[0020] The emitter of transistor **17*a*** is coupled to the base of transistor **19*a*** and the emitter of transistor **17*b*** is coupled to the base of transistor **19*b***. Transistors **19*a*** and **19*b*** form the differential pair **19**. The transistor **17*a*** and **17*b*** level shift the voltage from the differential pair **15** and allow connection from the collector load resistors, resistors **20*a*** and **20*b***, of the differential pair **15** to be applied to the differential pair **19**. Similar to the differential pair **15**, the differential pair **19** turn on and off based on the differential signals applied to the respective bases of the transistors **19*a*** and **19*b***.

[0021] Voltage from the differential pair **19** is supplied to the emitter follower transistors **21*a*** and **21*b***. The voltage level of the supplied voltage is based on the transistor **43*d*** and resistor **45*d*** acting as a current source and resistors **20*c*** and **20*d*** coupled to voltage V_{CC2A}. Transistors **21*a*** and **21*b*** level shift the voltage from the differential pair **19** and allow connection from the collector load resistors, resistors **20*c*** and **20*d***, of the differential pair **19** to be applied to differential pair **23**. FET **41*a*** and **41*b***, respectively coupled to the emitters of transistors **21*a*** and **21*b*** further effect a level shift to the voltage from the differential pair **19**, which is supplied to differential pair **23**. Differential pair **23** is formed by transistors **23*a*** and **23*b***. Voltage output from the differential pair **23** is based on the transistors **43*g,h*** and resistors **45*g,h*** acting as current sources and resistors **27*a-c*** coupled to voltage V_{CC2A}. The voltage is also supplied as an output via outputs **31** and **33** to a negative peak timer (**FIG. 1**).

[0022] Additionally, the voltage is supplied to respective emitter follower transistors **25*a*** and **25*b***. Like the other emitter follower transistors **25*a*** and b respectively level shift the voltage from the differential pair **23** and output the voltage via outputs **35** and **37** to a modulator (**FIG. 1**). Resistor **27*a*** provides a common mode level shift for outputs **31, 33, 35** and **37**.

[0023] The emitters of transistors **43*a-j*** are coupled to the respective resistors **45*a-j*** and act as current sources. For instance, when emitter follower transistors **17*a,b*, 21*a,b*,** and **25*a,b*** are on, current is forced through the transistors by respective current sources, transistors **43*b,c,e,f,i*** and *j*. Transistors **49*a,b*** and **47*a*** and resistors **47*b*** and **49*c*** bias transistors **43*a-j*** based on current from input **311**. Therefore, the input **311** allows for control of currents provided by transistors **43*a-j***.

[0024] Thus, the limiter receives differential input signals via inputs **11** and **13** and amplifies and shapes the inputs using differential pairs **15, 19,** and **23** and emitter follower transistors. As a result, the limiter generates output voltage pairs at outputs **31, 33, 35** and **37**, with the voltage at outputs **35** and **37** being in phase with outputs **31** and **33** but with a DC level voltage difference, the base to emitter voltage of respective transistors **25*a*** and **25*b***.

[0025] **FIG. 3** illustrates a circuit diagram of one embodiment of the modulator of **FIG. 1**. The modulator includes two differential amplifiers **55** and **57**. The first differential amplifier includes transistors **55*a*** and **55*b***. Likewise, the second differential amplifier includes transistors **57*a*** and **57*b***. Bases of transistors **55*a*** and **55*b*** receive respective differential inputs **51*a*** and **51*b***. Bases of transistors **57*a*** and **57*b*** also receive respective differential inputs **53*a*** and **53*b***. The output of both differential amplifiers **55** and **57** are coupled to the modulator output **65**. The first and second differential amplifiers **55** and **57** are respectively coupled to current sources **61** and **63**. Source **61** includes transistor **61*a*** and resistor **61*b*** and load **63** includes transistor **63*a*** and resistor **63*b***. The sources **61** and **63**, respectively, set the current for the respective differential amplifiers **55** and **57**. Sources **61** and **63** are coupled to respective current mirror circuits **67** and **69**. Mirror circuit **69** includes transistors **67*a*** and **67*b*** and resistor **67*c***. Transistor **67*a*** receives a current from input E1. Likewise, mirror circuit **69** includes transistors **69*a*** and **69*b*** and resistor **69*c***. The base of transistor **69*a*** receives a current from input E2.

[0026] The modulator also includes a current mirror **71** which includes transistors **71*a*** and **71*b***. Current flowing through transistor **71*b*** is mirrored by transistor **71*a***. The current mirror **71** supplies a bias current at the drain of transistor **71*a***. The current mirror is controlled by an ibias input coupled to the gates of the transistors **71*a,b***. The output signal **65** is coupled to the drain of transistor **71*a***. Also coupled to the drain of transistor **71*a*** are the differential amplifiers **55** and **57**. Thus, the output signal **65** depends on the input signals **51*a*, 51*b*** and **53*a*, 53*b*** and the extent to which the differential amplifiers **55** and **57** pull current from the current mirror **71** and the output **65**. In one embodiment, the differential signals **51*a*** and **51*b*** are both aligned with the falling edge of the differential signals **53*a*** and **53*b***. The amplitude of the output current thus corresponds to the drain current flowing through transistor **71*a*** minus the collector current flowing through transistor **57*b*** and the collector current flowing through transistor **53*b***. Also, the shape of the output current is determined by the input signals **51*a*, 51*b*, 53*a*** and **53*b***. Thus, the modulator turns the semiconductor laser on or off using output **65** based on the differential inputs **51*a*** and **51*b*** received from the negative peak timer and the differential input signals **53** and **53*b*** received from the limiter.

[0027] **FIG. 4** illustrates a circuit diagram of one embodiment of the negative peak timer of **FIG. 1**. The negative peak timer receives differential inputs L1 and L2 from the limiter of **FIG. 1**. The negative peak timer subsequently provides differential outputs N1 and N2 which are supplied to the modulator of **FIG. 1**. The differential inputs are buffered by respective transistors **81***a* and **81***b*. The emitters of transistors **81***a* and b are coupled to the collectors of the respective transistors **901***c,d* which are coupled to the respective resistors **903***c,d* and act as current sources. The differential inputs are also supplied to a differential amplifier **83**. The differential amplifier includes transistors **83***a* and **83***b*. Current flowing through respective transistors **81***a* and **81***b* are also supplied to inputs of a differential amplifier **85**. Differential amplifier **85** includes transistors **85***a* and **85***b*. Differential outputs from differential amplifier **83** are supplied to transistors **87***a* and **87***b*. Likewise, differential outputs from the differential amplifier **85** is supplied to transistors **89***a* and **89***b*. Two capacitors **91***a* and **91***b* are coupled in parallel and coupled to the sources of transistors **89***a* and **89***b* together. Also, coupled, respectively, to transistors **89***a* and **89***b* are transistors **93***a* and **93***b*. The transistors **93***a* and **93***b* are respectively coupled to resistors **93***c* and d and act as current sources for the respective transistors **89***a* and **89***b*. The capacitors **91***a* and **91***b* couples node A1 to node B1.

[0028] The signal swing is determined by resistors **97***a* and **97***b* respectively coupled to bases of transistors **89***a* and **89***b* and the current set by the transistor **99***c* and the resistor **99***e*, acting as a current source. Transistors **905***a,b,d* and resistors **905***c* and **905***e* sufficiently bias transistor **99***c* based on the input signal from input **315**. The capacitors **91***a* and **91***b* cause a slope to be added to the original input signal provided at inputs L1 and L2. By adjusting the amount of collector current of transistors **93***a* and **93***b*, the slopes of current at nodes A1 and B1 also change. Higher collector current causes the capacitors **91***a* and **91***b* to charge faster which thus causes shorter rise and fall times. Conversely, lower collector currents cause the capacitors to charge slower and thus cause longer rise and fall times. Transistors **99***a* and **99***b* and resistor **99***d* control the amount of current flowing through transistors **93***a* and **93***b* and respective resistors **93***d* and **93***c*, based on the input **109** provided to the transistors. Nodes A1 and B1 are coupled to transistors **95***a* and **95***b* and are compared to the differential inputs supplied to transistors **83***a* and **83***b*. The time delay between the differential signals at node A1 and node B1, as compared to the differential inputs L1 and L2, are thus used to generate the pulse output N1 and N2. The pulse output is proportional to the capacitors **91***a* and **91***b* and collector currents of transistors **99***c* and **93***b*.

[0029] Initially, transistors **83***a* and **95***a* are both on. A voltage drop is thus caused at resistors **103** and **ill** as the collector current of transistor **95***a* flows through resistors **103** and **111**. Initially, no current flows through transistor **83***a*. When the input signal L1 and L2 changes polarity, transistor **83***b* turns on. However, due to the time delay on nodes A1 and B1, current continues to flow through transistor **95***a* and resistors **103** and **111**. Thus, voltage drop on resistors **103** and **111** remains. Once the time delay has ended, transistor **95***b* turns on. As a result, current is routed to transistor **83***b* and voltage drop on resistors **103** and **111** persists. When the input signal L1 and L2 changes polarity again, current from transistor **95***b* is routed through transistor **83***a* thus causing a voltage drop on resistors **105** and **111**, as current flows through the resistors. When the time delay has passed, the transistor **95***a* turns on and a voltage drop on the resistors **103** and **111** is generated, as collector current flows through the resistor. As a result, a differential voltage is generated between the two transistors **87***a* and **87***b*. The differential voltage has an amplitude that corresponds to the voltage drop on the resistors **103** and **105**. The transistors **87***a* and **87***b* thus drive the modulator coupled to the negative peak timer. The transistors **87***a* and **87***b* also provide level shifting. In one embodiment, the value of the resistors **103** and **105** correspond to each other and to a predetermined resistance value. As such, the resistor has a constant differential signal swing equal to the current determined by the transistor **107***a* times the predetermined resistance value. The transistors **107***a* coupled to resistor **107***b* act as a current source for the differential amplifier comprised of transistors **95***a* and **95***b*. Similarly, transistors **901***a* and **901***b* are respectively coupled to resistors **901***a* and **901***b* and act as current sources for the respective transistors **87***a* and **87***b*.

[0030] **FIG. 5***a* illustrates a timing diagram of the output pulse **203** generated by the negative peak timer of **FIG. 4**. Voltage levels **201** of the output pulse are shown in relation to various levels of current applied to transistors **99***a* and **99***b*. The pulse width changes inversely to the current applied to the transistors **99***a* and **99***b*.

[0031] **FIG. 5***b* illustrates a graphical representation of the collector current **205** of transistor **55***b* of **FIG. 3**. The collector current is directly affected by the output pulse from the negative peak timer of **FIG. 4**. By adjusting the collector current of transistor **61***a*, the magnitude of the collector current of transistor **53***b* may be adjusted. As discussed in reference to **FIG. 3**, the collector current of transistor **53***b* is subtracted from the current supplied by the transistor **71***a*. As such, an increase in the collector current of transistor **53***b* causes a decrease in the current supplied by transistor **71***a* to the output of the modulator. Thus, as the semiconductor laser is turning off, the amount of collector current of transistor **53***b* controls the depth of a negative peak which in turn decreases the speed at which the semiconductor laser turns off.

[0032] **FIG. 6** illustrates a graphical representation of the output current from the modulator of **FIG. 3** that is supplied to a semiconductor laser. The current signal **305** that graphically represents the current from the output of the modulator describes a pulse in which the semiconductor laser is turned on at approximately 4 nano seconds from an arbitrary starting point and begins to turn off at approximately 1.6 nano seconds. The slope **301***a* is close to one, i.e., vertical thus represents a rapid fall time. Undershoot **303** represents the effect on the output current of the modulator by the negative peak timer.

[0033] **FIG. 7** illustrates a graphical representation of an eye diagram of the output voltage of the drive circuitry of **FIG. 1**. Undershoot **401** of the eye diagram illustrates the effect of the negative peak timer on the output from the modulator. As previously discussed, the undershoot causes the semiconductor laser to turn off quickly as current supplied to the semiconductor laser is removed faster than it was supplied to the laser when the laser was turned on. Also, the amount of current is significantly below the amount of bias current supplied to the semiconductor laser and thus charge stored on the semiconductor laser is quickly removed.

[0034] Accordingly, the present invention provides methods and systems that decrease the turn off time for a vertical cavity surface emitting laser. Although this invention has been described in certain specific embodiments, many additional modifications and variations would be apparent to those skilled in the art. For instance, although bipolar devices are illustrated and described, CMOS devices could be used instead to provide the same functionality, but perhaps for a lower data rate. It is therefore to be understood that this invention may be practiced otherwise than as specifically described. Thus, the present embodiments of the invention should be considered in all respects as illustrative and not restrictive. The scope of the invention to be determined by the appended claims, their equivalents and claims supported by the specification rather than the foregoing description.

What is claimed is:

1. A drive circuitry driving a semiconductor laser, the drive circuitry comprising:

a modulator coupled to the semiconductor laser and generating an output signal to control the semiconductor laser;

a negative peak timer coupled to the modulator;

a limiter coupled to the negative peak timer and the modulator;

wherein the negative peak timer causes the modulator to rapidly decrease magnitude of the output signal of the modulator to turn off the semiconductor laser.

2. The drive circuitry of claim 1 wherein the negative peak timer comprises a plurality of differential amplifiers configured to receive input signals from the limiter and generate an output pulse.

3. The drive circuitry of claim 2 wherein the output pulse has a pulse width having a variable rise and fall time.

4. The drive circuitry of claim 3 wherein the variable rise and fall time is controlled by a plurality of capacitors.

5. The drive circuitry of claim 4 wherein the plurality of capacitors bridge nodes between the output of a first one of the plurality of differential amplifiers to input of a second one of the plurality of differential amplifiers.

6. The drive circuitry of claim 4 wherein the plurality of capacitors accelerate fall times of the output signal of the modulator.

7. The drive circuitry of claim 2 wherein one of the differential amplifiers draws current supplied to the semiconductor laser away from the semiconductor laser.

8. The drive circuitry of claim 1 wherein an undershoot condition is created in which charge stored on the semiconductor laser is dissipated.

9. The drive circuitry of claim 1 wherein the semiconductor laser is a vertical cavity surface emitting laser.

10. A drive circuitry driving semiconductor lasers, the drive circuitry comprising:

a limiter receiving a differential input signal and configured to generate first differential output signals and second differential output signals;

a negative peak timer coupled to the limiter and receiving the first differential output signals from the limiter, the negative peak timer configured to generate third differential output signals;

a modulator coupled to the limiter and the negative peak timer and receiving the second differential output signals from the limiter and the third differential output signals from the negative peak timer, the modulator configured to generate an output pulse; and

a vertical cavity surface emitting laser coupled to the modulator and receiving the output pulse from the modulator turning the vertical cavity surface emitting laser on and off;

wherein the modulator is configured to remove excess charge stored when the vertical cavity surface emitting laser is turned off.

11. The drive circuitry of claim 10 wherein the output pulse is a voltage pulse having an adjustable undershoot.

12. The drive circuitry of claim 10 wherein the output pulse has an variable width and amplitude as determined by the negative peak timer.

13. The drive circuitry of claim 11 wherein the adjustable undershoot is determined by a negative peaking pulse from the negative peak timer.

14. The drive circuitry of claim 11 wherein the adjustable undershoot is determined by a positive peaking pulse from the negative peak timer.

15. A method of driving a semiconductor laser, the method comprising:

generating an output signal from a modulator to control the semiconductor laser; and

causing the modulator to rapidly decrease magnitude of the output signal of the modulator to turn off the semiconductor laser.

16. A drive circuitry driving a semiconductor laser, the drive circuitry comprising:

means for generating an output signal to control the semiconductor laser;

means for causing a rapid decrease in magnitude of the output signal of the modulator to turn off the semiconductor laser.

* * * * *

United States Patent [19]
Uebbing

[11] **Patent Number:** **4,952,949**
[45] **Date of Patent:** **Aug. 28, 1990**

[54] **LED PRINTHEAD TEMPERATURE COMPENSATION**

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[73] Assignee: **Hewlett-Packard Company**, Palo Alto, Calif.

[21] Appl. No.: **442,197**

[22] Filed: **Nov. 28, 1989**

[51] **Int. Cl.^{5}** **G01D 15/14**
[52] **U.S. Cl.** **346/154**
[58] **Field of Search** .... 346/154, 160, 107 R; 355/1; 400/53; 358/300

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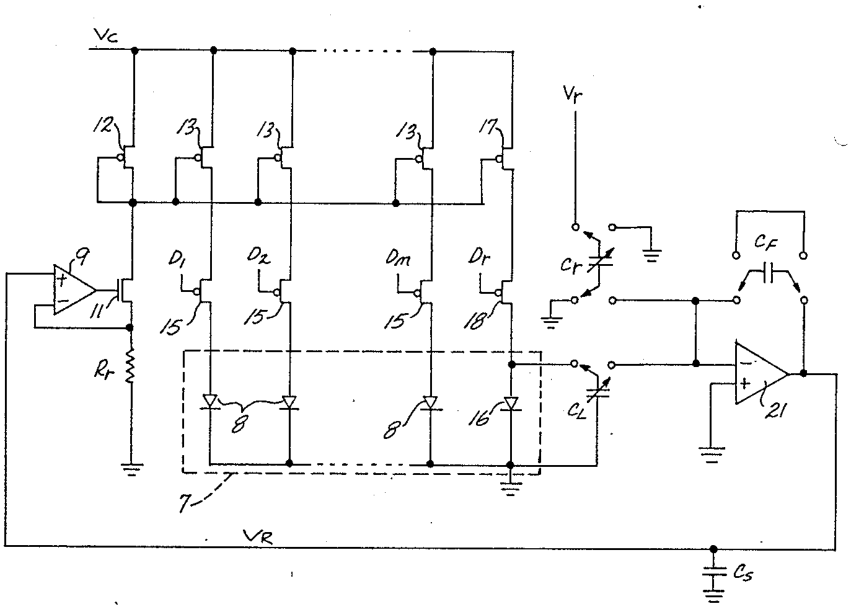
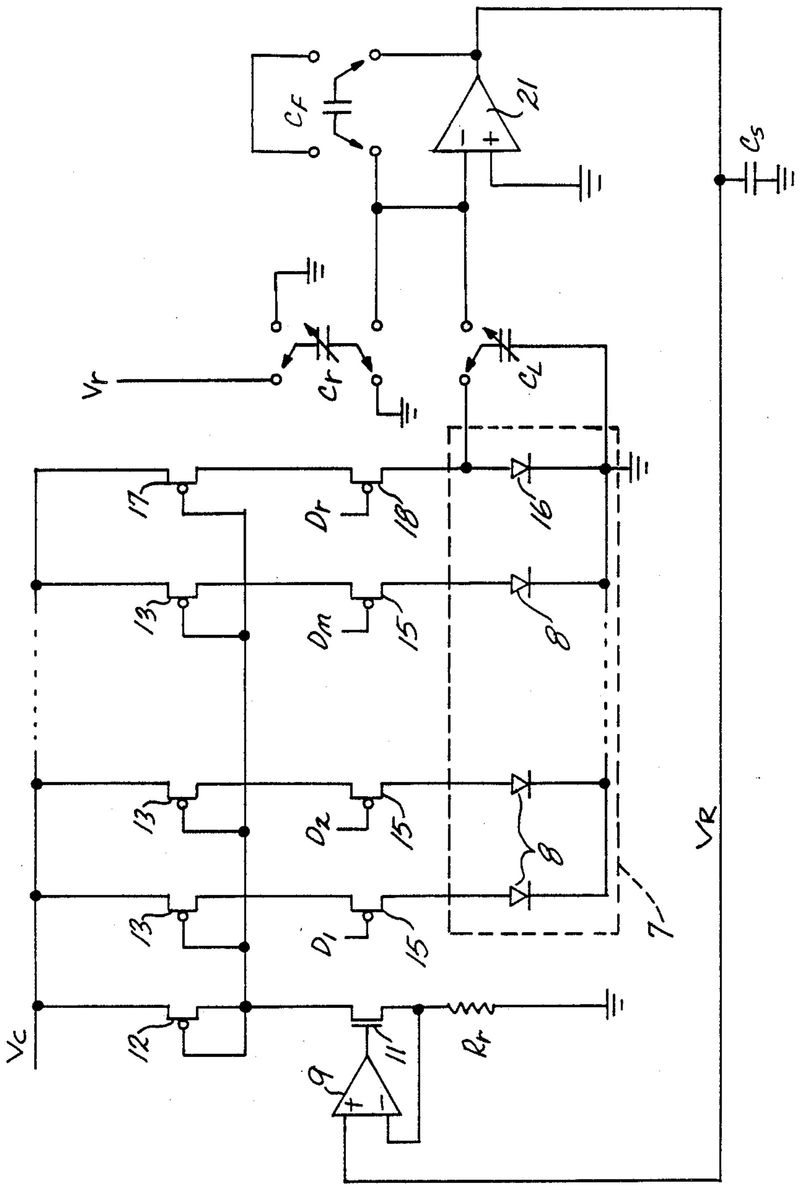
Primary Examiner—Donald A. Griffin

[57] **ABSTRACT**

The light output of light emitting diodes on an LED printhead for a photosensitive printer is temperature compensated so that light output remains constant regardless of temperature changes of the LED chips. An LED chip has a plurality of exposure LEDs and a dummy LED. The voltage across the dummy LED is sensed and combined with an adjustable reference voltage. This provides the input to an op-amp, the output of which provides a chip reference voltage which controls the current to the LEDs.

25 Claims, 1 Drawing Sheet

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LED PRINTHEAD TEMPERATURE COMPENSATION

BACKGROUND OF THE INVENTION

It has become desirable to employ non-impact xerographic or other photosensitive printers for text and graphics. In a xerographic printer, an electrostatic charge is formed on a photoreceptive surface of a moving drum or belt, and selected areas of the surface are discharged by exposure to light. A printing toner is applied to the drum and adheres to the areas having an electrostatic charge and does not adhere to the discharged areas. The toner is then transferred to a sheet of plain paper and is heat-fused to the paper. By controlling the areas illuminated and the areas not illuminated, characters, lines and other images may be produced on the paper.

One type of non-impact printer employs an array of light emitting diodes (commonly referred to herein as LEDs) for exposing the photoreceptor surface. A row, or two closely spaced rows, of minute LEDs are positioned near an elongated lens array so that their images are arrayed across the surface to be illuminated. As the surface moves past the line of LEDs, they are selectively activated to either emit light or not, thereby exposing or not exposing, the photoreceptive surface in a pattern corresponding to the LEDs activated.

To form good images in an LED printer, it is desirable that all of the light emitting diodes produce controlled light output when activated. This assures a uniform quality image all the way across a paper for black and white printing, and control of exposure for grey scale printing. The light output from an LED depends on a number of factors including current and temperature.

Light emitting diodes for print heads are formed on wafers of gallium arsenide or the like, suitably doped to conduct current and emit light. Long arrays of LEDs are formed on a wafer which is cut into separate chips each having an array of LEDs. A row of such chips are assembled end-to-end on the print head. The LEDs are driven by power supplies on nearby integrated circuit chips. Typically, an integrated circuit chip provides constant current for all the LEDs on an LED chip, or sometimes two integrated circuit chips each provide current for half of the LEDs on an LED chip.

The light output of an LED varies with temperature. It is important for some applications such as grey scale printing that the light output be uniform over time. For black and white printing it is important that the light output be reasonably uniform across the width of the printhead. Depending on the past history of power dissipation in the printhead, some LED chips may be much warmer than others, thereby causing a significant nonuniformity in light output. Hence, exposure of the photosensitive medium temperature may also vary with time.

The light output varies as much as −0.9% per degree Centigrade and since appreciable temperature differences may occur during operation of the printhead, there may be substantial exposure differences as temperature varies across the head and as a function of time. It is therefore desirable that compensation be provided for temperature changes that may occur during operation of an LED printhead.

SUMMARY OF THE INVENTION

There is, therefore, provided in practice of this invention according to a presently preferred embodiment, a temperature compensated power supply for a light emitting diode print head. Such a printhead has a plurality of LED chips, each of which has a plurality of exposure LEDs. A dummy diode is provided for each chip with means for passing current through the diode and sensing voltage across the diode. The current passed through the exposure LEDs on the respective chip are then adjusted in response to the sensed voltage across the dummy diode. Preferably the dummy diode is an LED on the same chip as the exposure LEDs.

In an exemplary embodiment, the temperature compensated LED printhead has a compensation op-amp and means for generating a compensation voltage as a function of the sensed voltage. The compensation voltage is applied to the inverting input of the compensation op-amp. The op-amp output is used for generating a chip reference voltage which controls current through the exposure LEDs.

BRIEF DESCRIPTION OF THE DRAWING

These and other features and advantages of the present invention will be appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawing which illustrates a temperature compensated power supply circuit for an LED chip.

DETAILED DESCRIPTION

An exemplary light emitting diode (LED) printer has a printhead with a row of LED chips along its length. An exemplary chip **7** has a plurality of exposure LEDs **8** along its length. The exposure LEDs are selectively activated for exposing the photosensitive surface of a xerographic printer in desired patterns. During printing, selected ones of the LEDs are activated for exposing selected pixels in a row across the surface. A short interval later selected LEDs across the row are again activated. Thus, the exposure comprises a series of rows of exposed dots. There is a brief interval between the rows. During this short interval temperature of the LED chip is sensed in the practice of this invention.

Power is supplied to the LEDs from integrated circuit chips mounted in close proximity to the LED chips. In an exemplary embodiment, an integrated circuit chip is located on each side of each LED chip and contains circuits for delivering current to half of the LEDs on the LED chip. Thus, an exemplary integrated circuit chip may have 48 current sources for the respective LEDs. Such a chip may include a variety of other print head operational circuits which do not form a part of this invention. For example, data signal multiplexing circuits may be included on the chip. The drawing illustrates schematically the power supply portion of an integrated circuit chip for providing current for activating the LEDs on an LED chip. The components illustrated are repeated several times across a printhead.

There may be differences between the various LED chips on the printhead due to processing variables during manufacture of the chips. It may also have different temperatures due to differences in the cycle during printing. Thus, power is separately controlled to each LED chip. Generally it is desirable that the current available for each LED on a chip be substantially the same so that the light output of each LED is substantially the same. For this purpose a plurality of current mirrors controlled by a high reference voltage are employed.

Each integrated circuit chip is provided with a reference resistor R_r, the value of which may be selected for assuring that all of the integrated circuit and LED chips on a given print head produce substantially the same light output.

A portion of the circuits on a representative integrated circuit chip are illustrated in the drawing. In this drawing, the dashed line indicates the portion on the LED chip. The balance or the circuit elements are typically on the integrated circuit chip, except for the reference resistor and a capacitor mentioned later. Contact pads for making connections to the chips are omitted from the drawing, as are many other details of circuits which are not material to an understanding of this invention.

A reference voltage, V_R, is applied to the noninverting input to a difference amplifier **9** (commonly referred to as an op-amp) of a reference current cell on each chip. There is nothing remarkable about the op-amp current controller, and its internal circuits are, therefore, not illustrated. It comprises a conventional comparator circuit, an output buffer for the comparator, a compensation capacitor to prevent oscillations, and a bias circuit for the comparator and buffer. The op-amp circuits are formed by the same processes employed for the balance of the circuitry on the integrated circuit chips.

The op-amp output is connected to the gate of an n-channel insulated gate field effect transistor **11** (IGFET or FET) which acts as a current regulator or current limiter. The source of the n-channel current regulator FET is connected to both the inverting input to the op-amp and the external reference resistor R_r. The drain of the current regulator FET is connected to the drain of a p-channel current source reference FET **12**. The reference FET **12**, as well as other components which provide current to the LEDs, are powered by a current supply voltage, V_c, common to the entire print head.

In the reference current cell the op-amp controls the gate of the n-channel current reference FET **12** and increases or decreases the gate voltage until the voltage at the reference resistor R_r matches the reference voltage V_R at the non-inverting input to the op-amp. The result is a chip reference current equal to V_R/R_r. Thus, the reference current cell produces a chip reference voltage at the drain of the reference FET **12**. The internal or chip reference voltage is not the same as the external or system reference voltage V_R.

The chip reference voltage is tied to the gate of the reference FET. It is also connected to the gate of each of a plurality of similar p-channel output driver FETs **13** which provide current for respective exposure light emitting diodes **8**. By having the gates of all of the output driver FETs **13** tied together to the chip reference voltage, the current for each driver is substantially identical. These can be thought of as current mirrors with the same current flow as in the constant reference current cell, or if desired, scaled to a uniform different current by having different parameters for the output FETs **13** as compared with the parameters of the reference FET **12**.

Each of the output drivers **13** is in series with a p-channel data FET **15**. The data FETs act as switches in response to presence or absence of a data signal D_l, D_2 . . . D_n applied to the gate of the respective data FET. By having independent drivers for each LED, the light output, rise time and the like is substantially identical for all of the LEDs. The current from each driver, and the respective rise and fall time, for each LED is substantially independent of the number of LEDs enabled. Nominal values for the reference resistor and chip reference voltage generate a nominal output current of five milliamps.

In addition to the exposure LEDs **8** on the LED chip, there is a dummy LED **16** which is essentially the same as the exposure LEDs but is covered with an opaque material so that light emitted by the dummy LED does not expose any of the photosensitive surface in the printer. A suitable opaque material is the metal used for making electrical contacts on the LED chip.

The dummy LED is in series with a driver FET **17**, the gate of which is connected to the internal reference voltage, the same as the other driver FETs **13**. The driver FET **17** for the dummy LED differs from the others by providing an appreciably lower current to the dummy LED, for example, in the order of **100** microamperes. The dummy LEd and its driver **17** are in series with a switching FET **18** which has a signal line D_r connected to its gate. During the interval between the periods when the exposure FETs are turned on for exposing a line on the photosensitive surface, the signal D_r switches the switching FET on for providing current to the dummy LED.

The dummy LED is used for sensing the temperature of the LED chip. The thermal conductivity of the chip material is high enough that the chip is substantially isothermal and a single dummy LED may be used for compensating for temperature variations for the entire chip. In an alternative embodiment, more than one dummy LED may be used on the chip and signals combined for providing a more sensitive temperature measurement and common mode rejection.

Temperature of the chip is sensed by sensing the forward voltage V_F across the dummy LED **16**. This voltage is then used to adjust the reference voltage V_R applied to the op-amp **9**. The temperature dependence of the light output of an LED can be very well represented by the equation $L=L_oe^{(-T/T_o)}$ where T_o is on the order of 110° C. The actual T_o may vary from chip to chip. Hence, the temperature coefficient for the chips may differ. Data representing the actual temperature coefficients for each LED chip are stored in a PROM (not shown) on the printhead and read out during operation of the printhead for adjusting the temperature compensation circuit as hereinafter described.

In addition, the light output of an LED is given as a function of current by the equation

$$L/k = I + (z/2) - \sqrt{(z/2)_2 + zI}$$

where k is a constant, I is current and z is a measure (in amperes) of the nonradiative current losses of the LED.

The forward voltage of a GaAsP diode emitting at 685 nanometers has the form

$$V_F = 1.54e^{-0.00145(T-25)}$$

where T is the temperature in degrees Centigrade. This forward voltage is sensed and used for compensating the LED chip for temperature changes. Briefly stated, the forward voltage is amplified, combined with a constant voltage and the resulting compensation voltage used to set the LED current by way of the internal reference voltage applied to the driver FETs **13**. In this way the light output of the LEDs on the chip is substantially uniform regardless of changes in temperature.

The forward voltage V_F across the dummy LED is used for charging an LED sensing capacitor C_L which thereby stores the voltage. At the same time a reference capacitor C_r is charged by an external reference voltage V_r which thereby stores the reference voltage. These capacitors are switched for storing the voltages during the interval when the switching FET **18** is ON for passing current through the dummy LED.

The capacitors are then switched to an output where the two capacitors are, in parallel, connected to the inverting input of a compensation op-amp **21**. At the same time, a feedback capacitor C_F is switched across the output to input of the compensation op-amp for influencing the gain of the op-amp. The output of the compensation op-amp provides the reference voltage V_R which is applied to the noninverting input to the reference current op-amp **9**.

A storage capacitor C_s is connected to the reference voltage line for remembering the reference voltage during the interval when the compensation op-amp is essentially turned off while the other capacitors are switched to sensing the LED forward voltage and the reference voltage. During this off period, the feedback capacitor C_F is shorted for draining its charge and not influencing the feedback of the compensation op-amp in the next compensation cycle. It may be desirable to have the storage capacitor C_s a discrete component off of the silicon integrated circuit chip so that it can have substantial capacitance and maintain the reference voltage without significant draining.

By switching the LED and reference capacitors C_L, C_r in parallel as shown in the drawing, the combined capacitance of the capacitors is applied to the input to the compensation op-amp **21**. The input compensation voltage V_i to the compensation op-amp is then

$$V_i = \frac{C_LV_F + C_rV_r}{C_r + C_L}$$

The gain of the compensation op-amp is

$$\frac{C_r + C_L}{C_F}$$

If we represent the voltage across an LED by the formula $V_F = V_{Fo} + k\Delta T$, then the current in an LED as a function of temperature is

$$I_L = \frac{1}{R_rC_F} C_rV_r - C_LV_{Fo} + C_Lk\Delta T$$

The reference capacitor C_r and LED voltage sensing capacitor C_L are adjustable by way of data stored in a PROM (not shown) on the printhead. As is well known, adjustable capacitors can be provided in an integrated circuit by having a plurality of capacitive areas of different sizes which are selectively switched into parallel to provide a desired capacitance. The data stored in the PROM for setting the adjustable capacitors is provided in an initial calibration of the printhead.

The technique for adjusting the reference and LED sensing capacitors comprises, in effect, measuring the external reference voltage V_r ambient temperature forward voltage V_{Fo} of the dummy LED and the constant k. A simple way to do this is to initially set the two adjustable capacitors to their nominal values by loading some beginning data into the PROM. In an exemplary embodiment where the external reference voltage is 2.5 volts, the ambient temperature forward voltage V_{Fo} of the LED is nominally 1.6 volts, the constant k is nominally 2 millivolts per degree Centigrade and the required compensation in the LED current I_L is about 1% per degree Centigrade, the capacitance of the LED sensing capacitor C_L should be about 1.5 times larger than the reference capacitor C_r.

After the nominal capacitance values are set, the capacitors are adjusted up and down together maintaining the 1.5:1 ratio until the appropriate LED current I_L is obtained. Then by measuring the coefficient of change of LED current I_L with small changes in the reference capacitance C_r and LED sensing capacitance C_L, the ratio of changes in capacitance R_C that will the LED current I_L constant can be determined.

Then the printhead is heated up to some temperature such as 50° C. The LED sensing capacitance C_L (which helps determine the gain of the temperature compensation) is then adjusted to give the same light output from an LED at 50° C. as it had at the starting temperature. However, when the LED sensing capacitance C_L is changed, the reference capacitance C_r is also changed by the ratio R_C previously determined. This assures that the nontemperature-dependent part of the LED current remains constant during the adjustment of the temperature compensation. By adjusting the two capacitances to give the proper current at two temperatures, the proper current is obtained throughout the temperature range.

Although but one embodiment of temperature compensated power supply for an LED printhead has been described and illustrated herein, many modifications and variations will be apparent to those skilled in the art. Thus, for example, although the switched capacitance technique for applying the sensed forward voltage of the dummy diode to an op-amp provides a simple technique easily implemented on a silicon integrated circuit chip, other techniques for employing the forward voltage of the LED for adjusting the chip reference voltage may be employed.

The calibration technique described adjusts the reference capacitor and the LED voltage sensor capacitor for obtaining the desired temperature compensation. This is probably the simplest calibration technique. One could, however, adjust the op-amp feedback capacitance instead of one of the input capacitances. The algorithm for doing this is somewhat more complicated and may require iterations to obtain the desired accuracy of calibration.

The temperature compensation is described as occurring between each line of printing, and that probably provides the optimum. It will be apparent that compensation between pages or at other intervals may also be practiced.

One may also choose to employ a diode on the silicon integrated circuit chip instead of the dummy LED on the LED chip. An approximation of the temperature compensation may be obtained since coefficients are similar and the temperature of the integrated circuit chip tends to be proportional to the temperature of the LED chip. This is the case since both are mounted on a common heat sink and the power dissipations in the

LED chip and integrated circuit chip are proportional during operation of the printhead.

The invention has also been described in the context of a xerographic printer where the surface exposed is selectively discharged by exposure to light. It will be apparent that this invention may be used with other photo-sensitive elements such as photographic film or paper.

With such possible variations in mind, it will, therefore, be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. A method for compensating for temperature variations in a light emitting diode printhead for a photosensitive printer comprising the steps of:

sensing the voltage across a dummy light emitting diode on the same chip with a plurality of exposure diodes; and

adjusting a chip reference voltage which controls LED current as a function of the sensed voltage for compensating for changes in the temperature of the dummy light emitting diode.

2. A method as recited in claim **1** wherein the adjusting step comprises combining the sensed voltage and a constant voltage for obtaining a compensation voltage, and applying the compensation voltage to the input of an op-amp, the output of the op-amp providing the chip reference voltage. ·

3. A method as recited in claim **2** further comprising the step of adjusting the gain of the op-amp as a function of variation of LED light output with respect to temperature.

4. A method as recited in claim **2** wherein the adjusting step comprises:

applying the compensation voltage to the inverting input of an op-amp; and

adjusting the gain of the op-amp based on the light output of the LEDs as a function of temperature.

5. A method as recited in claim **1** comprising sensing the voltage across the dummy LED when the exposure LEDs are turned off.

6. A method as recited in claim **1** comprising the step of storing the reference voltage during an interval when the exposure LEDs are enabled.

7. A method as recited in claim **1** comprising the steps of:

storing a reference voltage in a capacitor;

storing the sensed voltage in a capacitor; and

connecting both capacitors in parallel to the input of an op-amp, the output of the op-amp providing the chip reference voltage.

8. A method as recited in claim **7** wherein each of the capacitors is adjustable and is set at a capacitance value which collectively represents the temperature coefficient of the LEDs.

9. A method for compensating for temperature variations in a light emitting diode chip having a plurality of exposure diodes comprising the steps of:

sensing the voltage across a dummy diode;

adjusting an amplifier output as a function of the sensed voltage; and

applying the amplifier output as a chip reference voltage for controlling current to the exposure diodes.

10. A method as recited in claim **9** wherein the dummy diode comprises a light emitting diode on the same chip as the exposure diodes.

11. A method as recited in claim **9** wherein the adjusting step comprises adjusting the gain of the amplifier as a function of variation of LED light output with respect to temperature.

12. A method as recited in claim **9** wherein the adjusting step comprises capacitively connecting the sensed voltage to the input of the amplifier.

13. A method as recited in claim **12** wherein the step of capacitively coupling comprises:

storing the sensed voltage in a first capacitor;

storing a constant voltage in a second capacitor; and

connecting both capacitors in parallel to the input of the amplifier.

14. A method as recited in claim **9** wherein the adjusting step comprises adjusting the gain of the amplifier in response to variation LED light output as a function of temperature.

15. A method as recited in claim **9** wherein the adjusting step comprises combining the sensed voltage and a constant voltage for providing a compensation voltage, and applying the compensation voltage to the input of the amplifier.

16. A method as recited in claim **9** comprising the steps of:

storing a reference voltage in a first capacitor;

storing the sensed voltage in a second capacitor; and

connecting both capacitors in parallel to the inverting input of an op-amp, the output of the op-amp providing the chip reference voltage.

17. A temperature compensated LED printhead for a photosensitive printer comprising:

a light emitting diode chip having a plurality of exposure LEDs;

means for generating a compensation voltage bearing a known relation to the temperature of the chip;

a compensation op-amp;

means for applying the compensation voltage to the inverting input of the compensation op-amp;

means for adjusting the op-amp gain in response to changes in LED light output as a function of temperature;

means for generating a chip reference voltage as a function of the output of the op-amp; and

means for controlling current through the exposure LEDs in response to the chip reference voltage.

18. A temperature compensated LED printhead as recited in claim **17** wherein the means for generating a compensation voltage comprises a dummy LED on the chip, and the compensation voltage is a function of the voltage across the dummy LED.

19. A temperature compensated LED printhead as recited in claim **17** wherein the means for generating a compensation voltage comprises:

a diode having a voltage drop which is a function of temperature;

means for sensing a voltage across the diode; and

means for combining the voltage with a constant voltage for generating the compensation voltage.

20. A temperature compensated LED printhead as recited in claim **17** wherein the means for applying the compensation voltage to the compensation op-amp comprises:

first capacitive means for storing the compensation voltage;

second capacitive means for storing the sensed voltage; and

switching means for switching both capacitive means in parallel to the input of the compensation op-amp.

21. A temperature compensated LED printhead for a photosensitive printer, having a plurality LED chips on the printhead and a plurality of exposure LEDs on each chip comprising:

a dummy diode for each chip;

means for passing current through the diode;

means for sensing voltage across the diode; and

means for adjusting the current passed through the exposure LEDs on the respective chip in response to the sensed voltage.

22. A temperature compensated LED printhead as recited in claim **21** wherein the dummy diode comprises a dummy LED on each chip.

23. A temperature compensated LED printhead as recited in claim **21** comprising:

a capacitor selectively connectable across the diode for storing the sensed voltage;

means for combining the sensed voltage with a constant voltage for providing a compensation voltage;

an amplifier; and

means for applying the compensation voltage to the input of the amplifier, the current passed through the exposure LEDs being a function of the output of the amplifier.

24. A temperature compensated LED printhead as recited in claim **23** wherein:

the means for combining comprises an adjustable capacitor for storing the constant voltage; and

means for applying the voltages stored in both capacitors in parallel to the input of the amplifier.

25. A temperature compensated LED printhead as recited in claim **24** wherein the amplifier comprises an op-amp and comprising means for applying a feedback capacitor across the op-amp.

* * * * *

United States Patent [19]
Uebbing et al.

[11] **Patent Number:** **4,982,203**
[45] **Date of Patent:** **Jan. 1, 1991**

[54] METHOD AND APPARATUS FOR IMPROVING THE UNIFORMITY OF AN LED PRINTHEAD

[75] Inventors: **John J. Uebbing,** Palo Alto; **Peter H. Mahowald,** Mountain View, both of Calif.

[73] Assignee: **Hewlett-Packard Company,** Palo Alto, Calif.

[21] Appl. No.: **377,186**

[22] Filed: **Jul. 7, 1989**

[51] **Int. Cl.**^{5} **G01D 15/14;** G01D 2/45; H04N 1/036
[52] **U.S. Cl.** .... **346/107 R;** 346/160
[58] **Field of Search** .... 346/107 R, 108, 160, 346/153.1, 154; 358/300, 302

[56] **References Cited**

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4,780,731 10/1988 Creutzmann .... 346/107 R

Primary Examiner—Mark J. Reinhart
Assistant Examiner—Scott A. Rogers

[57] ABSTRACT

An apparatus and method are provided to correct for the amount of degradation in light output of the light source used with an electrophotographic recording medium of an optical printer. The percentage amount of degradation due to aging is predicted by measuring degradation over a short interval and used to adjust the light output of the individual LEDs by pulse width modulation or current modulation so that there is a uniform light output. Similarly, the percentage amount of degradation due to temperature changes is predicted and used to adjust the light output.

25 Claims, 3 Drawing Sheets

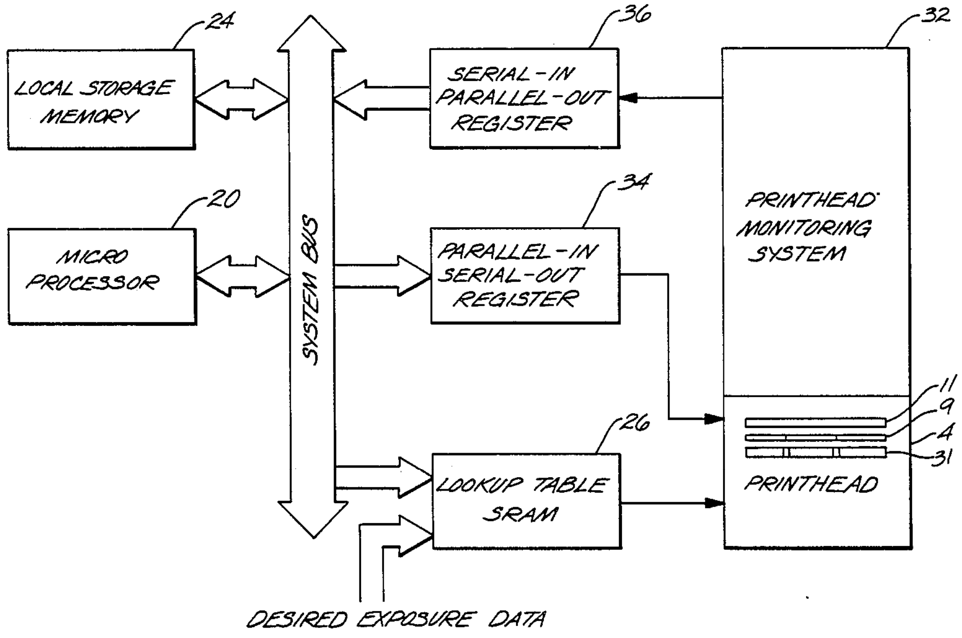
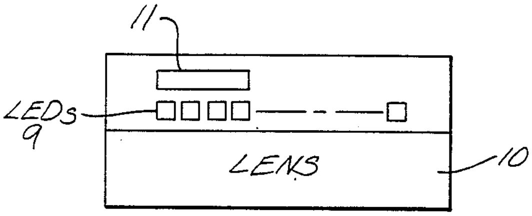


Fig. 2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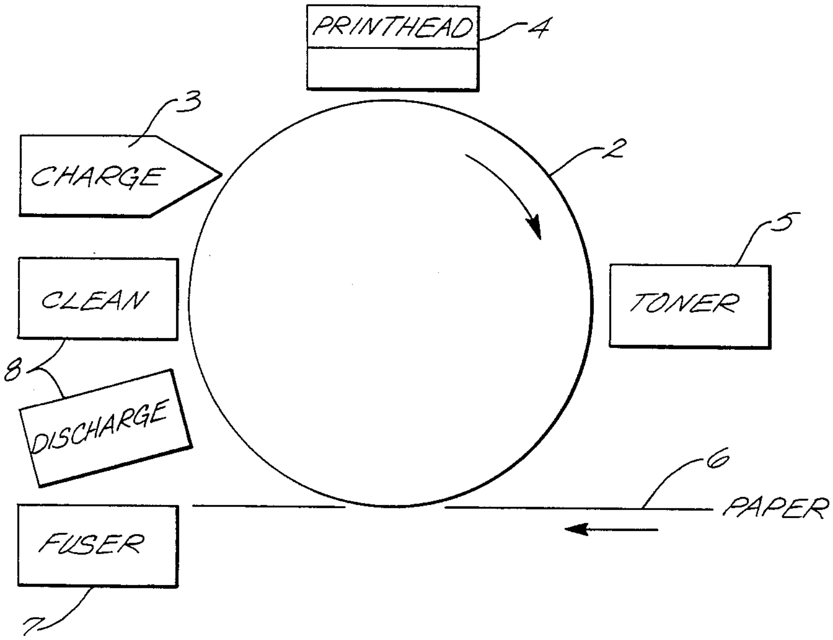
LEDs
9
LENS
10

Fig. 1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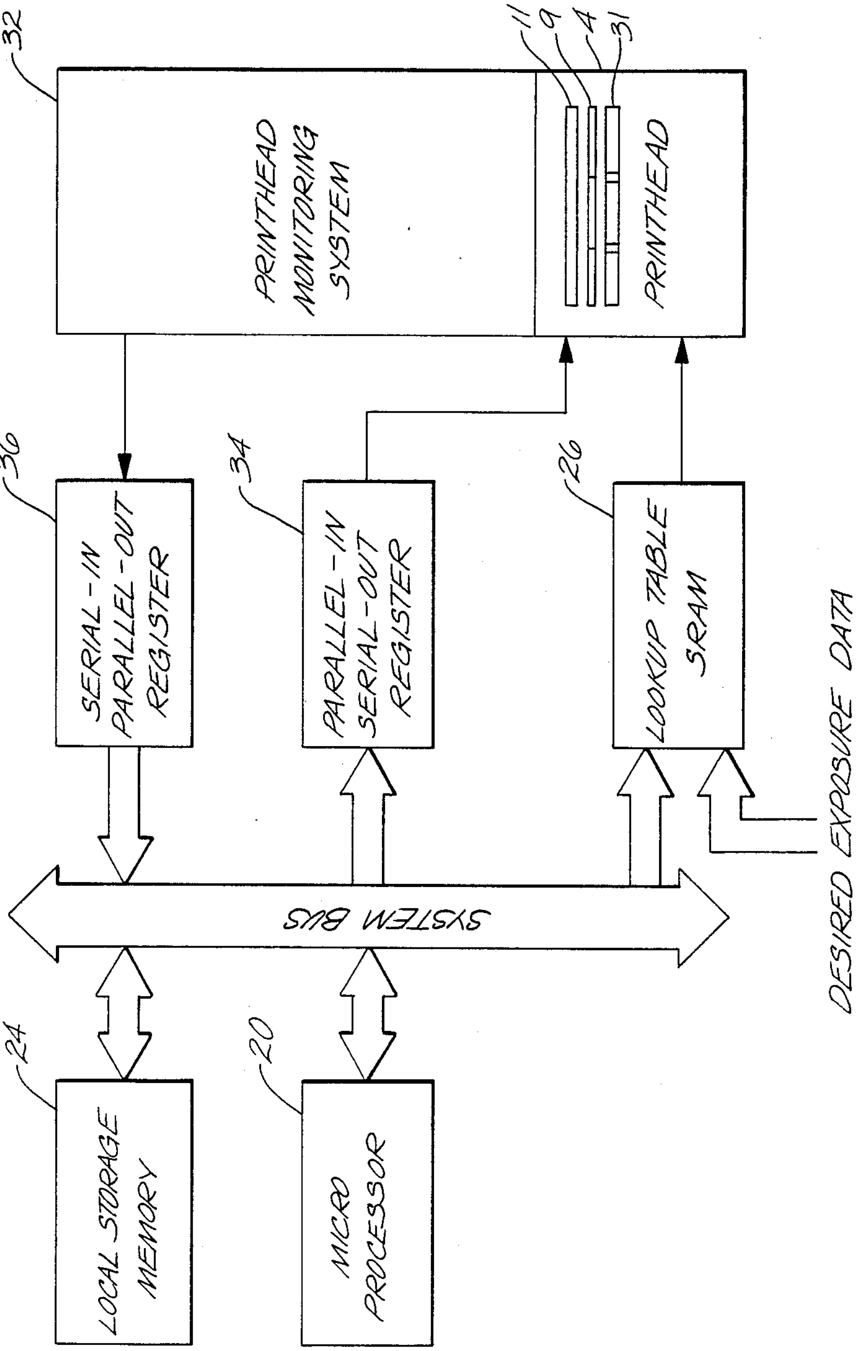
TONER
8
DISCHARGE
6
PAPER
FUSER
7

Fig. 3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11
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PRINTHEAD MONITORING SYSTEM
PRINTHEAD
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SERIAL-IN PARALLEL-OUT REGISTER
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LOOKUP TABLE SRAM
DESIRED EXPOSURE DATA
SYSTEM BUS
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LOCAL STORAGE MEMORY
20
MICRO PROCESSOR

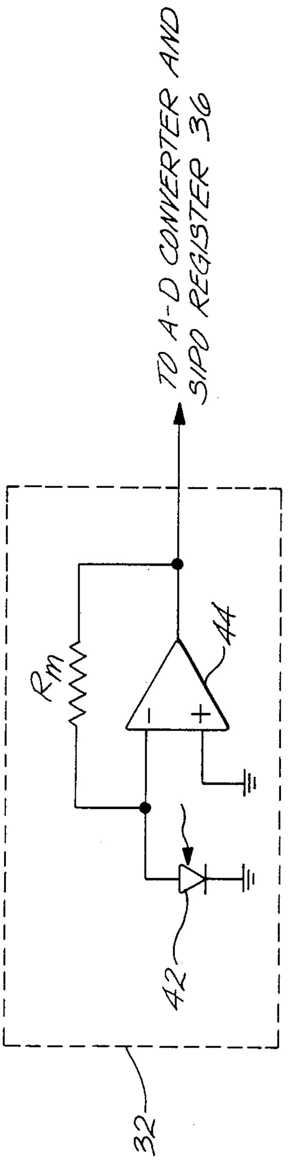
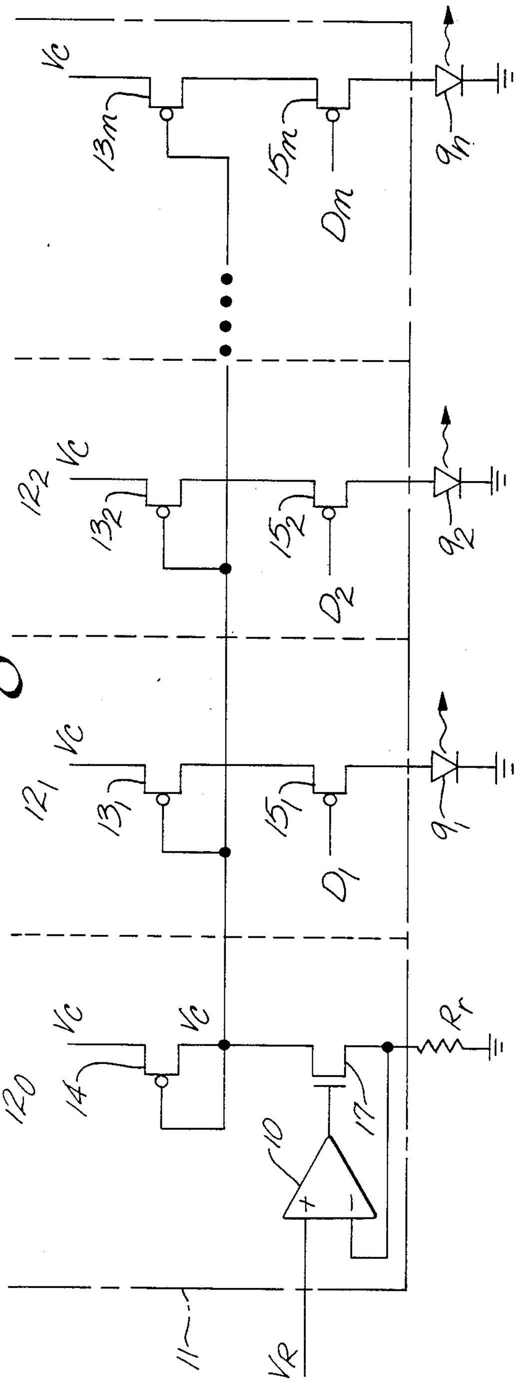

TO A-D CONVERTER AND
SIPO REGISTER 36
Rm
44
42
32

Fig. 4


Vc
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152
D2
q2
121
Vc
131
151
D1
q1
120
Vc
Vc
14
10
17
Rr
11
VR

Fig. 5

METHOD AND APPARATUS FOR IMPROVING THE UNIFORMITY OF AN LED PRINTHEAD

BACKGROUND OF THE INVENTION

Non-impact optical printers are becoming increasingly popular for producing texts and graphics, particularly in gray scale applications. In gray scale printing, multiple gradations and shades of gray can be printed in addition to black-and-white and "write white" or white-on-black printing. Gray-scale printing is typically used to create pictures rather than text.

In xerographic printers, an electrostatic charge is formed on the surface of a moving drum or belt. Selected areas of the drum or belt are discharged by exposure to light, e.g. from light emitting diodes (LEDs) or lasers. A printing toner is applied to the drum and adheres to the areas which have an electrostatic charge. The printing toner does not adhere to the discharged areas on the drum. The toner is then transferred from the areas on the drum having the electrostatic charge to a sheet of plain paper and is heat fused to the paper using well known methods. Characters are constructed in the well-known dot matrix fashion, with each character comprising a number of illuminated dots. Optical character generation devices are well known and are described in previous U.S. patents (e.g. U.S. Pat. No. 4,596,995).

In gray-scale printers, the shade of gray is determined by the amount of the electrostatic charge on the photoreceptive surface. Such printers may be used for reproducing photographs. For example, one type of optical printer uses arrays of light emitting diodes (LEDs) as the light source which exposes the photoreceptor surfaces. To create high quality images with an LED printer, each of the individual LEDs should produce the same amount of light output when they are activated by a specified signal. It is particularly important that each of the LEDs produce a uniform light output when the printer is a gray-scale printer. As the light output from each LED tends to vary significantly, a number of systems have been proposed to correct the variance in light output.

The amount of time that each LED has been on (its age) is one of two important time dependent factors which affect the amount of light output of each LED. It is believed that the rate at which the LED light output is reduced due to repeated use is unique to the particular LED. It is believed that the degradation rate is related to the number of defects or dislocations at the junctions in the crystalline lattice structure of the doped semiconductor of which LEDs are comprised as well as being related to the amount of strain in the material. Therefore, the degradation rate due repeated use or aging for an LED printhead is non-uniform between individual LEDs.

The other important time-dependent factor in the light output of the LED is the temperature of the junction. The light output decreases as the temperature increases, and by measuring the amount of decrease in light output due to temperature during manufacture and measuring the temperature during the operation of the printhead, the light output can be predicted. Compensation for the amount of degradation in light output due to temperature can therefore be accomplished. Since the amount of degradation due to temperature does not vary substantially from pixel-to-pixel, the compensation may be either performed by pulse-width modulation or by modifying the current at which the LEDs operate. With either technique, modifying the current or pulse-width modulation, it is unnecessary to measure the light output during operation, which increases the cost.

Prior art systems, such as U.S. Pat. No. 4,780,731 (Creutzmann), continuously monitor temperature and the LED light output and correct the light output at regular intervals based on the measured data. Such systems are expensive and a need has developed for a more cost effective system which does not sacrifice accuracy.

BRIEF SUMMARY OF THE INVENTION

It is, therefore, an object of the present invention to provide a low cost, highly uniform and accurate printhead suitable for precision gray scale electrophotographic printing. As an LED is used, the light output as a function of current will typically degrade due to aging. The present invention eliminates the necessity for repeated measurement of the light output as a prerequisite for correcting for the age degradation. The present invention provides a uniform LED light output to within as little as ±.15 percent error. The uniformity of the light output can be improved by approximately an order of magnitude using the present invention as compared to a LED printhead with no correction circuitry.

In addition to the array of LEDs, the system hardware of the present invention may include a microprocessor, memory and circuitry to control the current applied to the LEDs or the LED on-time during exposure, and optionally, a device for measuring light output.

To obtain the compensation for aging, before the printhead is installed in the printer, the amount of light output of each LED is measured first and then measured again after the printhead has been operating for a specified length of time. The amount of degradation is defined using the difference between the two measurements of the light output. After the printhead is installed, only the aging is measured by measuring the amount of time the printhead is on. The light output of the LEDs is adjusted based on predictions made from measuring the aging. Predicting the amount of degradation for each pixel is accomplished using a mathematical relationship between the LED on-time and the percentage amount of degradation. The predicted amount of degradation for each LED is stored in memory located on the printhead.

To obtain the amount of compensation for degradation in light output due to temperature increases, the average amount of light output for the printhead is measured at various temperatures before the printhead is installed, and a table of values of light output at various temperatures is stored in memory. After the printhead is installed, the temperature is measured and the light output is adjusted using the values stored in memory from the pre-installation measurements of temperature versus light output.

The light output can be expressed mathematically as a function of the current, the temperature, a current non-linearity coefficient, and a temperature dependent coefficient. A mathematical equation relating light output to current and temperature is used to predict the amount of correction needed at a later time to obtain uniformity. At least two different values of current and light output are needed to solve the equation for the current non-linearity coefficient and the temperature dependent coefficient.

The amount of correction required for each LED to achieve uniformity with all the other LEDs is computed using the equation in a software program. The parameters of the mathematical equations for each LED are stored in memory. The LED exposure-time (i.e. duty factor) and the drive current of the printhead system are adjusted using the correction factor which was computed by the microprocessor.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features and advantages of the present invention will be appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings wherein:

FIG. 1 illustrates, in block diagram form, an exemplary optical xerographic printing apparatus;

FIG. 2 is an enlargement of the printhead portion of the block diagram shown in FIG. 1;

FIG. 3 is a block diagram illustrating the interconnection of the control electronics and the printhead of the present invention;

FIG. 4 is an exemplary light output measurement circuit; and

FIG. 5 a circuit diagram illustrating an exemplary embodiment of the LED driver for the printhead of the present invention.

DETAILED DESCRIPTION

An exemplary, conventional, light emitting diode (LED) printer is shown in a block diagram in FIG. 1 to provide an overview of the environment of the present invention. A selected area of a rotating drum 2 receives an electrostatic charge from a charging station 3. Exposure to light from a printhead 4 causes selected areas within the charged area to be discharged. A printing toner 5 is applied to the drum and adheres to the areas which are charged and will not adhere to those areas which are not charged or have been discharged. Characters or images may be constructed by charging and then darkening appropriate pixels on the drum with toner. The toner is then transferred and heat-fused to the paper 6 at a fusing drum 7. The surface of the drum is thoroughly discharged and cleaned of any remaining toner at a cleaning station 8 before being recharged.

A block diagram of an exemplary printhead 4 is illustrated in FIG. 2 with a row of LEDs 9 , a lens 10 to focus the light emitted by the LEDs, and circuitry to control the actuation of the LEDs fabricated on an integrated circuit 11. The integrated circuit 11 receives power from a current supply voltage, V_c, which is typically five volts.

The interconnection of the major hardware components used in this invention can be seen in FIG. 3. A microprocessor 20 is interconnected to various memory elements, i.e. a look up table static random access memory (SRAM) 26, and a local memory storage 24, through the system bus 28. The microprocessor 20 is also interconnected to the printhead 4 through the system bus. The microprocessor is connected to the printhead monitoring system 32 through a parallel-in, serial-out (PISO) register 34. The printhead monitoring system measures the amount of light output of at least some of the LEDs and the temperature of various parts of the printhead. The signal representing the measured amount of light output is input to the microprocessor through a serial-in, parallel-out (SIPO) register 36.

The structure and operation of the printhead 30 will now be discussed. Referring to FIG. 5, power is supplied to a array of LEDs 9 (only one row is shown) from an integrated circuit (IC) chip 11 which is in electrical connection with, and mounted in close proximity to, the LEDs. Each of the cells 12_0, 12_1, 12_2, . . . 12_n cells are circuits for controlling each LED, 9_1, 9_2, . . 9_n. The LEDs are driven by output drivers which may advantageously be p-channel field effect transistors (FETs) 13_1,13_2,. . .13_n and switching FETs 15_1, 15_2, . . 15_n. Transistor pairs 13_1 and 15_1, 13_2 and 15_2, etc. are connected in series with each other and the LEDs. By having the gates of all the output driver transistors 13 connected to the chip reference voltage V_c, the magnitude of the current through each driver transistor is substantially identical.

Varying the system reference voltage, V_R controls the light output of all the LEDs in the array. The instantaneous current through each of the LEDs is V_R divided by R_r so that increasing the voltage V_R increases the current flow through the LED and increases the light output. Thus, V_R can be set to a desired level which also sets the magnitude of the current. Varying V_R is one method for compensating for the degradation in light output for variations in temperature if is assumed that the temperature of all the LEDs in the array is approximately the same. Alternatively, pulse width modulation can be used to separately control groups of LEDs (which can be as small as two) using the different measured temperatures of the LED groups.

The first cell of the printhead circuit, 12_0, sets the current through the LEDs. Cell 12_0 includes an operational amplifier 10 (also referred to as an "op-amp"). The output of the op-amp 10 is input to the gate of an n-channel, current setting FET 17. The source of the current setting FET 17 is the non-inverting input of the op-amp 10. In this configuration the op-amp increases its output voltage, until the inverting input to the op-amp is equal to V_R. When the voltage at the source 19 of the current setting FET 17 is equal to the system reference voltage, V_R, the voltage at its drain 18 is equal to V_c, the chip reference voltage. The current at the source 19 of the current setting FET 17 is the same as the current at the drain 18, which is equal to V_R/R_r. The current through each of the LEDs 9 is the same as the current at the source 18 of the current setting FET 17 and equal to V_R/R_r when there is an actuating pulse D at the gate of each driver FET 15. Global changes in the current may be accomplished by varying the system reference voltage V_R, or the reference resistor R_r.

In contrast to the system reference voltage V_R which controls the overall printhead current, adjustments to the pixel-by-pixel light output are made by pulse width modulation: Individual LEDs are controlled by regulating their exposure time, that is, the amount of time each LED is on. The switching FETs 15 (FIG. 5) act as switches in response to the presence or absence of a data signal D_1, D_2, . . . D_n applied to the respective gates of the switching FETs 15. Each of the signals D_1, D_2, ...D_n is typically a series of square-wave pulses which turn the switching transistors 15 "on" or "off". The signals have varying pulse widths which are equal to the exposure times for each LED.

In order to provide compensation for the variations in light output between LEDs due to aging, the amount of degradation in light output is predicted. By predicting the percentage amount of degradation, D_g, in light output and increasing the exposure time by the same percentage, compensation for the amount of degradation due to varying effects of age on each LED is accomplished.

The percentage degradation is defined in terms of the light output, q, at time t and time **0**:

$$\text{Percentage degradation} = D_g = \left[1 - \frac{q(t)}{q(0)} \right] 100\% \tag{2}$$

For example, if the first measurement of the light output of LED using a photodetector is 100 nanovolts and the second measurement of the same LED is 90, the percentage amount of degradation is 10 percent.

$$Dg=[1-(q(t)/\ q(0))]\ 100\%=[1\text{-}90/100]\ 100\%=10\%$$

Therefore, the pulse width of the actuating pulse D_1, which is equal to the exposure time, is increased by 10% to compensate. The actuating pulse for the second LED, D_2, may be corrected by 9.5%, for example, and so on. The different values for D_1, D_2, ...D_n are stored in a look-up table in memory for later use in controlling the exposure time of the LEDs. A fast static RAM **26** (SRAM) may advantageously be used as the memory device for storing the look-up table. In gray scale printers it is advantageous to place the look-up table within the picture data processing subsystem. In gray-scale printing applications, the different values for D_1...D_n are selected using the gray-scale exposure data.

It has been discovered that the percentage degradation as a function of time may be modeled by the equation:

$$Dg=k_D t^{1/3} \tag{3}$$

where k_D is a constant which is a characteristic of each LED and t is the amount of time that the printhead has been operating. The constancy of k_D for each LED allows the future light output of a specific LED to be accurately predicted when the LED age is known. Each LED has a different value for k_D. The value of k_D for each LED may be calibrated during the manufacture of the printhead by measuring the degradation at two different measurement times before the product is released from production.

The percentage amount of degradation D_g is predicted using equation (3) by substituting the amount of time the printhead has been operating for the variable, t. It will be appreciated that the operation time of the printhead may be determined in a number of different ways. One way is to approximate the operation time by keeping a count of the number of pages and estimating the resulting usage of each LED from number of pages.

The microprocessor **20** calculates $k_D\ t^{1/3}$ by retrieving the values of k_D stored in the look-up table **26** for each LED. The system software multiplies each value of k_D by the cube-root of the operating time, $t^{1/3}$ to obtain a value for the percentage degradation, D_g, for each LED.

The duty factor (the amount of time on divided by the amount of time off) of the LEDs is adjusted by increasing the pulse width of the actuating pulses D for each LED by the percentage degradation, D_g, to compensate for the degradation in output due to aging. Thus, the pulse widths of the signals D_n are modulated to compensate for the amount of aging that each LED has experienced.

The vast majority of the LED's follow equation (3). However, a certain small percentage require additional correction. The LEDs which require more correction than predicted by Equation (3) can be located before manufacture and either removed from use or an extra correction made in order to increase the accuracy.

Another way to estimate the amount of age-caused degradation of the LEDs, without using Equation (3), is to measure the degradation in light output of a few selected LEDs, e.g. those in close proximity to the center of the printhead. The light output may be measured at repeated intervals and the degradation measured during operation of the printer between the printing of each page. After a preselected time period, which has been found to be from a few minutes to a day of printhead operation, the light output of each of the selected LEDs may again be measured which will have decreased due to aging of the LEDs. The measured percentage amount of degradation is then used to increase the pulse width(s) of signal D by the same percentage to compensate for the aging.

Compensation for temperature variations will now be discussed. Increases in ambient temperature result in global degradation in the light output of all the LEDs. Before the printhead is installed, the system is calibrated by taking measurements of light output of each LED at two different amounts of current using the equation:

$$\frac{q}{k} = \frac{x}{2} - \sqrt{\left(\frac{x}{2}\right)^2 + (x\,I)} + I \tag{4}$$

where q is the light output, I is the current, k is the temperature-dependent coefficient, x is the current nonlinearity coefficient. By substituting the two measured values of q and I, the values of the temperature dependent coefficient k and the current non-linearity coefficient x can be determined. The values of k and x are stored in memory on the printhead.

The temperature is continuously monitored with a conventional temperature sensor **31**. For example, a temperature transducer, which produces an output voltage proportional to the temperature, may be used. If the temperature has changed after a predetermined operation time, e.g. **2** minutes, a new value for the temperature dependent "efficiency" coefficient, k, is calculated from equation (5) relating k to the temperature:

$$k=k_o e^{-T/T_O} \tag{5}$$

where T is the measured temperature and T_o and k_o are constants. Typically, T_o is equal to 111° C.. Equation (4) is solved for the current I and the calculated value of k from equation (5) is substituted for k and a new value for the current I is calculated by the system software. The value of the reference voltage V_R may be adjusted by a global correction signal generated by the microprocessor **20**. The magnitude of the instantaneous current flowing through all the LEDs is changed to correspond to the newly-calculated value of I, thereby effecting a global change in the light output.

Alternatively, because of the substantial computation time required for the software to make the necessary calculation using Equation (4) an approximation of the change in current, I, required to compensate for the increase in temperature, T, may be made to reduce the calculation time:

$$\Delta I = \frac{\frac{\partial \bar{q}}{\partial T}}{\frac{\partial \bar{q}}{\partial I}} \Delta T \tag{6}$$

where $\bar{q}$is the average light output for the printhead. The software approximates the partial derivatives in equation (6) by calculating the slope of equation (4). A similar approximation using partial derivatives may be used in lieu of Equation (3) if minimizing the computation time is more desirable than maximizing the accuracy.

The values for V_R and/or R_r are selected to provide a little more current than is required to produce the maximum amount of desired light output so that the values of D_n, the pulse widths, will always be less than 100%. It will be appreciated that V_R/R_r is the typical instantaneous current of the printhead circuit, while the pulse width-modulated current through the LEDs results from the varying pulse lengths of the signals D.

If the embodiment in which the light output of a few selected LEDs is periodically measured is used, there are a number of different circuits which can be used for measurement of the light output. Measurement of the light output is generally accomplished using photoconductive devices, such as a photodiode, placed in sufficient proximity to each LED to receive the light from the LEDs. An exemplary measurement circuit is shown in FIG. 7. A photodiode **42** is connected in series with a resistor R_m. Op-amp **44** measures the voltage across the resistor which is proportional to the light output.

The invention has been described in detail with particular reference to preferred embodiments thereof. However, it will be understood that variations and modifications may be effected within the spirit and scope of the invention.

What is claimed is:

1. An apparatus for improving the uniformity of a light emitting diode array printhead comprising:

means for predicting the amount of degradation in light output of each light emitting diode as a function of time;

means for generating correction data to compensate for he amount of degradation in the light output of each light emitting diode as a function of time using said predicted amount of degradation; and

means for adjusting the amount of light emitted by each light emitting diode using said correction data and the operating time of the light emitting diodes.

2. The apparatus of claim **1** further including:

means for measuring the temperature of said printhead and generating a temperature signal representing the measured temperature;

means for generating a correction factor signal using said temperature signal; and

means for controlling the amount of light output of all of the light emitting diodes as a group using said correction factor signal whereby said light output is increased to compensate for the degradation in light output caused by increases in temperature of the printhead.

3. The apparatus of claim **1** wherein the means for predicting the amount of degradation includes a means for measuring the light output of a number of selected light emitting diodes less than the total number of light emitting diodes.

4. An apparatus for improving the uniformity of a light emitting diode array printhead comprising:

means for predicting the amount of degradation in light output of each light emitting diode comprising means for calculating $k_d t^{1/3}$ wherein k_d is a constant for each LED and t is the operation time of the printhead;

means for generating correction data to compensate for the amount of degradation in the light output of each light emitting diode using said predicted amount of degradation; and

means for adjusting the amount of light emitted by each light emitting diode using said correction data.

5. The apparatus of claim **1** further comprising:

means for measuring the temperature of a selected group of light emitting diodes and generating a temperature signal representing the measured temperature for each of said groups; and

means for adjusting the amount of light emitted by each of said groups of light emitting diode using said temperature signal.

6. The apparatus of claim **2** wherein the means for predicting the amount of degradation includes a means for measuring the light output of a number of selected light emitting diodes less than the total number of light emitting diodes.

7. The apparatus of claim **2** wherein the means for predicting the amount of degradation comprises means for calculating $k_d t^{1/3}$ wherein k_d is a constant for each LED and t is the operation time of the printhead.

8. The apparatus of claim **2** wherein said means for controlling the amount of light output includes a means for calculating the temperature-dependent coefficient, from said temperature signal and a means for calculating the current required to drive the light emitting diodes to compensate for a change in temperature of the light emitting diodes.

9. The apparatus of claim **2** wherein the light emitting diode array includes a system reference voltage and said means for controlling the amount of light output includes a means for adjusting said system reference voltage.

10. The apparatus of claim **8** wherein said means for calculating said temperature dependent coefficient and said current comprises a microprocessor and a software program.

11. The apparatus of claim **9** wherein said means for adjusting said system reference voltage includes a microprocessor.

12. The apparatus of claim **10** wherein $k_o\, e^{-T/T_O}$ is calculated to obtain the temperature dependent coefficient where T_o and k_o are constants and T is said temperature.

13. The apparatus of claim **4** wherein said calculating means includes a microprocessor and a software program.

14. A method of improving the uniformity of a light emitting diode array printhead having a means for controlling the light output of each LED, said method comprising the steps of:

measuring the amount of degradation in light output of a selected group of light emitting diodes after a preselected time period;

using said measured amount of degradation to predict the amount of correction required for each light emitting diode to compensate for the amount of degradation in the light output of each light emitting diode occurring at times later than the time at which the degradation was measured; and

adjusting the light output of each light emitting diode using said predicted amount of correction for each light emitting diode and the operating time of the light emitting diodes.

15. The method of claim **14** wherein the adjusting step is accomplished by varying the input of said means for controlling the amount of light output of each light emitting diode.

16. The method of claim **14** wherein the adjusting step is accomplished by pulse width modulation of each light emitting diode.

17. The method of claim **13** further including:

measuring the temperature of said printhead; and

adjusting the light output of light emitting diodes as a group using said measured temperature.

18. The method of claim **14** further including:

measuring the temperature of a selected group of light emitting diodes and generating a temperature signal representing the measured temperature for each of said groups; and adjusting the amount of light emitted by each of said groups using said temperature signal.

19. The method of claim **18** wherein said adjusting step is accomplished by pulse width modulation.

20. The method of claim **17** further including:

determining the values for the temperature dependent coefficient and the current non-linearity coefficient.

21. A method for compensating for non-uniform age degradation of a plurality of light emitting diodes comprising the steps of:

measuring the light output from light emitting diodes after the light emitting diodes have been on for a first interval of usage;

predicting the aging of each light emitting diode after an additional interval of usage;

measuring the time of an additional interval of usage of the light emitting diodes; and

applying a selected additional increment of current to each light emitting diode after such an additional interval of usage and based on the predicted aging of each light emitting diode for obtaining substantially uniform light output from each of the light emitting diodes.

22. The method of claim **21** wherein said additional increment of current is applied by increasing the on-time of the light-emitting diode.

23. The apparatus of claim **1** wherein the means for correction data comprises measuring the amount of time each light emitting diode has been operating.

24. Apparatus for improving the uniformity of light output from a plurality of light emitting diodes comprising the steps of:

means for determining the amount of time at least a portion of the light emitting diodes have been operating;

means for storing a time dependent correction factor for at least a portion of the light emitting diodes;

means for determining the degradation of each such light emitting diode as a function of a stored correction factor and the time the light emitting diode has been operating; and

means for adjusting the duty cycle of each light emitting diode as a function of the degradation determined.

25. A method for correcting for aging of light emitting diodes comprising the steps of:

measuring the light output of a light emitting diode;

measuring the light output of the light emitting diode after an interval of operation;

determining a correction factor based on the degradation of light output between the two measurements;

storing the correction factor;

determining an additional time the light emitting diode has been in operation;

predicting the degradation of light output from the light emitting diode as a function of the stored correction factor and the additional operating time; and

adjusting the duty cycle of the light emitting diode for compensating for the predicted degradation.

* * * * *

United States Patent [19]
Uebbing

[11] **Patent Number:** **5,016,027**
[45] **Date of Patent:** **May 14, 1991**

[54] LIGHT OUTPUT POWER MONITOR FOR AN LED PRINTHEAD

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[73] Assignee: **Hewlett-Packard Company,** Palo Alto, Calif.

[21] Appl. No.: **445,404**

[22] Filed: **Dec. 4, 1989**

[51] **Int. Cl.**^{5} **H04N 1/21**
[52] **U.S. Cl.** .... **346/107 R;** 355/202
[58] **Field of Search** .... 346/76 L, 108, 160; 355/202

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Primary Examiner—Mark J. Reinhart

[57] **ABSTRACT**

A light output monitor for a light emitting diode printhead has a light detector internal to the printhead for measuring the light output power of each light emitting diode along a printhead. Calibration factors relating the light output power measured by the detector to the light output power transmitted to the photoreceptive surface of the printer are stored in memory on the printhead. An exposure control device regulates the amount of time each light emitting diode in the printhead exposes the photoreceptive surface with light. A processor periodically and aperiodically uses the light output measurements and the calibration factors to compensate the exposure control device for light output power non-uniformities and temporal irregularities.

20 Claims, 3 Drawing Sheets

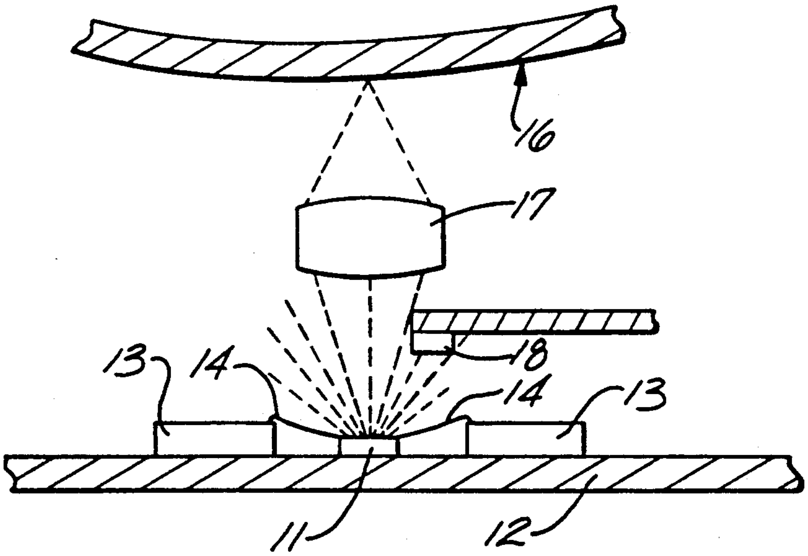


Fig. 1

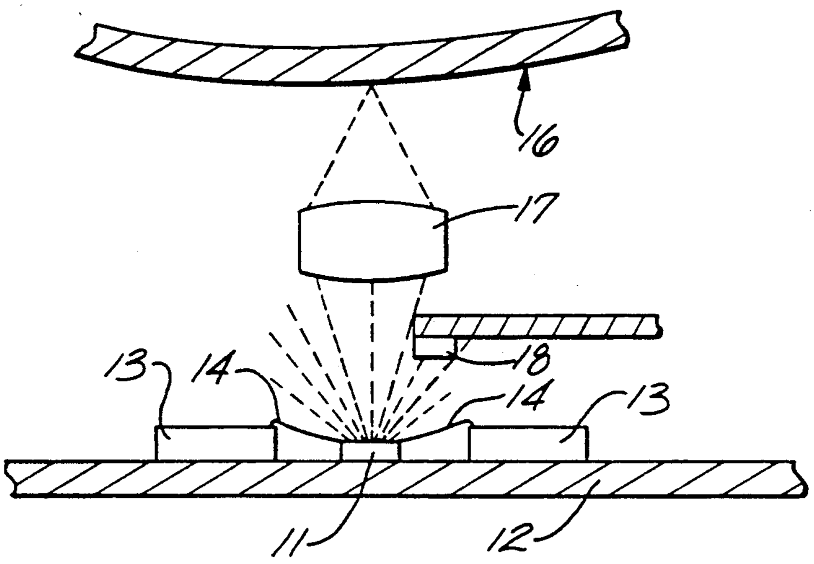
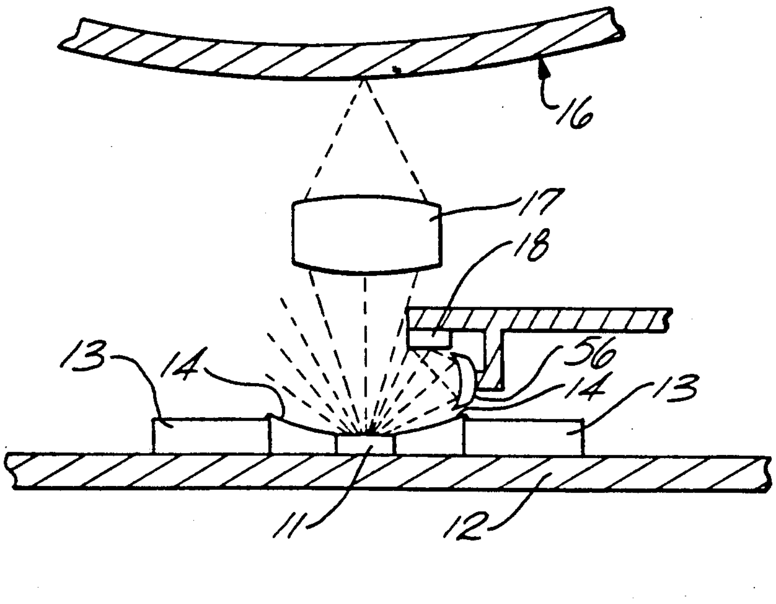


Fig. 3



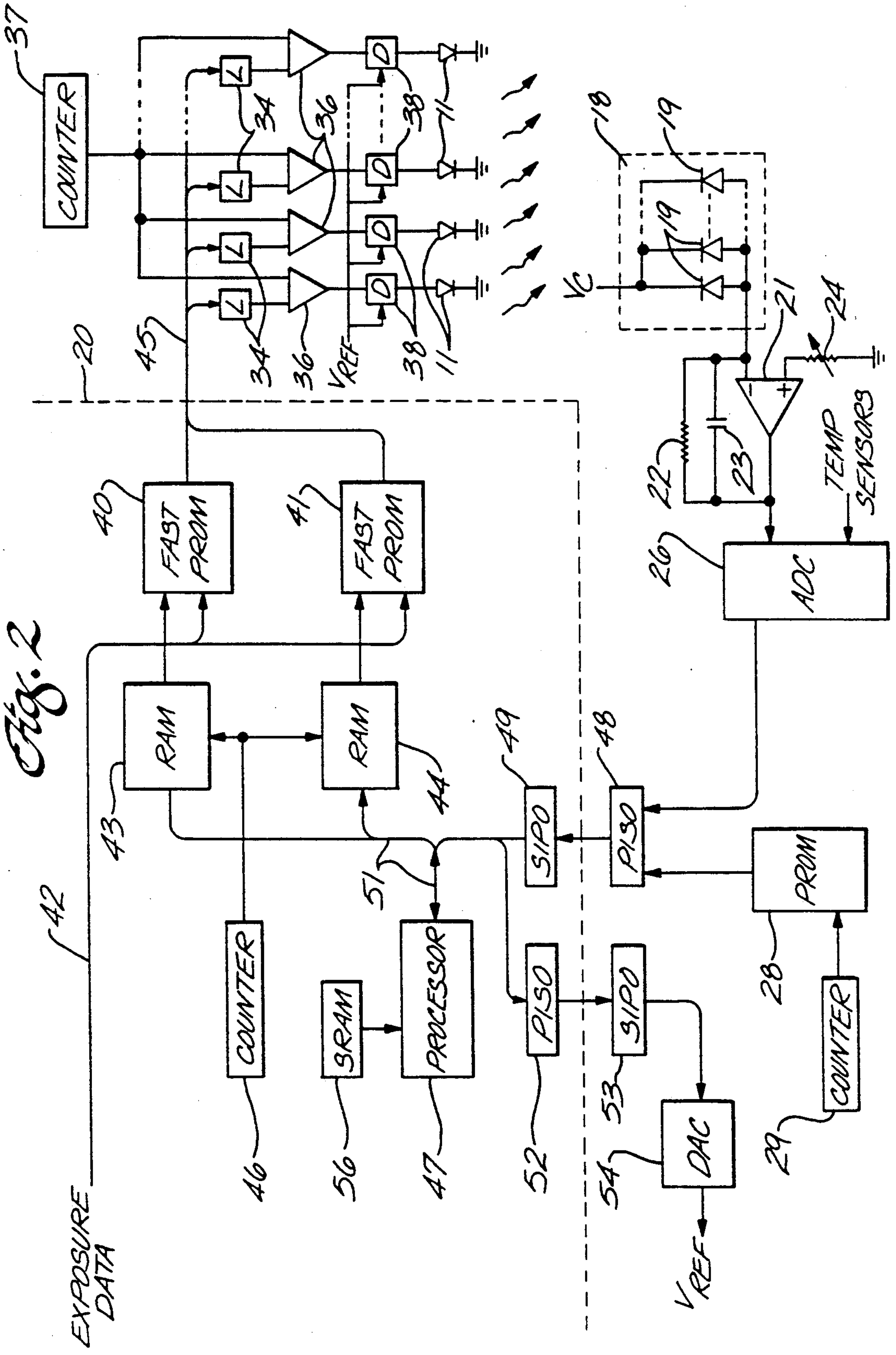
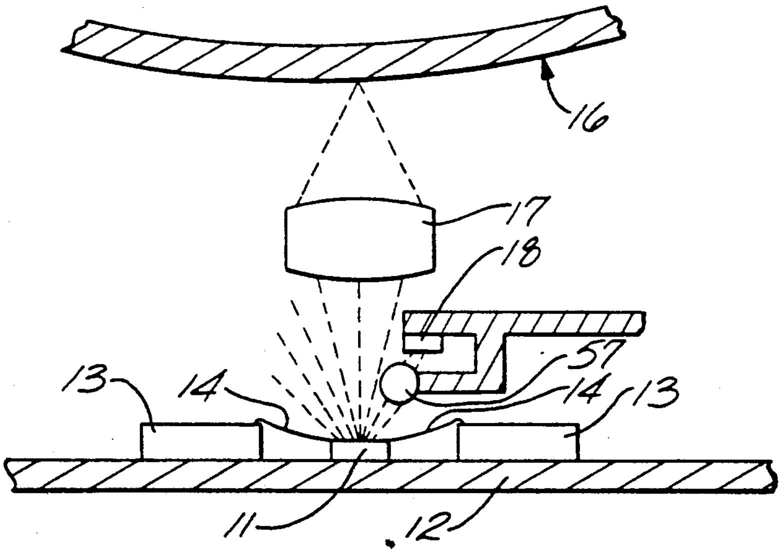

37
COUNTER
20
45
34
36
38
11
L
D
VREF
18
19
VC
21
24
22
23
TEMP SENSORS
26
ADC
40
FAST PROM
41
FAST PROM
43
RAM
44
RAM
49
SIPO
48
PISO
PROM
28
COUNTER
29
51
46
COUNTER
56
SRAM
47
PROCESSOR
52
PISO
53
SIPO
54
DAC
VREF
42
EXPOSURE DATA

Fig. 2

Fig. 4



LIGHT OUTPUT POWER MONITOR FOR AN LED PRINTHEAD

FIELD OF THE INVENTION

This invention is directed generally to a print quality regulator for a character generating electrophotographic printhead, and more specifically, to an apparatus and method for improving the uniformity of an LED printhead's light output power by periodically detecting and adjusting the light output of individual LEDs within the printhead.

BACKGROUND OF THE INVENTION

An LED printhead is part of a non-impact printer which employs an array of light emitting diodes (commonly referred to herein as LEDs) for exposing a photoreactive surface. The resulting pattern impressed upon the photoreactive surface is then transferred onto paper, or like material, in a way well known in the art.

In a typical LED printer, a row, or two closely spaced or staggered rows, of minute LEDs are positioned near an elongated lens array so that their images are focused onto the surface to be illuminated. The LEDs are driven by constant current integrated circuit power supplies which are switched on or off to create the desired image on the photoreactive surface.

In such a printer, all of the LEDs must produce substantially similar light output power (LOP) to produce a uniform print quality. However, left uncompensated, the light output of LEDs can vary greatly. Non-uniformities are introduced to the LOP in a variety of ways.

One cause of non-uniformities in LED output power is the variation in LED efficiency (light output as a function of current) due to the materials used in the LED wafers and fabrication of the LEDs themselves. Another cause of non-uniformities is variations in the drive current supplied by integrated power supplies due to similar concerns. These non-uniformities are inherent in the light output of the LEDs and they exist regardless of controlling other operating parameters such as temperature.

These non-uniformities are typically eliminated by individually calibrating the exposure time of each LED, thereby ensuring that the light output power for each LED exposure is approximately uniform. This is accomplished by measuring the LOP of each printhead LED, calculating the exposure time for each LED needed to produce a uniform LOP, and storing the calculated values in memory on the printer itself. Thereafter, when the printer is in use, these pre-determined values are used to control the exposure time of the LEDs.

This "one time" calibration of LED exposure power is often insufficient where precision LOP is required Temporal instability in the LED light output produces non-uniformities that must be eliminated on a periodic basis. One source of temporal instability is the long-term degradation of the LED light output power as the total LED on-time increases. This degradation is caused by the increase in the concentration and/or the cross section of non-radiative recombination centers near the LED junction. The concentration and type of crystalline defects associated with this recombination depends on many factors related to the fabrication of the LEDs and the magnitude of the degradation varies from LED to LED.

A second temporal instability is caused by the variation of LED light output power due to the heating and cooling of the entire printhead in use and to ambient temperature changes. For example, under normal operation, the printhead as a whole may see up to a 30° C. temperature rise which will cause a 27% loss in LOP.

A third source of temporal instability is the variation in LOP from LED to LED over short periods of time due to spatially varying power inputs into the LED printhead. Such non-uniformities are caused by the local heating of each LED as it and its neighbor LEDs are turned on and off. While the long-term temporal instabilities occur on the order of hundreds of hours, the short term spatially varying instabilities occur on the order of seconds. All of these non-uniformities must be corrected in a high precision and high speed printer.

U.S. Pat. No. 4,780,731, to Creutzmann discloses an electrophotographic printer that incorporates a "one time" calibration of LED exposure power on an LED-to-LED basis. The electrographic printer also includes a photoresponsive element positioned for acquiring the LOP transmitted onto the recording medium. To be precise, the photodetector element is positioned outside of the lens and is thus susceptible to toner build-up on its photoreactive surface. Also, the photodetector element is swivelably secured to the printhead and must be pivoted into the path of the focused light emitted from the lens each time the LOP is measured, thus adding to the mechanical complexity of the printhead. The LOP measured by the photodetector element is used periodically, in conjunction with the other operating parameters, to uniformly define a common operating parameter, such as LED drive current, for all of the LEDs. The assignee of the Creutzmann patent, Siemens Aktieageseilschaft, has published data specifications for a product implementing the subject matter of the Creutzmann patent which further discloses that several LED drive currents may be defined for each of a plurality of groups of LEDs. The printer thus compensates for the long-term temporal instabilities in the printhead which are uniform to all LEDs, or groups of LEDs.

However, as previously described, high precision printers are susceptible to other temporal instabilities that vary from LED to LED. It is desirable, therefore, to provide an LOP monitor and feedback system for an LED printhead that intermittently compensates for non-uniformities in LOP on an LED-to-LED basis, or at least in groups of LEDs.

SUMMARY OF THE INVENTION

Thus, there is provided in practice of this invention according to a presently preferred embodiment, a light output power monitor for an light emitting diode printhead having a row of light emitting diodes (LEDs) and a lens array for focusing light from the LEDs onto a photoreactive surface. The light output of each LED is controlled by modulating the exposure time of the LEDs supplied by a substantially constant current for all of the LEDs. The monitor has a detection means positioned between the LED array and the lens for measuring the light output power of the LEDs. Calibration memory means permanently store the ratio of LED power detected by the detection means and the power transmitted to the photoreactive surface. Exposure control means regulate the amount of time during which each LED is activated or deactivated. Correction means calculate exposure data for the exposure control means corresponding to each LED in response to the light output power measured by the detection means and calibration ratios for each LED stored in the calibration means.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features and advantages of the present invention will be better understood by reference to the following detailed description when considered in connection with the accompanying drawings wherein:

FIG. 1 is a schematic representation of a longitudinal view of an embodiment of an LED printhead and related components;

FIG. 2 is a block diagram of the LP monitor circuit; and

FIGS. 3 and 4 illustrate alternate embodiments of the LED printhead shown in FIG. 1.

DETAILED DESCRIPTION

Referring to FIG. 1, a row of light emitting diodes (LEDs) 11 can be viewed from the end of an exemplary printhead in a printer assembly. FIG. 1 is merely a schematic representation showing the relative positioning of various elements within a printhead. In such an exemplary embodiment, the row of LEDs includes 4992 individual LEDs formed on 39 semiconductor LED chips, each chip having 128 LEDs. The LED chips are bonded to a plurality of tiles 12 and the tiles are placed side-to-side on the printhead to form the row of LEDs 11. Integrated circuit driver chips 13 are attached to the tiles on either side of the LEDs. The driver chips 13 contain circuitry to control the illumination of the LEDs in the LED chips. Other circuitry necessary for control are not shown in this figure. The driver chips are electrically connected to the LED chips with wire bonds 14.

In an exemplary embodiment of the present invention, only a section of the LED row may be activated. For example, although the printhead may have 39 LED chips with 4992 total LEDs, an embodiment may only activate 4864 LEDs on the first 38 LED chips. Further, the number of LEDs activated may be a number which is not a multiple of 128. For example, 4820 LEDs may be activated, where all of the LEDs on 37 LED chips are used, and only 84 of the 128 LEDs on the thirty-eighth LED chip is used. The number of LEDs activated for a particular implementation depends upon the desired image width to be printed.

Illumination from the LED chips is focused onto a photoresponsive surface 16 by a conventional lens array 17 running the length of the row of LEDs. Samples of the LED light output are absorbed by a photodetector 18 which is located on the printhead inside of the lens array. The internal placement of the photodetector protects its detecting surface from collecting pollutants, such as printing toner, which can corrupt LOP measurement. These samples are used by the light output power monitor and control circuitry to regulate the illumination of the LEDs.

FIG. 2 shows a block diagram of the light output power monitor along with associated components in the printer assembly. The dashed line 20 represents the boundary between the printhead and the rest of the printer assembly. All elements shown below and to the right of the dashed line reside on the printhead itself. The photodetector 18 has an array of photodiodes 19 running the length of the row of LEDs. All of the photodiodes are connected in parallel. The cathode of each photodiode is connected to a common voltage V_c while the anode of each photodiode is connected to the non-inverting input of an operational amplifier (op-amp) 21. In an exemplary embodiment, fifty photodiodes are used to make up the photodetector 18. The photodiodes indiscriminately sense LOP from any of the LEDs. For example, when light from one of the LEDs 11 illuminate the photodetector 18, one or more of the photodiodes 19 are activated and begin to generate a current. The parallel orientation of the photodiodes causes the current generated in each photodiode to be added together to produce a composite LOP measurement. Thus, assuming that two LEDs have comparable LOP, the photodetector will produce comparable LOP measurements for each LED even if one LED is aligned adjacent to a photodiode 19, and the other LED is aligned somewhere between two photodiodes 19 in the photodetector 18.

A feedback resistor 22 and feedback capacitor 23 are connected between the inverting terminal and the output terminal of the op-amp 21. The non-inverting terminal of the op-amp is connected to one end of an offset resistor 24. The other end of the offset resistor is connected to ground. The op-amp 21 amplifies the current generated by the detector and converts it to a voltage. The offset resistor 24 provides an adjustable offset setting for the op-amp 21.

The output of the op-amp is connected to an input of a multi-channel analog to digital converter (ADC) 26 which converts the analog voltage representation of the detected light measured by the detector to a 10-bit digital word. In an exemplary embodiment, the ADC 26 has six channels. One channel is used to convert the light output power data from the operational amplifier 21, and the other five channels are used to convert temperature information from temperature sensors placed throughout the printhead.

By turning on a single LED with a standard drive current, the light output power (LOP) of the LED is measured. The resulting value is digitally subtracted from the value of the LOP measured at a time when no LEDs are turned on. Likewise, the LOP of the very same LED can be measured on the far side of the lens array 17 shown in FIG. 1 (i.e. in the proximity of the photoreactive surface 16). This measurement represents the light output power that appears at the photoreactive surface 16. These measurements are used to calculate drive factor ratios where the drive factor (DF) for each LED equals the LOP of that LED (LOP) minus the LOP with all LEDs off (LOP_{off}), this value then divided by the LOP of the same LED measured at the photoreactive surface (LOP_L), the drive factor is given by the equation:

$$DF=(LOP-LOP_{off})/LOP_L$$

In other words, the drive factor compensates for losses, etc., due to the lens system. An initial calibration of the printhead determines these losses and the resultant drive factor is stored for making corrections of LOP during operation of the printer.

The drive factor for each LED is stored in a drive factor PROM 28. The PROM contains 8k bytes of memory, each drive factor using one byte of the available memory. An address counter 29 is connected to the drive factor PROM 28 to select memory locations corresponding to the LED positions along the printhead. Since the detector 18 only measures light coming from the LEDs **11** at a point on the LED side of the lens array **17**, it cannot compensate for LED-to-LED variation in the transmission of light through the lens array, or variation in exposure density caused by variation in the end-to-end spacing of the LED chips. The drive factors for each LED stored in the drive factor PROM **28** are used to compensate LOP measurements output from the ADC **26** for these variations.

In an exemplary embodiment, the exposure energy of each LED is controlled by pulse width modulation. The modulation is accomplished by loading a 6-bit parallel exposure data word **45** for each LED into a 6-bit exposure register **34** corresponding to that LED. The words loaded are the data for a line of printing. The output of each exposure register **34** is connected to one input of a comparator **36**. The other input to the comparator is connected to the output of a 6-bit up/down counter **37**. The output of the up/down counter **37** begins at zero, counts up to 63 and back down to zero for each line of printed image to be formed. A comparator **36** operates such that each time equality exists at its two inputs, the output of the comparator switches between two logic states. The output of each comparator is connected to a switchable current source **38** each of which provides current for an LED. The magnitude of the current is set by a reference voltage, $V_{REF}$and the time during which the current is applied to the LED is determined by the comparator **36** output.

For example, at the beginning of each exposure cycle, where an exposure cycle is the interval when one line of text is printed, the up/down counter begins to count up from zero. When the output of the up/down counter equals the value loaded into the exposure register **34** of a particular LED, the comparator **36** switches the current source **38** ON for that LED and the LED begins to produce light. The up/down counter continues to count up to 63, at which point it begins to count down to zero. When the output of the up/down counter again reaches a value equal to the number loaded into the exposure register as it counts down from 63 to 0, the comparator turns the current source OFF.

Since there is a separate exposure register **34**, comparator **36** and current source **38** corresponding to each LED **11**, the LOP of each individual LED can be independently controlled. In an exemplary embodiment, a separate up/down counter is used in each driver chip **13**.

As previously mentioned, non-uniformities and temporal instabilities may occur in the LOP of the printhead. A non-uniformity occurs when adjacent LEDs or groups of LEDs do not produce the same LOP when supplied with equivalent current. Temporal instabilities occur when the LOP of individual LEDs or the entire printhead drift over a period of time.

To compensate for these LOP variations, a pair of correction curve Fast PROMs **40**, **41** are used to compensate raw exposure data **42**. The correction curve PROMs contain a family of curves which are indexed by correction curve index numbers generated by a pair of correction RAMs **43**, **49**. The correction curve Fast PROMs **40**, **41** are addressed by the raw exposure data for each LED position, and by the seven-bit correction curve index number output of the correction RAMs **43**, **44**. The correction curve Fast PROMs **40**, **41** operate to correct raw exposure data **42** using data stored in the correction RAMs **43**, **44** and thus producing exposure data **45** for the LEDs.

The correction curves loaded in the correction curve Fast PROMs essentially create a look-up table multiplier for the two inputs to the Fast PROMs (i.e. the raw exposure data and the correction curve index numbers). The correction curve index numbers are calculated based on LOP measurements by the photodetector **18** and indicate the factor that the raw exposure data must be multiplied by to achieve the desired exposure time for each LED and thus a stable LOP output. In an exemplary embodiment, the relationship between LOP and exposure time is linear. The correction curve index number is then linearly related to the multiplier that the raw exposure data is multiplied by.

Memory locations for these memory devices are partitioned between even and odd LEDs. For example, correction curve number for odd numbered LEDs are stored in the odd correction RAM **43**, and correction curve numbers for even numbered LEDs are stored in the even correction RAM **44**. Likewise, exposure data for odd numbered LEDs are compensated with the odd correction curve Fast PROM **41**, and exposure data for even numbered LEDs are compensated with the even correction curve Fast PROM **42**. A RAM address counter **46** is connected to the address inputs of the correction RAMs **43**, **44**.

The correction curve index numbers are computed with a data processor **47** based on information generated by the drive factor PROM **28** and the ADC **26**. The outputs of the drive factor PROM and the ADC are connected to the inputs of a local parallel-in/serial-out data register (PISO) **48**. The output of the local PISO leaves the printhead and is connected to the input of a remote serial-in/parallel-out data register (SIPO) **49**. The output of the remote SIPO **49** is connected to the data processor **47** via a bidirectional parallel data bus **51**. The data bus is also connected to the data inputs to the correction RAMs **43**, **44**. This configuration provides for the transmission of data from the ADC **26** and drive factor PROM **28** to the data processor **47** and from the data processor to the correction RAMs **43**, **44**.

Data is returned from the data processor **47** to the printhead electronics by connecting the data bus **51** to the inputs of a remote PISO **52**. The serial output of the remote PISO **52** is connected to the input of a local SIPO **53**. The outputs of the local SIPO **53** are connected to an eight-bit digital-to-analog converter (DAC) **54** which produces the reference voltage V_{REF}.

The correction curve index numbers stored in the correction RAMs are intermittently updated while the printer is in service. New values for the correction curve index numbers are determined by one of two algorithms, a long-term compensation algorithm and a short-term compensation algorithm. The long-term compensation algorithm is performed, in an exemplary embodiment, each time power is applied to the printhead or perhaps once every day if the printer is left on around the clock. This algorithm individually measures and calibrates every LED on the printhead.

First, $V_{REF}$is set by data from the data processor **47** to a standard value used each time the LOP is calibrated. Next, the first LED is turned on and the LOP is measured by the detector **18** and converted to a digital representation by the ADC **26**. Next, the drive factor corresponding to the first LED is read from the drive factor PROM **28**. The next step is to calculate, using integer arithmetic, the correction curve index number (C_N) for the first LED. The data processor **47** takes the measured LOP and the drive factor (DF) for the first LED and computes the curve number by

$$C_N = (DF \cdot 127/LOP) - 127$$

The correction curve index number is then stored in the odd correction RAM **43** and the process is repeated for each LED position, the only deviation being that curve numbers for even numbered LEDs are stored in the even correction RAM **44**. Some of the LOP measurements are stored in scratch pad memory for use in the short-term compensation algorithm. A random access memory **56** is connected to the data processor for this purpose.

The correction curve index numbers stored in the correction RAMs **43** and **44** are used by the correction curve Fast PROMs **41, 42** to compensate the raw exposure data **42** until the correction curve index numbers are updated. These numbers are periodically updated between long-term compensation by performing the short-term compensation algorithm. It should be understood that the monitoring process implementing these algorithms can also be performed aperiodically. In an exemplary embodiment, the short-term algorithm is performed between each printed page. Because of time limitations, it may not be feasible to measure each of the LED's light output power that often. Therefore, the LEDs are divided into groups and the LOP of only one LED from each group is measured. The single LOP measurement for each group is used to calibrate the LOP for each LED in the group.

In an exemplary embodiment, the LOP of one LED per LED chip is measured, and in the short-term algorithm that measurement is used to calibrate all of the LEDs on that LED chip. Therefore, the LOP of thirty-nine individual LEDs will be measured. It should be understood that it is not necessary for this many measurements to occur. Temporal instabilities can be removed from the printhead LOP with as little as six individual LOP measurements per printhead for most printer applications.

For the sake of simplicity, the short-term algorithm is described using 38 LED groups of 128 LEDs each (i.e., the row of 4864 active LEDs of the entire row of 4992 LEDs, is divided into six groups). This algorithm requires both the current LOP (LOP_{new}) and the previous LOP (LOP_{old}) for each of the six measurements. Thus, the applicable LOP measurements are stored in scratch pad memory **56**. This algorithm also reads curve correction index number data from the correction RAMs. Generally, the short-term algorithm measures the LOP of one LED and uses that measurement to calculate correction curve index numbers (C_N) for that LED and the 127 LEDs that follow it. This is repeated for the remaining 37 groups of 128 LEDs along the printhead. The algorithm for calculating correction curve index numbers for each LED group in the above embodiment is

```
factor =      $(LOP_{old} \cdot 255)/LOP_{new}$
for i =       0 to 127
C_N[i] =      $factor \cdot (C_N[i] + 127)/255) - 127$
next i
```

The number of active LEDs and size of the LED groups may differ in alternative embodiments. Accordingly, the short-term algorithm may be generalized as follows:

```
for h =        0 to x − 1
for i =        0 to y − 1
factor[h] =    $(LOP_{old}[y \cdot h] \cdot 255)/LOP_{new}[y \cdot h]$
C_N[h,i] =     $factor[h] \cdot (C_N[h,i] + 127)/255) - 127$
next i
next h
```

where x equals the number of LED groups and y equals the number of LEDs in each group.

The long-term compensation and the short-term compensation methods described above overcome shortcomings of the prior art wherein the LOP of the LEDs were uniformly compensated on an interim basis. The present invention allows for the individual compensation of each LED, or groups of LEDs, on an interim basis. In doing so, the present invention corrects for long-term and short-term temporal instabilities, such as aging and local temperature variations, that individually effect LEDs.

In addition to these two algorithms which compensate the LOP based on measurement of LOP, the present invention also compensates LOP based on measurement of printhead temperature. In an exemplary embodiment, five temperature sensors are connected to the printhead in the vicinity of the LEDs. The temperature sensors are connected to the ADC **26** to produce a digital word that can be manipulated by the data processor **47**. A rise in temperature will cause a lower LOP at a constant LED drive current. Thus, when a rise in temperature occurs, the data processor adjusts the reference voltage V_{REF} by changing the digital inputs to the DAC **54**. V_{REF} in turn, uniformly adjusts the current sources to produce a larger current for the LEDs.

This compensation method is used in conjunction with the LOP monitoring system where the temperature compensation provides a fairly rough correction and the LOP monitoring system provides fine tuning to enhance the printhead LOP.

For example, in an exemplary embodiment, the LED printhead is initially compensated for focusing losses in the lens array **17** by measuring the light output power of each LED and determining a correction drive factor for each LED. The drive factor for each LED is stored on the printhead and used in the operation of the printhead so that the ON-time of each LED is proportional to the respective stored drive factors. Long-term instabilities are roughly compensated by measuring the temperature of the printhead in the vicinity of the LEDs and then adjusting the current supplied to the LEDs. Long-term instabilities are further corrected by intermittently measuring the light output power of each LED and selecting a correction curve for each LED in response to the measured light. The ON-time of each LED is thereafter adjusted in proportion to the respective selected correction curve. Short-term instabilities in the light output power of the printhead are corrected by intermittently, over a relatively shorter interval than the long-term correction, measuring the light output power of a representative LED in a group of LEDs. These measurements are used to individually select a correction curve for each LED within the group in response to the light output power of the represenative LED. The ON-time of each LED is then adjusted in proporation to the newly selected correction curve.

In the exemplary embodiment shown in FIG. 1, the detector is placed directly in the path of the light emanating from the LEDs. Alternative embodiments are shown in FIGS. 3 and 4 wherein the light from the LED is focused onto the detector via an elongated elliptical mirror 56 and a cylindrical detector lens 57, respectively. Use of these focusing methods reduces the size of the photodiodes 14 needed in the detector to produce an LOP measurement. The placement of the photodetector in each of these embodiments overcomes shortcomings in the prior art which required that the detector swivel into a position where it could measure LOP. In the present no moving parts are required to perform LOP measurements.

It should be apparent to one skilled in the art that other embodiments exist that are within the nature and principle of this invention. For example, other arrangements can be imagined to focus light from the LED onto the detector surface. Further, within the framework of the present invention, additional algorithms may be used to compensate for particular inconsistencies in the printhead LOP. One example is the use of arbitrary correction curve contents in the correction curve PROMs 43, 44 along with a variable frequency up/down counter 37 to accommodate highly nonlinear electrophotographic process corrections. It is, therefore, intended that the above description shall be read as illustrative and not as limited to the preferred embodiments as described herein.

What is claimed is:

1. A light output power monitor for an LED printhead which has an array of individually time modulated LEDs for exposing a photoreactive surface through a lens array, comprising:

detector means for detecting light output power of each LED in the LED array;

calibration means for storing calibration ratios corresponding to the loss of light output power through the lens array for each LED;

means for selectively supplying current to each LED;

exposure control means for individually regulating the activation and deactivation times of each current supply means in response to modified exposure data; and

correction means coupled to the exposure control means for acquiring raw exposure data, light output values from the detection means and calibration ratios from the calibration memory means and individually defining modified exposure data for each LED controlled by the exposure control means based on the detected light output values, the raw exposure data and the stored calibration ratios.

2. A light output power monitor as recited in claim 1 wherein the detector means is located inside the printhead.

3. A light output power monitor as recited in claim 2 wherein the detector means is immovably secured in the printhead.

4. A light output power monitor as recited in claim 1 wherein the correction means comprises:

processing means for calculating index numbers corresponding to each LED based on the light output values and calibration ratios;

memory means for storing the index numbers; and

multiplier means coupled to the memory means and exposure control means for correcting the raw exposure data corresponding to each LED based on the calculated index numbers corresponding to each LED, each index number selecting a unique multiplication curve, a point on which comprises the modified exposure data selected by the correction means based on the raw exposure data.

5. A light output power monitor as recited in claim 4 wherein the multiplier means comprises a programmable read-only-memory.

6. A light output power monitor as recited in claim 1 wherein the detection means detects the light output power of selected LEDs in the LED array.

7. A light output power monitor as recited in claim 1 further comprising:

temperature sensing means for measuring the printhead temperature; and

compensation means coupled to the temperature sensing means and the current supply means for uniformly adjusting the current supplied to each LED in response to the printhead temperature.

8. An LED printhead comprising:

illumination means for generating unfocused light in response to exposure data;

photoreactive means for generating an image in response to light;

means for focusing the unfocused light from the LEDs onto the photoreactive means; and

monitor means for detecting the unfocused light and for compensating the exposure data to remove non-uniformities and temporal instabilities in the focused light, the monitor means including calibration memory means for storing calibration ratios corresponding to the loss of light output power through the focusing means.

9. An LED printhead as recited in claim 8 further comprising means for concentrating a portion of the unfocused light onto the monitor means.

10. An LED printhead as recited in claim 9 wherein the concentrating means comprises an elliptically shaped mirror.

11. An LED printhead as recited in claim 9 wherein the concentrating means comprises a optical lens.

12. An LED printhead as recited in claim 9 wherein the monitor means comprises a row of photodiodes connected in parallel along the printhead.

13. An LED printhead as recited in claim 9 wherein the illumination means comprises a plurality of light emitting diodes in a row along the printhead.

14. An LED printhead as recited in claim 13 further comprising means for compensating for variations in light output power of each light emitting diode due to light output power loss through the focusing means.

15. A method for stabilizing the light output power from a plurality of light emitting diodes on a light emitting diode printer wherein each diode is illuminated for a length of time determined by a raw exposure value and a correction curve, the method comprising the steps of:

providing current to each light emitting diode for a calibrating length of time;

measuring the light output power of each light emitting diode;

selecting a correction curve for each light emitting diode in response to the measured light output power;

calculating modified exposure data as a function of the raw exposure data and the selected correction curve;

- thereafter, each time each light emitting diode is illuminated, adjusting the time each light emitting diode is turned ON in proportion to the modified exposure data; and
- repeating the providing current, measuring and selecting steps.

16. A method as recited in claim **15** wherein the repeating step is performed each time power is applied to the printer.

17. A method for stabilizing the light output power from a plurality of light emitting diodes on a light emitting diode printer for printing images on paper sheets wherein each diode is illuminated for a length of time determined by a raw exposure value and a correction curve, the method comprising the steps of:

- providing current to each light emitting diode for a calibrating length of time;
- dividing the plurality of light emitting diodes into groups;
- measuring the light output power of one light emitting diode within each group;
- selecting a correction curve for each light emitting diode in a group in response to the measured light output power of the measured light emitting diode in that group;
- calculating modified exposure data as a function of the raw exposure data and the selected correction curve;
- thereafter, each time each light emitting diode is illuminated, adjusting the time each light emitting diode is turned ON in proportion to the modified exposure data; and
- repeating the providing current, measuring and selecting steps periodically.

18. A method as recited in claim **17** wherein the repeating step is performed in the time between each printed sheet.

19. A method as recited in claim **17** wherein the repeating step is performed aperiodically.

20. A method for minimizing light output variations in an LED printhead in which LED output is pulse width modulated, comprising the steps of:

- measuring light output power of each LED in an array of LEDs and determining a correction drive factor for each LED;
- storing the drive factor for each LED;
- adjusting the time each LED is turned ON in proportion to the respective stored drive factor;
- intermittently over a relatively longer interval measuring light output power of each LED;
- selecting a correction curve for each LED in response to the intermittently measured light output power;
- adjusting the time each LED is turned ON in proportion to the respective selected correction curve;
- intermittently over a relatively shorter interval measuring light output power of a representative LED in a group of LEDs;
- changing the correction curve, as appropriate, for each LED in the group in response to the light output power of the representative LED;
- adjusting the time each LED is turned ON in proportion to the changed correction curve in lieu of the selected correction curve;
- measuring temperature in the vicinity of the LEDs; and
- adjusting current for the LEDs in response to changes in temperature.

* * * * *

United States Patent [19]
Ohashi

[11] **Patent Number: 5,018,154**
[45] **Date of Patent: May 21, 1991**

[54] SEMICONDUCTOR LASER DRIVE DEVICE

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[21] Appl. No.: **578,270**

[22] Filed: **Sep. 6, 1990**

[30] **Foreign Application Priority Data**

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Oct. 5, 1989	[JP]	Japan	1-261833

[51] **Int. Cl.**^{5} **H01S 3/131**
[52] **U.S. Cl.** **372/29**; 372/31; 372/33; 372/34; 372/38
[58] **Field of Search** 372/29, 31, 32, 33, 372/34, 26, 38

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Primary Examiner—Frank Gonzalez
Assistant Examiner—Galen J. Hansen
Attorney, Agent, or Firm—Oliff & Berridge

[57] **ABSTRACT**

A semiconductor laser drive device modulates optical output of a semiconductor laser in accordance with an externally provided modulation signal comprises a compensation circuit for calculating a compensation coefficient and for generating a compensation modulation signal, a threshold value current generation circuit for generating and a threshold value current to the compensation modulation signal and sending the added current as a drive current, and a current drive circuit for driving the semiconductor laser based on the drive current sent from the threshold value current generation circuit. In accordance with the semiconductor laser, the optical output error caused by the temperature change of the semiconductor laser is compensated.

21 Claims, 4 Drawing Sheets

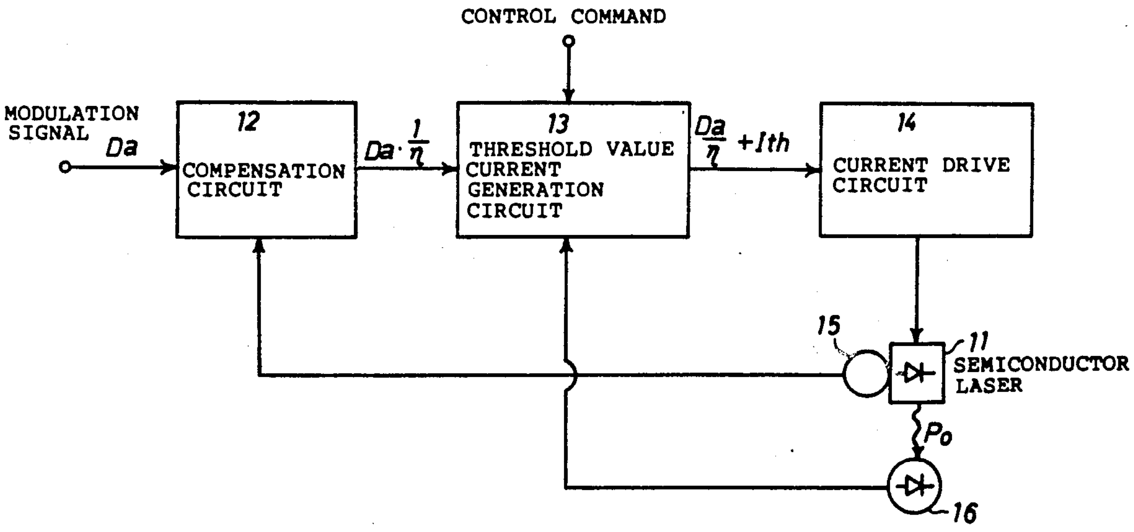
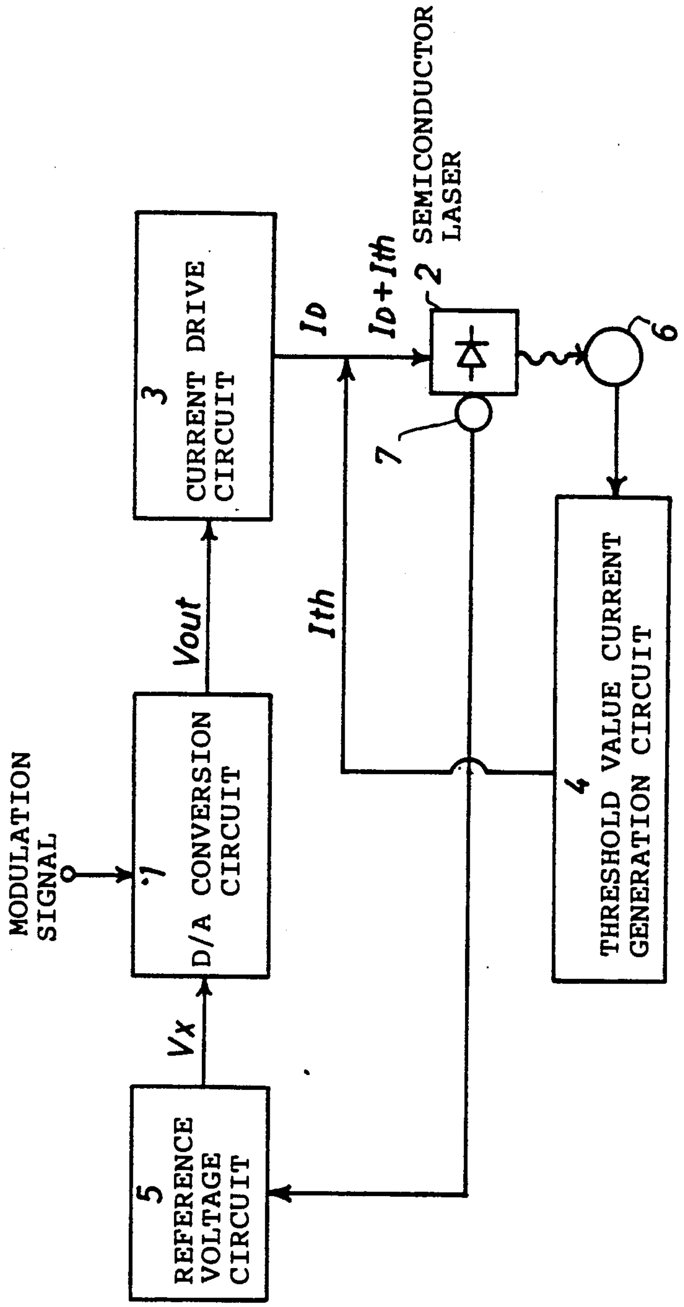


FIG. 1


MODULATION SIGNAL
1
D/A CONVERSION CIRCUIT
Vout
3
CURRENT DRIVE CIRCUIT
ID
ID+Ith
2
SEMICONDUCTOR LASER
6
7
Ith
4
THRESHOLD VALUE CURRENT GENERATION CIRCUIT
Vx
5
REFERENCE VOLTAGE CIRCUIT

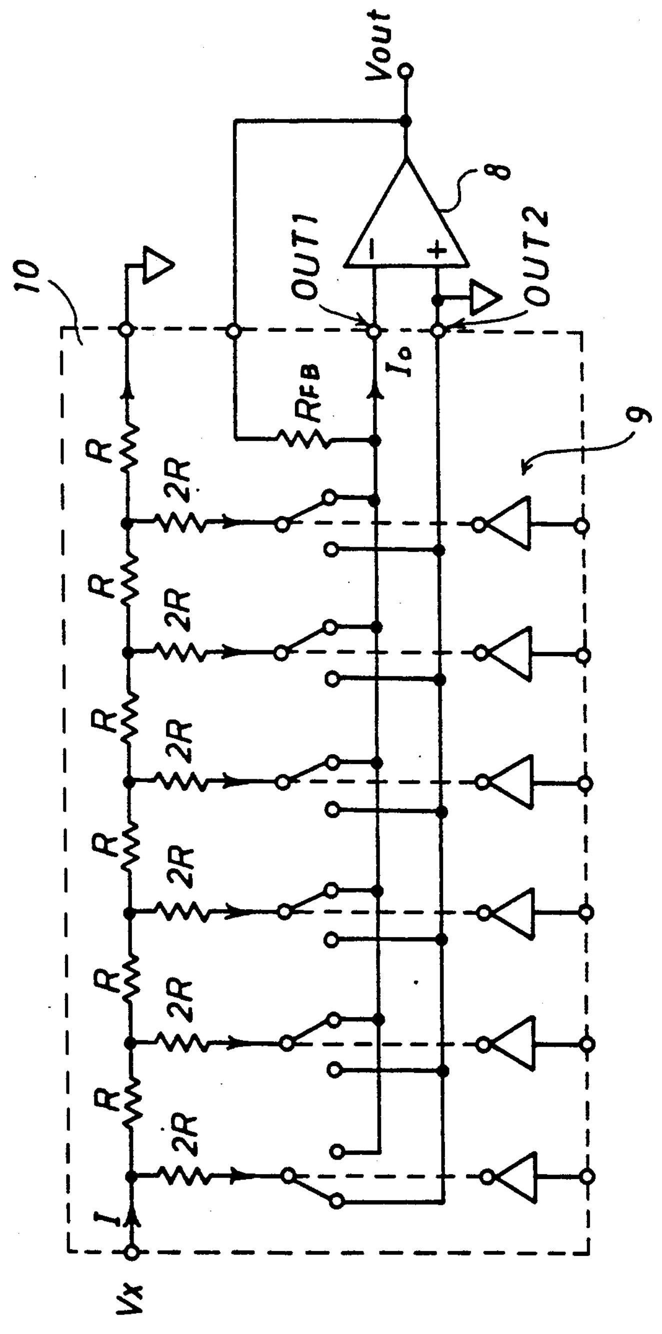


FIG. 2

FIG. 3

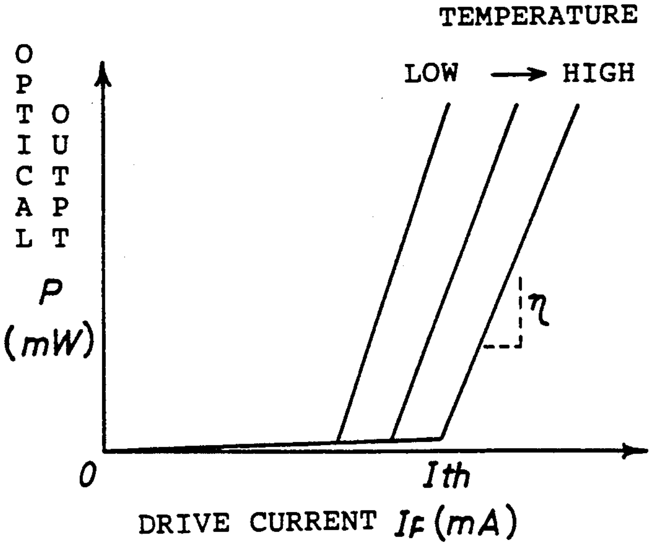

TEMPERATURE
LOW ⟶ HIGH
OPTICAL OUTPUT
P
(mW)
η
0
Ith
DRIVE CURRENT I_F (mA)

FIG. 4

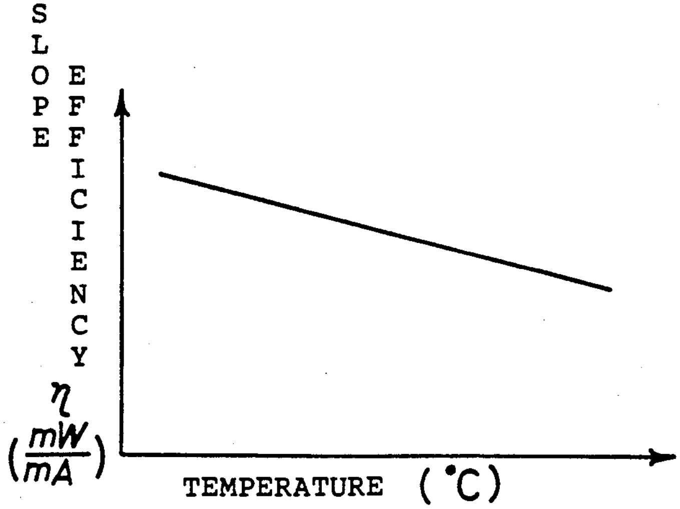
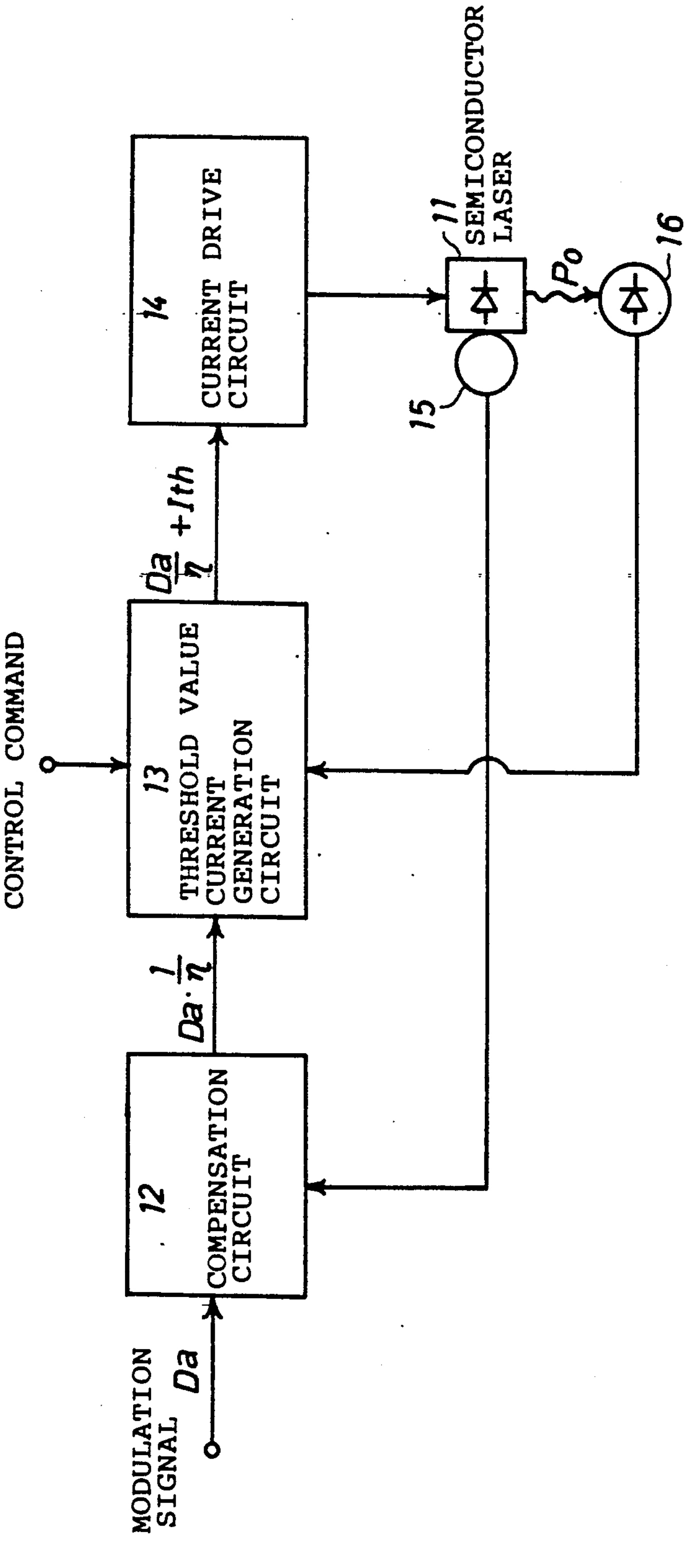

SLOPE EFFICIENCY
η
(mW/mA)
TEMPERATURE (°C)

FIG. 5


MODULATION SIGNAL
Da
12
COMPENSATION CIRCUIT
$Da \cdot \frac{1}{\eta}$
CONTROL COMMAND
13
THRESHOLD VALUE CURRENT GENERATION CIRCUIT
$\frac{Da}{\eta} + Ith$
14
CURRENT DRIVE CIRCUIT
11
SEMICONDUCTOR LASER
Po
15
16

SEMICONDUCTOR LASER DRIVE DEVICE

BACKGROUND OF THE INVENTION

The present invention relates to a semiconductor laser drive device used in exposure apparatuses. More particularly, the present invention relates to a semiconductor laser drive device which modulates the intensity of a laser beam corresponding to an externally provided digital modulation signal.

Related Art

In a semiconductor laser drive device which electrically drive a semiconductor laser based on an analog control signal converted from an externally provided digital modulation signal and modulates the intensity of optical output of the semiconductor laser, various measurements are taken in order to minimize the error of the optical output caused by temperature change of the semiconductor laser. Such measures include, for instance, temperature control by keeping the temperature of the semiconductor laser constant and threshold value current compensation in which a threshold value current, which changes in accordance with the temperature change of the semiconductor laser, is detected and the operating point of the semiconductor is accordingly adjusted.

The above temperature control of a semiconductor laser is effected by heating a semiconductor laser or storing a semiconductor in a constant temperature oven. However, since this measure is incapable of accurate temperature control and not a reliable measure, the other measure, threshold value current compensation is ordinarily adopted to minimize an error.

A semiconductor laser drive device provided with a mechanism to compensate a threshold value current detects change in the threshold value current by monitoring the optical output of a semiconductor laser using a photodetective element such as a photodiode. Then, the semiconductor laser drive device controls the drive current of the semiconductor laser based on the detected change in the threshold value current and compensates for the change, thus minimizing the error of the optical output corresponding to a digital modulation signal even though the threshold value current changes due to the temperature change of the semiconductor laser.

As explained above, the optical output change is caused by threshold value current change which in turn is caused by the temperature change of a semiconductor laser. Moreover, external differential quantum efficiency which is the luminous efficiency of a semiconductor laser (referred to as slope efficiency hereinafter) also changes corresponding to the temperature change.

FIG. **3** shows the relation between the optical output P of a semiconductor laser and the drive current I_F. If the threshold value current is I_{th} at a certain temperature and slope efficiency, which is the ratio of an increase of the drive current I_F to an increase of the optical output P, is η, P is expressed as follows:

$$P=(I_F-I_{th})\eta \tag{1}$$

As shown in FIG. **4**, the change in slope efficiency is known to be in approximate proportion to the change in temperature. Therefore, in a semiconductor laser drive device which modulates the optical output of a semiconductor laser corresponding to an externally provided digital modulation signal, compensation of threshold value current alone does not solve the problem of an error of the optical output occurring due to a change of slope efficiency caused by the temperature change. More specifically, as shown in the above equation (1), when the temperature of a semiconductor rises, slope efficiency decreases, thus reducing the optical output. On the other hand, when the temperature lowers, slope efficiency increases, thus increasing the optical output. The variable slope efficiency has made it difficult to obtain stable optical output which is in proportion to an externally provided digital modulation signal.

SUMMARY OF THE INVENTION

The object of the present invention made to overcome the above-identified problem is to provide a semiconductor laser drive device that can stably modulate the output of a semiconductor laser without causing an output error by compensating change in threshold value current and slope efficiency caused by temperature change of the semiconductor laser.

The present invention attains the above-mentioned object by adding a slope efficiency compensation means to a semiconductor laser drive device provided with a threshold value current compensation means.

A semiconductor laser drive device of the first embodiment of the present invention comprises: a D/A conversion circuit for converting an externally provided digital modulation signal to an analog signal based on a reference voltage; a current drive circuit for electrically driving a semiconductor laser based on the output signal sent from the D/A conversion circuit; and a threshold value current generation circuit for generating a threshold value current of the semiconductor laser based on which the drive current of the semiconductor laser is compensated. The semiconductor laser further is also provided with a reference voltage compensation means for calculating a compensation coefficient, which is the reciprocal of the slope efficiency, based on the temperature information of the semiconductor laser and compensating the reference voltage of the D/A conversion circuit with the compensation coefficient.

In operation, the threshold value current generation circuit reduces the error in optical output modulation caused by change in the threshold value current while the reference voltage compensation means reduces the error in optical output modulation caused by changes in slope efficiency. Consequently, the optical output of a semiconductor laser can be accurately modulated in proportion to an externally provided digital modulation signal.

A semiconductor laser drive device of a second embodiment of the present invention is provided with a threshold value current compensation means for compensating change in the threshold value current and a slope coefficient compensation means for compensating change in slope efficiency. More particularly, a semiconductor laser drive device of the second embodiment that modulates optical output of a semiconductor laser in accordance with an externally provided modulation signal comprises: a compensation circuit for calculating a compensation coefficient, which is the reciprocal of slope efficiency, based on the temperature of the semiconductor laser and for generating a compensation modulation signal obtained by multiplying the externally provided modulation signal by the compensation coefficient; a threshold value current generation circuit for generating and a threshold value current to the compensation modulation signal and sending the added current as a drive current; and a current drive circuit for driving the semiconductor laser based on the drive current sent from the threshold value current generation circuit.

In the operation of the semiconductor laser drive circuit of the second embodiment, the compensation circuit sends a compensation modulation signal which has been compensated for the change in slope efficiency due to the temperature change of a semiconductor laser to the threshold value current generation circuit. The threshold value current generation circuit drives the semiconductor laser by sending a drive current which is the addition of a threshold value current variable to the temperature change and the compensation modulation signal. Then, the semiconductor laser is driven to generate the optical output in proportion to the modulation signal which has been compensated for slope efficiency and threshold value current. In other words, the semiconductor laser accurately generates the optical output without making little error caused by the temperature change.

BRIEF EXPLANATION OF THE ATTACHED DRAWINGS

FIG. **1** is a block diagram of a semiconductor laser drive device of a first embodiment of the present invention.

FIG. **2** is a wiring diagram of a D/A conversion circuit included in FIG. **1**.

FIG. **3** is a graph showing characteristics of the optical output and the drive current of a semiconductor laser.

FIG. **4** is a graph showing the relationship between the slope efficiency and the temperature of a semiconductor laser.

FIG. **5** is a block diagram of a semiconductor laser drive device of a second embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

First Embodiment

A semiconductor laser embodying the present invention is explained in reference to FIGS. **1** and **2** hereinafter.

As shown in a block diagram of FIG. **1**, the semiconductor laser drive device comprises a D/A conversion circuit **1** for converting an externally provided digital modulation signal into an analog signal based on a reference voltage V_x, which is explained below, a current drive circuit **3** for electrically driving a semiconductor laser **2** according to an output voltage Vout of the D/A conversion circuit **1**, a threshold value current generation circuit **4** for generating a threshold value current of the semiconductor laser **2**, and a reference voltage compensation circuit **5** for compensating for change in slope efficiency of the semiconductor laser **2**.

The threshold value current generation circuit **4** generates a threshold value current corresponding to the temperature of the semiconductor laser **2** based on a signal sent from a photodetective element, such as photodiode **6**, photocoupled with the semiconductor laser **2**. Then, the threshold value current generation circuit **4** adds the threshold value current corresponding to the temperature of the semiconductor laser **2** to output current I_D, thereby compensating for variations the output of the semiconductor laser **2** caused by change in the threshold value current.

The reference voltage circuit **5** determines a compensation coefficient, which is the reciprocal of slope efficiency, based on the temperature of the semiconductor laser **2** sent in the form of temperature information from a temperature sensor **7** that is thermally coupled with the semiconductor laser **2**. The reference voltage circuit **5** compensates a reference voltage V_o with the compensation coefficient and sends a compensation reference voltage V_x, which is the compensated reference voltage V_o, to the D/A conversion circuit **1**.

More detailed explanation of the compensation operation is given below.

As shown in FIG. **2** explaining the constitution of the D/A conversion circuit **1**, an addition circuit **9** provided with operation amplifier **8** uses a ladder-like resistance circuit **10** to receive the compensation reference voltage V_x. The resistance circuit **10** is weighted by 2^n, where n is the number of bits in a digital notation signal code. The compensation reference voltage V_x is applied to the resistance circuit **10**.

Therefore, in the resistance circuit **10** of the D/A conversion circuit **1**, weighted currents flow through each resistor based on the compensation reference voltage V_x and, if switched on, which is determined by the state of each bit of the digital modulation signal code, combines the currents and generates a composite current I_o therefrom. The current I_o, which flows at a terminal OUTl, is expressed by the following equation:

$$I_o = \sum_{n=1}^{6} \tfrac{1}{2}^{n}\, bn \tag{2}$$

In the equation (2), I is the input current; and bn is the state of each bit, either 1 or 0.

The output voltage Vout of the D/A conversion circuit **1** is expressed by the following equation:

$$Vout = -R_{FB} \cdot I \cdot \sum_{n=1}^{6} bn/2^n \tag{3}$$

In the equation (3), R_{FB} is the feedback resistance. In the present circuit, R_{FB} is designed to be R.

Because $V_x = R\ I = R_{FB}\ I$, the equation (3) is expressed by the following equation:

$$Vout = -V_x \cdot \sum_{n=1}^{6} bn/2^n \tag{4}$$

The output voltage Vout of the D/A conversion circuit **1** is sent to the current drive circuit **3**. The output current I_D of the current drive circuit is expressed by the following equation:

$$I_D = K \cdot Vout \tag{5}$$

In the equation (5), K (a constant) is the drive capacity of the current drive circuit **3**; and I_D is the output current.

The output current I_D is added to the threshold value current I_{th} (see FIG. **3** for reference) to obtain current I_F which is expressed by the following equation:

$$I_F = I_D + I_{th} \tag{6}$$

The current I_F drives the semiconductor laser **2**. As is the equation (1) explained above, the optical output P of the semiconductor laser **2** is expressed by the following equation:

$$P=(I_F-I_{th})\cdot\eta \tag{7}$$

In the above equation (7), η is the slope efficiency.

The reference value circuit **5** calculates a compensation coefficient which is the reciprocal $1/\eta$ of slope efficiency η and determines the compensation reference voltage V_x to be sent to the D/A conversion circuit **1** after compensating the reference voltage V_o by the compensation coefficient. The compensation reference voltage V_x is expressed by the following equation:

$$V_x=-1/\eta\cdot V_o \tag{8}$$

Therefore, if the right sides of the equations (7) and (5) are substituted for I_F and I_D, respectively, in the equation (7), the following equation is obtained:

$$\begin{aligned} P &= (I_D + I_{th} - I_{th})\eta \\ &= \eta \cdot I_D \\ &= \eta \cdot K\ Vout \end{aligned} \tag{9}$$

Furthermore, if the right sides of the equations (4) and (8) are substituted for Vout and V_x, respectively, the following equation is obtained:

$$\begin{aligned} P &= \eta \cdot K \cdot (-V_x) \cdot \sum_{n=1}^{6} bn/2^n \\ &= \eta \cdot K \cdot 1/\eta\ V_o \sum_{n=1}^{6} bn/2^n \\ &= K\ V_o \cdot \sum_{n=1}^{6} bn/2^n \end{aligned} \tag{10}$$

The equation (10) clearly shows that change in either the threshold value current I_{th} or the slope efficiency η due to the temperature change of the semiconductor laser **2** does not cause the error of the optical output of the semiconductor laser **2**: the semiconductor laser **2** sends accurate optical output in proportion to the externally provided digital modulation signal.

While the described embodiment represents the preferred form of the invention, it is to be understood that changes and variations can be made without departing from the spirit and the scope of the invention.

For example, the added signal of the digital data corresponding to the threshold value current of a semiconductor laser and the digital data of the externally provided modulation signal may be converted to an analog signal by the D/A conversion circuit.

Second Embodiment

A second embodiment of the present invention is explained hereinafter, referring to a block diagram of FIG. **5** showing the overall constitution of the present embodiment of the semiconductor laser drive device.

The semiconductor laser drive device comprises a compensation circuit **12** for compensating an externally provided modulation signal D_a for change in slope efficiency η of a semiconductor laser **11**, a threshold value current generation circuit **13** for generating a threshold value current of the semiconductor laser **11**, a current drive circuit **14** for electrically driving the semiconductor laser **11**, a temperature sensor **15** for detecting the temperature of the semiconductor laser **11** and sending a electrically converted signal to the compensation circuit **12**, and a photodiode **16**, a photodetective element, for converting the optical output of the semiconductor laser **11** to an electrical signal and sending the electrical signal to the threshold value current generation circuit **13**. The temperature sensor **15** is thermally coupled with the semiconductor laser **11** and sends information conveying the temperature of the semiconductor laser **11** that determines slope efficiency. The photodiode **16** is photocoupled with the semiconductor laser **11** and sends a signal which determines the threshold value current of the semiconductor laser **11** to the threshold value current generation circuit **13**.

The following is a more detailed explanation of the operation of the semiconductor laser drive device of the present embodiment.

The compensation circuit **12** calculates a compensation coefficient $1/\eta$, which is the reciprocal of slope efficiency η, and generates a compensated modulation signal $D_a\,1/\eta$ obtained by multiplying the compensation signal $1/\eta$ by the externally provided modulation signal D_a.

The threshold value current generation circuit **13** generates a threshold value current I_{th} corresponding to the temperature of the semiconductor laser **11** based on the signal sent from the photodiode **16** and send a drive current $D_a/\eta+I_{th}$, which is the addition of the generated threshold value current I_{th} and the compensation modulation signal D_a/η from the compensation circuit **12**, to the current drive circuit **14**.

To generate a threshold value current, the threshold value current generation circuit **13** first sends only the threshold value current by blocking the modulation data sent from the compensation circuit **12** upon receiving a control instruction signal externally provided at regular intervals. Second, the threshold value current is gradually raised from zero until the photodiode **16** detects the rapidly increasing optical output of the semiconductor laser **11** reaching a predetermined level. At the predetermined level the threshold value current I_{th} is fixed. Consequently, the block of the modulation data sent from the compensation circuit **12** is removed.

The current drive circuit **14** drives the semiconductor laser **11** based on the drive current $(D_a/\eta+I_{th})$ from the threshold value current generation circuit **13**. The optical output P is expressed by the following equation in accordance with the graph of FIG. **3**:

$$P=(I_F-I_{th})\eta \tag{11}$$

In the equation, I_F is the drive current.

If the drive current $D_a/\eta+I_{th}$ of the present embodiment is substituted for I_F in the equation (11), the optical output P is expressed by the following equation:

$$\begin{aligned} P &= (D_a/\eta + I_{th} - I_{th})\eta \\ &= D_a \end{aligned} \tag{12}$$

As shown in the equation (12), the optical output of the semiconductor **11** is in proportion to the externally provided modulation signal D_a, not affected by change in the threshold value current I_{th} or slope efficiency.

As shown in the foregoing explanation, in accordance with the present invention, a threshold value current generation means compensates the optical output for change in a threshold value current cased by temperature change of the semiconductor laser while a slope efficiency compensation means compensates the optical output for change in slope efficiency. Therefore, temperature change of a semiconductor laser does not affect the stable optical output and guarantees accurate, reliable optical output in proportion to externally provided modulation signal. Furthermore, because it is not necessary to keep the temperature of a semiconductor laser constant, size-reduction and weight-reduction can be easily achieved.

What is claimed is:

1. A drive circuit for driving a semiconductor laser, comprising:

control signal generating means electrically coupled to the semiconductor laser for generating a control signal for driving the semiconductor laser based on an externally provided modulation signal;

detecting means for detecting a temperature of the semiconductor laser;

compensating means electrically coupled to the control signal generating means for altering the control signal based on the temperature of the semiconductor laser to compensate for changes in slope efficiency η of the semiconductor laser.

2. The drive circuit of claim **1**, in which the compensating means compensates for changes in slope efficiency η by altering the control signal based on a compensation coefficient $1/\eta$.

3. The drive circuit of claim **2**, in which each compensation coefficient $1/\eta$ is predetermined for a plurality of temperatures of the semiconductor laser.

4. The drive circuit of claim **1**, in which the compensating means alters the control signal by multiplying the modulation signal by a compensation coefficient $1/\eta$.

5. The drive circuit of claim **1**, in which the modulation signal is converted from binary form into an analog signal based on a reference voltage, and the compensating means alters the control signal by multiplying the reference voltage by a compensation value equal to $1/\eta$.

6. The drive circuit of claim **1**, in which:

the control signal comprises a drive current I_f for driving the semiconductor laser; and

the slope efficiency η is the ratio of an increase of the drive current I_f to an increase of an optical output P of the semiconductor laser.

7. The drive circuit of claim **6**, in which the relation of the output P of the semiconductor laser to the slope efficiency η is given by the following equation:

$$P=(I_f-I_{th})\eta,$$

where I_{th} is a threshold current representing a drive current of the semiconductor laser at which the optical output P of the semiconductor laser rapidly begins to increase.

8. The drive circuit of claim **7**, further comprising threshold current determination means for determining the threshold current I_{th}.

9. A drive circuit for driving a semiconductor laser, comprising:

threshold current determination means electrically coupled to the semiconductor laser for determining a threshold current, where the threshold current is a drive current of the semiconductor laser at which the optical output P of the semiconductor laser rapidly begins to increase;

detecting means for detecting a temperature of the semiconductor laser;

reference voltage generating means for generating a compensated reference voltage based on a reference voltage and the temperature of the semiconductor laser;

digital/analog converting means for converting an externally provided modulation signal into an output voltage based on the compensated reference voltage; and

control current generating means for generating a control current based on the output voltage and the threshold current, where the control current controls an optical output of the semiconductor laser.

10. The drive circuit of claim **9**, in which:

the control current comprises a drive current for driving the semiconductor laser; and

the slope efficiency η is the ratio of an increase of the drive current to an increase of the optical output of the semiconductor laser.

11. The drive circuit of claim **9**, in which the reference voltage generating means generates the compensated reference voltage to compensate for changes in slope efficiency η of the semiconductor laser.

12. The drive circuit of claim **11**, in which the compensating means compensates for changes in slope efficiency η by multiplying the reference voltage by a compensation coefficient equal to $1/\eta$.

13. The drive circuit of claim **12**, in which each compensation coefficient $1/\eta$ is predetermined for a plurality of temperatures of the semiconductor laser.

14. The drive circuit of claim **13**, in which the control current generating means generates the control current by generating a drive current from the output voltage and adding the drive current to the threshold current.

15. The drive circuit of claim **9**, in which the threshold current determination means comprises:

a photodiode for generating an output signal indicating the optical output of the semiconductor laser; and

a threshold value generation means for generating the threshold current by determining a drive current at which the output signal begins to change rapidly.

16. A drive circuit for driving a semiconductor laser, comprising:

detecting means for detecting a temperature of the semiconductor laser;

compensating means for generating an altered modulation signal from an externally provided modulation signal based on the temperature of the semiconductor laser;

threshold signal determination means for determining a threshold signal and adding the threshold signal to the altered modulation signal to form a control signal, where the threshold signal corresponds to a drive current at which an optical output of the semiconductor laser rapidly begins to increase; and

drive means for generating a control current based on the control signal, where the control current drives the semiconductor laser to generate an optical output.

17. The drive circuit of claim **16**, in which:

the control current comprises a drive current for driving the semiconductor laser; and the slope efficiency η is the ratio of an increase of the drive current to an increase of the optical output of the semiconductor laser.

18. The drive circuit of claim **17**, in which the compensating means generates the altered modulation signal by multiplying the modulation signal by a compensation coefficient equal to $1/\eta$.

19. The drive circuit of claim **18**, in which each compensation coefficient $1/\eta$ is predetermined for a plurality of temperatures of the semiconductor laser.

20. The drive circuit of claim **19**, in which the threshold signal determination means determines the threshold signal by generating a plurality of test threshold signals, generating a plurality of corresponding test control signals only from the test threshold signals, and setting the threshold signal equal to the test threshold signal for which the optical output of the semiconductor laser approximates a predetermined value.

21. The drive circuit of claim **16**, in which the threshold current determination means comprises:

a photodiode for generating an output signal indicating the optical output of the semiconductor laser; and

a threshold value generation means for generating the threshold current by determining a drive current at which the output signal begins to change rapidly.

* * * * *

United States Patent [19]

Levinson

[11] **Patent Number: 5,019,769**

[45] **Date of Patent: May 28, 1991**

[54] SEMICONDUCTOR LASER DIODE CONTROLLER AND LASER DIODE BIASING CONTROL METHOD

[75] Inventor: **Frank H. Levinson**, Redwood City, Calif.

[73] Assignee: **Finisar Corporation**, Menlo Park, Calif.

[21] Appl. No.: **583,178**

[22] Filed: **Sep. 14, 1990**

[51] **Int. Cl.**^{5} **H01S 3/10**

[52] **U.S. Cl.** **372/31**; 372/29

[58] **Field of Search** 372/29, 31, 38, 32

[56] **References Cited**

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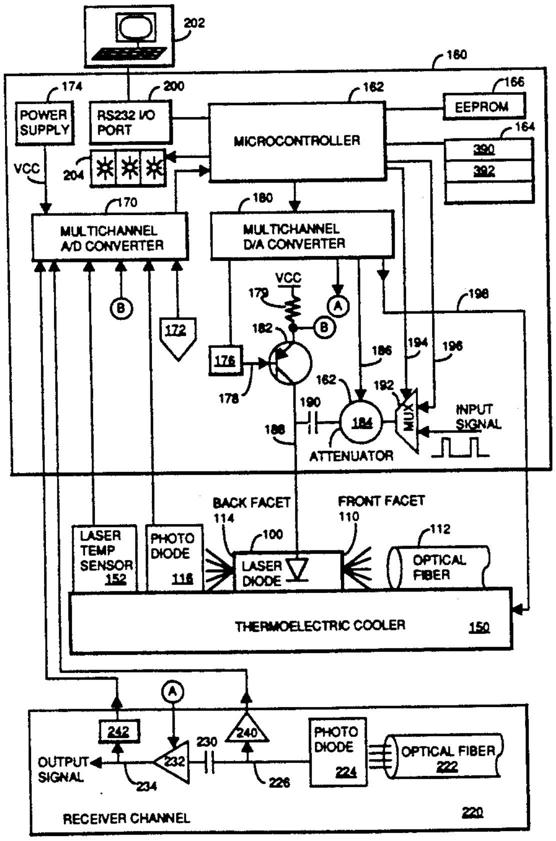
Primary Examiner—James W. Davie
Attorney, Agent, or Firm—Flehr, Hohbach, Test, Albritton & Herbert

[57] **ABSTRACT**

A laser diode controller uses a programmed microcontroller to accurately control the process of turning on and selecting the operating point of the laser diode. The laser diode has a front facet for transmitting light, and a back facet for monitoring the laser diode's optical output power. Once the back facet of the laser diode is calibrated, the controller can accurately monitor the laser diode's operating characteristics, and can select the best operating point current based on the current operating characteristics of the laser diode. During calibration of the laser diode, the controller can check the linearity of the laser diode's optical output power as a function of drive current, and can thereby detect defects in the laser diode. In a full duplex optical link, the controller of the present invention prevents the laser diodes from generating light at their full normal intensity until the integrity of the link has been established, thereby preventing light from the laser diode's from accidentally damaging user's eyes. Furthermore, the controllers can use the full duplex link to establish lower operating point drive currents that would otherwise be used, thereby significantly lengthening the lifetime of the laser diodes. A laser diode's operating characteristics change over time in such a way as to enable the controller to predict when the laser will fail. The controller records the operating characteristics of the laser diode in a nonvolatile memory, analyzes changes in those characteristics, and generates a failure warning message when those changes match predefined failure prediction criteria.

25 Claims, 7 Drawing Sheets



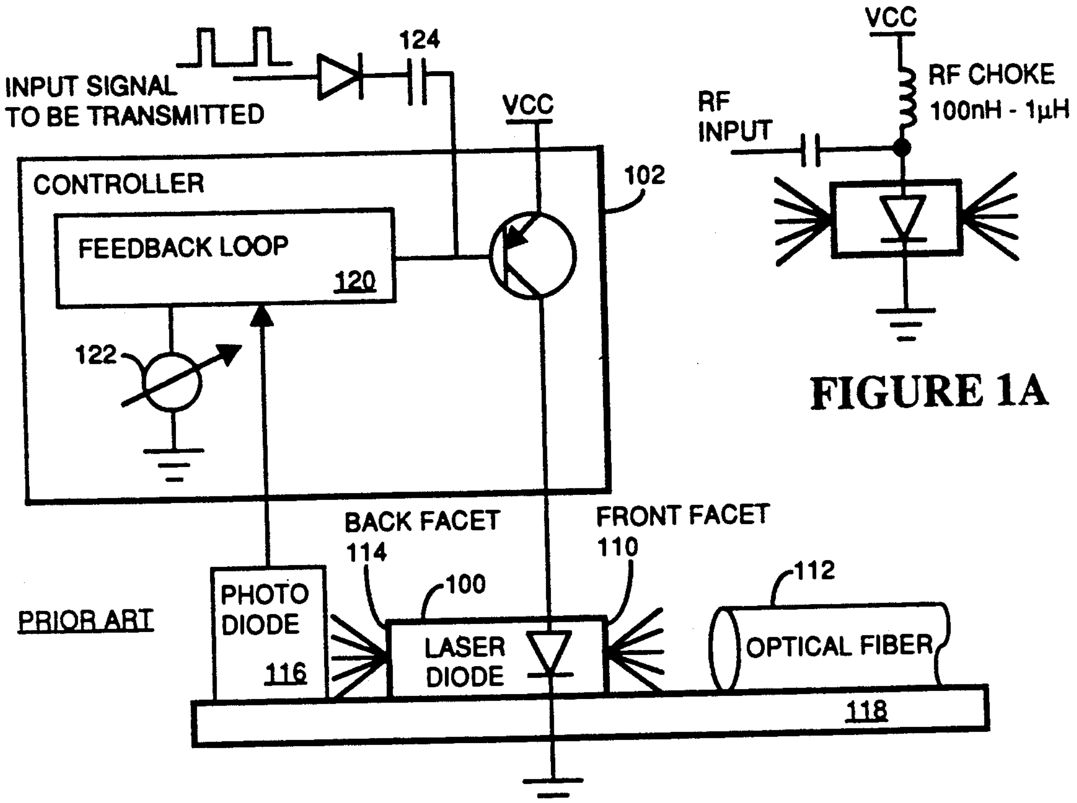


FIGURE 1A

FIGURE 1

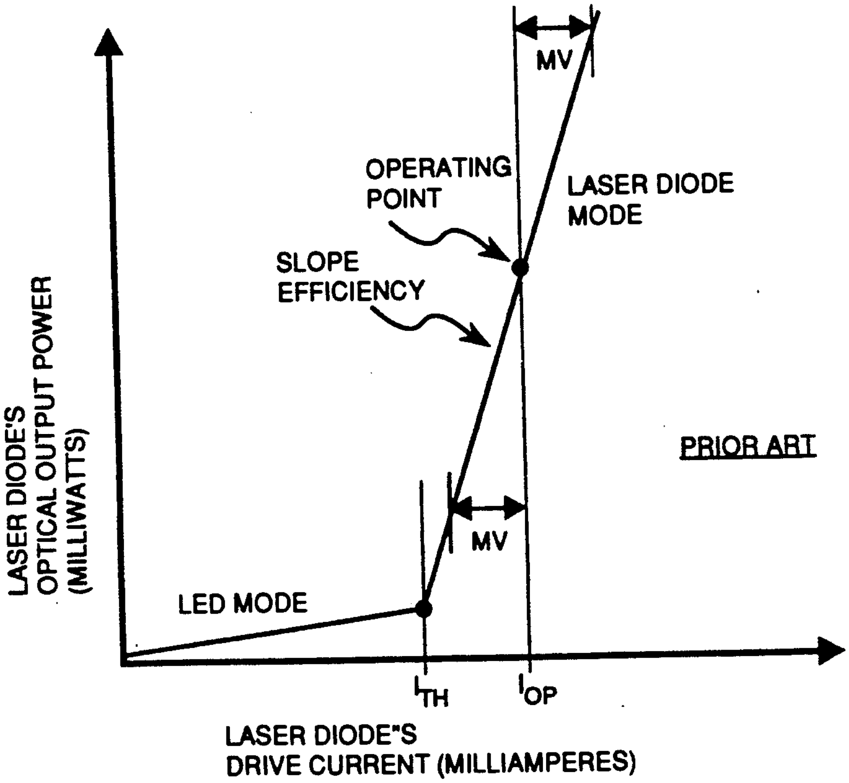


FIGURE 2

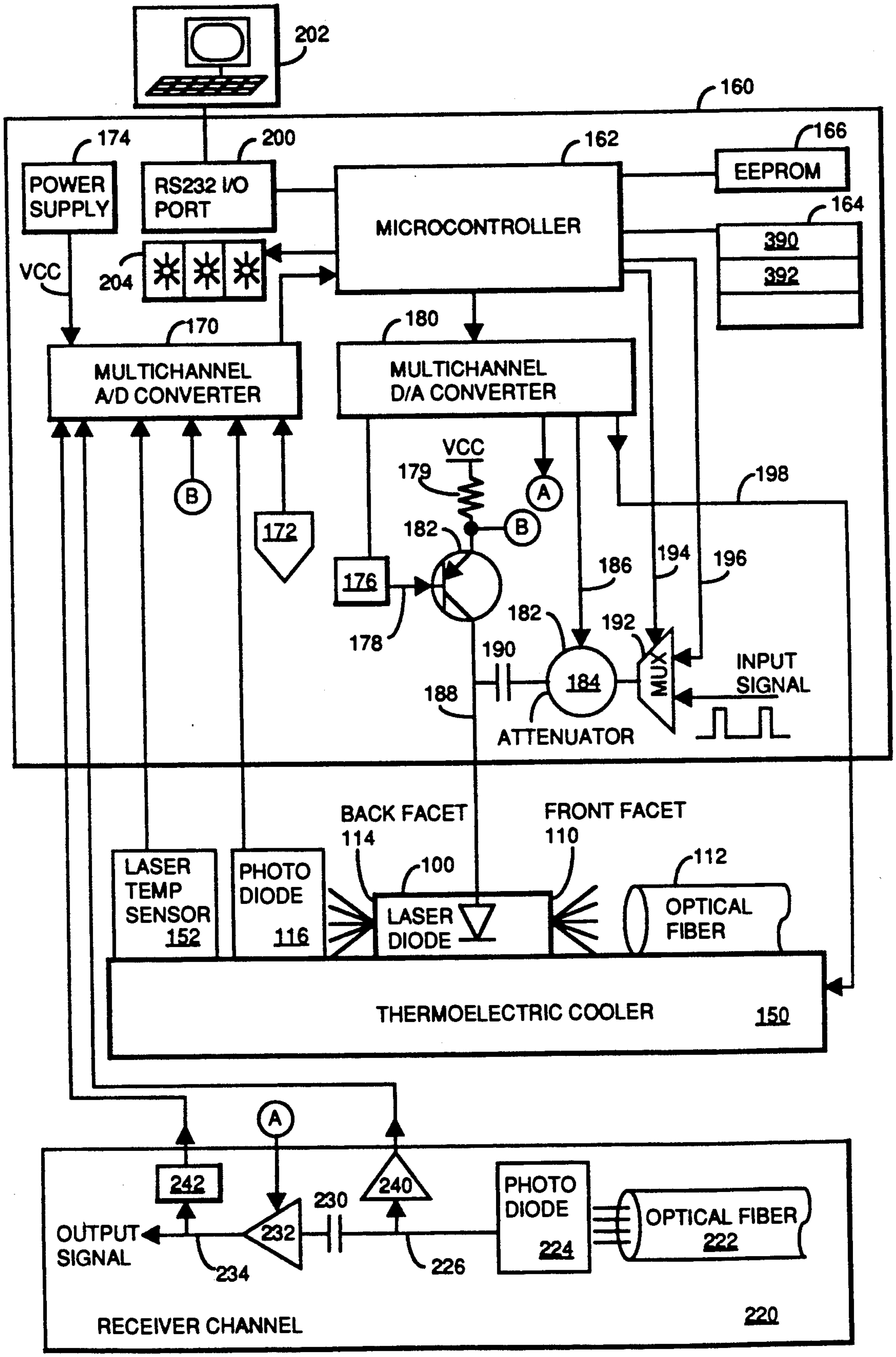

202
160
174
POWER SUPPLY
200
RS232 I/O PORT
162
MICROCONTROLLER
166
EEPROM
164
390
392
VCC
204
170
MULTICHANNEL A/D CONVERTER
180
MULTICHANNEL D/A CONVERTER
VCC
179
A
B
182
B
172
176
178
198
186
194
196
182
192
190
188
184
MUX
INPUT SIGNAL
ATTENUATOR
BACK FACET 114
FRONT FACET 110
100
112
LASER TEMP SENSOR 152
PHOTO DIODE 116
LASER DIODE
OPTICAL FIBER
THERMOELECTRIC COOLER
150
A
242
240
230
232
OUTPUT SIGNAL
234
226
PHOTO DIODE 224
OPTICAL FIBER 222
RECEIVER CHANNEL
220

FIGURE 3

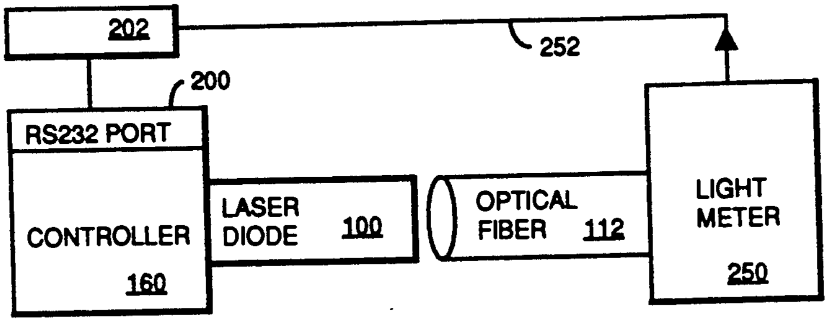


FIGURE 4

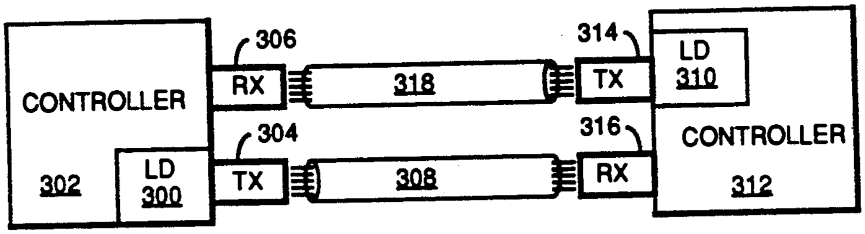


FIGURE 5

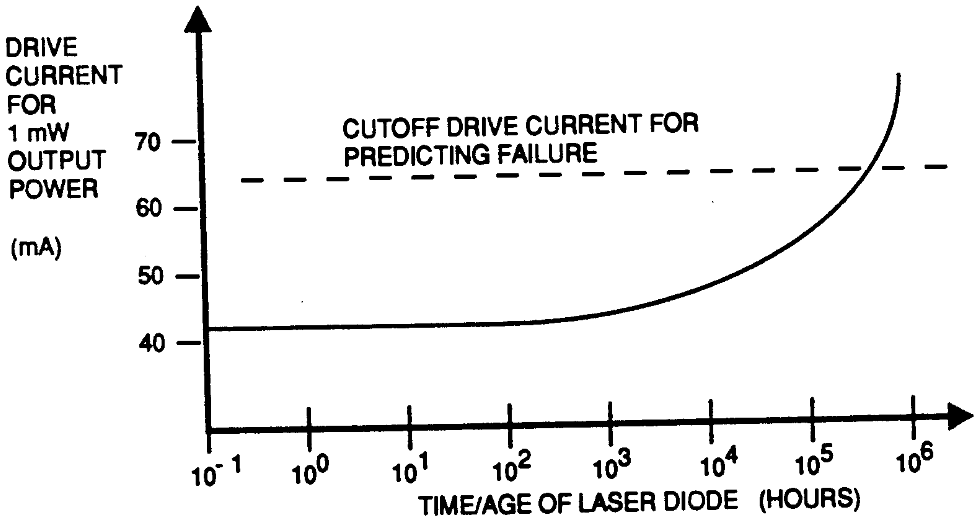


FIGURE 6

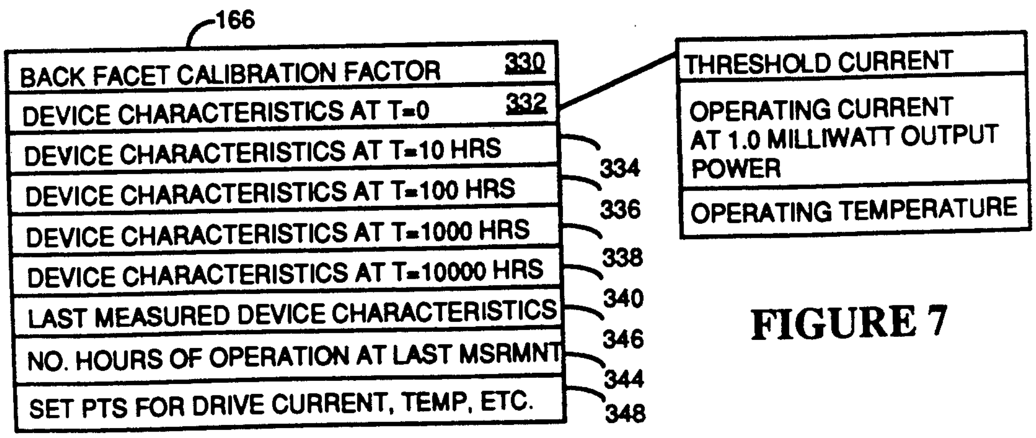


FIGURE 7

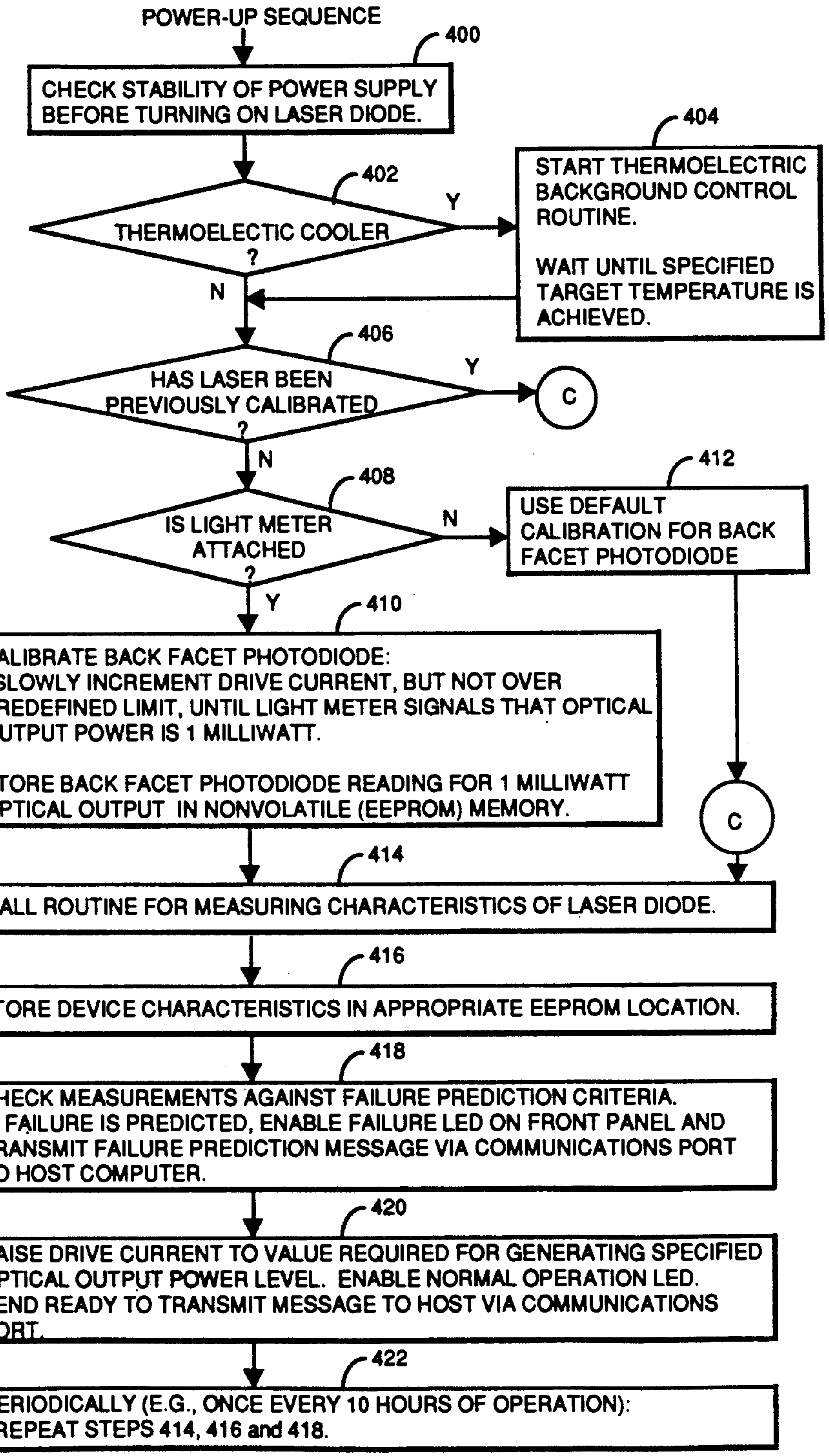

POWER-UP SEQUENCE
400
CHECK STABILITY OF POWER SUPPLY BEFORE TURNING ON LASER DIODE.
402
THERMOELECTIC COOLER ?
Y
404
START THERMOELECTRIC BACKGROUND CONTROL ROUTINE.
WAIT UNTIL SPECIFIED TARGET TEMPERATURE IS ACHIEVED.
N
406
HAS LASER BEEN PREVIOUSLY CALIBRATED ?
Y
C
N
408
IS LIGHT METER ATTACHED ?
N
412
USE DEFAULT CALIBRATION FOR BACK FACET PHOTODIODE
Y
410
CALIBRATE BACK FACET PHOTODIODE:
SLOWLY INCREMENT DRIVE CURRENT, BUT NOT OVER PREDEFINED LIMIT, UNTIL LIGHT METER SIGNALS THAT OPTICAL OUTPUT POWER IS 1 MILLIWATT.
STORE BACK FACET PHOTODIODE READING FOR 1 MILLIWATT OPTICAL OUTPUT IN NONVOLATILE (EEPROM) MEMORY.
C
414
CALL ROUTINE FOR MEASURING CHARACTERISTICS OF LASER DIODE.
416
STORE DEVICE CHARACTERISTICS IN APPROPRIATE EEPROM LOCATION.
418
CHECK MEASUREMENTS AGAINST FAILURE PREDICTION CRITERIA.
IF FAILURE IS PREDICTED, ENABLE FAILURE LED ON FRONT PANEL AND TRANSMIT FAILURE PREDICTION MESSAGE VIA COMMUNICATIONS PORT TO HOST COMPUTER.
420
RAISE DRIVE CURRENT TO VALUE REQUIRED FOR GENERATING SPECIFIED OPTICAL OUTPUT POWER LEVEL. ENABLE NORMAL OPERATION LED. SEND READY TO TRANSMIT MESSAGE TO HOST VIA COMMUNICATIONS PORT.
422
PERIODICALLY (E.G., ONCE EVERY 10 HOURS OF OPERATION):
REPEAT STEPS 414, 416 and 418.

FIGURE 8

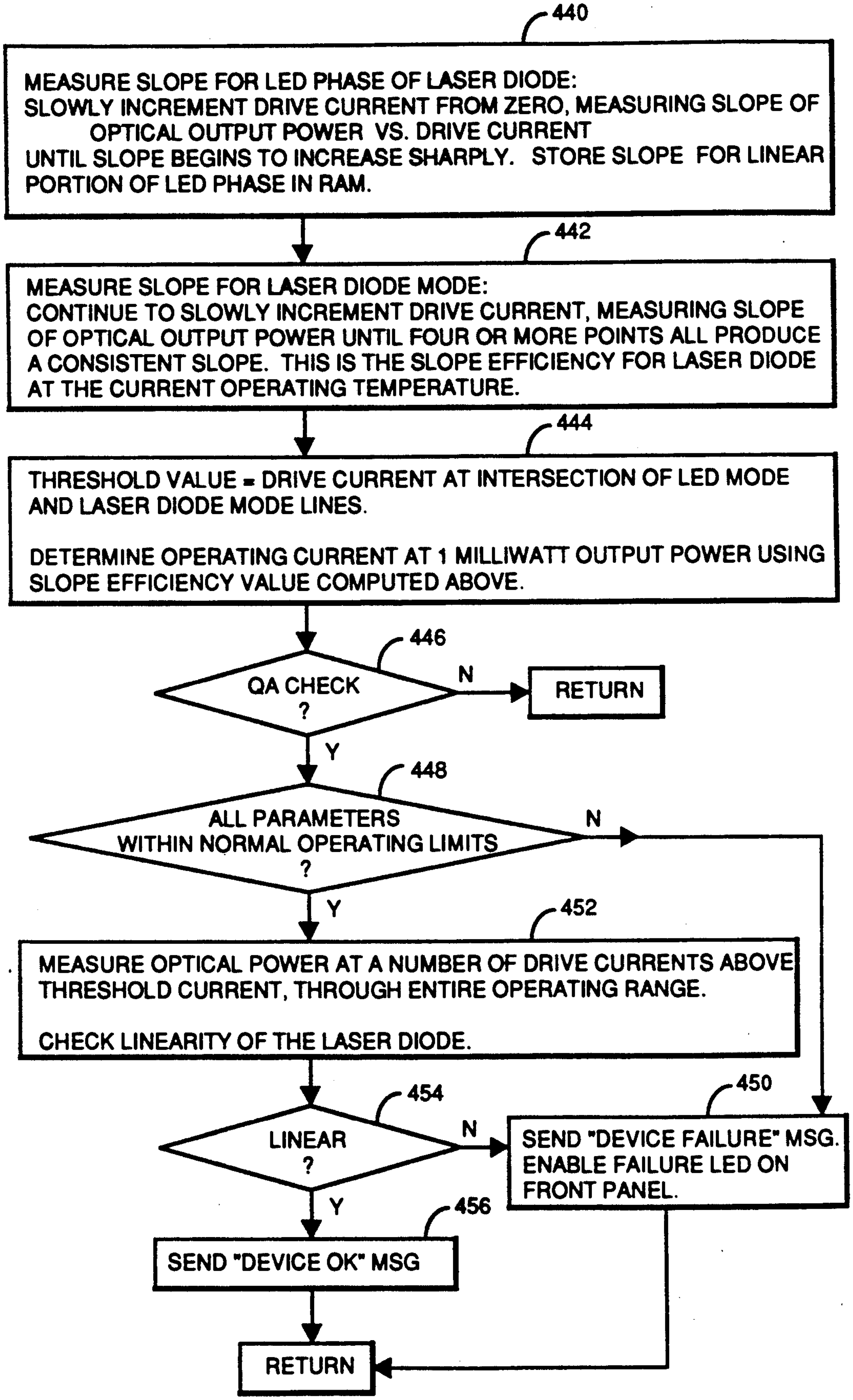

440
MEASURE SLOPE FOR LED PHASE OF LASER DIODE:
SLOWLY INCREMENT DRIVE CURRENT FROM ZERO, MEASURING SLOPE OF OPTICAL OUTPUT POWER VS. DRIVE CURRENT
UNTIL SLOPE BEGINS TO INCREASE SHARPLY. STORE SLOPE FOR LINEAR PORTION OF LED PHASE IN RAM.
442
MEASURE SLOPE FOR LASER DIODE MODE:
CONTINUE TO SLOWLY INCREMENT DRIVE CURRENT, MEASURING SLOPE OF OPTICAL OUTPUT POWER UNTIL FOUR OR MORE POINTS ALL PRODUCE A CONSISTENT SLOPE. THIS IS THE SLOPE EFFICIENCY FOR LASER DIODE AT THE CURRENT OPERATING TEMPERATURE.
444
THRESHOLD VALUE = DRIVE CURRENT AT INTERSECTION OF LED MODE AND LASER DIODE MODE LINES.
DETERMINE OPERATING CURRENT AT 1 MILLIWATT OUTPUT POWER USING SLOPE EFFICIENCY VALUE COMPUTED ABOVE.
446
QA CHECK ?
N
RETURN
Y
448
ALL PARAMETERS WITHIN NORMAL OPERATING LIMITS ?
N
Y
452
MEASURE OPTICAL POWER AT A NUMBER OF DRIVE CURRENTS ABOVE THRESHOLD CURRENT, THROUGH ENTIRE OPERATING RANGE.
CHECK LINEARITY OF THE LASER DIODE.
454
LINEAR ?
N
450
SEND "DEVICE FAILURE" MSG. ENABLE FAILURE LED ON FRONT PANEL.
Y
456
SEND "DEVICE OK" MSG
RETURN

FIGURE 9

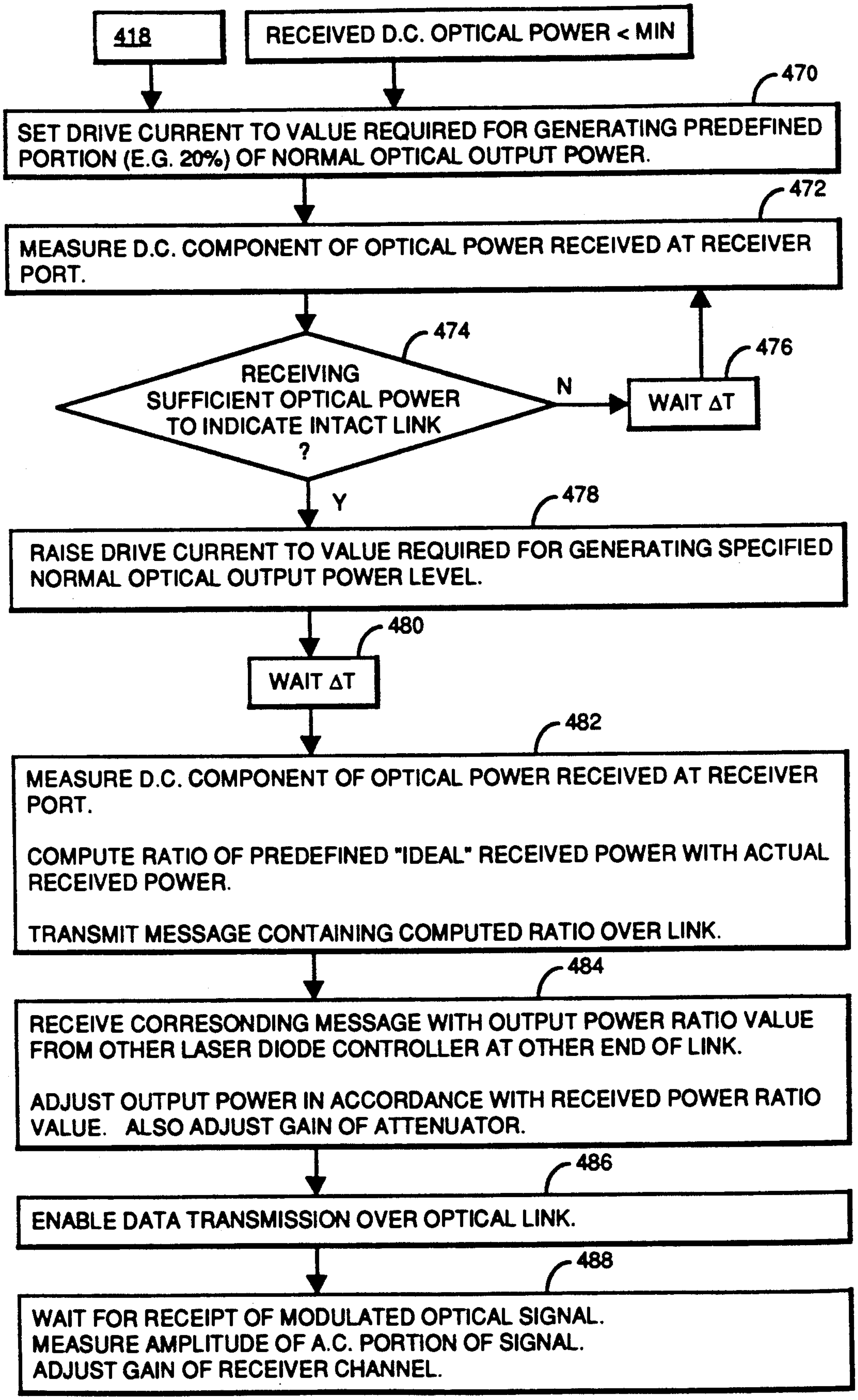
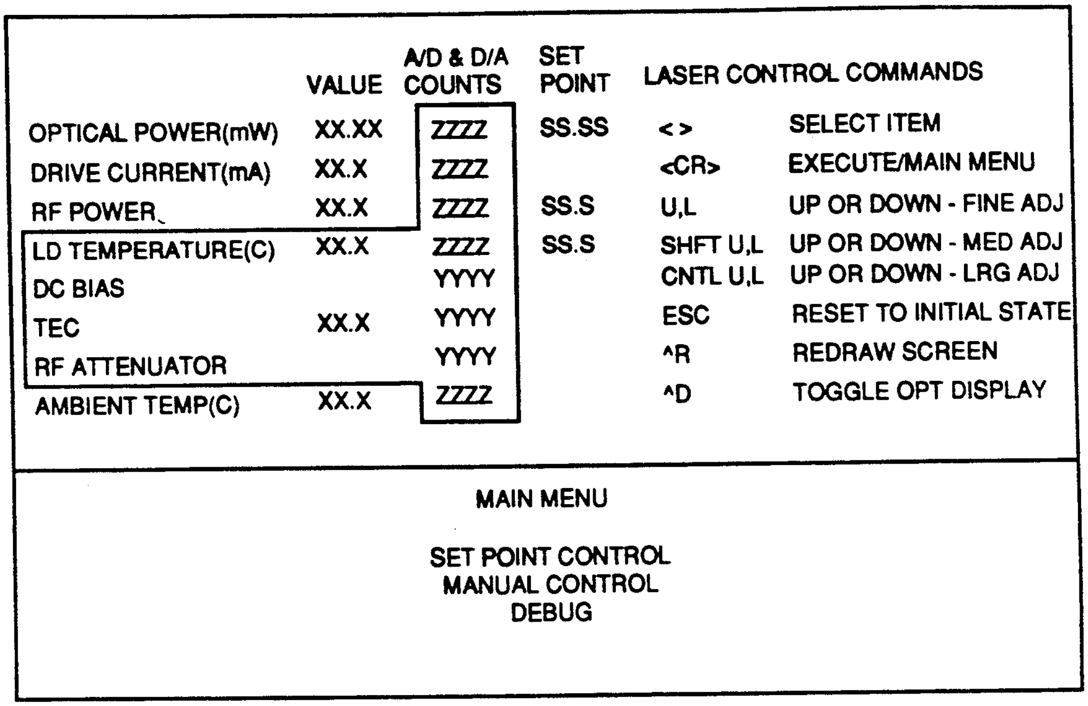

418
RECEIVED D.C. OPTICAL POWER < MIN
470
SET DRIVE CURRENT TO VALUE REQUIRED FOR GENERATING PREDEFINED PORTION (E.G. 20%) OF NORMAL OPTICAL OUTPUT POWER.
472
MEASURE D.C. COMPONENT OF OPTICAL POWER RECEIVED AT RECEIVER PORT.
474
RECEIVING SUFFICIENT OPTICAL POWER TO INDICATE INTACT LINK ?
N
476
WAIT ΔT
Y
478
RAISE DRIVE CURRENT TO VALUE REQUIRED FOR GENERATING SPECIFIED NORMAL OPTICAL OUTPUT POWER LEVEL.
480
WAIT ΔT
482
MEASURE D.C. COMPONENT OF OPTICAL POWER RECEIVED AT RECEIVER PORT.
COMPUTE RATIO OF PREDEFINED "IDEAL" RECEIVED POWER WITH ACTUAL RECEIVED POWER.
TRANSMIT MESSAGE CONTAINING COMPUTED RATIO OVER LINK.
484
RECEIVE CORRESONDING MESSAGE WITH OUTPUT POWER RATIO VALUE FROM OTHER LASER DIODE CONTROLLER AT OTHER END OF LINK.
ADJUST OUTPUT POWER IN ACCORDANCE WITH RECEIVED POWER RATIO VALUE. ALSO ADJUST GAIN OF ATTENUATOR.
486
ENABLE DATA TRANSMISSION OVER OPTICAL LINK.
488
WAIT FOR RECEIPT OF MODULATED OPTICAL SIGNAL.
MEASURE AMPLITUDE OF A.C. PORTION OF SIGNAL.
ADJUST GAIN OF RECEIVER CHANNEL.

FIGURE 10



	VALUE	A/D & D/A COUNTS	SET POINT	LASER CONTROL COMMANDS	
OPTICAL POWER(mW)	XX.XX	ZZZZ	SS.SS	< >	SELECT ITEM
DRIVE CURRENT(mA)	XX.X	ZZZZ		<CR>	EXECUTE/MAIN MENU
RF POWER	XX.X	ZZZZ	SS.S	U,L	UP OR DOWN - FINE ADJ
LD TEMPERATURE(C)	XX.X	ZZZZ	SS.S	SHFT U,L	UP OR DOWN - MED ADJ
DC BIAS		YYYY		CNTL U,L	UP OR DOWN - LRG ADJ
TEC	XX.X	YYYY		ESC	RESET TO INITIAL STATE
RF ATTENUATOR		YYYY		^R	REDRAW SCREEN
AMBIENT TEMP(C)	XX.X	ZZZZ		^D	TOGGLE OPT DISPLAY

MAIN MENU

SET POINT CONTROL
MANUAL CONTROL
DEBUG

FIGURE 11

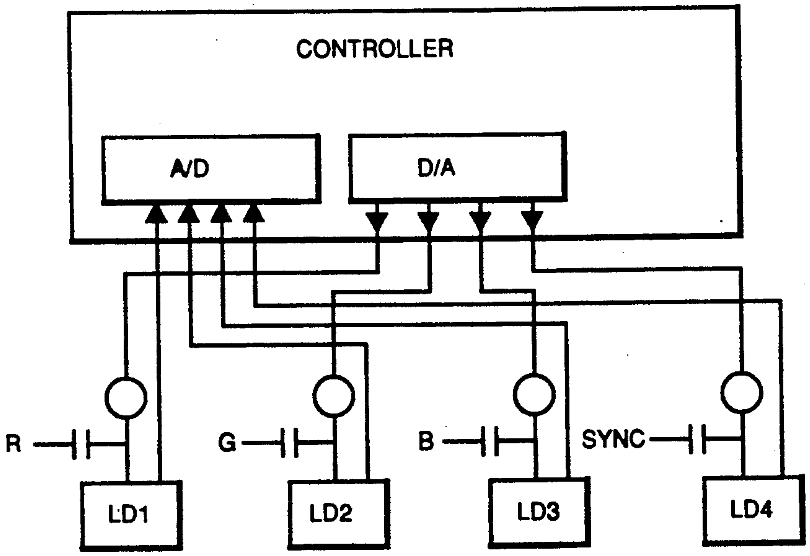


FIGURE 12

SEMICONDUCTOR LASER DIODE CONTROLLER AND LASER DIODE BIASING CONTROL METHOD

The present invention relates generally to semiconductor laser diodes and particularly to the controllers and control methods used to bias and drive laser diodes.

BACKGROUND OF THE INVENTION

Referring to FIG. **1**, there is shown a laser diode **100** and a prior art analog laser diode controller **102**. The laser diode **100** has a front facet **110** which emits coherent light that is to be transmitted, usually into some optical component such as an optical fiber **112**, and a back facet **114**. Light emitted by the back facet **114** is received by a photodiode **116** which is used to continuously monitor the optical power being output by the laser diode **110**. In general, the amount of optical power output by the front facet **110** is directly proportional to the optical power output by the back facet **114**:

Power(front facet) = Power(back facet) / K

While K is often equal to 1, the amount of back facet power received by the photodiode **116** varies considerably from package to package, and therefore must be separately calibrated for each laser diode.

Typically, the laser diode **100**, the back facet photodiode **116**, and the outgoing optical fiber **112** (or a mechanism for holding the outgoing optical fiber) are all mounted on a common platform or housing **118**. In some cases, the housing **118** includes a solid state thermoelectric cooler for maintaining the laser diode **100** at a specified temperature.

Referring to FIG. **2**, the optical output power of the laser diode is a non-linear function of the laser diode's drive current. In particular, when forward bias current is applied to a semiconductor laser it begins to emit light in a manner similar to light emitting diodes (LEDs). This type of emission is known as spontaneous emission because it happens randomly from excited atoms in the laser diode's cavity, and is commonly called LED mode.

At a certain drive current, herein called the threshold current, I_{TH}, the laser diode's efficiency in converting current into light increases dramatically. This is the point where the laser diode changes from the LED mode of operation to the lasing mode of operation.

While various classes of laser diodes will have thresholds in the same general range of currents, the threshold current I_{TH} varies considerably among laser diodes of the same type and also varies with the temperature and age of the laser diode. For example, the threshold current of some laser diodes can vary by as much as fifty percent or more with changes in temperature. The effect of this temperature sensitivity is that at a given drive current the laser diode could be operating above its recommended levels at one temperature while not even lasing at another temperature.

When the laser diode is operating in the lasing mode, that is at a drive current in excess of the threshold current, there is a characteristic slope that determines the laser diode's efficiency. More specifically, each laser diode's "slope efficiency" is equal to the ratio of changes in the laser's optical output power to changes in the drive current while operating in the lasing mode. Slope efficiency varies from laser diode to laser diode, and also varies with temperature and with the age of the diode.

The "operating point" or bias current, I_{OP}, for a diode laser is a generally set by the user of the laser diode so that it is within the current range for lasing mode of operation, and so that the laser diode remains in lasing mode when the current is modulated by an input signal. Thus, if the maximum variation of the input signal below the operation point is MV, the operation point must be greater than $I_{TH}+MV$. In addition, the operation point must be set sufficiently high that a receiving photodiode will be able to receive the transmitted light, and yet the operation point must not be set so high as to burn out the laser diode.

Referring back to FIG. **1**, prior art diode controllers **102** typically contain an analog feedback loop **120** coupled to a potentiometer **122**, or some other similar mechanism, for manually adjusting the laser's operating point. The user typically turns the gain of the feedback loop **120** down before powering on the laser diode's controller, and then manually adjusts the gain upwards until the desired amount of optical output power is achieved. Optical output power is typically measured using another photodiode coupled to the front facet by an optical fiber **112**, or by some similar set up (not shown in FIG. **1**). After the laser diode's controller **102** is calibrated using potentiometer **112**, signals to be transmitted are superimposed on the laser diode's operating point current I_{OP} by a capacitor **124**, thereby modulating the output power of the laser diode **110**. Some analog controllers employ multiple potentiometers to separately set threshold current, operating bias current and back facet photodiode feedback control, which components make such analog controllers both difficult to tune and expensive to manufacture.

In general, any laser diode will be destroyed if its optical output power exceeds a certain limit. Given the very sharp slope of the optical output when operation in lasing mode, it is generally quite easy to destroy a laser diode while trying to select its operating point. In fact, many very expensive lasers, such as those used by telephone companies for transmitting telephone signals over optical fibers and those used in the cable television industry, have been destroyed during calibration. Such losses may be caused by adjusting the calibration potentiometer too quickly, by problems in the equipment monitoring the output of the front facet during calibration, causing the laser diode to be turned on too hard, and by many other hazards.

In general, the setup procedure for calibrating laser diodes is time consuming and expensive, and subject to various forms of operator error.

Another important limitation in prior art laser diode controllers is that they cannot be used to predict device failures in advance of when it occurs. Many semiconductor laser diodes are used in vital communications systems, and when such lasers fail, they can cause entire communications systems to fail. If the failure of laser diodes could be accurately predicted, a preventative maintenance program could be implemented to prevent system failures by replacing such laser diodes prior to the time that failure is predicted. Currently, such laser diodes are replaced solely based on their time in service without regard to their actual operability.

SUMMARY OF THE INVENTION

In summary, the present invention is a laser diode controller which uses a programmed digital controller to accurately measure a laser diode's operating characteristics and to control the process of turning on and selecting the operating parameters of the laser diode. Light from the laser diode's front facet is used for transmitting light and light from the laser diode's back facet is used for monitoring the optical output power generated by the laser diode. Once the back facet photodiode of the laser diode is calibrated, the controller can accurately monitor the laser diode's operating characteristics, and can select the best operating point current based on the current operating characteristics of the laser diode.

During calibration of the laser diode, the controller can check the linearity of the laser diode's optical output power as a function of drive current, and can thereby detect defects in the laser diode. A unique transistor d.c. power and a.c. signal connection arrangement is used to reduce RF noise.

In a full duplex optical link, with digital controllers used at both ends of the optical link, the controller of the present invention prevents the laser diodes from generating light at their full normal intensity until the integrity of the link has been established. Once the link is established, the controller continues to monitor the integrity of the link and reduces the laser diode's output power if the link is interrupted. In this way the controller can prevent light from the laser diode's from accidentally damaging user's eyes. Furthermore, the controllers can use the full duplex link to establish lower operating point drive currents that would otherwise be used, thereby significantly lengthening the lifetime of the laser diodes.

The operating characteristics of a laser diode change over the device's lifetime in such a way as to enable the controller to predict when the laser diode will fail. The controller of the present invention records the operating characteristics of the laser diode in a nonvolatile memory, analyzes changes in those characteristics, and generates a failure warning message when those changes match predefined failure prediction criteria.

BRIEF DESCRIPTION OF THE DRAWINGS

Additional objects and features of the invention will be more readily apparent from the following detailed description and appended claims when taken in conjunction with the drawings, in which:

FIG. **1** is a block diagram of a prior art laser diode and controller. FIG. **1A** shows a prior art RF choke arrangement used with some prior art laser diodes.

FIG. **2** depicts a graph of the relationship between drive current and optical output power for a laser diode.

FIG. **3** is a block diagram of a laser diode controller in accordance with the present invention.

FIG. **4** depicts the connection of a laser diode and its controller to a light meter for calibration of the laser's back facet photodiode.

FIG. **5** is a block diagram of a full duplex optical link.

FIG. **6** depicts a graph of the aging characteristics of a typical laser diode.

FIG. **7** depicts data stored in nonvolatile memory in the preferred embodiment of a laser diode controller.

FIGS. **8** and **9** are flow charts of the laser diode calibration and initialization method of the present invention.

FIG. **10** is a flow chart of a method of initializing each laser diode in a full duplex optical link.

FIG. **11** depicts the display generated by the user interface of the preferred embodiment of a laser diode controller.

FIG. **12** is a block diagram of a multichannel laser diode controller in accordance with the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to FIG. **3**, there is shown a laser diode **100** and back facet photodiode **116** which are mounted onto a thermoelectric cooler **150**. The purpose of the thermoelectric cooler **150** is to permit the laser diode **100** to operate in a constant temperature or temperature controlled environment. In addition, there is a temperature sensor **152** (e.g., a thermocouple) mounted near or adjacent the laser diode **100** for measuring the temperature of the laser diode.

The operation of the laser diode **100** is controlled by a digital controller **160**. The central component of the digital controller **160** is a microcontroller **162**, such as a **68HC11** or **68HC05** (both of which are manufactured by Motorola). Software for the microcontroller **162** is stored in a read only memory (ROM) or in an (erasable) electrically programmable read only memory (EPROM) **164**, including a power on sequence control program **390**, and a continuously running device monitoring and control program **392**. Device characteristics of the laser diode **100**, as measured by the controller **160**, are stored in an nonvolatile memory **166** such as an EEPROM, as will be described in more detail below.

A multichannel analog to digital (A/D) converter **170** is used by the microcontroller to monitor the output signals generated by the laser's temperature sensor **162**, the back facet photodiode **116**, and an ambient temperature sensor **172**. The ambient temperature sensor **172** is monitored by the microcontroller **160** so that the laser diode **100** can be shut down when excessive ambient temperatures are experienced. Typically, the thermoelectric cooler **150** will not be able to keep the laser diode **100** at a satisfactory temperature when the ambient temperature rises above a specified level. By automatically shutting the laser diode down when an overtemperature condition is detected, valuable laser diodes can be protected from burning out.

The multichannel A/D converter **170** can also be used to monitor the stability of the controller's power supply **174**. Laser diodes are particularly susceptible to electronic damage from surge currents or other power supply variations. Therefore, in one preferred embodiment the digital controller **160** is programmed to measure the power supply **174** for stability before initializing the laser diode **100** and to continue to monitor it after start up as well.

A multichannel digital to analog (D/A) converter **180** is used (1) to set the bias current of the laser diode **100**, (2) to control the gain of an input signal attenuator **184**, and (3) to control the thermoelectric cooler **150**. In particular, the microcontroller **162** generates a digital value for the laser diode's bias current, and the D/A converter **180** converts that into an analog voltage signal. The resulting signal is then low passed filtered by an RC filter **176** with a long time constant (on the order of 0.1 to 0.5 seconds, depending on the embodiment of the invention being used), and the filtered control signal on line **178** drives the bases of a PNP transistor **182**, which in turn drives the laser diode **100**.

The controller **160** measures the current flowing through the laser diode by monitoring the voltage drop across a high precision resistor **179**, in particular by monitoring the Vcc voltage from the power supply **174** and the voltage at node B on the emitter of transistor **182**. As shown in FIG. **3**, both of these voltages are read by the microcontroller **162** via the A/D converter **170**. The laser diode current is then computed by using Ohm's law: current equals the voltage drop across the resistor divided by the resistance of the resistor. That computed value could then be reduced by the base current, which is a known fraction (1/Beta) of the emitter current, but this correction is usually so small that it is not necessary. The microcontroller **162** computes a running average of the laser diode current so as to filter out the effects of any current fluctuations caused by input signals being transmitted, which modulate the laser diode's drive current.

Many laser diode manufacturers and optical link builders have found it advantageous to either feed a.c. signals to the laser diode through the base of a drive transistor **102**, as shown in FIG. **1**, or to use the RF choke arrangement shown in FIG. **1A**. One supplier has actually placed the RF choke shown in FIG. **1A** inside the hermetic laser diode's package so as to minimize the capacitance of the a.c. signal feed line and to thereby reduce RF coupling problems (e.g., signal distortion).

It is unexpectedly advantageous to use the collector of transistor **182** as a high impedance d.c. source for the laser diode **100**. No RF choke is used. The bipolar transistor **182** is preferably a transistor with very low collector capacitance, typically an "RF" transistor, which will create minimal RF bandwidth attenuation of the a.c. input signal being transmitted. This d.c. power sourcing arrangement is believed to generate significantly less noise than the best commercially available link using the RF choke arrangement.

Because the "RF" transistor **182** has very fast response as well as low capacitance, it is important to have a RC filter **176** which protects the laser diode **100** from current spikes. In general, it has been found that the lifetime of laser diodes is significantly degraded by current spikes. As will be described in more detail below, the RC filter **176** is modified so as to change its RC time constant to a value of about 0.01 seconds in full duplex link applications so that the d.c. signal level of the link can be used to transmit information between a pair of laser diode controllers.

An optical, electronically tunable (i.e., variable) attenuator **184** controls the amplification or attenuation of input signals that are to be optically transmitted by the laser diode **100**. Thus the control signal from the D/A converter **180** on line **186** is essentially an automatic gain control signal. The attenuated input signals are a.c. coupled to the laser diode's drive line **188** by a capacitor **190**. Input signals are typically high frequency digital or analog signals that are generated externally to the laser diode controller **160**.

However, in one embodiment of the present invention a multiplexer **192** is provided on the input signal path so that the microcontroller **162** can transmit data over the optical link. For this purpose the microcontroller **162** generates an input selection signal on line **194** for controlling the multiplexer **192**, and sends data to be transmitted on line **196** to one of the multiplexer's input ports. This capability is used in certain embodiments of the invention in which a pair of full duplex link controllers minimizes the optical power used for transmitting information over the optical link, as will be described in more detail below.

The amount of cooling by the thermoelectric cooler **150** depends on the amount of current running through the cooler **150**, which is in turn controlled by the microcontroller **162** by sending a digital control signal to the D/A converter **180**, which converts the control signal into analog form and then transmits the resulting signal on line **198** to the cooler **150**.

If a solid state thermoelectric cooler (TEC) **150** is present, the controller unit must use a feedback signal from a thermistor **152** or other temperature sensing device inside the laser diode's housing (not shown). The controller is set up to hold the laser diode at a particular temperature over the life of the laser diode.

In general it is difficult to specify an operating temperature to an analog controller. Moreover, analog controllers have been known to overdrive and burn out the TEC **150** by trying to maintain a set point temperature even during conditions in which it is impossible for the TEC to maintain that temperature. In fact, it has been found that TEC failure is a significant failure mechanism for packaged laser diodes.

The digital controller of the present invention overcomes the prior art problems with TEC burnout (1) by specifying the laser diode operating temperature such that TEC operation is minimal and only for stabilization rather than for gross continual cooling, and/or (2) by specifying, in software, temperature boundaries for "normal operation", and curtailing full power operation of the laser diode (i.e., forcing the laser diode to operate at lower output power) when the operating conditions fall outside the normal operation specifications so as to avoid damaging or excessively aging the laser diode. Furthermore, the drive current for the TEC is limited to a predefined maximum value at which it is known that the TEC can operate indefinitely, thereby preventing TEC burnout.

An RS232 input/output port **200** couples the microcontroller **162** to external devices, such an ASCII terminal or desktop computer **202**. The computer **202** can read data stored in the EEPROM **166**, and can set parameters for the controller **160**, such as the target temperature for the laser diode, a target optical output power setting, and so on. The RS232 port **200** is also used during initial calibration of the back facet photodiode **116**, as will be described in more detail below.

The digital controller often runs a fiber optic data link for some type of computer host, and thus the link can be considered to be a subsystem of a host computer. The RS232 port can also be used by the host computer system to communicate with the data link subsystem. Information such as link status, laser diode aging, are passed up to a monitoring software routine running in the host computer system. The host computer can also command the link to preform various functions such as self test, automatic gain control, and so on.

Finally, a set of front panel LEDs **204** are coupled to the microcontroller **162**. The LEDs **204** communicate the status of the laser diode **100** without having to plug a computer **202** into the microcontroller's communication port **200**. In particular, there is a green LED denoting normal operation, a yellow LED denoting that the controller **162** is in the process of initializing the laser diode, and a red LED denoting that the laser diode has either failed or is in need of replacement.

RECEIVER CHANNEL.

One preferred embodiment of the present invention is a controller for a full duplex optical channel, and therefore the controller **160** is also coupled to a receiver channel **220** that will be described next. However, it should be understood that many features of the present invention apply to unidirectional laser channels.

The receiving channel **220** has an incoming optical link **222**, which is typically an optical fiber of standard construction. The light transmitted by the optical link **222** is converted into an electric signal by a photodiode **224**. The resulting signal, which has both d.c. and a.c. components is asserted on line **226**. The a.c. component of the received signal is separated from the d.c. component by a capacitor **230**, and the resulting a.c. signal is amplified by a variable gain amplifier **232** before being transmitted on line **234** to devices external to the controller **160** for whatever type of signal processing is required.

The gain of the a.c. signal amplifier **232** is controlled by the microprocessor **162** via the D/A converter **180**. In particular, the gain of the a.c. signal amplifier **232** has a nominal standard setting, corresponding to a predefined digital value set in the microprocessor **162**. The gain of the amplifier can then be increased if a.c. component of the received signal is observed (using peak detector **242**, discussed below) to be weaker than normal, or decreased if the received signal is stronger than normal.

The d.c. component of the received optical signal is monitored by using an operational amplifier **240** to measure the d.c. signal level on line **226**, and transmitting the resulting value to the microcontroller **226** via the A/D converter **170**. The magnitude of the output a.c. signal on line **232** is monitored by using a peak detector **242** to measure the magnitude of the a.c. signal.

AUTOMATIC SELF INITIALIZATION OF LASER DIODE, AND INITIAL CALIBRATION OF BACK FACET PHOTODIODE.

Referring to FIGS. **3**, **4** and **5**, there are three primary physical situations to be considered when initializing the laser diode upon powering on the laser diode controller.

The first situation is the one shown in FIG. **3**, in which it is not known where the output of the laser diode **100** is being sent. Thus, there is no feedback, other than that provided by the back facet photodiode **116** as to the operation of the laser diode **100**. This situation requires that the controller's control software be provided some a priori knowledge of the back facet photodiode's characteristics and its coupling to the laser diode.

The second situation, shown in FIG. **4**, is used when the controller **160** and its laser diode **100** are being turned on for the first time. In this situation, a light meter **250** is coupled to the output of the front facet of the laser diode **100**, typically via an optical fiber **112**. The light meter is coupled both to the output of the laser diode **100** and to a computer or work station **202** that is used during the laser calibration process. The computer **202**, in turn, is coupled to the communications port **200** of the controller.

In the preferred embodiment, the light meter **250** monitors the optical output of the laser diode **100** until the optical output power reaches a specified level, which is 1 milliwatt in the preferred embodiment. When the measured optical output power reaches that level, the light meter sends a signal to the computer **202**, and the computer sends a corresponding message to the controller's microcontroller via the communications port **200**. In this way, the controller **160** can determine what reading from the laser's back facet photodiode corresponds to a predefined level of optical output power from the front facet.

The ratio of back facet to front facet optical output power can vary considerably among laser diodes. However, this ratio is constant for any single laser diode, and therefore only this one measurement is required for calibrating the back facet photodiode of the laser diode, providing the photodiode responds linearly to the laser diode. The measured calibration value, which is the back facet photodiode measurement value for 1 milliwatt of optical output power on the front facet, is stored in the controller's nonvolatile memory **166**. From this point on, the controller can determine the amount of optical output power being generated by the front facet of the photodiode as being:

$$\text{Power(front facet)} = \text{Power(back facet)} / K$$

where "Power(front facet)" is measured in units of milliwatts, "Power(back facet)" is measured in terms of the current flowing through photodiode **116**, digitized by the A/D converter **170**, and K is the calibration value for the back facet of the laser diode which is stored in the nonvolatile memory **166**.

Some laser diode packages have back facet photodiodes which do not respond linearly to the laser diode's optical output. In this case the controller is programmed to use a more complex mathematical equation to specify the relationship between photodiode measurements and the laser diode's output power, such as a second or third order polynomial. To determine the coefficients of such an equation the relationship between back facet photodiode measurement and front facet optical output power must be calibrated at several points (typically at eight to twelve points) distributed over the expected operating range.

The third situation, shown in FIG. **5** depicts a full duplex optical link, including two interconnected laser diodes **300** and **310**. Each laser diode has its own digital controller **302**, **312**, and the optical transmitting port **304**, **314** of each laser diode is coupled to a receiving port **306**, **316** of the other laser diode by an optical fiber **308**, **318**.

Control functions for each of these three situations will be discussed below with reference to the flow charts shown in FIGS. **8**, **9** and **10**.

An important characteristic of laser diodes is that these devices age with use, even when the devices are not exposed to excessive currents and temperatures, and eventually fail. FIG. **6** depicts a logarithmically scaled graph of the aging characteristics of a typical laser diode, using drive current measurements taken over a period of time at constant operating temperature. As shown, the drive current required for generating a constant level (e.g., one milliwatt) of optical output power increases with the age of the laser diode. Typically, there will be very little increase in the required drive current during the first thousand hours of operation of the laser diode, an acceptable level of increase through a few tens of thousands of hours of operation, with a large increase in the required drive current shortly before device failure.

Storing measurement data in the nonvolatile memory **166** of the controller **160**, as shown in FIG. **7**, enables the preferred embodiment of a laser diode controller to predict failure of the laser diode and to send a warning to a host computer, prior to failure of the device, that the laser diode needs to be replaced. In particular, when the controller finds that drive current required for generating a predefined level of optical output power exceeds the original level of drive current needed when the device was new by a predefined percentage (e.g., ten percent), after compensating for any temperature differences between the measurements being compared, failure of the device is imminent and the controller **162** will generate a warning message.

As shown in FIG. **7**, the memory locations in the nonvolatile memory **166** are structured and used by the microcontroller **162** to store the back facet calibration factor for the laser diode **3** (slot **330**), device measurements for the laser diode taken when the laser diode is turned on for the first time (slot **332**), device measurements after 10, 100, 1000, and 10,000 hours of operation (slots **334**, **336**, **338**, **340**), the number of hours of operation of the laser diode (slot **344**). Furthermore, device measurements are taken by the controller periodically during operation of the laser diode (e.g., once every ten hours of operation) and the last of those device measurements is stored in slot **346** of the nonvolatile memory **166**. Each set of device measurements comprises the measured threshold current for the laser diode, the drive current required for one milliwatt of optical output power, and the operating temperature of the laser diode at the time that the measurements were made. Also stored in slot **348** of the nonvolatile memory are set point values for the laser diode's drive current, operating temperature and RF power.

When the laser diode **100** and its controller are initially manufactured, the EEPROM **166** contains no data.

Referring to FIGS. **8** and **9**, whenever the laser diode controller is powered on, it performs a sequence of self initialization steps, under the control of a power on sequence program **390**, before turning on the laser diode. During this initialization sequence, a front panel LED flashes, indicating that the laser diode is being initialized.

The controller checks the stability of the power supply **174** by measuring the voltage provided by the power supply, and waits for that value to settle down before proceeding any further (step **400**).

If the laser diode is a high performance laser diode which includes a thermoelectric cooler (step **402**), the controller turns on the thermoelectric cooler and waits until the laser diode's temperature sensor indicates that the temperature has stabilized at the specified target temperature for the laser diode **404**. The controller continues thereafter to run a background temperature control routine **404** which modulates the TEC's drive current so as to try to maintain the laser diode at the specified temperature. In the preferred embodiment, the temperature control routine prevents TEC burnout by preventing the drive current for the TEC from exceeding a predefined level at which it is known the TEC can operate indefinitely without burning out. If the TEC is unable to keep the laser diode close to its specified target temperature, the temperature control routine forces the controller to reduce the optical output power by a predefined percentage, such as twenty-five percent, so as to reduce the amount of heat generated and so as to prevent premature aging of the laser diode. Alternately, the temperature control routine can simply shut down the laser diode subsystem until better operating conditions are restored.

Next, the microcontroller accesses nonvolatile (EEPROM) memory **166** to see whether there is a calibration value stored in that memory (box **406**). If no calibration value is stored, that indicates that this is the first time that the laser diode has been turned on, and therefore proceeds with the next step, which is to determine whether a light meter is coupled to the output of the laser diode (box **408**) using a physical connection scenario such as the one shown in FIG. **4**. The presence of a light meter is determined by sending a message via the communications port **200**. If a light meter is in place, the computer **202** sends back a corresponding message.

If a light meter is not connected to the laser diode, the power on sequence control program will use a default calibration value for the back facet photodiode, and the program will skip over the calibration step **410**. The default calibration value used is an "average" value for the type of laser diode and photodiode being used (step **412**). While this is tolerable, in some embodiments of the present invention, if the laser diode has not yet been calibrated, the power up sequence program for the controller will prevent operation of the laser diode until a light meter is connected so as to enable calibration.

Calibration (step **410**) is performed by slowly increasing the drive current of the laser diode until the light meter signals that the optical output power has reached a predefined level such as one milliwatt. Typically, the drive current will be started at a low value, such as 10 milliamps, and then increased at a very slow rate, such as 1 milliamp per second, with a limit on the maximum drive current, such as 50 milliamps (plus a temperature compensation value, if necessary). When the light meter signal is received, the drive current is held steady while the back facet photodiode current is measured and then stored in location **330** of the nonvolatile memory **166** as the calibration value, thereby establishing the ratio of back facet photodiode current to front facet optical output power. If the back facet photodiode is nonlinear, measurements are made at the additional calibration required for computing the coefficients of a nonlinear equation which defines the relationship between back facet photodiode current and front facet optical output power.

Next, the routine for measuring the laser diode's device characteristics is called (step **414**). That routine is shown in FIG. **9**, and will be discussed below. That routine measures the optical output of the laser diode at a range of drive currents, and then computes the slope efficiency of the laser diode, the threshold current for the laser diode, and the operating current for a predefined level of optical output power, such as one milliwatt.

At step **416** the power up sequence routine then stores the threshold current for the laser diode, and the operating current for the predefined level of optical output power, as well as the current operating temperature in the appropriate location in the EEPROM **166**. If this is the first time that the laser diode has been turned on (as can be determined by inspecting location **332** of the EEPROM to see whether it is empty), these values are stored location **332**. Otherwise, they are stored in location **346** of the EEPROM.

Next, at step **418** the device measurements from step **414** are compared with a set of predefined device failure criteria. For example, in one preferred embodiment the device failure criterion is that the drive current required to generate the predefined optical output level, after any required temperature compensation has been taken into account, be greater than the original drive current required (when the device was new) by ten percent or more. If that criterion is met, failure of the device is imminent, and therefore the failure LED **204** on the front panel of the controller is enabled, and a failure prediction message is transmitted via the controller's output port **200**.

Assuming that the laser diode has not failed, the drive current of the laser diode is increased by the controller to the level required for normal operation, which is typically specified as a particular d.c. optical output power level (step **420**). The drive current required is computed from the threshold current and the slope efficiency of the laser diode, both of which were previously determined during step **414**. Furthermore, the output power is checked, by measuring the current generated by the back facet photodiode and scaling that measurement by the calibration value for the laser diode, and adjusted if necessary by adjusting the drive current. Then the "normal operation" LED on the front panel of the controller is enabled, and a "ready to transmit" message is sent to the host computer **202** via the communications port. The "ready to transmit" message indicates to the host computer that the optical link coupled to the laser diode is ready for normal operation.

After the laser diode begins normal operation, steps **414** through **418** are repeated periodically (step **422**), such as once every ten hours of operation, so that the controller can monitor the operability of the laser diode. The data from these periodic maintenance checks are stored in the appropriate locations in the EEPROM **216**, which also allows this maintenance data to be retrieved and analyzed by the host computer **202**.

Referring to FIG. **9**, the routine for measuring the device characteristics of the laser diode (called by step **414** of the program shown in FIG. **8**) starts at step **440**, which measures the slope of the laser diode's optical output power in the LED mode. To do this, the drive current of the laser diode is slowly increased from an initial low value, such as 5 milliamps, measuring the optical output power at each 1 milliamp interval, and computing the slope of the optical output power. The optical output power is measured using the back facet photodiode, as described above. This sequence continues until the slope of the optical output power begins to increase, indicating that the laser diode is entering lasing mode.

At step **442**, the drive current for the laser diode continues to be slowly incremented in small steps, measuring the slope of the optical output power until four or more points are measured which produce a consistent slope, thereby indicating that the laser diode is lasing. This slope is the slope efficiency for the laser diode at the current operating temperature.

Next, at step **444**, the threshold value for the laser diode is determined by finding the intersection of the optical output power lines for LED mode and for lasing mode, as measured by steps **440** and **442**. Furthermore, the slope efficiency of the laser diode in lasing mode is used to compute the operating current required for generating a predefined level of optical output power, such as one milliwatt.

Additional quality assurance checks can be performed using the controller, such as for checking a batch of laser diode that were not thoroughly checked by the manufacturer. Typically, these additional quality assurance checks will be performed only the first time that the laser diode is turned on.

If further quality assurance checking is enabled (step **446**), the routine will first check that all the parameters previously measured are within predefined normal operating limits (step **448**). If not, a "device failure" message is sent to the host computer **202**, and the device failure LED on the controller's front pane is enabled (step **450**).

If the first quality assurance check is passed (step **446**), the routine next checks the linearity of the laser diode. This is done by stepping the laser diode through a number of drive current values, covering the entire normal operating range of the laser diode, such as the drive currents required for generating optical output power levels ranging from 0.5 milliwatt to 4.0 milliwatts, using the previously measured slope efficiency value (step **452**). The optical output power at each drive current is measured, using the back facet photodiode, and then these measurements are checked to see if they all fall along a line (step **454**). Linearity is checked by performing a least squares fit on the measurement data to determine the position of the line which best fits the measurement data, and then finding the distance of each measurement point from that line. If the distances of the points from the line exceed a predefined value, particularly at the highest normal output powers, this is an indication that the diode may be damaged (e.g., dark line defects), and a device failure message is sent to the host computer **202** (step **450**). If the laser diode measurements show that the laser diode passes the linearity test of step **454**, a "device okay" message is sent to the host computer.

Note that when the characteristics of the laser diode are being rechecked pursuant to step **422** of FIG. **8**, step **440** is omitted because the LED phase of the laser does not change significantly over the life of the laser diode. Furthermore, in the preferred embodiment the d.c. drive current is tested only over a small range so as not to interfere with the transmission of data over the optical link. This range of test points need only vary the d.c. drive current by a small amount, such as ten percent of the previously selected bias point, so as to enable the controller to recompute the slope efficiency of the laser diode and the threshold value of the laser diode by finding the intersection of the lasing mode characteristic with that of the previously measured LED phase characteristic curve (see FIG. **2**). In an alternate embodiment, just before performing the periodic self tests, the controller sends a message to the host computer **202** via the RS232 port **200** telling it to stop data transmissions until the self test is completed.

FULL DUPLEX LINK INITIALIZATION.

The power up sequence is somewhat different for full duplex optical links (see full duplex link in FIG. **5**). In particular, step **420** in FIG. **8**, at which point the drive current is increased to initiate normal operation of the laser diode, is replaced for full duplex links by the sequence of steps shown in FIG. **10**.

Laser diodes emit very bright and coherent radiant energy that is normally invisible to the human eye. This energy could cause harm to human eyes if the output of the laser diode is misdirected. In the context of a full duplex link, it is possible to use the digital controller of the present invention to insure that the link is intact before the controller enables normal operation of the laser diode.

In particular, after the initial device measurements are performed, and after step **418** in FIG. **8** has been performed, the power up sequence control program for full duplex links switches to step **470** in FIG. **10**. At step **470**, the drive current for the laser diode is initially set so as to output much less power than during normal operation, such as ten percent of normal power (e.g., 0.20 milliwatts instead of 2.0 milliwatts). This initial output level is selected so as to be sufficient for the two controllers **302** and **312** shown in FIG. **5** to test the integrity of the full duplex link. Note that such links can be designed to have a predictable and often very low amount optical loss (i.e., a low loss of power caused by the transmission of the generated light through optical fiber **308** or **318**) eVen for links which are up to a couple of kilometers in length. Furthermore, note that both controllers **302** and **312** in FIG. **5** will be executing the same power up sequencing routine, and therefore the steps shown in FIG. **10** are executed more or less in parallel in the two controllers.

After turning on the laser diode at a low optical output level, the controller measures the d.c. component of the optical power received at its receiver port **306** (step **472**). If the link is intact, and the other laser diode has been powered on, the received optical power will be sufficient to indicate that the link is intact (step **474**). If the required level of optical power is not being received, this means that either the link is not intact, or the other laser diode has not been turned on. In either case, the routine waits for a short period of time (step **476**), and then repeats steps **472** and **474** until the presence of an intact optical link is established.

Once the presence of an intact link has been established, the drive current for the laser diode is increased to the level required for normal operation (step **478**). Then, after a short wait (step **480**), the controller once again measures the d.c. component of the optical power received at its receiver port **306** (step **482**). Since link operation assumes both devices are working, if each receiver does not sense full power operation in a reasonable period of time (typically less than one hundred milliseconds) then the system resets to step **470** and the start up procedure for the link begins again.

In an alternate embodiment, the full duplex link is brought up by first transmitting at five percent of full power on the outgoing link until light above a threshold level is received on the incoming link, at which point the transmitted optical power is increased to a slightly higher level which is still much less than full power, such as ten percent of full power. When, and if, the intensity of light received on the incoming link increases by a similar amount, then the integrity of the outgoing link has been established and the outgoing link is brought to full power and data transmission is enabled. This alternate methodology avoids transmission at full power until such time that the integrity of both branches of the full duplex link has been fully established.

The controller also computes the ratio of a predefined "ideal" received optical power level to the actual received d.c. optical power level. Note that the useful life of a laser diode can be approximately doubled by halving the optical output power used during normal operation. Therefore the "ideal" received optical power will typically be a relatively low power level, such as 0.75 milliwatts. In any case, the computed ratio is then transmitted by the controller over the optical link. The purpose of the transmitted message is to notify the controller on the other end of the link as to how it should modify the optical output power of its laser diode. In most situations, this will enable the controller to use a significantly lower optical output power than would be required in a system without this capability, thereby significantly extending the lifetime of the laser diodes being used. The reason that the output power will be lower than would otherwise be required is that systems without this power adjustment feature need to be able to handle "worst case" situations. Therefore such systems must generate sufficient optical output power to make an link operational in a wide variety of environments, even though most links will not actually need to use such a high optical output level in order to function properly.

In one preferred embodiment, this transmission is performed by modulating the d.c. level of the laser diode (i.e., modulating the signal on line **178** shown in FIG. **3**), using a relatively slow data transmission rate, such as ten or twenty bits per second. Since the entire message needed is only about sixteen bits long (e.g., five synchronization bits, plus an eight bit ratio value, plus a three bit error correction code), this process will only take one or two seconds, even at such slow data rates. The reason that data transmission is so slow is due to the need to protect the laser diode from sudden current fluctuations through the use of an RC circuit **176** having a relatively long time constant, as explained above.

In other embodiments, the transmission is performed by sending data through multiplexer **192**. This allows data transmission at much higher rates, such as 100 kilobits per second. However, in these embodiments the controller must have a data receiver circuit (not shown in the Figures) in the receiver channel for receiving such messages, which significantly increases the cost of the controller.

In the preferred embodiment, the transmitted ratio value is 100 if no adjustment in power is required. Values above 100 indicate that the output power should be increased by X percent, where X is the transmitted value divided by 100. Values below 100 indicate that the output power should be decreased, where the ideal output power is the current output power multiplied by X and then divided by 100.

In any case, at about the same time that the controller is transmitting its power ratio message over the link, the other controller at the other end of the link is doing the same thing. Therefore, the controller will receive a corresponding message with an output power ratio value from the other laser diode controller at the other end of the link (step **484**). Then the controller adjusts its output power in accordance with the received power ratio value X, as follows:

$$\text{New Power Level} = (\text{Old Power Level}) \times X/100.$$

In addition, the gain of the controller's transmission data attenuator **184** will be adjusted in a similar fashion so that the depth of modulation caused by data transmission remains at approximately the same as before.

At this point, both controllers at both ends of the link will enable data transmission over the link (step **486**).

Finally, the controller monitors the peak-to-peak amplitude of the a.c. portion of the received optical signal, waiting for the receipt of modulated optical signals. Once data transmission begins, the controller measures the amplitude of the a.c. portion of the received optical signal, and adjusts the gain of the amplifier **232** in the receiver channel, if necessary, so as to ensure reliable data transmission (step **488**).

With regard to the security of data transmitted over optical links, it has been established that it is a relatively easy matter to tap into an optical link by bending an optical fiber, causing a portion of the optical energy in the fiber to be transmitted and "lost" through the fiber's cladding. The light exiting the fiber at the location of the bend can be read using standard optical and electro-optical components, thereby compromising the security of the transmitted data. Once the integrity of an optical link has been established, the controller of the present invention can be programmed to detect decreases in the received optical power. For example the controller can be programmed to detect any decrease of more than five percent, as compared to the previously established level of received d.c. power, and to transmit a message to a host computer whenever such a fluctuation is detected. Such a message will notify the system monitor that the security of the optical link may have been compromised.

USER INTERFACE.

Referring to FIGS. **3** and **11**, the controller's software includes a user interface routine **392** which allows the user to access status information in the controller via a host computer **202**, to view the data stored in the controller's nonvolatile memory **166**, and to set and/or reset various parameters such as the optical output power (i.e., the number of milliwatts of optical output power to be produced by the laser), the target temperature for the laser diode if it is coupled to a thermoelectric cooler, and the attenuator setting for controlling the RF power of the signals being transmitted.

FIG. **11** shows the display generated by the user interface routine **392** on the display of the host computer, and also shows the commands used to modify the laser diode's parameters. The displayed "XX.X" values are measurements calculated by converting count values for the A/D and D/A converters. The displayed "ZZZZ" values are raw A/D converter values, and the displayed "YYYY" values are raw D/A converter values. The displayed "SS.S" values are specified set point values in units of milliwatts for the optical output power and RF transmission power, and in units degrees Centigrade for temperature.

The display items in the boxed area are optionally displayed items that are viewed if the keyboard command <CNTRL>D is entered. The four parameters shown in this boxed area can be modified by selecting "Manual Control" from the Main Menu on the bottom half of the display and then adjusting the displayed values up or down using the commands shown in FIG. **11**.

The three set point values shown in the display can be modified by selecting "Set Point Control" from the Main Menu, when enables the user to adjust the set points up or down using the commands shown in the Figure.

The Debug command on the Main Menu brings up a new display, not shown, which lists the supply voltages in the device, the data stored in the EEPROM, and also allows the user to view all the initialization data for the laser diode. Thus the Debug command is primarily intended for use by the manufacturer when first testing new laser diodes and when performing post mortems on laser diodes that have either failed initial tests or which have aged or otherwise become nonfunctioning.

ALTERNATE EMBODIMENTS

It is important to note that the back facets of some laser diodes are coated with a reflective material, such as aluminum, making the back facet unavailable for monitoring the optical output power of the device. In such laser diodes, the front facet is tapped so as to divert a portion of the laser diode's power to a monitoring photodiode. Typically a beam splitter is coupled to or placed near the front facet with a photodiode positioned to receive the diverted portion of the laser diode's optical output. This laser diode/photodiode configuration is functionally equivalent to the apparatus in the preferred embodiment, and thus the more general term for the "back facet photodiode" is "a photodiode for monitoring the laser diode's optical output power".

Referring to FIG. **12**, another link configuration which is envisioned by the inventor is using a single digital controller to control the operating point and other operating parameters of multiple laser diodes. For example, four laser diodes may be used in the link between a computer and a color monitor, with distinct optical channels being used for red, green, blue and synchronization signals. A single controller can be used for multiple laser diodes because it takes very little time to execute the software required for setting up and monitoring each laser diode, and because the quantity of data required to be stored for each laser diode in nonvolatile memory is typically much, much less than the amount of such memory which is available in either a single EEPROM device or even in an EEPROM embedded in a microcontroller.

While the present invention has been described with reference to a few specific embodiments, the description is illustrative of the invention and is not to be construed as limiting the invention. Various modifications may occur to those skilled in the art without departing from the true spirit and scope of the invention as defined by the appended claims.

What is claimed is:

1. A controller for a laser diode, comprising:

an optical power sensor which receives a portion of the light emitted from a laser diode and generates an optical power measurement signal corresponding to the optical power of the light received by said power sensor;

a drive current circuit, coupled to said laser diode, which applies a specified level of drive current through said laser diode; and

a digital data processor, coupled to said optical power sensor and to said drive current circuit, which sets said specified level of drive current applied to said laser diode and receives said optical power measurement signal from said optical power sensor; said digital data processor being programmed to step said drive current through a sequence of values, to compute operating characteristics of said laser diode based on received optical power measurement signals for each drive current value, and to select a drive current level for said laser diode based on said received optical power measurement signals.

2. The laser diode controller of claim **1**, further including a nonvolatile memory coupled to said digital data processor, said digital data processor being further programmed to detect aging of said laser diode by (A) storing data denoting said computed operating characteristics of said laser diode in said nonvolatile memory, and (B) periodically checking the operability of said laser diode by stepping said drive current through a sequence of values, computing a set of operating characteristics of said laser diode based on received optical power signals for each drive current value, and generating an error signal when said computed set of operating characteristics fail to meet predefined criteria with respect to said operating characteristics stored in said nonvolatile memory.

3. The laser diode controller of claim **1**, said digital data processor being further programmed to perform quality assurance tests on said laser diode, where said quality assurance tests compare said computed operating characteristics of said laser diode with predefined criteria and generate an error signal when said computed operating characteristics fail to meet said predefined criteria.

4. The laser diode controller of claim **1**, said digital data processor being programmed to test said laser diode for linearity based on said received optical power measurement signals, wherein linearity comprises a consistent rate of increase in optical power with increases in drive current, and to generate an error signal when said laser diode fails to meet predefined linearity criteria.

5. The laser diode controller of claim **1**, further including a receiver channel, for receiving light generated by a second laser diode, said two laser diodes forming a full duplex optical link;

monitoring means, coupling said receiver channel to said digital data processor, for generating a received power signal corresponding to the d.c. optical power of said received light from said second laser diode;

said digital data processor including means for receiving said received power signal; said digital data processor being programmed (A) to compare said received power signal with predefined criteria and to thereby determine whether a full duplex optical link has been established between said two laser diodes; (B) to set said drive current level for said laser diode at a first level prior to determining that a full duplex link has been established; and (C) to set said drive current level for said laser diode at a second level after determining that a full duplex link has been established;

wherein said second drive current level causes said laser diode to generate at least twice as much optical output power as said first drive current level.

6. The laser diode controller of claim **5**, said digital data processor being programmed to monitor said received power signal so as to detect a breach of said full duplex link and to reset said drive current level back to said first level after detecting said breach.

7. The laser diode controller of claim **5**, said digital data processor being programmed to detect decreases of at least a preselected magnitude in said received power signal, and to generate a warning signal whenever such a decrease is detected; whereby said digital data processor can detect an attempt to eavesdrop on data transmitted via said full duplex optical link.

8. The laser diode controller of claim **1**, said drive current circuit comprising:

a bipolar transistor having an emitter coupled to a power source, a base coupled to said digital data processor, and a collector directly connected to said laser diode; and

a capacitor, connected to said collector, which a.c. couples said collector to an input signal line, said input signal line carrying high frequency signals to be optically transmitted by said laser diode.

9. The laser diode controller of claim **1**, further including a nonvolatile memory coupled to said digital data processor,

said digital data processor being further programmed to store data in said nonvolatile memory denoting a calibration coefficient for said optical power sensor, initialization values, and said computed operating characteristics of said laser diode, and to use said stored data to set said drive current level for said laser diode each time that said controller is turned on;

whereby said laser diode can be restarted each time that said controller is turned on without having to recalibrate and reinitialize said controller.

10. Multichannel laser diode apparatus, comprising:

a plurality of laser diodes;

a separate optical power sensor positioned near each of said laser diodes so as to receive a portion of the light emitted from said laser diode, said optical power sensor generating an optical power measurement signal corresponding to the optical power of the light received by said power sensor;

a separate drive current circuit coupled to each said laser diode, each said drive current applying a separately specified level of drive current through a corresponding one of said laser diodes; and

a single digital data processor, coupled to all of said optical power sensors and to all of said drive current circuits, which sets said specified drive current levels applied to said laser diodes and which receives said optical power measurement signals from said optical power sensors; said digital data processor being programmed to step said drive current for each laser diode through a sequence of values, to compute operating characteristics of each said laser diode based on received optical power measurement signals for each drive current value, and to select a drive current level for each said laser diode based on said received optical power measurement signals.

11. The multichannel laser diode apparatus of claim **10**, each said drive current circuit comprising:

a bipolar transistor having an emitter coupled to a power source, a base coupled to said digital data processor, and a collector directly connected to said laser diode; and

a capacitor, connected to said collector, which a.c. couples said collector to an input signal line, said input signal line carrying high frequency signals to be optically transmitted by said laser diode.

12. The multichannel laser diode apparatus of claim **10**, further including a nonvolatile memory coupled to said digital data processor,

said digital data processor being further programmed to detect aging of each said laser diode by (A) storing data denoting said computed operating characteristics of said laser diode in said nonvolatile memory, and (B) periodically checking the operability of said laser diode by stepping said drive current through a sequence of values, computing a set of operating characteristics of said laser diode based on received optical power signals for each drive current value, and generating an error signal when said computed set of operating characteristics fail to meet predefined criteria with respect to said operating characteristics stored in said nonvolatile memory.

13. The multichannel laser diode apparatus of claim **10**, further including a nonvolatile memory coupled to said digital data processor,

said digital data processor being further programmed (A) to store data in said nonvolatile memory denoting a calibration coefficient for each said optical power sensor, initialization values for said laser diodes, and said computed operating characteristics of said laser diodes, and (B) to use said stored data to set said drive current levels for said laser diodes each time that said controller is turned on;

whereby said laser diodes can be restarted each time that said controller is turned on without having to recalibrate and reinitialize said controller.

14. A controller for a laser diode having a back facet and a front facet, including:

a back facet photodiode which receives light emitted from a laser diode's back facet and generates an optical power measurement signal corresponding to the optical power output by said back facet of said laser diode;

a drive current circuit, coupled to said laser diode, which applies a specified level of drive current through said laser diode; and

a digital data processor, coupled to said back facet photodiode and to said drive current circuit, which sets said specified level of drive current applied to said laser diode and receives said optical power measurement signal from said back facet photodiode; said digital data processor being programmed to step said drive current through a sequence of values, to compute operating characteristics of said laser diode based on received optical power measurement signals for each drive current value, and to select a drive current level for said laser diode based on said received optical power measurement signals.

15. A method of controlling a laser diode, the steps of the method comprising:

applying a drive current to a laser diode so as to generate light;

measuring said generated light's optical power;

providing a digital data processor; and

under control of said digital data processor, automatically stepping said drive current through a sequence of values, receiving said optical power measurement for each drive current value, computing operating characteristics of said laser diode based on said received optical power measurement for each drive current value, and selecting a drive current level for said laser diode based on said received optical power measurement signals.

16. The method of controlling a laser diode set forth in claim **15**, further including the steps of

storing data denoting said computed operating characteristics of said laser diode in a nonvolatile memory, and

periodically checking the operability of said laser diode by stepping said drive current through a sequence of values, receiving a measurement of optical power for each drive current value, computing a set of operating characteristics of said laser diode based on said received optical power measurement for each drive current value, and generating an error signal when said computed set of operating characteristics fail to meet predefined criteria with respect to said operating characteristics stored in said nonvolatile memory.

17. The method of controlling a laser diode set forth in claim **15**, further including the steps of

comparing said computed operating characteristics of said laser diode with predefined criteria; and

generating an error signal when said computed operating characteristics fail to meet said predefined criteria.

18. The method of controlling a laser diode set forth in claim **15**, further including the steps of

testing said laser diode for linearity based on said received optical power measurements, wherein linearity comprises a consistent rate of increase in optical power with increases in drive current, and generating an error signal when said laser diode fails to meet predefined linearity criteria.

19. The method of controlling a laser diode set forth in claim **15**, further including the steps of

providing a receiver channel which receives light generated by a second laser diode, said two laser diodes forming a full duplex optical link;

measuring the d.c. optical power of said received light from said second laser diode;

under the control of said digital data processor, receiving said d.c. optical power measurement for said second laser diode, comparing said d.c. optical power measurement with predefined criteria and to thereby determining whether a full duplex optical link has been established between said two laser diodes, setting said drive current level for said laser diode at a first level prior to determining that a full duplex link has been established, setting said drive current level for said laser diode at a second level after determining that a full duplex link has been established;

wherein said second drive current level is higher than said first drive current level.

20. The method of controlling a laser diode set forth in claim **19**, further including the steps of

monitoring said d.c. optical power measurement so as to detect a breach of said full duplex link, and resetting said drive current level back to said first level after detecting said breach.

21. The method of controlling a laser diode set forth in claim **19**, further including the steps of

detecting decreases of at least a preselected magnitude in said d.c. optical power measurement, and generating a warning signal whenever such a decrease is detected; whereby attempts to eavesdrop on data transmitted via said full duplex optical link are detected.

22. The method of controlling a laser diode set forth in claim **15**, said step of applying a drive current including the steps of providing a bipolar transistor having an emitter coupled to a power source, a base coupled to said digital data processor, and a collector directly connected to said laser diode; and providing a capacitor, connected to said collector, which a.c. couples said collector to an input signal line, said input signal line carrying high frequency signals to be optically transmitted by said laser diode.

23. The method of controlling a laser diode set forth in claim **15**, further including the steps of

storing data denoting said computed operating characteristics of said laser diode in a nonvolatile memory, a calibration coefficient for measuring said generated light's optical power, and initialization values; and

setting said drive current level for said laser diode each time that said controller is turned on using said data stored in said nonvolatile memory.

24. A method of controlling a plurality of laser diodes, the steps of the method comprising:

applying a separate drive current to each of a plurality of laser diodes, thereby causing each laser diode to generate light;

measuring said generated light's optical power for each laser diode;

providing a single digital data processor; and

under control of said single digital data processor, automatically stepping said drive current for each laser diode through a sequence of values, measuring optical power for the light generated by each laser diode at each drive current value, computing operating characteristics of each said laser diode based on said measured optical power for each drive current value, and selecting a drive current level for each said laser diode based on said optical power measurements.

25. The method of controlling a plurality of laser diodes set forth in claim **24**, further including the steps of:

providing a nonvolatile memory coupled to said digital data processor,

under the control of said digital data processor, detect aging of each said laser diode by (A) storing data denoting said computed operating characteristics of said laser diode in said nonvolatile memory, and (B) periodically checking the operability of said laser diode by stepping said drive current through a sequence of values, computing a set of operating characteristics of said laser diode based on measurements of optical power for each drive current value, and generating an error signal when said computed set of operating characteristics fail to meet predefined criteria with respect to said operating characteristics stored in said nonvolatile memory.

* * * * *

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United States Patent [19]

Queniat et al.

[11] **Patent Number: 5,383,208**

[45] **Date of Patent: Jan. 17, 1995**

[54] **DEVICE AND METHOD TO CONTROL THE OUTPUT POWER OF LASER DIODES**

[75] Inventors: **Jean-François Queniat**, Trebeurden; **Andre Jaillard**, Lannion, both of France

[73] Assignee: **France Telecom**, Paris, France

[21] Appl. No.: **99,842**

[22] Filed: **Jul. 30, 1993**

[30] **Foreign Application Priority Data**

Jul. 30, 1992 [FR] France 92 09487

[51] **Int. Cl.**^{6} **H01S 3/13**

[52] **U.S. Cl.** **372/29**; 372/34; 372/38; 372/43; 372/109; 372/50

[58] **Field of Search** .... 372/9, 18, 20, 29, 30, 372/31, 32, 33, 34, 38, 36, 43, 46, 50, 108, 109; 250/205; 369/116, 121; 346/76 L

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Primary Examiner—Brian Healy
Attorney, Agent, or Firm—Nilles & Nilles

[57] **ABSTRACT**

A device for the control of the output power of laser diodes designed to be coupled to an optical fiber for the tranmission of data comprises a photodiode that can be used to acquire a characteristic signal of the power emitted by the laser diode; digital means to drive the laser diode comprising a central processing unit associated with servo-control computation program memorizing means to keep a constant output power whatever may be the drift and change of slope of the characteristic of the laser diode in response to ageing phenomena or to a change in temperature or to a loss of power due to the coupling of this diode with an optical fiber or to variations in the response of the photodiode as a function of the temperature. Application to digital transmission by optical fiber.

17 Claims, 7 Drawing Sheets

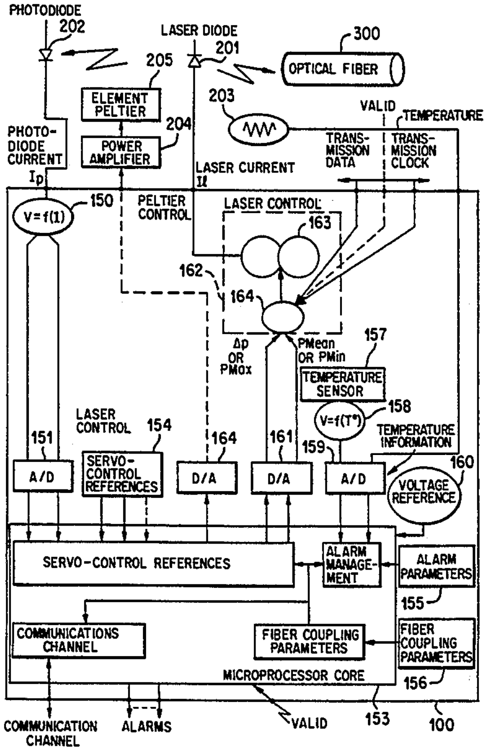


FIG_1

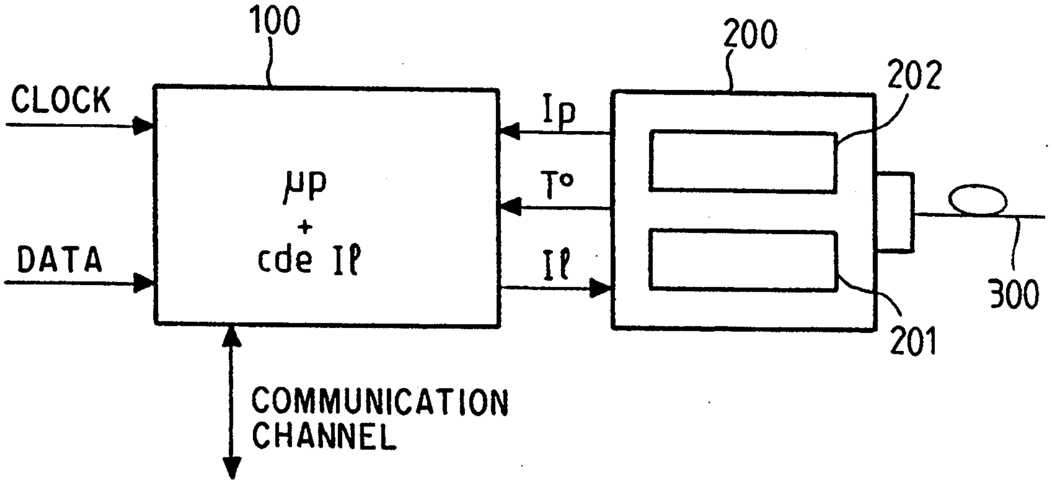

100
CLOCK
DATA
µp
+
cde Iℓ
Ip
T°
Iℓ
200
202
201
300
COMMUNICATION CHANNEL

FIG_2

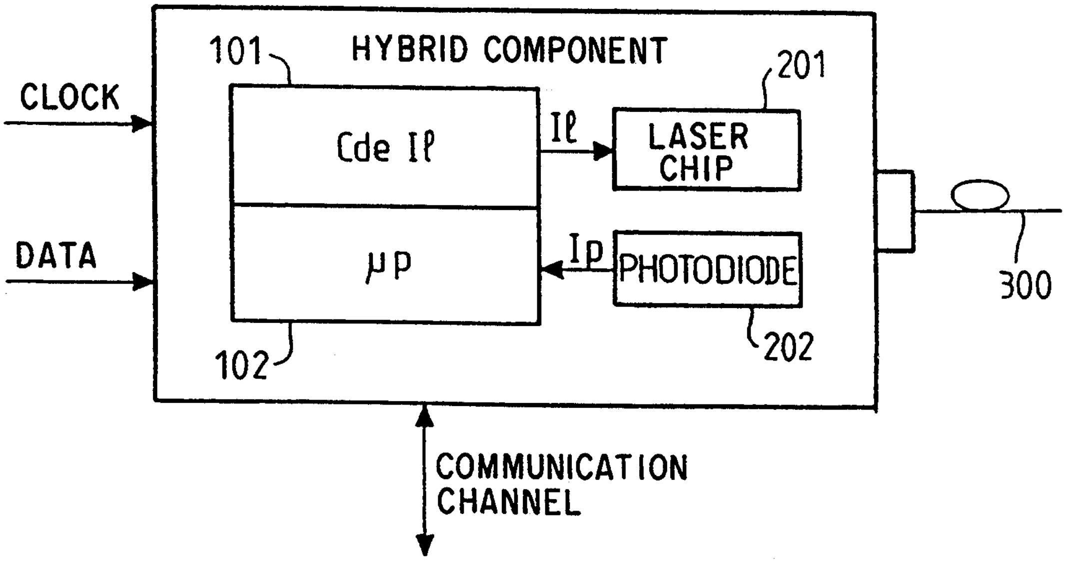

HYBRID COMPONENT
101
102
CLOCK
DATA
Cde Iℓ
µp
Iℓ
Ip
LASER CHIP
PHOTODIODE
201
202
300
COMMUNICATION CHANNEL

FIG_3

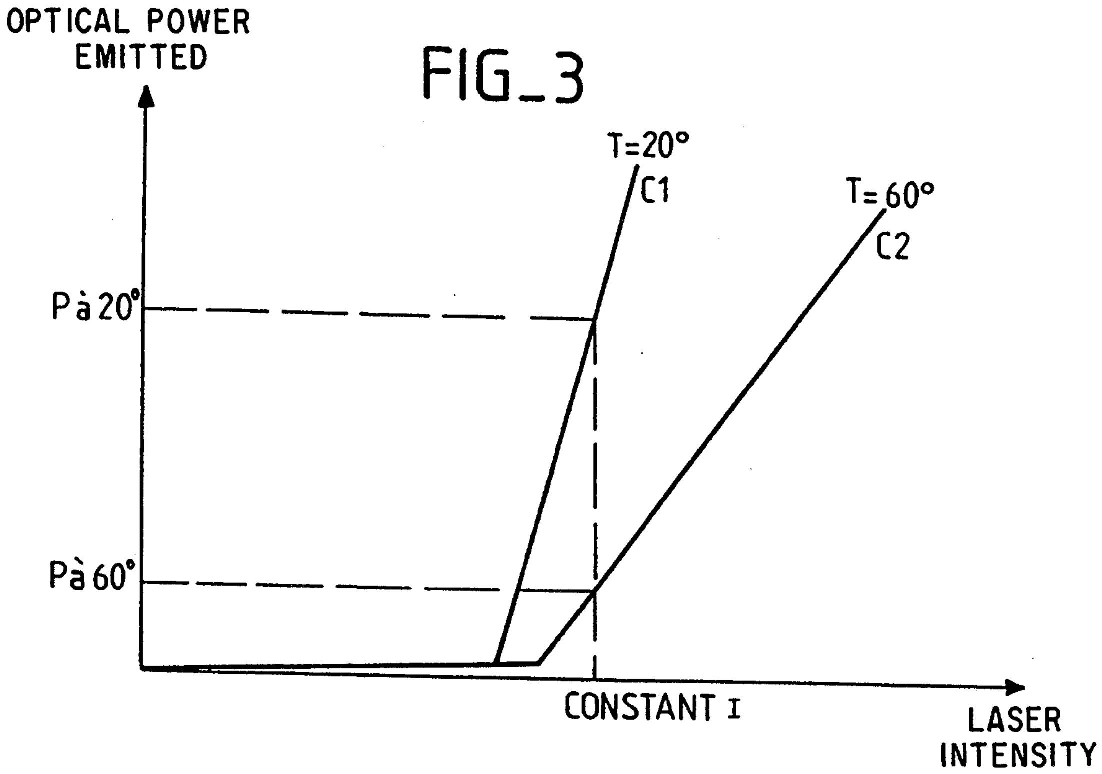

OPTICAL POWER EMITTED
T=20°
C1
T=60°
C2
P à 20°
P à 60°
CONSTANT I
LASER INTENSITY

FIG_4

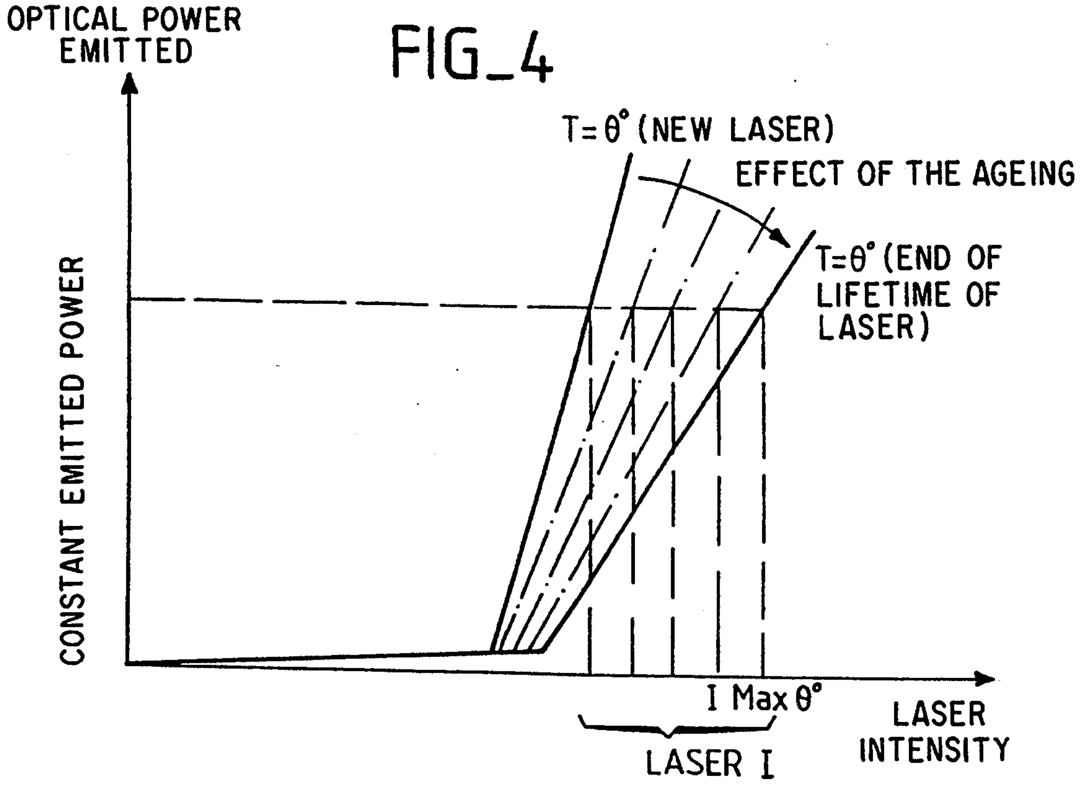

OPTICAL POWER EMITTED
CONSTANT EMITTED POWER
T=θ° (NEW LASER)
EFFECT OF THE AGEING
T=θ° (END OF LIFETIME OF LASER)
I Max θ°
LASER I
LASER INTENSITY

FIG_5

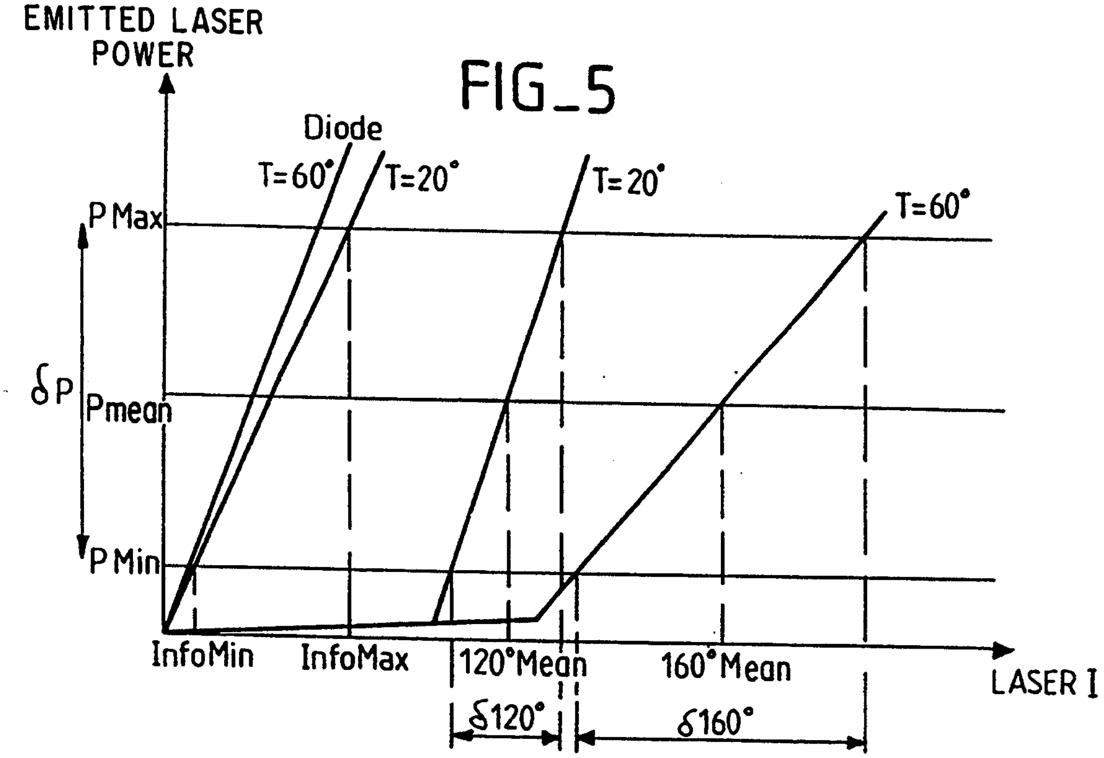
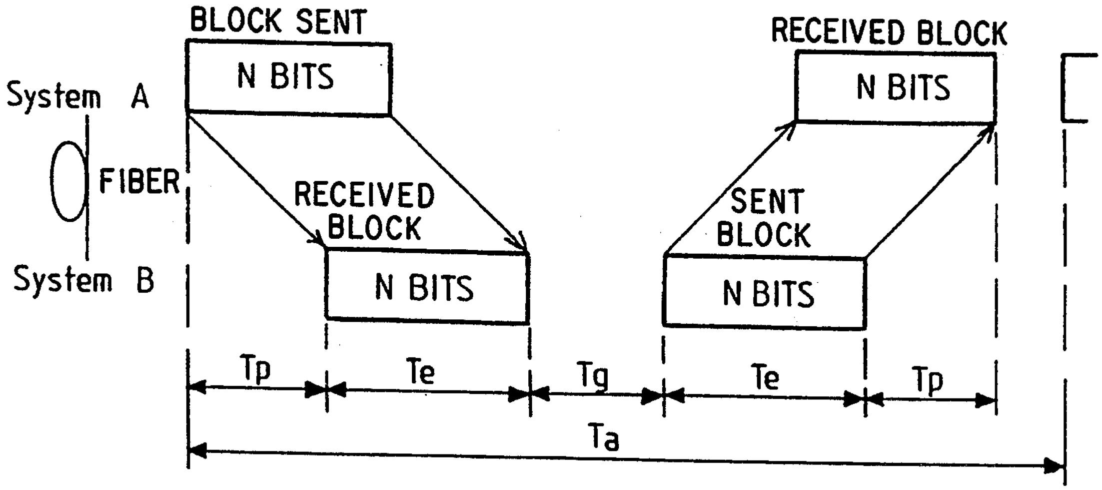

EMITTED LASER POWER
Diode
T=60°
T=20°
T=20°
T=60°
P Max
δP
Pmean
P Min
InfoMin
InfoMax
120°Mean
160°Mean
LASER I
δ120°
δ160°

FIG_7


BLOCK SENT
N BITS
System A
FIBER
System B
RECEIVED BLOCK
N BITS
SENT BLOCK
N BITS
RECEIVED BLOCK
N BITS
Tp
Te
Tg
Te
Tp
Ta

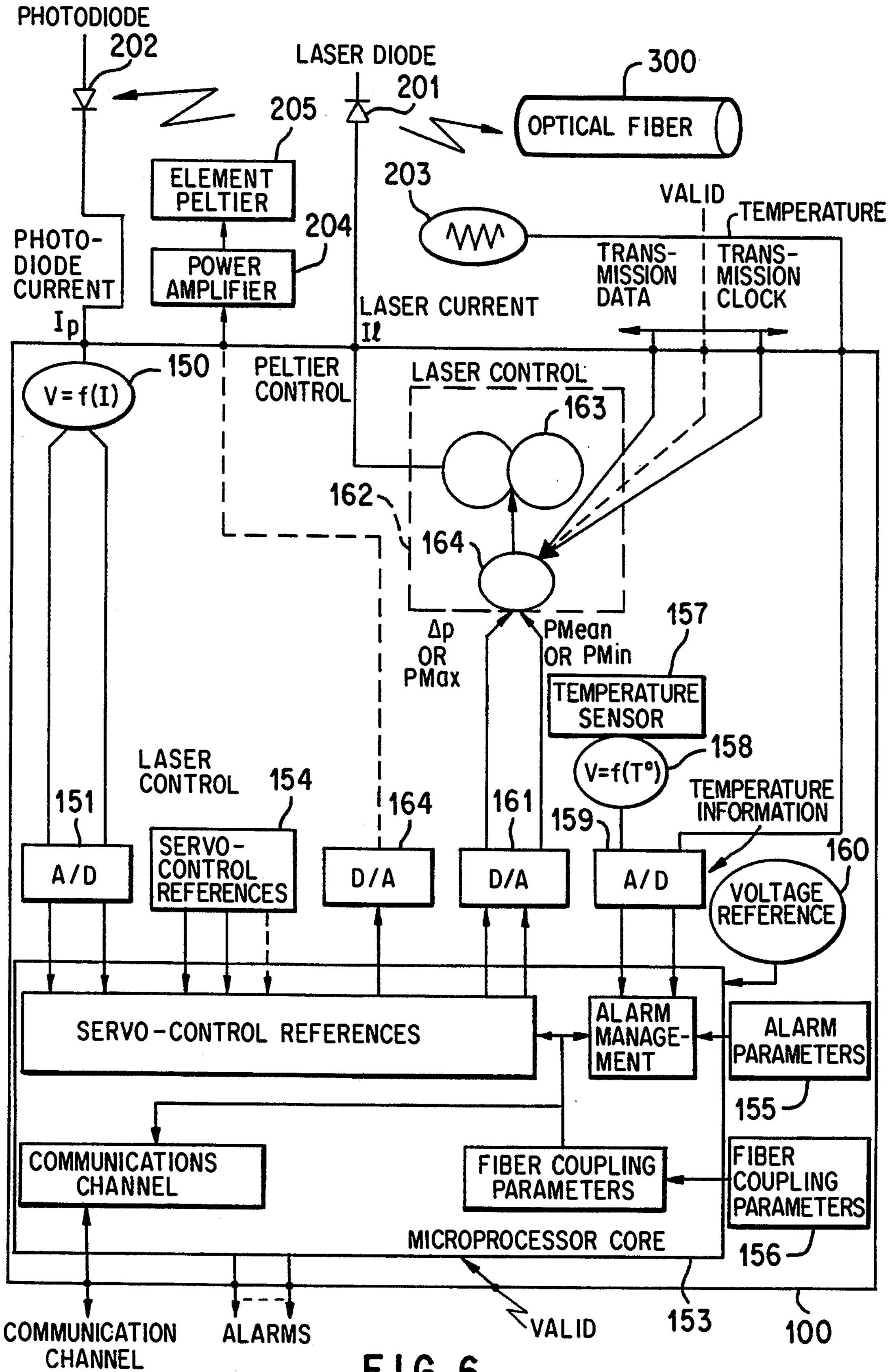

PHOTODIODE
202
LASER DIODE
201
300
OPTICAL FIBER
205
ELEMENT PELTIER
203
VALID
TEMPERATURE
204
POWER AMPLIFIER
PHOTO-DIODE CURRENT
Ip
LASER CURRENT
Il
TRANS-MISSION DATA
TRANS-MISSION CLOCK
150
V=f(I)
PELTIER CONTROL
LASER CONTROL
163
162
164
Δp OR PMax
PMean OR PMin
157
TEMPERATURE SENSOR
158
V=f(T°)
LASER CONTROL
154
151
164
161
159
TEMPERATURE INFORMATION
160
A/D
SERVO-CONTROL REFERENCES
D/A
D/A
A/D
VOLTAGE REFERENCE
SERVO-CONTROL REFERENCES
ALARM MANAGE-MENT
ALARM PARAMETERS
155
COMMUNICATIONS CHANNEL
FIBER COUPLING PARAMETERS
FIBER COUPLING PARAMETERS
156
MICROPROCESSOR CORE
COMMUNICATION CHANNEL
ALARMS
VALID
153
100

FIG. 6

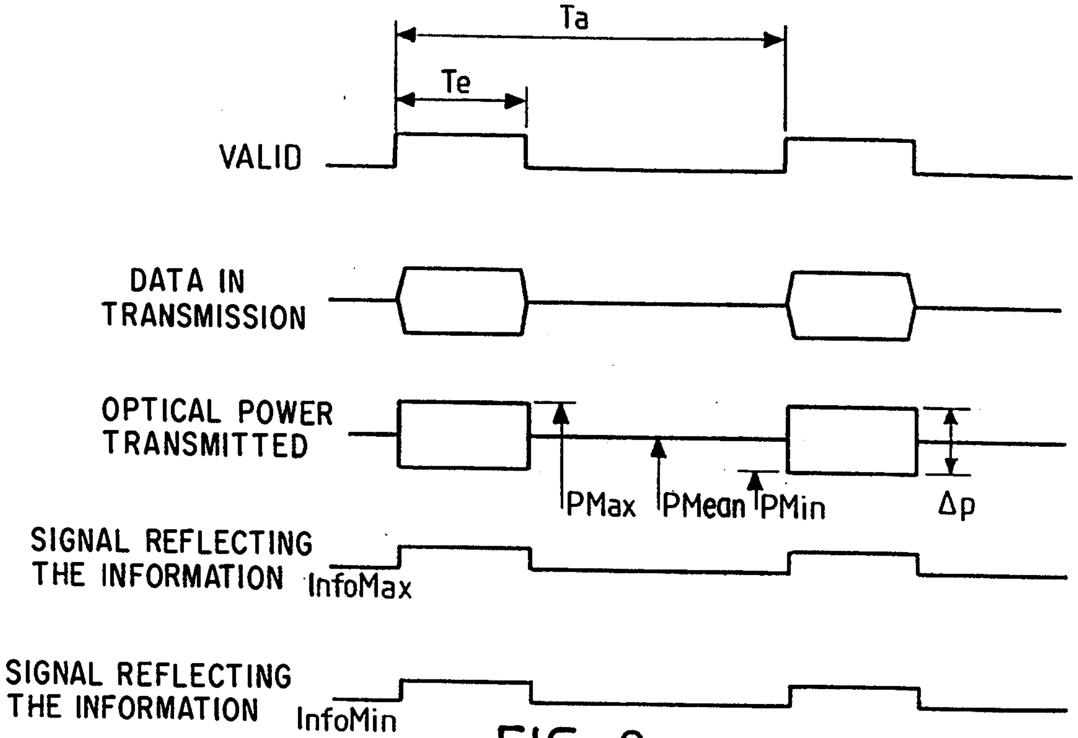

Ta
Te
VALID
DATA IN TRANSMISSION
OPTICAL POWER TRANSMITTED
PMax
PMean
PMin
Δp
SIGNAL REFLECTING THE INFORMATION
InfoMax
SIGNAL REFLECTING THE INFORMATION
InfoMin

FIG_8

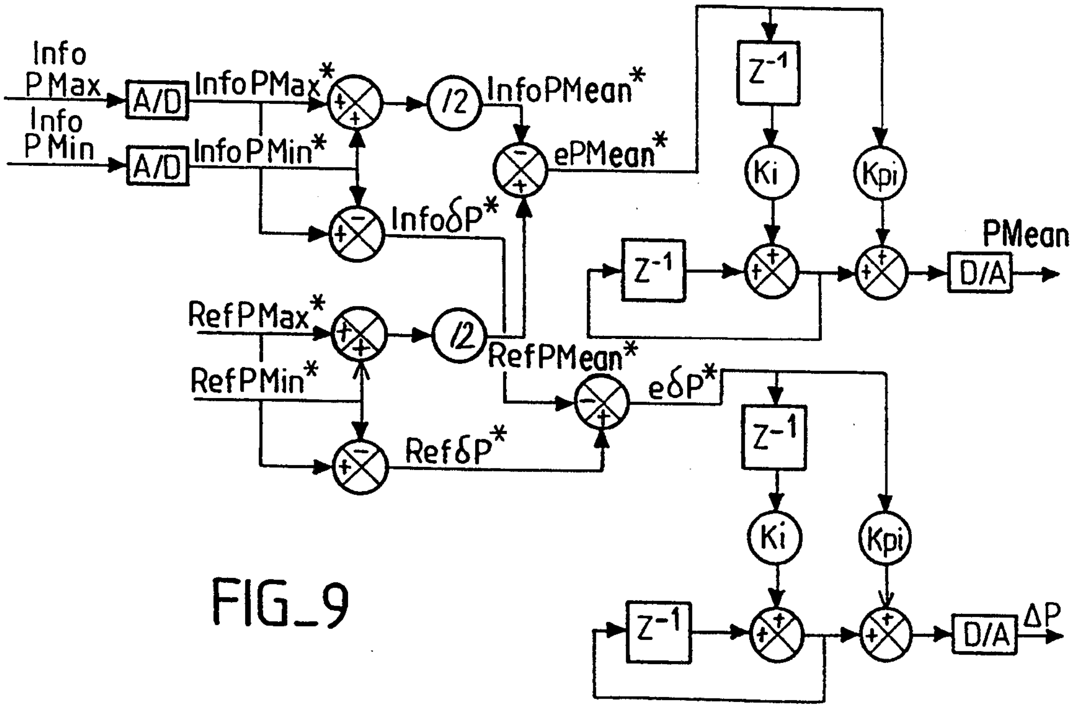

Info PMax
A/D
InfoPMax*
Info PMin
A/D
InfoPMin*
/2
InfoPMean*
ePMean*
InfoδP*
RefPMax*
RefPMin*
/2
RefPMean*
eδP*
RefδP*
Z-1
Ki
Kpi
D/A
PMean
ΔP

FIG_9

FIG_10

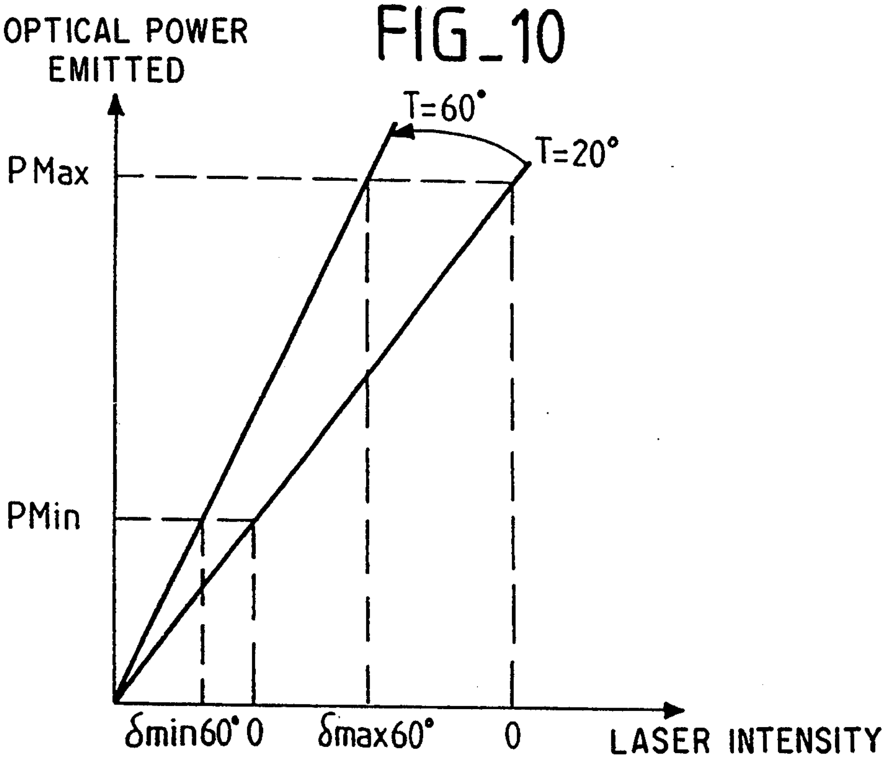
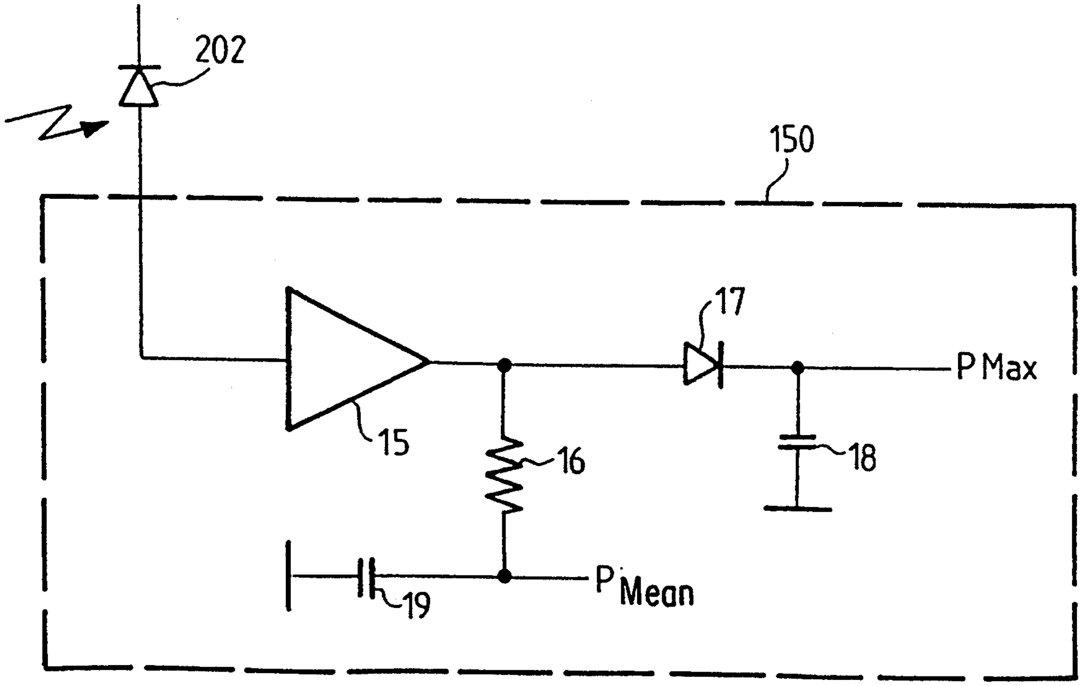

OPTICAL POWER EMITTED
T=60°
T=20°
P Max
PMin
δmin60° 0
δmax60°
0
LASER INTENSITY

FIG_11


202
150
17
P Max
15
16
18
19
P Mean

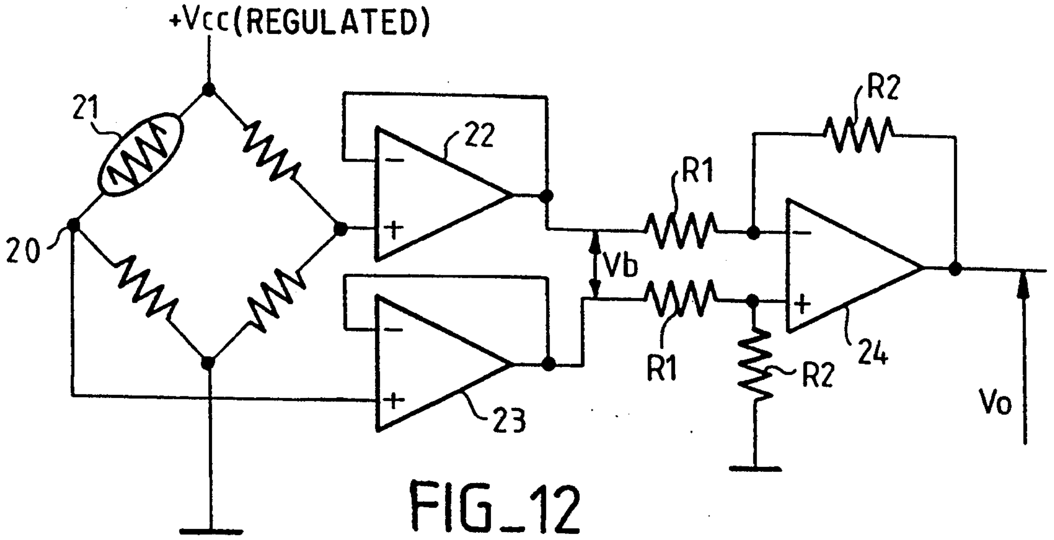

+Vcc(REGULATED)
21
20
22
R2
R1
Vb
R1
R2
24
23
Vo

FIG_12

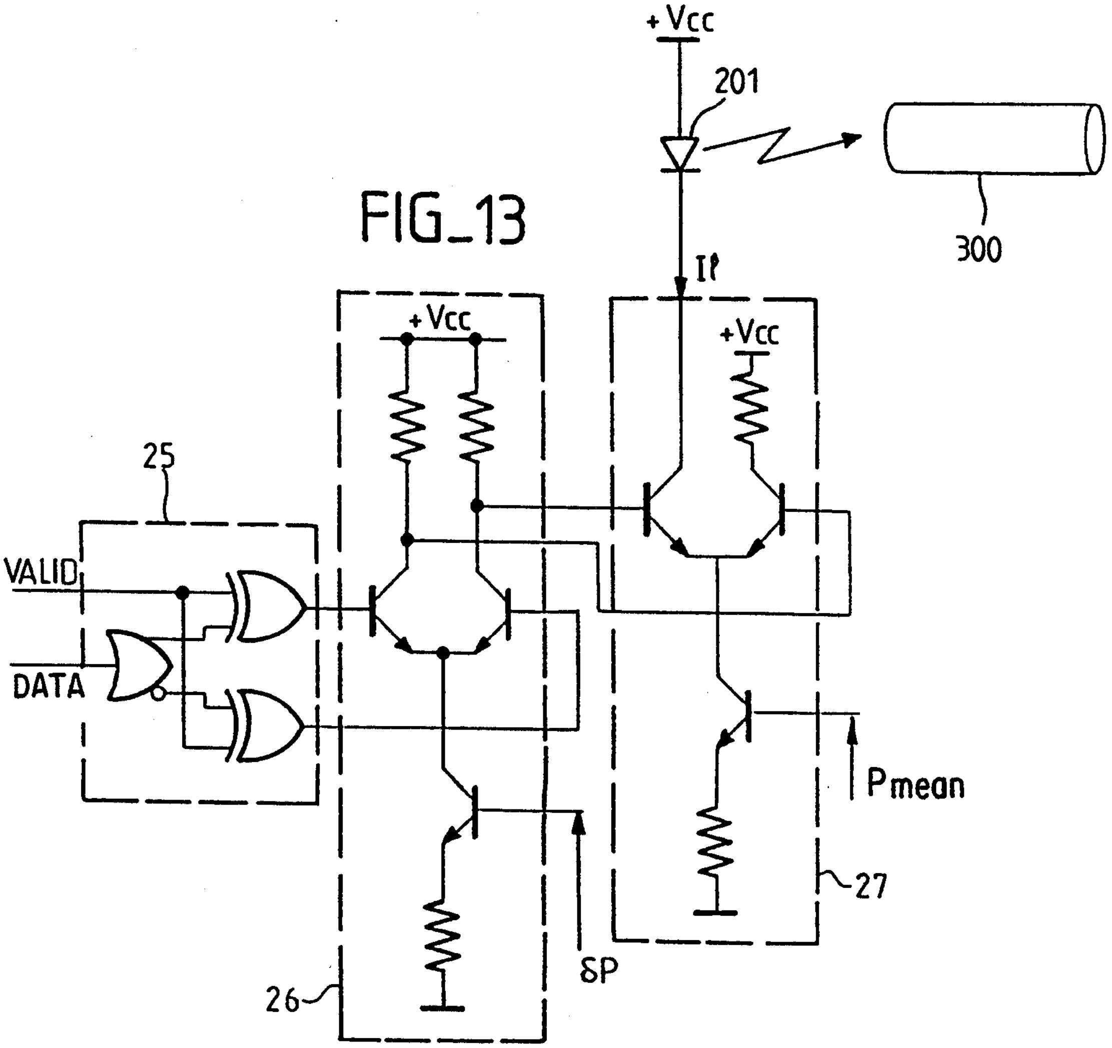

+Vcc
201
300
Il
25
+Vcc
+Vcc
VALID
DATA
Pmean
27
δP
26

FIG_13

DEVICE AND METHOD TO CONTROL THE OUTPUT POWER OF LASER DIODES

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to a device for controlling the output power of laser diodes likely to be coupled to an optical fiber for the transmission of digital signals on optical fibers.

Laser diodes are widely used in the field of digital transmissions on optical fibers, but have the drawback of showing major variations of the luminous power emitted in response to a change in temperature or an ageing of the diode.

The diagrams of FIGS. **3** and **4** can be referred to for a clearer understanding of these phenomena.

FIG. **3** shows the variations of the characteristic curve of a laser as a function of the temperature. For a temperature T=20° C., the curve **C1** is obtained and for a temperature T=60° C., the curve **C2** is obtained. It is thus observed that, for a constant supply current I, the optical power emitted when the temperature is equal to 20° C. is greater than the optical power emitted when the temperature is equal to 60° C.

FIG. **4** shows two characteristic curves of laser diodes, one of which corresponds to a new laser diode and the other to a laser diode at the end of its lifetime. These characteristic curves have been plotted for a constant temperature equal to Θ °C.

It can also be seen in this FIG. **4** that the optical power emitted is weaker for a given current I when the laser is at the end of its lifetime.

2. Background of the Invention

There is a regulation method used to compensate for the variations in the output power emitted by the diode laser that are due to a variation of the temperature. This method consists in carrying out an analog regulation of the luminous power emitted by a laser diode by comparing a signal representing said power with a reference signal to obtain an error signal that is used to modify the electrical supply current of the laser diode.

It has been observed that this method has the drawback of very low efficiency when the sending out of the data is periodic. Indeed, the loop which achieves a continuous regulation is found wanting for, as a representative signal, it uses a signal representing the sporadic power emitted.

Another known method consists solely of a temperature regulation. The regulation is done by cooling by means of a Peltier effect element controlled by a negative feedback loop, the input signal of which is constituted by the difference between the measured temperature of the laser and an instructed value of temperature. This servo-control system has the drawback of being costly and of consuming a great deal of energy, and of not taking account of the drift due to the ageing of the laser.

There also exist systems that foresee the end of the lifetime of the laser diode. These systems have a regulation arrangement to overcome the effects of variation due to the ageing of the diode, and also an active element to keep the operating temperature constant. Thus, the maximum current I indicating the end of the lifetime of the laser takes a fixed value, depending on the operating temperature which is kept constant. The diagnosis then amounts to a simple comparison of the value of the supply current of the laser with the value of current

Imax that was fixed beforehand. A rudimentary system such as this remains costly and consumes a great deal of energy.

Apart from these drawbacks, the present applicant has also observed that there is a loss of optical power due to the coupling of the laser diode with the optical fiber, and that there is no system, at present, that enables total mastery to be achieved over this phenomenon. The applicant has also observed that the element which enabled the image of the information to be retrieved, generally a photodiode on the rear face of the laser, is generally disturbed by a change in temperature and that, consequently, the signal representing the luminous power emitted, is also subjected to variations due the variations in temperature. No existing regulation system enables this phenomenon to be taken into account.

SUMMARY OF THE INVENTION

The present invention is aimed at overcoming all these problems.

An object of the invention, more particularly, is a device to control the output power of the laser diodes capable of being coupled to an optical fiber, comprising:

a photodiode that can be used to acquire a characteristic signal of the power emitted by the laser diode;
digital means to drive the laser diode;
program memorizing means;
parameter memorizing means;
a communications channel.

The device may comprise a temperature sensor if necessary. The digital means for the driving of the diode are capable of receiving and processing the characteristic signal to give a current drive signal so as to maintain a constant luminous output power of the laser diode, these means comprising a central processing unit associated with servo-control computation program memorizing means, keeping a constant output power whatever may be the drift and change of slope of the characteristic of the laser diode in response to ageing phenomena or to a change in temperature or to a loss of power due to the coupling of this diode with an optical fiber or to variations in the response of the photodiode as a function of the temperature.

The program memorizing means are also loaded with an alarm management program that can be used to trigger alarms upon the detection of an operating anomaly. The parameter memorizing means are loaded with characteristic parameters of the laser diode, alarm parameters and fiber coupling parameters that are determined beforehand.

The communications channel enables the processing unit to send information elements to and/or receive information elements from a management center.

According to another aspect of the invention, the device can be made in the form of a component in which the driving means are formed by a single integrated circuit chip on a substrate according to a bi-CMOS technology.

According to another aspect of the invention, the device may be made in the form of a hybrid component in which the driving means, the laser diode and the photodiode are formed by integrated circuit chips on distinct substrates.

BRIEF DESCRIPTION OF THE DRAWINGS

Other features and advantages of the invention shall appear clearly in the following description, given on a non-restrictive, exemplary basis with reference to the appended drawings, of which:

FIG. 1 shows a drawing of the device according to a first embodiment;

FIG. 2 shows a drawing of the device according to a second embodiment;

FIG. 3 shows two response curves of a laser diode as a function of the variations in the temperature;

FIG. 4 shows two response curves of a laser diode at the beginning and end of its lifetime;

FIG. 5 shows response curves of a laser diode as a function of the temperature variations and of the photodiode giving the characteristic signal of the power emitted by the laser diode, also as a function of the temperature variations;

FIG. 6 shows a functional diagram of the device according to the invention;

FIGS. 7 and 8 show a timing diagram illustrating a mode of transmission in alternation between a system A and a system B;

FIG. 9 shows the structural diagram of the servo-control computation according to the invention;

FIG. 10 is used to illustrate the power differences as a function of temperature on the response curve of a laser diode;

FIG. 11 shows an exemplary embodiment of the circuit 150;

FIG. 12 shows an exemplary embodiment of the circuit 158;

FIG. 13 shows an exemplary embodiment of the circuit 152.

DESCRIPTION OF PREFERRED EMBODIMENTS

The device for the control of the output power of laser diodes liable to be coupled to an optical fiber may be made, as already mentioned, in the form of a monochip or hybrid component as the case may be.

FIG. 1 illustrates a monochip component. The component has digital driving means made by means of a microprocessor core and peripherals, such as analog-digital-analog converters, a temperature sensor, ROM, Flash EPROM or EEPROM type memories and a current drive for the laser head.

The monochip component bearing the reference **100** in FIG. 1 will therefore be liable to carry out the function of digital driving of a laser head mounted in a hybrid component **200**. The component has one input to receive a clock signal, one transmission data input, one input to receive a characteristic signal of the power emitted by the laser head, one input to receive the temperature prevailing around the laser head, one output corresponding to the laser head modulation current, and one interface towards a communications channel enabling an operating system or a monitoring system to be connected through this communications channel to the components and to monitor the component and, possibly, to modify parameters recorded in an electrically erasable non-volatile memory.

FIG. 2 corresponds to the schematic diagram of an alternative embodiment of a device such as this wherein a microprocessor **102**, a current drive **101**, the laser chip **201** and the photodiode **202** are brought together in a hybrid type component. The component also has a clock input, a data input and a link with the switch-over channel. Naturally, in both variants, coupling means that are standard per se enable an optical fiber **300** to be coupled to the laser chip so that the power emitted by the laser head is transmitted by the fiber.

The diagram of FIG. 6 is a functional diagram of the device according to the invention. The component **100** enables a current drive signal to be given to the laser diode **201** which sends signals, under the control of the component, to the optical fiber **300** which is at constant power.

The photodiode supplies the component with a current that is characteristic of the power emitted by the laser diode.

A circuit **150** is used to obtain a function V=f(I) so as to obtain two information elements on emitted power from the current IP, namely the maximum power and the minimum power or the peak power and the mean power. Hereinafter in the description, the terms PMax and PMin shall be used to designate maximum power and the minimum power respectively, and PPeak, PMean shall be used to designate the peak power and the mean power respectively. These two information elements are applied to the inputs of the analog/digital converter **151** which transmits them, after digitization, to the microprocessor **153**. The microprocessor furthermore receives a set of parameters and, especially, servo-control parameters, alarm parameters and fiber coupling parameters that come respectively from memory zones **154**, **155** and **156** of an EEPROM or Flash EPROM type memory.

A temperature sensor **157** is planned in order to provide an information element on the ambient temperature. This information element is converted by a circuit **158** which enables the obtaining of the function V=f(T), namely the obtaining of a voltage as a function of the temperature. This voltage is applied to the input of an analog/digital converter **159** which transmits the digitized temperature signal to the microprocessor **153**. This function is active when the laser diode and the control circuit are located in a same hybrid circuit. This same converter, through an input of the circuit **100**, can also receive another information element on temperature, namely external temperature, which may be given by a temperature sensor **203** placed in the vicinity of the laser diode. This function is active when the laser diode and the control circuit are located in two distinct components.

There is also provision for a circuit **160** used to supply a voltage reference to the various analog/digital converters, it being possible for this circuit to be made in a manner that is standard per se.

The microprocessor **153** and the different programs that perform the servo-control computation, the management of the alarms and the correction of the fiber coupling, which are loaded in a ROM or EEPROM or Flash EEPROM used to provide signals for adjusting the maximum and minimum current levels of the laser current and the mean level of this current.

The microprocessor **153** gives two information elements on power to be emitted. These information elements may be either the power values PMax and PMin or δP and Pmean, δP being a difference between PMax and PMin.

A digital/analog converter **161** converts these information elements on power into analog signals which are applied to the inputs of a current drive circuit **162** of the laser diode.

This laser drive circuit **162** has a current source **163** and an upline circuit to modulate the current of the laser diode as a function of the transmission data elements.

The device may also include means **204**, **205** for the regulation of the temperature by Peltier effect controlled by the processing unit **153**. The signal is given by the unit **153**, converted by the digital-analog amplifier **164** and applied to a power amplifier **204** which transmits it to the Peltier element **205**.

Hereinafter, for a clearer understanding of the invention, a description shall be given of the working of a circuit such as this, applied to a system of alternating digital transmission on optical fiber.

It may be recalled that the alternation is actually a time-division multiplexing of both directions of transmission. This transmission system is used to give the perfect illusion of a duplex mode integral to the user. In each direction, the digital information to be transmitted is memorized temporarily and then cut up into blocks and sent alternately. The term "Ping Pong" transmission is sometimes used. The instantaneous flow rate of the transmission of the information element into a block should be greater than twice the real flow rate of the resultant digital channel to be transmitted in order to compensate for the effect of the propagation times in each direction. For a clearer understanding, reference may be made to the drawing of FIG. **7** which illustrates the principle of the alternation. A transmission by optical fiber is achieved between a system A and a system B. The duration Tp corresponds to the propagation time taken, in the fiber, to go from the system A to the system B and vice versa.

The duration Te corresponds to the time taken to send the data block.

The duration Tg corresponds to the standby time of the remote system.

The duration Ta corresponds to the cycle time of the system.

It is noted that the transmission of data from the system A to the system B is done during the period Te″, this being done during the period Ta″ as shown in FIG. **8**. To make it easier to set up the receiver, the power sent by the transmitter may be done at three levels:

PMax for a "binary 1" level,
PMin for a "binary 0" level,
PMean when there is no data element.

According to the exemplary embodiment that is described, the photodiode **202** enables the component to prepare two information elements reflecting the maximum level of power (value corresponding to the sending of a data element in the state 0) and the minimum power level (value corresponding to the sending of a data element in the low state) emitted by the laser in the form of an analog voltage as shown in FIG. **6**.

The element chosen is preferably a photodiode having a response curve that varies very little with the operating temperature, it being possible however for this variation to be modelized and recorded in the memory in the form of a table of values of points of the characteristic curve Y=f(T).

The diode laser enables the system to be controlled at two levels so that it is possible to adjust the levels PMean (mean power) and δP (maximum power—-minimum power) coming out of the laser.

According to the exemplary application that has been taken, an information block is sent during "Ta" and this is done every "Ta" with, quite naturally Te<Ta. A VALID signal frames the transmission data (the VALID signal is in the state 1 during Te″). The laser diode is servo-controlled in such a way that it emits constant power levels in the course of time. The level PMean is sent when there are no data elements. The images of the information elements PMax and PMin produced by the photodiode are available only during the transmission of the data elements (Cf. FIG. **8**).

The signal VALID is used to interrupt the microprocessor which can then convert the available information elements of the photodiode to use them in the servo-control algorithm loaded in the program memory.

The structural diagram of this algorithm is shown in FIG. **9**. The principle of the algorithm is based on the use of two proportional-integral discrete regulators to enable the controlling of the laser diode in terms of PMean and δP.

The discrete regulator prepares a discrete control quantity as a function of the difference in discrete adjustment obtained between the information resulting from the photodiode and a fixed reference with a well-defined value. This regulator is a combination of a proportional regulator and an integrating regulator. The function that it fulfils may be defined from the basic relationship given here below in which u*(k) is the discrete control quantity and e*(K) is the discrete adjustment divergence:

$$
\begin{aligned}
u^*[K] &= x^*[k-1] + K_{pi}e^*[k] \\
\text{avec}\quad x^*[k-1] &= K_i \sum_{j=0}^{k-1} e^*[j] \\
&= x^*[k-2] + K_i e^*[k-1]
\end{aligned}
$$

In this relationship, the asterisk means that the values are discrete values (of samples), k corresponds to the numbers of samples, K to the proportional factor, j to the index of variation of the samples.

In the drawing of FIG. **9**, the blocks bearing the reference A/D are analog/digital converters, the blocks bearing the indications "+" or "−" are adders/-subtractors, the blocks bearing a fraction bar are dividers, the blocks bearing a factor K_i or Kp_i are multipliers, the blocks bearing the reference z^{-1} introduce delays into the samples.

The discrete control values that are prepared according to this example are:

InfoPMax and InfoPmin

The discrete adjusting differences are PMean and δP.

The adjusting algorithm that is implanted in the microprocessor is therefore the following:

Acquisition of the information elements InfoPMax and InfoPMin

Evaluation of the command PMean

```
InfoPMean=(InfoPMax+InfoPMin)/2
RefPMean=(RefPMax+TabMax (T°)+RefPMin+TabMin(T°)/2
eOldPMean=ePMean
ePMean=RefPMean−InfoPMean
PMean=Kpi.ePMean+OldPMean
OldPMean=eOldPMean+Ki.eOldPMean
```

Evaluation of the command δP:

```
InfoδP=InfoPMax−InfoPMin,
RefδP=RefPMax+TabMax(T°)−RefPMin+TabMin(T°)
eOldδP=eδP
eδP=RefδP−InfoδP
δP=Kpi.Eδp+OldδP
```

-continued

```
OldδP=OldδP+Ki.eOldδP
```

The reference Old signifies the former value for a given information element, for example eOldPMean signifies the former value of the divergence of ePMean.

According to the invention, the variations of the slope of the characteristic curve of the photodiode as a function of the operating temperature of the laser are taken into account. For this purpose, we consider the references RefPMax and RefPMin which are variable as a function of the temperature in the algorithm. Naturally, this characteristic curve which has been shown in FIG. **5** and will be in the form of a table loaded in the memory will have been modelized beforehand.

Indeed, if a temperature of 20° is taken as the starting point, a laser working at 60° must have a correction of δMax60° for REfPMax and δMin60° for RefPMin as can be seen in FIG. **9**. Knowing the drift of the slope as a function of the temperature for each laser head, a correction table is prepared as a function of the temperature TabMax and TabMin. These tables may be loaded or remote-loaded through the communications channel, whenever the component is put into operation.

According to the invention, the alarm management program will make it possible to indicate the end of the lifetime of the laser which depends on its working temperature. To this end, an alarm will be triggered by the component when the current IMean sent to the laser exceeds a value IMaxMean which depends on the temperature contained in the table TabMax.

An alarm will be triggered to indicate a lack of power of the laser when the laser current IMean is lower than a value IMeanMin.

An alarm will be triggered to indicate an abnormal temperature of the laser when the measured temperature of the laser is greater than a value TempMax.

All the specific laser values used are loaded into the component or remote loaded through the communications channel when the component is put into operation.

The following is the algorithm corresponding to the generation of the alarms:

```
if IMean>temperature Max(T°)
then alarm: end of laser life
end if
then IMean<IMeanMin
then alarm: lack of laser power
end if
if laser Temperature>TemperatureMax
then alarm abnormal Temperature of the laser
end if
```

According to the invention, the program memory comprises a program to achieve a cut-off of the laser diode. The program consists in causing a minimum current to be sent to the laser head.

According to the invention, the program memory has a control program to determine the characteristic curve of the laser diode. The program consists in stopping the transmission of data, successively sending a constant current to the laser and recovering, through the photodiode, the power emitted by the laser. The results obtained are transmitted by the communications channel and enable the making of the characteristic curve of the laser.

FIG. **11** shows an exemplary embodiment of the circuit **150** used to obtain a function of the type V=f(I). According to this example, the circuit **150** comprises a transimpedance amplifier **15**. The output PMax of this amplifier **15** is taken at the terminals of a capacitor **18** through the passage of a diode **17**. The output PMean is taken at the terminals of a capacitor **19** through the passage in a resistor **16**.

FIG. **12** shows an exemplary embodiment of the circuit **158** that can be used to obtain a function of the type V=f(T°).

The circuit **158** according to this example has a Wheatstone bridge **20** including a thermistor **21**. The voltage Vb obtained at the output of the two operational amplifiers **22** and **23** varies as a function of the temperature. A voltage Vo proportional to the voltage Vb is obtained at the output of this circuit. This voltage Vo is taken at the output of an operational amplifier **24** and is defined by the relationship VO=−Vb(R2/R1).

FIG. **13** shows an exemplary embodiment of the circuit **162**.

This circuit has a logic circuit **25** and two differential pairs.

The first differential pair **26** can be used to adjust the level IMax−IMin of the current Il from δP. The second differential pair **27** enables the adjusting of the level IMean of this current Il from PMean.

Furthermore, this circuit **160** is used to obtain a voltage reference internally. This voltage reference is used for the analog-digital converters.

A voltage reference such as this can be obtained by means of a commercially available component.

Thus, according to the invention, the device comprises a driving element made by a microprocessor in which the ROM or EEPROM or Flash EPROM contains the program that can be used to manage all the different functions of the optical head:

servo-control computation,

management of the alarms (end of the lifetime of the laser, abnormally high temperature, lack of reception power, line cut-off etc.),

cut-off of the laser,

correction of the coupling to the fiber,

management of the communications channel; the information elements stored in the Flash EPROM (or EEPROM) memory enable the individualizing of each laser head used. The fact that the Flash EPROM has the particular feature of keeping the information even when there is no power supply means that it is possible, in this way, to avoid reconfiguring the laser head after a cut-off in the power supply. The information elements stored will therefore be the following ones:

servo-control references (to adjust the levels of luminous power at output of the laser);

parameters of the fiber-laser coupling (this function having been modelized);

parameters of the variation of the response curve of the photodiode as a function of the temperature;

alarm parameters (triggering thresholds of the different alarms).

Provision may be made for choosing a Flash-EPROM of a fairly large capacity for the storage therein of the main program (apart from a small part corresponding to the booting) to enable updatings of the software through the communications channel.

What is claimed is:

1. A device to control the output power of a laser diode capable of being coupled to an optical fiber, comprising:

a photodiode which acquires a characteristic signal of the power emitted by said laser diode; and

a digital laser diode driver capable of receiving and processing said characteristic signal to give a current drive signal so as to maintain a constant luminous output power of said laser diode, said driver comprising memorizing means and a central processing unit associated with a servo-control computation program for carrying out a servo-control of the output power on the basis of two levels of power emitted by said laser diode and two levels of power given by the recorded characteristic parameters of said laser diode, maintaining a constant output power despite changes in drift and change of slope of said characteristic signal of said laser diode in response to aging phenomena or to a change in temperature or to a loss of power due to the coupling of said laser diode with an optical fiber or to variations in the response of the photodiode as a function of the temperature.

2. A control device according to claim 1, comprising program memorizing means to achieve a cut-off of the laser diode.

3. A control device according to claim 1, comprising control program memorizing means to determine the characteristic curve of the laser diode.

4. A control device according to claim 1, wherein the processing unit carries out a servo-control of the output power on the basis of two levels of power emitted by the laser diode and two levels of power given by the recorded characteristic parameters of the recorded laser diode.

5. A control device according to claim 1, comprising means for the acquisition of the two levels of power emitted by the laser diode and means for the analog/digital conversion of these two levels of power.

6. A control device according to claim 5, wherein the current drive signal corresponds to two output power levels, wherein the device furthermore comprises means for the supply of current to the laser diode comprising two inputs and digital/analog conversion means to convert the two output power levels and apply them to the current supply means.

7. A control device according to claim 1, comprising means to measure the ambient temperature prevailing around the laser diode and means for the analog/digital measurement of the measurements to be made in order to transmit them to the processing unit.

8. A control device according to claim 1, comprising means for the regulation of the temperature by Peltier effect controlled by the processing unit.

9. A control device according to claim 1, wherein the program memorizing means comprise a reading memory (ROM or EEPROM or Flash EEPROM), wherein the reference parameter memorizing means comprise an electrically erasable programmable memory (EEPROM).

10. A control device according to claim 1, wherein the processing unit comprises a microprocessor furthermore associated with a reading and writing working memory (RAM).

11. A control device according to claim 1, wherein the means for the acquisition of the two levels of power emitted comprises a transimpedance receiver.

12. A control device according to claim 6, wherein the current supply means comprise a differential amplifier connected at output to a current source.

13. A device according to claim 1, made in the form of an electronic component in which the driving means are formed by a single integrated circuit chip on a substrate according to a bi-CMOS technology.

14. A device according to claim 1, made in the form of a hybrid component in which the driving means, the laser diode and the photodiode are formed by integrated circuit chips on distinct substrates.

15. A method of servo-controlling the output power of a laser diode, said method comprising the steps of:

acquiring a characteristic signal, said characteristic signal including two levels of output power emitted by said laser diode;

accessing recorded characteristic parameters of said laser diode; and

driving said laser diode with current on the basis of said characteristic signal and said characteristic parameters.

16. The method of claim 15, wherein the two levels of power are the maximum output power and the minimum output power emitted by said laser diode.

17. The method of claim 16, wherein the recorded characteristic parameters of said laser diode are the mean output power and the difference between the maximum output power and minimum output power stored as a function of drive current and of temperature.

* * * * *

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United States Patent [19]

Olsen

[11] **Patent Number: 5,623,355**

[45] **Date of Patent: Apr. 22, 1997**

[54] **ERROR-RATE-BASED LASER DRIVE CONTROL**

[75] Inventor: **James J. Olsen**, Concord, Mass.

[73] Assignee: **Massachusetts Institute of Technology**, Cambridge, Mass.

[21] Appl. No.: **397,738**

[22] Filed: **Feb. 27, 1995**

Related U.S. Application Data

[63] Continuation of Ser. No. 125,534, Sep. 22, 1993, abandoned.

[51] **Int. Cl.**^{6} **H04B 10/08**

[52] **U.S. Cl.** **359/110**; 359/161; 359/187; 371/5.1; 455/69

[58] **Field of Search** 359/110, 113, 359/143, 152–154, 161, 177, 180, 187, 194; 371/5.1, 5.5; 372/29; 455/69

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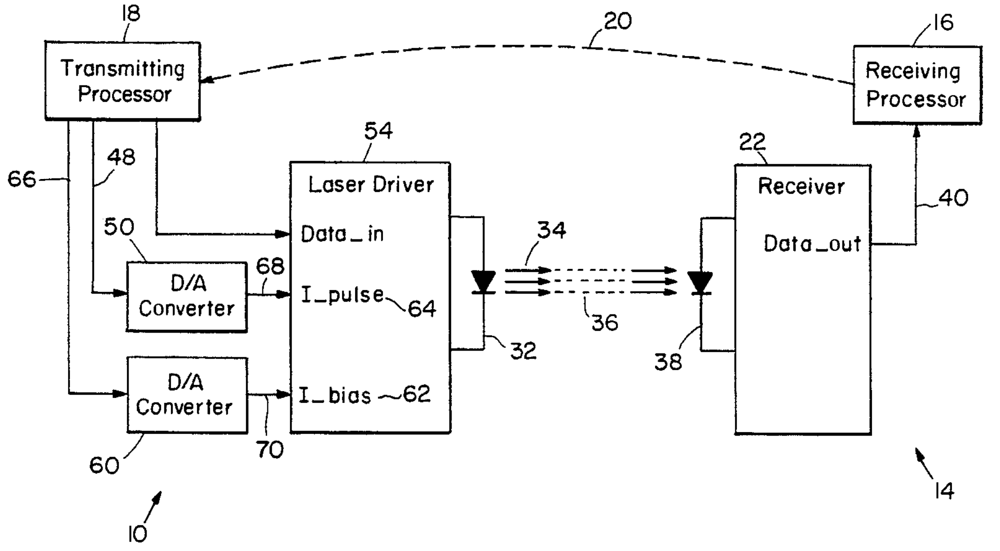
Assistant Examiner—Kinfe-Michael Negash
Attorney, Agent, or Firm—Hamilton, Brook, Smith & Reynolds, P.C.

[57] **ABSTRACT**

A laser data transfer system includes a laser for transmitting data, a communication link and a receiver which detects light transferred over the link and monitors the data encoded by the light for transmission errors. There are numerous causes for transmission errors, including: laser fatigue due to aging, fluctuations in temperature, a partially or fully occluded optical data path, or a laser lens which is out of focus. The receiver compensates for these errors by communicating occurrences to the transmitting processor which reacts by adjusting the laser drive current.

22 Claims, 4 Drawing Sheets



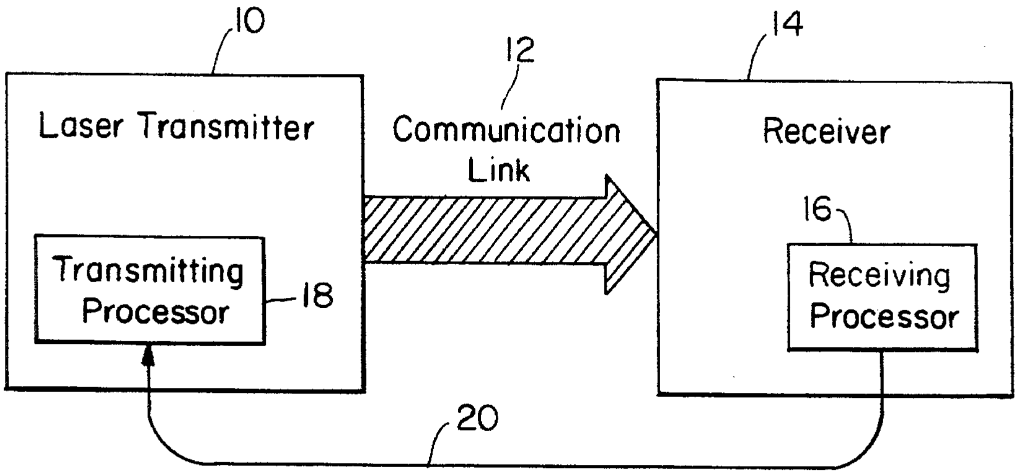

10
Laser Transmitter
Transmitting Processor
18
12
Communication Link
14
Receiver
16
Receiving Processor
20

FIG. 1

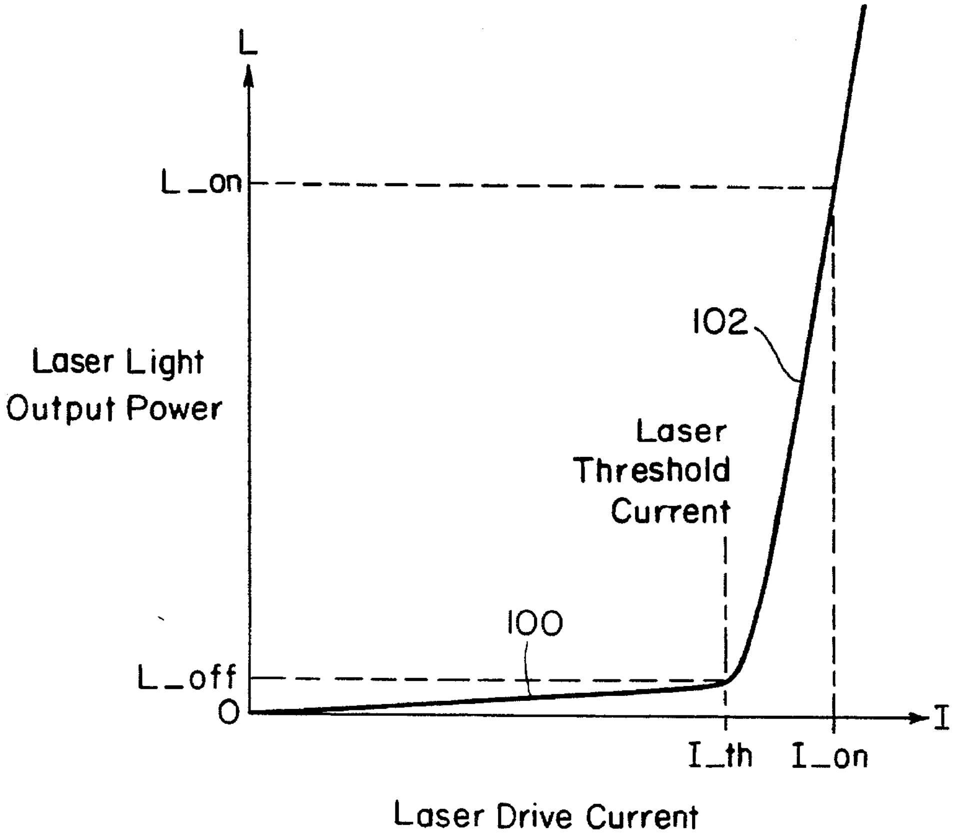

L
L_on
Laser Light Output Power
102
Laser Threshold Current
100
L_off
0
I
I_th
I_on
Laser Drive Current

FIG. 3

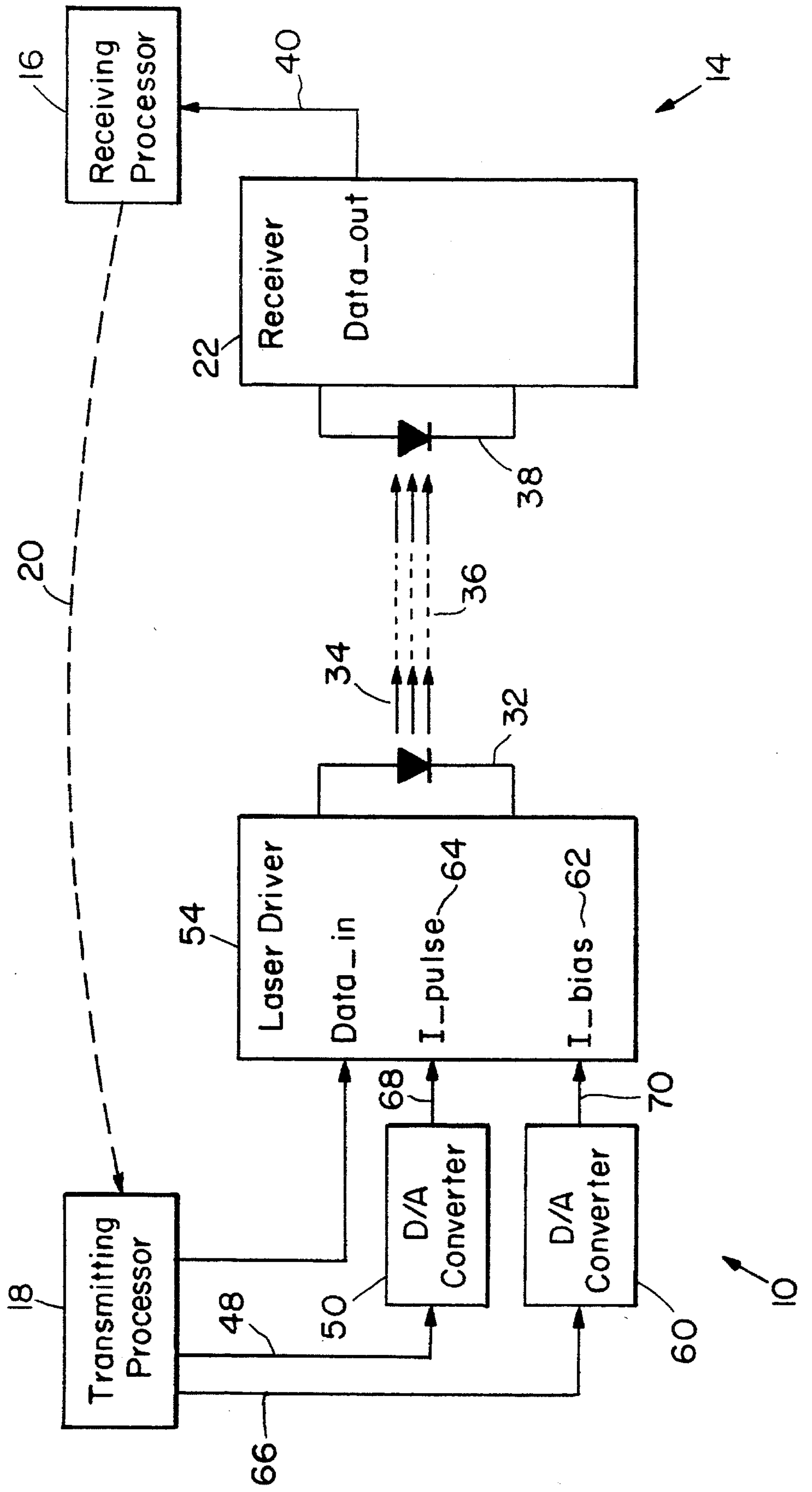

Receiving Processor
16
40
14
Receiver
Data_out
22
38
36
34
32
20
Laser Driver
Data_in
I_pulse
64
I_bias
62
54
68
70
D/A Converter
50
D/A Converter
60
Transmitting Processor
18
48
66
10

FIG. 2

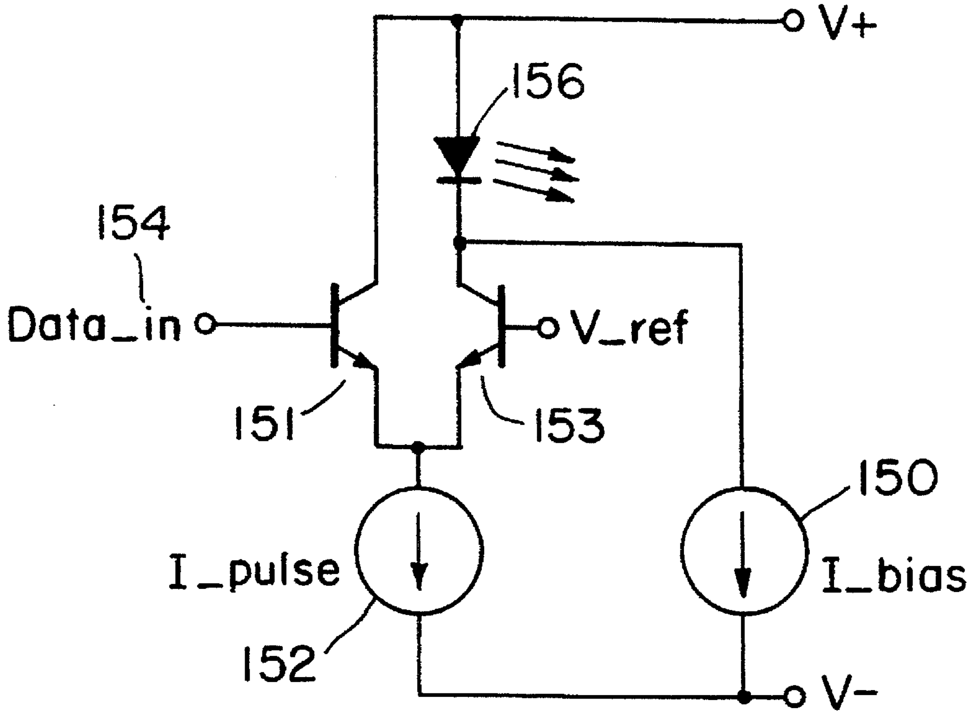


FIG. 4

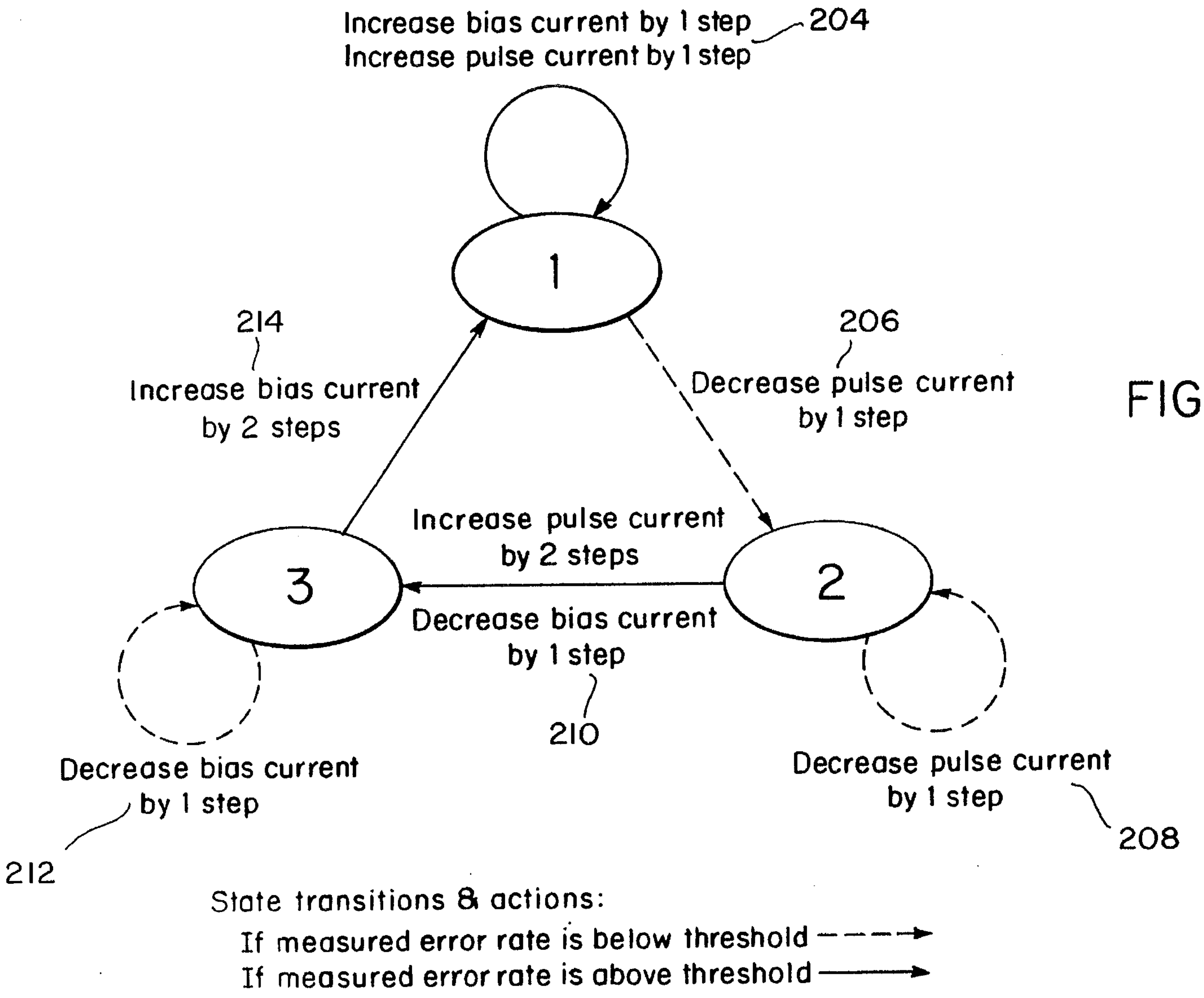

Increase bias current by 1 step
Increase pulse current by 1 step
204
1
214
Increase bias current
by 2 steps
206
Decrease pulse current
by 1 step
Increase pulse current
by 2 steps
3
2
Decrease bias current
by 1 step
210
Decrease bias current
by 1 step
212
Decrease pulse current
by 1 step
208
State transitions & actions:
If measured error rate is below threshold
If measured error rate is above threshold

FIG. 5

ERROR-RATE-BASED LASER DRIVE CONTROL

GOVERNMENT FUNDING

This invention was made with Government support under Contract Number F19628-90-C-0002 awarded by the Department of the Air Force. The Government has certain rights in the invention.

RELATED APPLICATION

This application is a continuation of application Ser. No. 08/125,534 filed on Sep. 22, 1993 now abandoned.

BACKGROUND OF THE INVENTION

Optical data communication systems rely heavily on semiconductor lasers as optical sources. Such lasers present a number of reliability problems. In the field of telecommunications, where lasers have become quite popular, many of these problems have been resolved.

As a laser ages, it fatigues and becomes less efficient. More power is then required to drive the communication link. Temperature variations can also affect the laser's ability to drive the channel. A laser which is running hot requires more power for proper operation.

The simplest approach to resolving these problems is to fix the laser drive current at a level which provides acceptable performance over expected laser temperature extremes and expected laser lifetime. The problem with this approach is that higher drive current levels hasten laser fatigue, resulting in premature aging. Elevated drive current also increases temperature levels, which can shorten component lifetimes.

Another solution, widely used in telecommunication networks, employs an analog feedback loop to control the laser drive current. A photodetector, mounted in close proximity to the laser source, monitors the laser light as it is emitted. The photodetector generates an analog signal proportional to the intensity of the laser light. This signal is amplified and fed back to adjust the laser drive current.

Recent advances in optical technology suggest that optical channel interconnects will soon be viable for use in massively parallel processing systems. Such systems require large laser arrays to provide for interprocessor communication. Designers of these systems are inclined to borrow from existing telecommunication technology.

SUMMARY OF THE INVENTION

Analog feedback drive current controllers are not practical for use in systems which involve massively parallel optical data channels. For very wide channels, redundant use of photodetectors and feedback circuitry would consume space and power which otherwise would be available for additional circuitry. Neither of the above drive control methods is capable of detecting a communication link anomaly, such as a partial or complete blockage in an optical path or a lens that is out of focus.

The present invention is directed to a laser data transfer system and method for controlling laser drive current by monitoring transmission errors. The system includes a laser used for transmitting data, a communication link and a receiver which detects light from the laser passed through the communication link. The receiver detects errors in the transmitted data and communicates with the transmitter for controlling drive to the laser based on the occurrence of data errors.

Drive current may be adjusted based on transmission error rate. An error rate above allowed limits indicates that the drive current should be increased. An error rate below allowed limits indicates that the drive current should be decreased. Error rate may be controlled by the receiver, and that rate may be sent to the transmitter for a control decision. Alternatively, a simple control command may be sent to the transmitter.

Error detection may be embedded in an error correction process. In that case, retransmission of data would not be required, but the laser drive would be controlled to minimize the correction rate as well as the possibility of larger errors than can be handled by the correction system.

This system eliminates the need for extraneous feedback circuitry which consumes board space and power, while still providing adequate laser drive current control. This system compensates for laser fatigue and temperature fluctuations and, unlike prior systems, can detect communication link anomalies.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

FIG. **1** schematically depicts the major components of a laser data transfer system with software-based laser drive current control.

FIG. **2** schematically depicts a preferred embodiment of a laser data transfer system with software-based laser drive current control.

FIG. **3** is a plot of the relationship between laser drive current and laser light output power for a semiconductor laser.

FIG. **4** schematically depicts a semiconductor laser drive current control circuit.

FIG. **5** is a state flow diagram for semiconductor laser drive control software.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. **1** is a block diagram of a laser data transfer system in accordance with the present invention. The system includes a laser transmitter **10** for producing a stream of light encoded binary data which is passed over a communication link **12** to a data receiver **14**. The data receiver **14** detects errors in the data transmitted by the laser light and uses the receiving processor **16** to communicate an error signal **20** back to the transmitting processor **18**. The transmitting processor **18** processes the error signal **20** and compensates for the error.

A preferred embodiment of the laser data transfer system is illustrated in FIG. **2**. The entire system is digital, with the exception of the laser driver **54** itself and the digital-to-analog (D/A) converters **50**, **60** controlling it.

The transmitting processor **18** produces a serial stream of error detection encoded binary data **30** which is sent to the laser driver **54**. The laser diode **32** converts the binary data

30 from electrical energy into light energy **34** which is channeled over an optical medium **36** to the receiver **22**. A photosensitive diode **38** reconverts the light encoded data **34** from light energy to electrical energy. The reconverted data **40** is then passed to the receiving processor **16**.

The receiving processor **16** checks the data for errors and communicates transmission error occurrences to the transmitting processor **18** by sending an error signal **20**. The error signal may be returned with each error, or the receiving processor **16** may compute an error rate and occasionally return the rate or a laser drive command to the transmitting processor **18**. The error signal **20** can be sent by any of the several methods of interprocessor communication, including shared memory, interrupt, shared stack, shared data bus, serial port, parallel port, or optical link. The transmitting processor **18** processes the error signal **20** and compensates for the error.

After receiving an error signal, the transmitting processor **18** may choose to compensate by adjusting the laser drive current to an appropriate level. Laser drive current is a combination of the laser pulse current **64** and the laser bias current **62**. The transmitting processor **18** may also resend the data which was erroneously transmitted.

The transmitting processor **18** controls the laser bias current **62** by programming a digital-to-analog converter **60** which in turn produces an analog signal for the proper laser bias current level **62**. The transmitting processor **18** sends a binary word **66** to the digital-to-analog converter **60** which quantizes the binary word **66**, producing an analog voltage level **70**. The analog voltage level **70** is used by the laser driver **54** in controlling the laser bias current **62**. The laser pulse current **64** would be adjusted in a similar fashion.

Many factors contribute to high error rates, including: age of the laser driver **54**, temperature fluctuations and degradation of the optical path **36**. The transmitting processor **18** compensates for high error rates by elevating the laser drive current. The higher drive current produces a stronger, more reliable laser light signal **34**. A low transmission error rate indicates that the channel may operate with reduced laser drive current. By reducing the laser drive current, the power consumption of the transmitter **10** is decreased, conserving power and extending the life of the laser diode **32**.

To transmit data via a laser, one may employ any of a number of modulation techniques, such as frequency, phase, or amplitude modulation. The preferred embodiment uses the simplest, most widely used laser modulation method: on-off signalling.

FIG. **3** graphically depicts the relationship between laser drive current, on the I axis, and laser light output power, on the L axis, for a semiconductor laser. To achieve the desired laser light output power level L_on or "laser light on" the laser drive current must be raised to a corresponding current level I_on.

The level for L_off or "laser light off" must be distinguishable from the L_on level. The easiest method for setting the laser light to "off", would simply involve setting the drive current to zero. However, this solution is not practical for use in high speed applications, since the laser output will take considerable time to increase from zero light to the level corresponding to I_th or "threshold current". The laser operates as a light emitting diode for drive currents less than I_th **100**. Once drive current is raised above I_th, lasing commences at **102**. Therefore, high speed operation requires that a bias current I_bias be applied to the laser, so that it never operates in the light emitting diode realm, and is continuously able to lase. In a preferred embodiment I_bias would be set at I_th so that the corresponding level for L_off is at the threshold for lasing.

FIG. 4 schematically depicts a laser drive circuit which satisfies the constraints discussed above. The current source I_bias **150** is constantly applied to the laser diode **156** and the current source I_pulse **152** is applied depending on the input data Data_in **154**. When Data_in is high, transistor **151** conducts and transistor **153** turns off, so diode **156** does not lase. When Data_in is low, transistor **151** is off, transistor **153** is on and the diode lases. When the laser is emitting light at an intensity level which would be considered "on", a current equal to I_on is flowing through the laser diode **156**, with I_bias **150** and I_pulse **152** both contributing to I_on. When the laser is operating at the intensity level "off", the current I_off is flowing through the laser diode **156**. I_bias **150** alone contributes to I_off, exclusive of I_pulse **152**. The following equations describe how I_bias **150** and I_pulse **152** contribute to laser intensity levels:

I_off=I_bias

I_on=I_bias+I_pulse

Laser wear out failures can be modeled as a gradual increase in laser threshold current over time. As the laser ages, it fatigues, resulting in a decrease in laser light output unless the laser drive circuit compensates by increasing the drive current to the new lasing threshold level. Each individual laser driver has its own unique threshold current level.

There is also a more immediate laser threshold current problem: temperature dependence. Laser threshold current increases exponentially with temperature, so the controller must compensate for this as well.

In a wide data channel with many optical data links operating in parallel, there can be significant non-uniformity in the characteristics of the various links which form the channel. One must cope not only with device variations due to age and temperature, but also with inherent variations among the links which comprise the channel. With the fixed-current method of laser drive control, the drive current must be set to accommodate the hottest, oldest and weakest link that is likely to be used during channel operation. The software-based method of drive control disclosed here, in addition to its other advantages, allows for individual control of each link, and therefore can compensate for individual link variations without having to change the drive level for the entire channel.

In the preferred embodiment, software running on the receiving processor **16** monitors the communication link error performance to make decisions regarding laser drive current levels. The algorithm operates according to a simple rule: if the measured error rate is below threshold error rate, then decrease the drive current; if the measured error rate is above threshold error rate, then increase the drive current. When making adjustments, the feedback algorithm treats bias and pulse currents equally. However, more sophisticated software could adjust them individually with greater precision. For example, when faced with an excessively high error rate, the software could assume that only the bias current need be increased, and proceed to increase the pulse current only if the bias current increase does not resolve the problem. Sophisticated control software may decrease the drive current in response to an increased error rate, or vice-versa, if the situation arose where the light power output was so high that the receiver was over-driven.

FIG. **5** depicts a flow diagram for the drive current control algorithm. The program increases or decreases the bias and pulse currents depending on the performance of the bit error rate. An acceptable threshold for bit error rate is unique to each system. The bit error rate may be monitored periodically, either frequently or infrequently, depending on system requirements. For the preferred embodiment, one current step represents approximately 1% of the normal operating level.

Beginning in State **1**, if measured error rate is greater than the threshold error rate, then the bias current and pulse current levels are increased by one step **204**. The increase continues, step by step, until the measured error rate equals the threshold error rate, at which time, the pulse current is decreased by one step **206** and State **2** becomes active, with State **1** becoming inactive.

While in State **2**, the pulse current is decreased one step at a time **208** until the measured error rate becomes too high. When the measured error rate becomes greater than the threshold error rate, the pulse current is increased by 2 steps and the bias current is decreased by one step **210**. State **2** then becomes inactive, and State **3** is activated.

While in State **3**, if the measured error rate is less than the threshold error rate then the bias current is decreased by one step **212**. This continues, one step at a time, until the measured error rate once again becomes too high, at which point the bias current is increased by two steps **214**, State **3** is deactivated, State **1** again becomes active, and the process starts all over again.

This algorithm assures that the laser is operating with just enough bias current and pulse current to keep the measured error rates within tolerable limits. This method is energy efficient, limiting extraneous power consumption. This method also increases component lifetime. Reduced current levels result in lower component temperatures, which can have a positive impact on the lifetime of the laser and any surrounding circuitry.

Another embodiment may employ error correction techniques in providing feedback to the laser drive controller. In that case, minimization of the correction rate, rather than the error rate, would be the primary factor in making drive current control decisions. With data correction, retransmission of the data would not be required.

Drive current control decisions may be based on many factors including: occurrence of a single error, occurrence of multiple errors, error rate, and correction rate. Error rate may be calculated by the receiving processor **16** and that rate could be sent **20** to the transmitting processor **18** for a control decision. Alternatively, the receiving processor **16**, if programmed to make control decisions, could send a simple control command **20** to the transmitting processor **18**, which would act on that command. Error rate could be calculated by the transmitting processor **18**, if the receiving processor **16** were programmed to send an error signal **20** when a single error or multiple errors occurred.

This laser current drive control method is software dependent, unlike the existing hardware-based analog feedback drive control method. The analog feedback loop is an excellent approach for telecommunications applications, where the size, optical complexity, and expense of such a feedback loop is easily absorbed in an already large and expensive support system for each laser.

However, the multiprocessor context is different. When one considers the use of dozens of lasers on each channel, and many thousands of lasers in each system, the complexity and size of each laser link becomes much more relevant. Implementation of an analog feedback loop in a multiprocessor network would require an oppressive hardware overhead. Fortunately, we can exploit the software based laser drive control method previously described by applying it in a massively parallel environment.

By virtue of the fact that the feedback loop comprises both the transmitter **10** and receiver **14**, this software-based laser drive control method is capable of detecting communication link anomalies, unlike the hardware-based analog feedback loop method. The software-based system is capable of detecting partial or full occlusions in the optical link, a laser lens which is out of focus, and many other optical link problems.

The addition of the two digital-to-analog converters **50**, **60** may seem like a significant increase in complexity, but this application is particularly undemanding for the digital-to-analog converters **50**, **60**, requiring neither high speed, nor high precision, nor high accuracy. They are easily implemented in large quantities using very-large-scale-integration (VLSI) integrated circuit technology. As space and power consumption concerns are minimal, they lend themselves well to use in a massively parallel semiconductor laser array.

Further details of an initial implementation of the invention can be found in the Massachusetts Institute of Technology Ph.D. Thesis of James J. Olsen, 1993, which is incorporated herein by reference.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

What is claimed is:

1. A data transfer system comprising:

a transmitter having a laser for transmitting data, said data being encoded for error correction;

a communication link;

a receiver for detecting light from the laser through the communication link; and

a processor for detecting data with error correction and for detecting data error rate in data transmitted by the laser light, the processor communicating with the transmitter such that the data error rate controls drive current to the laser during data transmission.

2. A data transfer system as claimed in claim **1** wherein drive current to the laser is increased with increased data error rate.

3. A data transfer system as claimed in claim **2** wherein drive current to the laser is decreased to a level which provides acceptable data error rate.

4. A data transfer system as claimed in claim **1** wherein the receiver communicates error rate to the transmitter for controlling drive current to the laser.

5. A data transfer system as claimed in claim **1** wherein the laser is operated at a drive current level which is less than that required for elimination of transmission errors.

6. A data transfer system as claimed in claim **1** wherein the laser is operated at a drive current level which is less than that required for elimination of transmission errors.

7. The system of claim **1** wherein the processor controls drive current to the laser without regard to the detected light level.

8. A method of transferring data in a data transfer system, comprising the steps of:

transmitting data by laser over a communication link to a receiver;

detecting the communicated laser light;

detecting data error rate in the transmitted data; and

controlling the laser drive current with the data error rate without regard to the detected light level; such that the system operates with an acceptable error rate regardless of changes in system characteristics which result in a varying relationship between error rate and drive current.

9. A method of transferring data as claimed in claim **8** wherein the step of controlling the laser drive current causes the laser drive current to be increased when error rate increases.

10. A method of transferring data as claimed in claim **7** wherein the step of controlling the laser drive current causes the laser drive current to be decreased to a level which provides acceptable data error rate.

11. A method of transferring data as claimed in claim **6** wherein the receiver communicates error rate to the transmitter for controlling drive current to the laser.

12. A method of transferring data as claimed in claim **6** wherein the data is encoded for error correction to enable the receiver to detect and correct errors in the transmitted data.

13. A method of transferring data as claimed in claim **8** wherein the laser is operated at a drive current level which is less than that required for elimination of transmission errors.

14. A method of transferring data as claimed in claim **8** wherein the step of controlling the laser drive current is in response to the monitoring of data error rate by the receiver during data transmission.

15. A method of transferring data as claimed in claim **13** wherein the data is encoded for error correction to enable the receiver to detect and correct errors in the transmitted data.

16. A method of transferring data as claimed in claim **14** wherein the laser is operated at a drive current level which is less than that required for elimination of transmission errors.

17. A data transfer system comprising:

a transmitter having a laser for transmitting data encoded for error correction;

a communication link;

a receiver for detecting light from the laser through the communication link; and

a processor for detecting data error rate in data transmitted by the laser light, the processor monitoring data error rate during data transmission and communicating with the transmitter for controlling drive current to the laser during data transmission based on the data error rate, the receiver being able to detect and correct errors in the transmitted data and the laser being operated at a drive current level which is less than that required for elimination of transmission errors; such that the system operates with an acceptable error rate regardless of changes in system characteristics which result in a varying relationship between error rate and drive current.

18. A data transfer system as claimed in claim **17** wherein data error rate controls the drive current to the laser.

19. A method of transferring data in a data transfer system comprising the steps of:

transmitting data encoded for error correction by laser over a communication link to a receiver;

detecting the communicated laser light;

monitoring the data error rate in the transmitted data during data transmission; and

controlling the laser drive current during data transmission based on data error rate without regard to the detected light intensity level, the receiver detecting and correcting errors in the transmitted data and the laser being operated at a drive current level which is less than that required for elimination of transmission errors; such that the system operates with an acceptable error rate regardless of changes in system characteristics which result in a varying relationship between error rate and drive current.

20. A method of transferring data as claimed in claim **19** wherein the step of controlling further comprises the step of controlling the laser drive current with the data error rate.

21. A data transfer system comprising:

a transmitter having a laser for transmitting data;

a communication link;

a receiver for detecting light from the laser through the communication link; and

a processor for detecting data error rate in data transmitted by the laser light, the processor communicating with the transmitter for controlling drive current to the laser based solely on the data error rate; such that the system operates with an acceptable error rate regardless of changes in system characteristics which result in a varying relationship between error rate and drive current.

22. A data transfer system comprising:

a transmitter having a laser for transmitting data;

a communication link;

a receiver for detecting light from the laser through the communication link; and

a processor for detecting data error rate in data transmitted by the laser light, the processor communicating with the transmitter such that the data error rate controls drive current to the laser without regard to the detected light level; such that the system operates with an acceptable error rate regardless of changes in system characteristics which result in a varying relationship between error rate and drive current.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 5,623,355
DATED : April 22, 1997
INVENTOR(S) : James J. Olsen

It is certified that error appears in the above-indentified patent and that said Letters Patent is hereby corrected as shown below:

In claim 10, column 7, line 9, change "claim 7" to ---claim 9---.

In claim 11, column 7, line 13, change "claim 6" to ---claim 8---.

In claim 12, column 7, line 16, change "claim 6" to ---claim 8---.

In claim 15, column 7 line 27, change "claim 13" to ---claim 14---.

Signed and Sealed this

Twenty-sixth Day of August, 1997

Attest:

Bruce Lehman

BRUCE LEHMAN

Attesting Officer

Commissioner of Patents and Trademarks

US005638390A

United States Patent [19]

Gilliland et al.

[11] **Patent Number: 5,638,390**

[45] **Date of Patent: Jun. 10, 1997**

[54] **OPTOELECTRONIC TRANSCEIVER MODULE LASER DIODE STABILIZER AND BIAS CONTROL METHOD**

[75] Inventors: **Patrick B. Gilliland**, Chicago; **Andy A. Goryachev**, Lombard, both of Ill.

[73] Assignee: **Methode Electronics, Inc.**, Chicago, Ill.

[21] Appl. No.: **508,093**

[22] Filed: **Jul. 27, 1995**

[51] **Int. Cl.^{6}** **H01S 3/00**

[52] **U.S. Cl.** **372/38**; 372/31; 323/314

[58] **Field of Search** 372/31, 38; 307/297; 323/314

[56] **References Cited**

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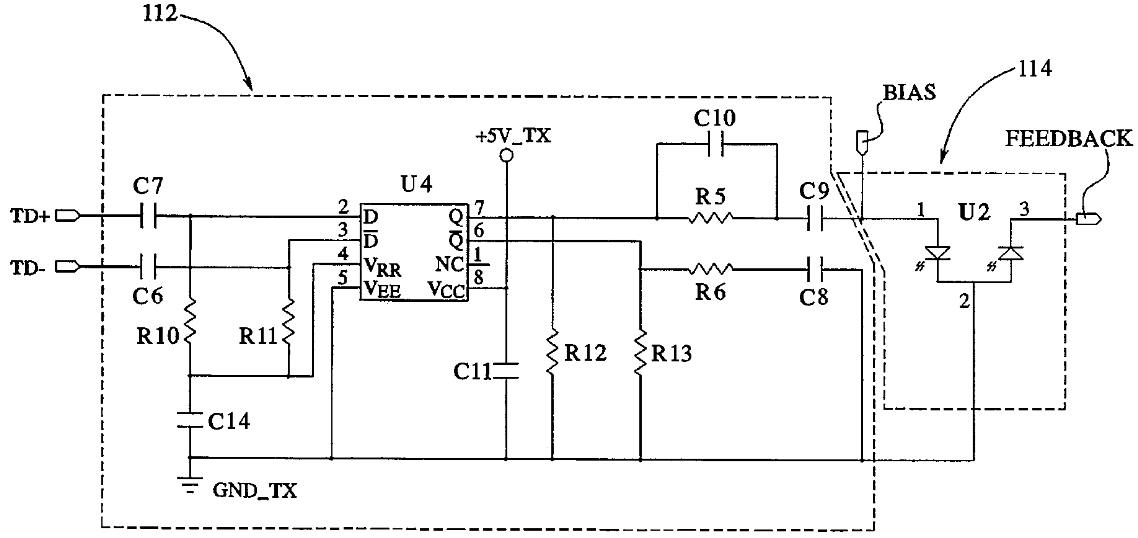
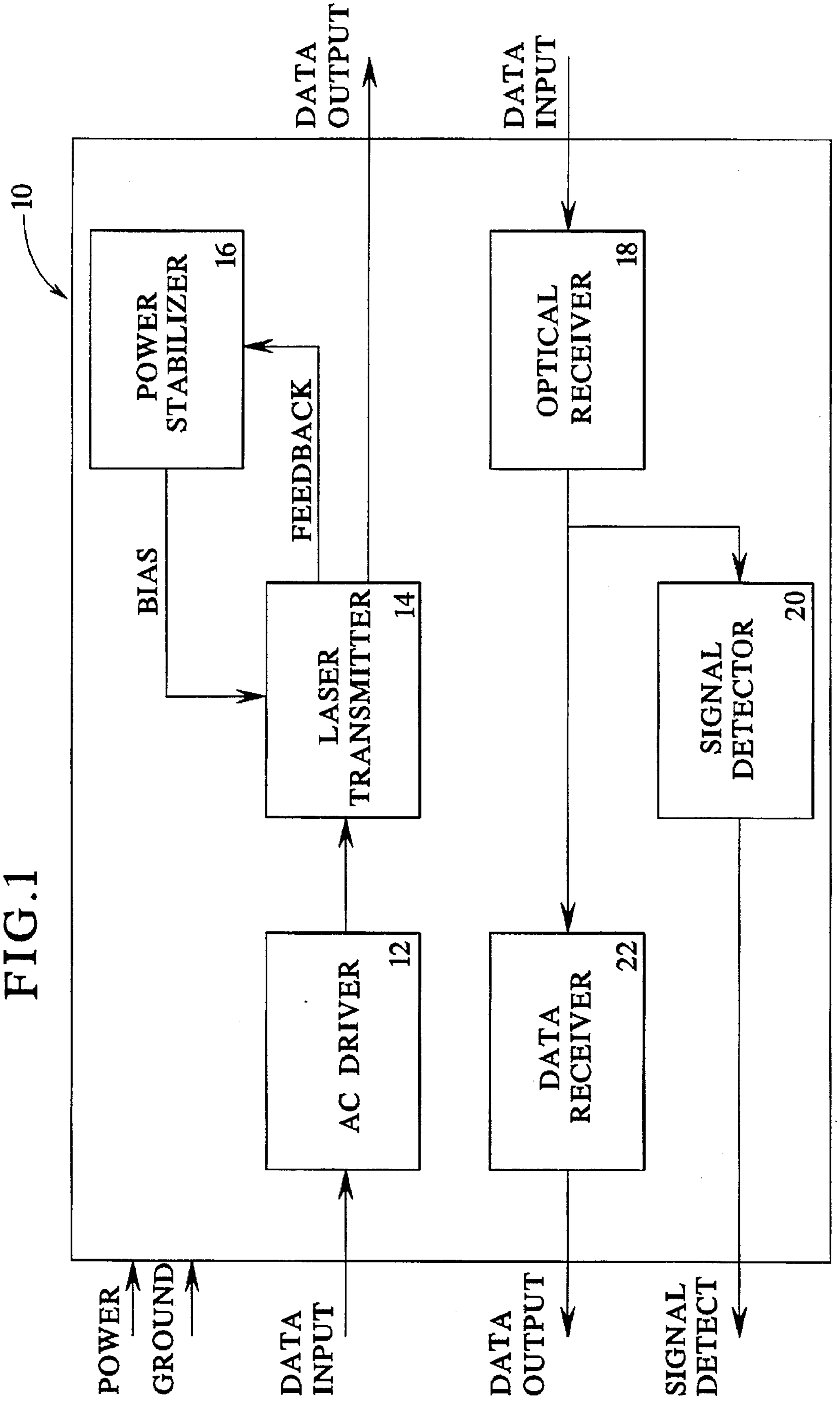
Primary Examiner—Leon Scott, Jr.
Attorney, Agent, or Firm—Jeffrey H. Canfield; David L. Newman

[57] **ABSTRACT**

A power stabilizer for maintaining a constant level of output power from a laser transmitter. The laser transmitter has a laser diode which produces a optical output which corresponds to the level of bias current received. In addition, the laser transmitter has a photodiode which produces a feedback signal which corresponds to the optical output power being produced by the laser diode. Furthermore, the power stabilizer consists of a digitally controlled potentiometer for producing a reference input signal and an op-amp for comparing the feedback signal and the reference input signal to produce a control signal to supply bias current.

8 Claims, 3 Drawing Sheets

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16
FEEDBACK
BIAS
LASER TRANSMITTER
14
AC DRIVER
12
OPTICAL RECEIVER
18
SIGNAL DETECTOR
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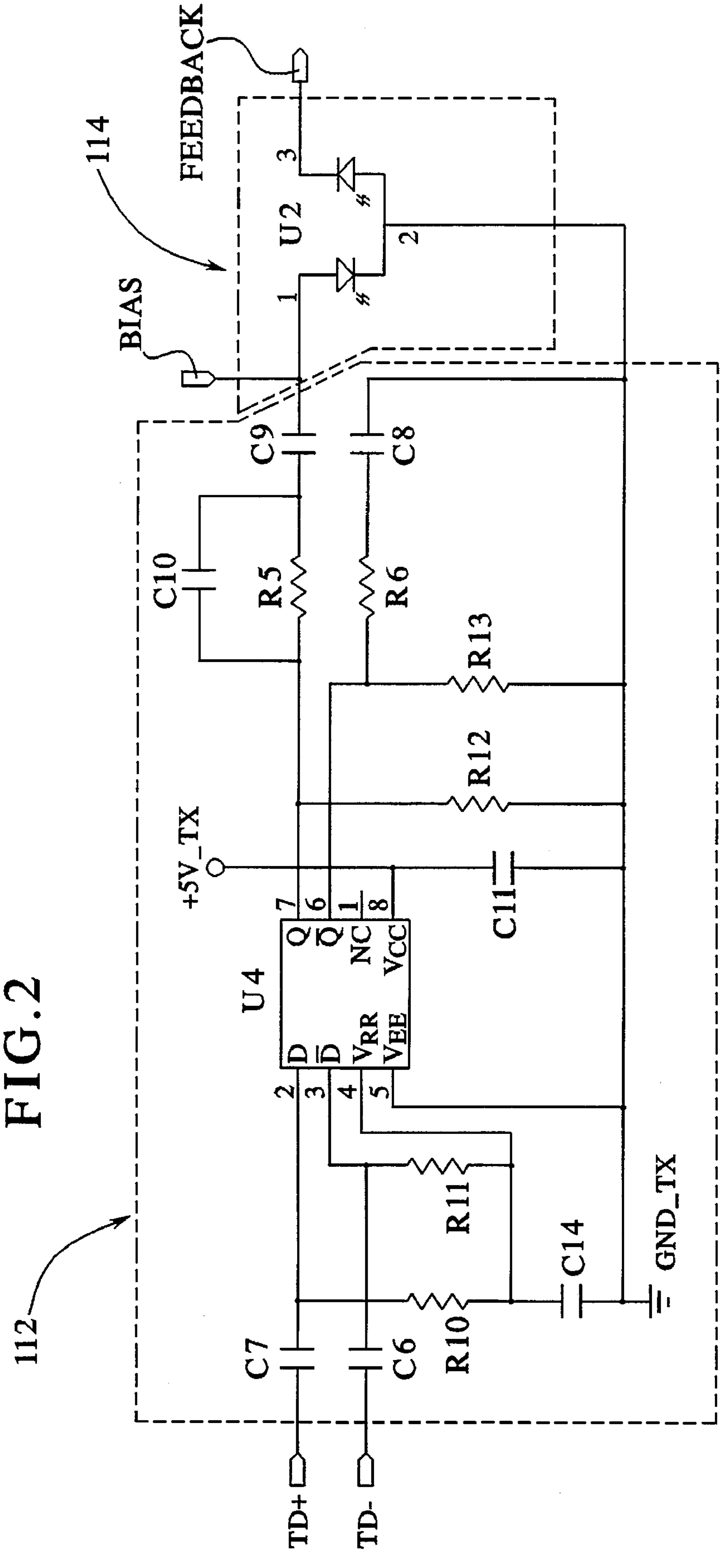
DATA RECEIVER
22
DATA OUTPUT
DATA INPUT
POWER
GROUND
DATA INPUT
DATA OUTPUT
SIGNAL DETECT

FIG.1

FIG. 2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6
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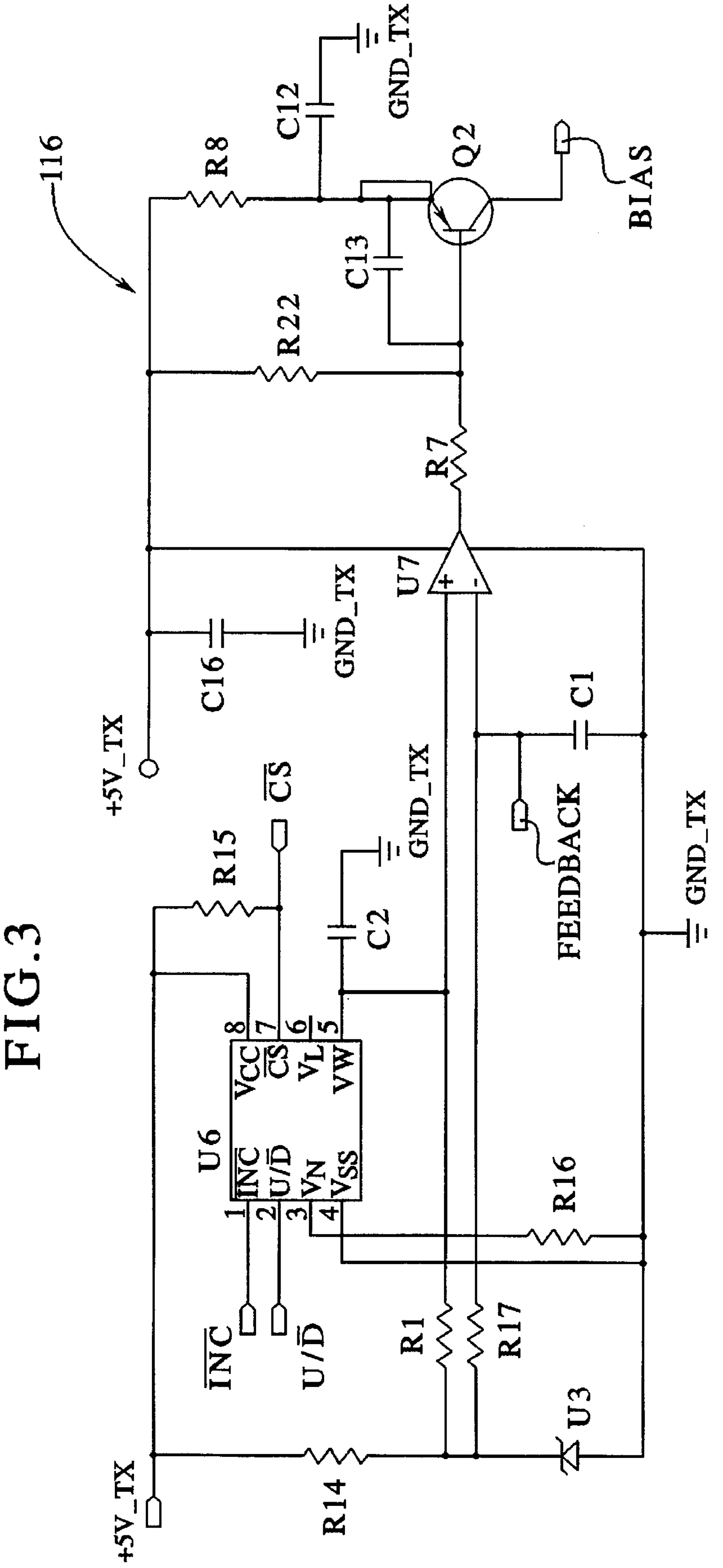
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GND_TX
$\overline{CS}$
R15
GND_TX
C2
U6
8 VCC
7 $\overline{CS}$
6 VL
5 VW
1 $\overline{INC}$
2 U/$\overline{D}$
3 VN
4 VSS
R16
$\overline{INC}$
U/$\overline{D}$
R1
R17
U3
+5V_TX
R14

FIG. 3

OPTOELECTRONIC TRANSCEIVER MODULE LASER DIODE STABILIZER AND BIAS CONTROL METHOD

BACKGROUND OF THE INVENTION

The present invention relates generally to optoelectronic transceiver modules which utilize semiconductor laser diodes for transmitting data, and in particular to a power stabilizer and a stabilization method for biasing the laser diodes.

Optoelectronic transceiver modules provide an interface between an electrical system and an optical transfer medium such as an optic fiber. Correspondingly, most optoelectronic transceiver modules contain electrical and optical conversion circuitry for transferring data both to and from the electrical system and the optical transfer medium.

Normally, transceiver modules use laser diodes, which produce coherent light, for performing high speed data transfers between the electrical system and the optical transfer medium. Typically, each laser diode is packaged with optical power-monitoring circuitry. For example, the RLD-85PC diode package by ROHM, Inc. contains both a laser diode for transmitting data and a photodiode for performing power-monitoring.

The power-monitoring photodiode within the diode packaging provides a monitor current I_m which varies as the optical power being generated by the laser diode changes. Normally, the changes in the monitor current I_m are directly proportional (i.e., linear) to the changes in the optical power generated by the laser diode. However, the ratio of monitor current I_m with regard to the laser diode's optical power can vary widely from one diode package to the next. Therefore, each diode package must be calibrated separately in order to determine its specific ratio of monitor current I_m to laser diode optical power.

The primary purpose of providing a monitor current I_m is for ensuring that, during operation, the laser diode is within its lasing mode of operation. The minimum current which must be supplied to the laser diode to cause lasing is referred to as the threshold current I_m.

When the current being supplied to the laser diode is less than the required threshold current I_{th}, the laser diode is said to be operating in the LED mode. In the LED mode, the current supplied to the laser diode is only sufficient enough to excite atoms in the laser diode's cavity which cause light to be emitted in a manner similar to that produced by light emitting diodes (LEDs).

When the current being supplied to the laser diode reaches a level which is either greater than or equal to the threshold current I_{th}, the laser diode's efficiency of converting electrical current into light will increase dramatically and thus the laser diode changes from the LED mode of operation to the lasing mode of operation.

While various classes of laser diodes will have threshold currents in the same general range, the threshold current I_{th} can still vary considerably between laser diodes. For example, the threshold current of some types of laser diodes can vary by as much as fifty percent between their typical and maximum values.

Furthermore, when the laser diode is operating in the lasing mode, there is a characteristic slope that is used to determine the laser diode's output efficiency η. As commonly known in the art, the output efficiency η is defined as the ratio of the changing in the laser diode's optical output power in relation to the changing in the operating current while in the lasing mode. However, as with the monitor current I_m, the actual output efficiency η varies from one laser diode to another.

Based on the variance in the monitor current I_m, the threshold current I_{th}, and output efficiency η of each laser diode, the operating current range for a given laser diode must be calibrated in order to ensure that the laser diode will always be operating within the lasing mode while transmitting data.

The primary method of ensuring that a laser diode will remain in the lasing mode is to provide the diode with a sufficient bias current. In addition, the laser diode is normally supplied with a second signal which is superimposed onto the bias current and corresponds to the data signals to be transmitted. Thus, the data signals are optically transmitted by the modulation of the laser diode's optical power output which is caused by the superimposing of the data signals onto the bias current. Typically, the bias current and the superimposed data signal are generally referred to as the laser diode's operating current I_{op}.

As indicated previously, great care must be taken to ensure that the maximum variation caused by superimposing the data signals onto the bias current will not cause the laser diode's operating current to fall below the required threshold current level I_{th}. If the laser diode's operating current falls below the required threshold current level I_{th}, then as indicated above, a failure to transmit data will occur because the laser diode will revert to the LED mode of operation.

In addition, besides not going below the threshold current level, the operating current must also be maintained at a sufficiently high enough level that a receiving photodiode can detect the modulated light signal. Furthermore, the laser diode's operating current must not be allowed to go so high as to burn out or significantly reduce the useful life of the laser diode.

Normally, transceivers use an analog feedback loop coupled to a mechanical potentiometer for manually adjusting the laser's output power. The optical power is set by adjusting the reference voltage for the analog feedback loop, via the mechanical potentiometer, until the desired amount of optical output power is achieved.

The use of a mechanical potentiometer for setting the output power level presents many problems due to the electrical characteristics of laser diodes. For example, as indicated above, a laser diode will be destroyed if its optical output power exceeds a certain limit. However, accidentally exceeding the laser diode's power limit by trying to set the bias current is generally quite easy since laser diodes typically have a very sharp optical output efficiently slope η once they are in the lasing mode of operation. Thus, losses are commonly caused by adjusting the calibration potentiometer too quickly. Correspondingly, the setup procedure for calibrating laser diodes is generally time consuming and expensive since extreme care must be used in setting the output power via a mechanical potentiometer.

One method proposed for solving the problems of tuning laser diodes is to use a programmed digital controller as set forth by U.S. Pat. No. 5,019,769 which is incorporated herein by reference. The digital controller is used to measure the laser diode's operating characteristics and to control the process of turning on and selecting the operating parameters of the laser diode. However, the use of a digital controller is expensive, consumes additional power, and occupies an inordinate amount of circuit board real estate. Thus, the use of a digital controller is adverse to the wave of inexpensive, low-power, and miniaturized circuitry which is required of today's electrical products.

Furthermore, the use of a digital controller in the control loop (i.e., power stabilizer circuitry) of the laser diode results in adjustments to the laser bias current being made in only certain discrete time intervals, with the time intervals being defined by the operating speed of the digital controller and its software algorithm. Accordingly, the use of a digital controller cannot immediately compensate for power fluctuations which may occur in the optical power output of the laser diode due to power spikes, noise, and other variations in the system.

In view of the above, it is an object of the present invention to provide an optoelectronic transceiver which employs a power stabilization and a stabilization method for efficiently biasing the operating current supplied to a laser diode.

It is another object of the present invention to prevent the destruction of a laser diode during calibration of the output power.

It is still another object of the present invention to provide a cost effective and automated means for selecting the bias current supplied to a laser diode.

A further object of the present invention is to provide a means for biasing a laser diode while minimizing the amount of circuit board space required for such laser diode biasing.

A still further object of the present invention is to provide a stable means for laser diode biasing.

Another object of the present invention is to immediately compensate for power fluctuations which may occur in the optical power output of a laser diode.

Furthermore, other objects, features, and advantages of the present invention will be apparent from the following detailed description taken in connection with the accompanying drawing.

SUMMARY OF THE INVENTION

In one form of the invention, a power stabilizer is provided for maintaining a constant power level from a laser transmitter. The laser transmitter has a laser diode which produces an optical output which corresponds to the level of bias current received. In addition, the laser transmitter has a photodiode which produces a feedback signal which corresponds to the optical output power being produced by the laser diode. Furthermore, the power stabilizer consists of a digitally controlled potentiometer for producing a reference input signal and an op-amp for comparing the feedback signal with the reference input signal to produce a control signal to supply bias current.

In a further embodiment, the invention also includes a bias current drive transistor which supplies bias current when the control signal is received. In addition, the control signal may be filtered by an RC circuit or an integrator.

In addition, the invention also provides for a method of maintaining a constant level of output power from a laser transmitter wherein the laser transmitter has a laser diode and a photodiode. The laser transmitter's laser diode produces an optical output power which corresponds to the level of bias current received. In addition, the laser transmitter's photodiode produces a feedback signal which corresponds to amount of optical output power produced by the laser diode. Based on the above, the method consisting of: (1) setting the resistance of a digitally controlled potentiometer to produce a reference input signal at a specific voltage level; and (2) comparing the feedback signal with the reference input signal to produce a control signal to supply bias current to a laser diode.

Various means for practicing the invention and other advantages and novel features thereof will be apparent from the following detailed description of an illustrative preferred embodiment of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

There is shown in the drawing a presently preferred embodiment of the present invention, wherein like numerals in the various figures pertain to like elements, and wherein:

FIG. **1** is a functional block diagram of a transceiver module;

FIG. **2** is a detailed schematic circuit diagram of an AC driver and a laser transmitter constructed in accordance with the present invention; and

FIG. **3** is a detailed schematic diagram of a power stabilizer constructed in accordance with the present invention.

DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENTS

Referring to the drawing, and particularly to FIG. **1**, a functional block diagram of a transceiver module **10** is depicted with an AC driver **12**, laser transmitter **14**, power stabilizer **16**, optical receiver **18**, signal detector **20**, and data receiver **22**. Within the functional bock diagram a single block may indicate several individual circuits which collectively perform a single function; a single line (for example, "data input" to the AC driver **12**) may indicate a set of similar electrical connections or signals which collectively perform a single function or transmit a similar collection of data. From this level of description, it would be clear to one of ordinary skill in the art, after perusal of the specification, drawing, and claims herein, how to make and use the invention, without undue experimentation.

The AC driver **12**, laser transmitter **14**, and power stabilizer **16** shown in FIG. **1** provide the electrical-to-optical conversion circuitry required to transfer data from an electrical system to an optical transfer medium. The AC driver **12** receives data input, in the form of electrical signals, and supplies a corresponding data signal to the laser transmitter **14** for transmittal onto the optical transfer medium. Furthermore, the laser transmitter **14** receives a bias signal from the power stabilizer **16** and transmits a corresponding monitor (i.e., feedback) signal in order to keep the laser transmitter **14** within the lasing mode of operation.

Turning to the portion of the transceiver module **10** which provides for optical-to-electrical signal conversion, the required circuitry consists of the optical receiver **18**, signal detector **20**, and data receiver **22** which are of standard construction. The optical receiver **18** is used to receive data signals, in the form of optical signals, from an optical transfer medium. The optical signals which are received by the optical receiver **18** are converted into electrical signals by conventional means such as a photodiode. The optical receiver **18** then transmits the electrical signals to both the data receiver **22** and the signal detector **20**.

Furthermore, the electrical signals received by the signal detector **20** are used to provide a signal detect output which indicates when optical power is sufficient to allow for proper detection and conversion of optical signals into electrical data by the transceiver **10**. Likewise, the signals received by the data receiver **22** are processed for transmission as data output, in the form of electrical signals.

Since transceiver modules are well known in the art, no further explanation is provided of the circuitry or methodology of the transceiver circuitry required to convert optical signals into electrical signals. Conversely, the conversion of electrical signals into optical signals in accordance with the present invention is further described below.

Turning to FIG. **2**, the preferred embodiment of the circuitry required for the AC driver **112** and the laser transmitter **114** is depicted. The AC driver **112** is shown to consist of a differential receiver U4 for receiving electrical data signals at the differential input terminals labeled TD+ and TD–. Likewise, the differential receiver U4 supplies a data signal to pin **1** of the laser diode U2 which corresponds to the logic levels supplied to the inputs TD+and TD–. Both of the differential inputs TD+ and TD– are provided with blocking capacitors C7 and C6, respectively, which provide for the AC coupling of the input signal paths associated with the differential receiver U4. Furthermore, each of the input signal paths to U4 are connected to resistors **R10** and **R11**, respectively, which have their opposite ends connected to a grounded capacitor **C14**. Both the resistors **R10**,**R11** and the capacitor **C14** provide for AC termination of the input signals TD+ and TD–.

As previously indicated above, the differential outputs of the differential receiver U4 are provided by pins **7** and **6**. Pin **6** of the differential receiver U4 is connected to resistors **R13** and R6 with resistor **R6** being tied to ground and resistor **R13** being tied to a grounded capacitor **C8**. The resistors **R13**,**R6** and the capacitor **C8** provide for the proper termination of the signal transmitted by pin **6** of the differential receiver U4. Resistors **R12** and **R13** provide necessary pull down of the U4 outputs.

Correspondingly, pin **7** of the differential receiver U4 is connected to a resistor **R5** and a capacitor **C10** with the other ends of both the resistor **R5** and the capacitor **C10** being tied to capacitor **C9**. Furthermore, the opposite end of the capacitor **C9** is tied to the anode of the laser diode U2. The combination of **R5**, **C10**, and **C9**, provides for a termination impedance matched with the output pin **6** of the differential receiver U4 and for the attenuation of the output signal transmitted by pin **7**. The attenuation of the output signal provided by pin **7** allows for the data signal to be superpositioned on the bias current as described further herein while still providing adequate optical power modulation without causing the laser diode to revert to the LED mode. Furthermore, capacitor **C9** provides for decoupling of the output signal provided by U4 so that only the AC component of the data signal will be provided to the anode of the laser diode U2.

Also connected to the anode of the laser diode U2 is a bias current signal from the power stabilizer circuitry **116** shown in FIG. **3**. The bias current signal, as described above, consists of a variable current which ensures that the laser diode U2 will continuously operate in the lasing mode of operation. The power stabilization circuitry **116** is used to generate the bias current signal as described further herein. In addition, the power stabilization circuitry **116** requires a monitor current signal (i.e., feedback) from the laser transmitter **116**. Correspondingly, as indicated above, both the laser diode and the photodiode shown in FIG. **2** are provided by U2. The cathode of the laser diode is tied to ground along with the anode of the photodiode. Thus, the reverse biased photodiode U2 is used to provide the monitor current signal (i.e., feedback signal) to the power stabilizer circuitry **116**.

Referring back to FIG. **3**, a detailed schematic diagram of a power stabilizer **116** constructed in accordance with the present invention is provided. As stated above, the power stabilizer **116** monitors the feedback signal provided by the photodiode U2 and thus produces a corresponding bias current to the laser diode U2. As shown in FIG. **3**, the power stabilizer **116** uses an operation amplifier U7 (i.e., "op-amp"), which is configured to operate like a high gain difference amplifier, to monitor the feedback signal. The output of the op-amp U7 is used to provide a corresponding signal which controls the bias current supplied to the laser diode U2. Thus, when the output voltage of the op-amp decreases, the bias current to the laser diode U2 will be increased. Likewise, when the output voltage of the op-amp increases, the bias current to the laser diode U2 will be reduced.

Attached to the non-inverting and inverting inputs of op-amp U7 are resistors **R1** and **R17**, respectively. The opposite ends of resistors **R1** and **R17** are tied to a +2.5 voltage reference which is provided by the reverse biased reference diode U3.

Also attached to the inverting input of the op-amp U7 is the monitor current signal (i.e., feedback signal) from the photodiode U2 along with a capacitor C1 which is tied to ground. The capacitor **C1** provides for the removal of the modulated signal current provided by the differential receiver U4, via capacitor **C9**, and also provides for a "soft start" in supplying bias current to the photodiode U2 during initial power on. Thus, after power on, capacitor C1 ensures that the op-amp U7 will only respond to changes in the bias current and thus the capacitor C1 removes the effect of the AC portion of the optical signal detected by the monitor photodiode U2.

Furthermore, since the feedback signal generated by the photodiode U2 will cause a voltage drop across **R17**, the resistor **R17** and the +2.5 voltage reference diode U3 provide a means for generating a feedback input signal at the inverting input of the op-amp U7 which corresponds to the level of feedback generated by the photodiode U2.

Likewise, attached to the non-inverting input of the op-amp U7 is the wiper terminal VW (i.e., pin **5**) of a digitally controlled potentiometer **U6** which provides a means for producing a reference input signal voltage the non-inverting input of the op-amp U7. Also capacitor **C2** is connected to the op-amp non-inverting input. This capacitor prevents reference diode noise from being amplified by the op-amp U7. In the preferred embodiment, the digitally controlled potentiometer U6 operates as a resistor array which consists of **99** resistive elements with tap points being located between each resistive element and accessible by the wiper.

The position of the wiper is controlled by the chip select input -CS (i.e., pin **7**), up/down input U/-D (i.e., pin **2**), and increment input -INC (i.e., pin **1**) of the potentiometer **U6**. In the preferred embodiment, the increment input -INC and the up/down input U/-D are unconnected. Additionally, the chip select input -SC is connected to a pullup resistor **R15** which is connected to +5 volts.

The digitally controlled potentiometer **U6** also has a high terminal VH (i.e., pin **3**) and a low terminal VL (i.e., pin **6**) which are equivalent to the fixed terminals of a mechanical potentiometer. In the preferred embodiment, the low terminal VL of the potentiometer U6 is unconnected and the high terminal VH is tied to a resistor **R16** which is connected to ground.

With the potentiometer **U6** connected as described above, the potentiometer provides for resistance trimming of the total resistance between the non-inverting input of the op-amp U7 and ground. Controlling the ratio of **R1**:[**R16**+ U6] sets the voltage of the reference input signal seen at the non-inverting input of the op-amp **U7**. It is preferred that the maximum resistance provided by the potentiometer be 10K ohms. Therefore, the digital potentiometer **U6** provides resistance values in increments of 101 ohms since, as described above, the potentiometer provides a resolution which is equal to the maximum resistance value divided by 99. In addition, since the high terminal VH of the potentiometer **U6** is tied to resistor **R16**, the resistance provided at the wiper terminal VW is equal to the value selected by the digital controlled potentiometer **U6** plus the resistance value of **R16**.

In the preferred embodiment, the potentiometer **U6** consists of the X9C103 digitally controlled potentiometer manufactured by XICOR. Compared to a digital controller as prescribed by U.S. Pat. No. 5,019,769, the use of a digital potentiometer requires the use of substantially less circuit board area. Furthermore, the digitally controlled potentiometer is less expensive, less complex, and thus more cost effective, than using a complex digital microprocessor.

Referring to the output of op-amp **U7**, the op-amp's output is connected to a resistor **R7** which is connected to a pullup resistor **R22**, a capacitor **C13**, and the base of a PNP transistor **Q2**. Furthermore, the opposite ends of the pullup resistor **R22** and the capacitor **C13** are connected to +5 volts and the emitter of the PNP transistor, respectively.

The pullup resistor **R22** turns transistor **Q2** off when the output voltage of op-amp **U7** reaches its maximum. In addition, resistors **R7** and **R22**, along with capacitor **C13**, result in an RC filter with a time constant on the order of 50 nsec. Furthermore, the emitter of the transistor **Q2** is also tied to a resistor **R8** and a capacitor **C12** which are connected to +5 volts and ground, respectively. The resistor **R8** and capacitor **C12** are use to provide filtering of the +5 volts supplied to the emitter of transistor **Q2**. In addition, the collector of the PNP transistor **Q2** is used to provide the bias current to the laser diode **U2**.

As indicated above, before the laser transmitter **114** is ready to begin transmitting data, the bias current to the laser diode must initially be set. The laser diode output power level is set by adjusting the resistance of the digital controlled potentiometer **U6**. To adjust the wiper resistance of the potentiometer **U6**, the device is selected by pulling the potentiometer's chip select -CS input (i.e., pin **7**) to a low logic level. Once the -CS input is pulled low, the -INC input (i.e., pin **1**) is used to either increase or decrease the resistance at the wiper terminal VW, while the output power of the laser diode is monitored by a calibrated power meter. Correspondingly, the resistance is increased by pulling the U/-D input to a high logic level and, conversely, the resistance is decreased by pulling the U/-D input to a low logic level. This procedure allows the operator to set the laser output power level via control of the digital potentiometer.

Once the laser power is selected, the resistor **U15** is allowed to pull the chip select input -CS of the potentiometer **U6** to a high logic level. Furthermore, in the preferred the embodiment, the potentiometer **U6** has a nonvolatile memory so that it is capable of storing the position of the wiper. Therefore, the same wiper position will be maintained upon a subsequent power-on operation.

Correspondingly, in a preferred embodiment, the position of the wiper in the potentiometer **U6** is pre-set by its manufacturer so that the highest resistance value is provided, via the wiper terminal VW, when power is first applied to the potentiometer. Therefore, only minimal bias current will be supplied to the laser diode **U2** when power is first applied to the stabilizer circuitry **114**.

In the preferred embodiment, the optical power output of the laser diode is measured by conventional means as known by those persons skilled in the art. Furthermore, since the optical power of the laser diode corresponds to the feedback supplied by the power stabilization circuitry **116**, the potentiometer **U6** allows for the power stabilization circuitry **116** to be adjusted so that it provides a specific bias current which corresponds directly to the feedback.

Using the digitally controlled potentiometer **U6** to adjust the voltage of the reference input signal, and thus the bias current supplied by the power stabilizer circuitry **116**, will eliminate the possibility of accidently destroying the laser diode **U2** and provides for a stable means of setting the laser output power. The laser output power can be effectively set since the resistance of the potentiometer **U6** cannot be adjusted without supplying toggled signals to the -INC input. Therefore, the reference input signal, and thus the corresponding optical power output of the laser diode, cannot be accidentally adjusted since only deliberate steps will cause changes to the voltage level of the reference input signal.

In addition, the use of a digital potentiometer allows for the automatic adjustment of the reference voltage and therefore the laser output power. Automatic adjustments can be accomplished by having a device, such as a properly calibrated optical power meter traceable to the standards established by the National Institute of Standards and Technology (NIST), receive the optical output power from the laser diode **U2** and, based on the level of optical output power measured, a device such as a computer or microprocessor can transmit control signals to the potentiometer **U6** to either increase or decrease the optical power output of the laser diode **U2** accordingly.

Operationally speaking, the power stabilization circuit **116** will either increase or decrease the bias current supplied to the laser diode depending, respectively, on if the feedback signal supplied by the photodiode **U2** is too low or too high. As depicted in FIG. **3** and indicated above, the feedback signal effectively governs the inverting input received by the op-amp **U7**. In addition, the voltage level at the non-inverting input of op-amp **U7** (i.e., the reference input signal) is selected by adjusting the potentiometer **U6** as described above. Therefore, a comparison of the feedback signal and the reference input signal determines the output voltage level of op-amp **U7**.

Consequently, the PNP transistor **Q2** will increase the bias current to the laser diode **U2** as the output voltage level of the op-amp **U7** decreases due to the feedback signal being too low. Likewise, the transistor **Q2** will decrease the bias current to the laser diode **U2** as the output voltage level of the op-amp **U7** increases due to the feedback signal being too high.

It should be noted that the bias current supplied by the collector of transistor **Q2** will only be gradually changed due to the RC circuitry provided by **R7**, **R22**, and **C13** on the output of op-amp **U7**. Furthermore, as stated above, the feedback generated by the photodiode **U2** will vary directly with changes in the optical power being generated by the laser diode **U2**.

Consequently, the use of analog circuitry in the power stabilizer as described above provides for the immediate compensation of power fluctuations which may occur in the optical power output of a laser diode.

Once the resistance of the digital potentiometer **U6** is set to the correct level, the AC driver **112** and laser transmitter **114** are ready to convert electrical data input signals into optical data output signals. As shown in FIG. **2**, the AC driver **112** receives differential data input signal via inputs TD+ and TD–. The data input signals TD+ and TD– are AC coupled by capacitors **C6** and **C7**, received by the differential receiver **U4**, and terminated by **R10**, **R11**, and **C14**. The data input signals received by the differential receiver **U4** are then transmitted via pins **6** and **7**.

Output pin **6** of the differential receiver **U4** is terminated by resistors **R13**, **R6**, and capacitor **C8**. Likewise, output pin **7** of the differential receiver **U4** is attenuated by resistor **R5** and capacitor **C10**. Furthermore, the output provided by pin **7** is AC coupled by capacitor **C9** so that only the AC component of the output signal, which directly corresponds to the electrical signal received by the AC driver, is superimposed onto the bias current signal used to drive the laser diode **U2**. Therefore, the optical power output of the laser diode will vary in accordance with the electrical signals received by the AC driver and will be transmitted as data output over an optical medium such as an optic fiber.

For completeness in the disclosure of the above-described AC driver **112**, laser transmitter **114**, and power stabilizer **116**, but not for purposes of limitation, the following representative values and component identifications are submitted. These values and components were employed in a transceiver that was constructed and tested and which provides a high quality performance. Those skilled in the art will recognized that many alternative elements and values may be employed in constructing the circuitry in accordance with the present invention.

Part	TYPE or VALUE
C1	.1 uF
C2	.1 uF
C6	.1 uF
C7	.1 uF
C8	.1 uF
C9	.1 uF
C10	5 pF
C11	.1 uF
C12	.1 uF
C13	100 pF
C14	.1 uF
C16	.1 uF
R1	100 Ohms
R5	46.4 Ohms
R6	51 Ohms
R7	1K Ohms
R8	26.7 Ohms
R10	51 Ohms
R11	51 Ohms
R12	180 Ohms
R13	180 Ohms
R14	1K Ohms
R15	1K Ohms
R16	1K Ohms
R17	100 Ohms
R22	1K Ohms
Q2	MRF5211
U2	RLD-85PC
U3	LM40400IM3-2.5
U4	MC100EL16
U6	X9C103
U7	TA75S01F

Although the above power stabilizer **116** depicted in FIG. **3** is used in a transceiver module, it should be understood that the power stabilizer could be used in any application where a laser diode is used for transmitting optically encoded data onto an optical transfer medium.

Furthermore, it should also be understood that other various changes and modifications to the presently preferred embodiment described herein will be apparent to those skilled in the art. Such changes and modifications may be made without departing from the spirit and scope of the present invention and without diminishing its attendant advantages. For example, the digitally controlled potentiometer can be constructed using various discrete components. Therefore, it is intended that such changes and modifications be covered by the appended claims.

We claim:

1. A power stabilizing circuit for maintaining a constant level of output power from a laser transmitter, wherein said laser transmitter includes a laser diode configured to emit an optical output signal having an output power level corresponding to a bias current input to said laser diode. and a photodiode for monitoring said optical output signal, providing a voltage feedback signal proportional to said output power level, said power stabilizing circuit comprising:

a) a digitally controlled potentiometer, said potentiometer including a wiper contact having a variable output resistance for supplying an adjustable voltage reference signal; and

b) an op-amp having first and second inputs, said adjustable voltage reference signal connected to said first input, and said voltage feedback signal connected to said second input, such that said op-amp compares said voltage reference signal and said voltage feedback signal to generate an output control signal corresponding to the voltage difference between said first and second input: and

c) a bias current driver driven by said output control signal for supplying said bias current to said laser diode.

2. The power stabilizing circuit of claim **1**, wherein said current driver comprises a current drive transistor, having a base electrically connected to said output control signal, a collector connectted to said laser diode, and an emitter connected to a voltage source, whereby said transistor provides a bias current to said laser diode inversely proportional to said output control signal.

3. The power stabilizing circuit of claim **2**, further comprising an RC filter disposed between said op-amp and said transistor such that said output control signal is filtered prior to connection to said base of said transistor.

4. The power stabilizing circuit of claim **1** wherein said potentiometer provides resistance trimming of said adjustable voltage reference signal by selectably altering said output resistance in a number in a number of incremental steps between a maximum resistance value and zero ohms.

5. The power stabilizing circuit of claim **4** wherein said maximum resistance is 10k ohms.

6. The power stabilizing circuit of claim **4** wherein said number of incrimental steps equals ninety-nine.

7. An apparatus for transmitting electrical data signals onto an optical transfer medium, said apparatus comprising:

a) an AC driver for receiving said electrical data signals and providing corresponding data signal;

b) a laser transmitter having a laser diode and a photodiode, said laser diode for producing optical power modulated by said data signal and transmittable over said optical transfer medium, and said photodiode for producing a feedback signal proportional to said optical output power produced by said laser diode; and

c) a power stabilizing circuit comprising;

i) a digitally controlled potentiometer for producing a reference input signal;

ii) an op-amp for comparing said feedback and said reference input signal, said op-amp generating a output control signal; and

iii) a bias current drive transistor, responsive to said control signal, for supplying said bias current to said laser diode.

8. A method of maintaining a constant level of output power from a laser transmitter, comprising the steps of:

a) providing a laser transmitter having a laser diode and a photodiode, said laser diode responsive to a reference voltage input which produces a level of bias current to produce a corresponding level of optical output power and said photodiode responsive to said optical output signal to produce a feedback signal which corresponds to said optical output power produced by said laser diode;

b) setting the resistance of a digitally controlled potentiometer to produce a reference input signal; and

c) comparing said feedback signal and said reference input signal to produce a control signal to supply said bias current.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 5,638,390 Page 1 of 4
DATED : June 10, 1997
INVENTOR(S) : Patrick B. Gilliland, et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Abstract, line 3, delete "a" and insert --an--.

Column 1 line 41delete "I_m" and insert --I_{th}-- in place thereof.

Column 2 line 34 delete "bum" and insert --burn-- in place thereof.

Column 3 line 35 delete "drawing" and insert --drawings-- in place thereof.

Column 3 line 61 between the words "to" and "amount" insert the word --the--.

Column 6 line 39 between the words "voltage" and "the" insert the word --to--.

Column 6 line 54 delete "-SC" and insert -- -CS—in place thereof.

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 5,638,390
DATED : June 10, 1997
INVENTOR(S) : Patrick B. Gilliland, et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

IN THE CLAIMS:

Correct typographical errors in Claims 1, 4, and 7 as follows:

1. A power stabilizing circuit for maintaining a constant level of output power from a laser transmitter, wherein said laser transmitter includes a laser diode configured to emit an optical output signal having an output power level corresponding to a bias current input to said laser diode[.], and a photodiode for monitoring said optical output signal, providing a voltage feedback signal proportional to said output power level, said power stabilizing circuit comprising:

a) a digitally controlled potentiometer, said potentiometer including a wiper contact having a variable output resistance for supplying an adjustable voltage reference signal; [and]

b) an op-amp having first and second inputs, said adjustable voltage reference signal connected to said first input, and said voltage feedback signal connected to said second input, such that said op-amp compares said voltage reference signal and said voltage feedback signal to generate an output control signal corresponding to the voltage difference between said first and second input[:]; and

c) a bias current driver driven by said output control signal for supplying said bias current to said laser diode.

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 5,638,390
DATED : June 10, 1997
INVENTOR(S) : Patrick B. Gilliland, et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

4) The power stabilizing circuit of claim 1 wherein said potentiometer provides resistance trimming of said adjustable voltage reference signal by selectably altering said output resistance in a number [in a number] of incremental steps between a maximum resistance value and zero ohms.

7) An apparatus for transmitting electrical data signals onto an optical transfer medium, said apparatus comprising:

a) an AC driver for receiving said electrical data signals and providing a corresponding data signal;

b) a laser transmitter having a laser diode and a photodiode, said laser diode for producing optical power modulated by said data signal and transmittable over said optical transfer medium, and said photodiode for producing a feedback signal proportional to said optical output power produced by said laser diode; and

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 5,638,390
DATED : June 10, 1997
INVENTOR(S) : Patrick B. Gilliland, et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

c) a power stabilizing circuit comprising;

- i) a digitally controlled potentiometer for producing a reference input signal;
- ii) an op-amp for comparing said feedback and said reference input signal, said op-amp generating a output control signal; and
- iii) a bias current drive transistor, responsive to said control signal, for supplying said bias current to said laser diode.

Signed and Sealed this

Twenty-fifth Day of August, 1998

Attest:

Bruce Lehman

BRUCE LEHMAN

Attesting Officer

Commissioner of Patents and Trademarks

US005734672A

United States Patent [19]
McMinn et al.

[11] **Patent Number: 5,734,672**
[45] **Date of Patent: Mar. 31, 1998**

[54] SMART LASER DIODE ARRAY ASSEMBLY AND OPERATING METHOD USING SAME

[75] Inventors: **Theodore S. McMinn**, St. Peters; **Dana A. Marshall**, Frontenac; **Michael A. Hope**, Brentwood; **Geoffrey O. Heberle**, Chesterfield, all of Mo.

[73] Assignee: **Cutting Edge Optronics, Inc.**, St. Louis, Mo.

[21] Appl. No.: **692,600**

[22] Filed: **Aug. 6, 1996**

[51] **Int. Cl.**^{6} **H01S 3/19**

[52] **U.S. Cl.** **372/50**; 372/33; 372/38; 372/43; 372/36; 372/68

[58] **Field of Search** 372/7, 9, 29, 33, 372/34, 36, 43, 45, 50, 68, 108, 109, 38

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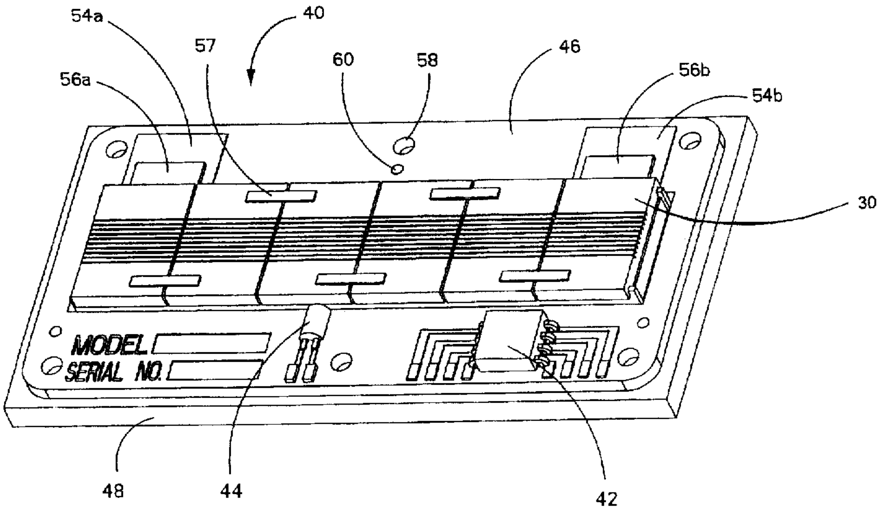
Coherent Laser Group. Laser Diodes and Bars (article) (5 pages) (no date of publication).

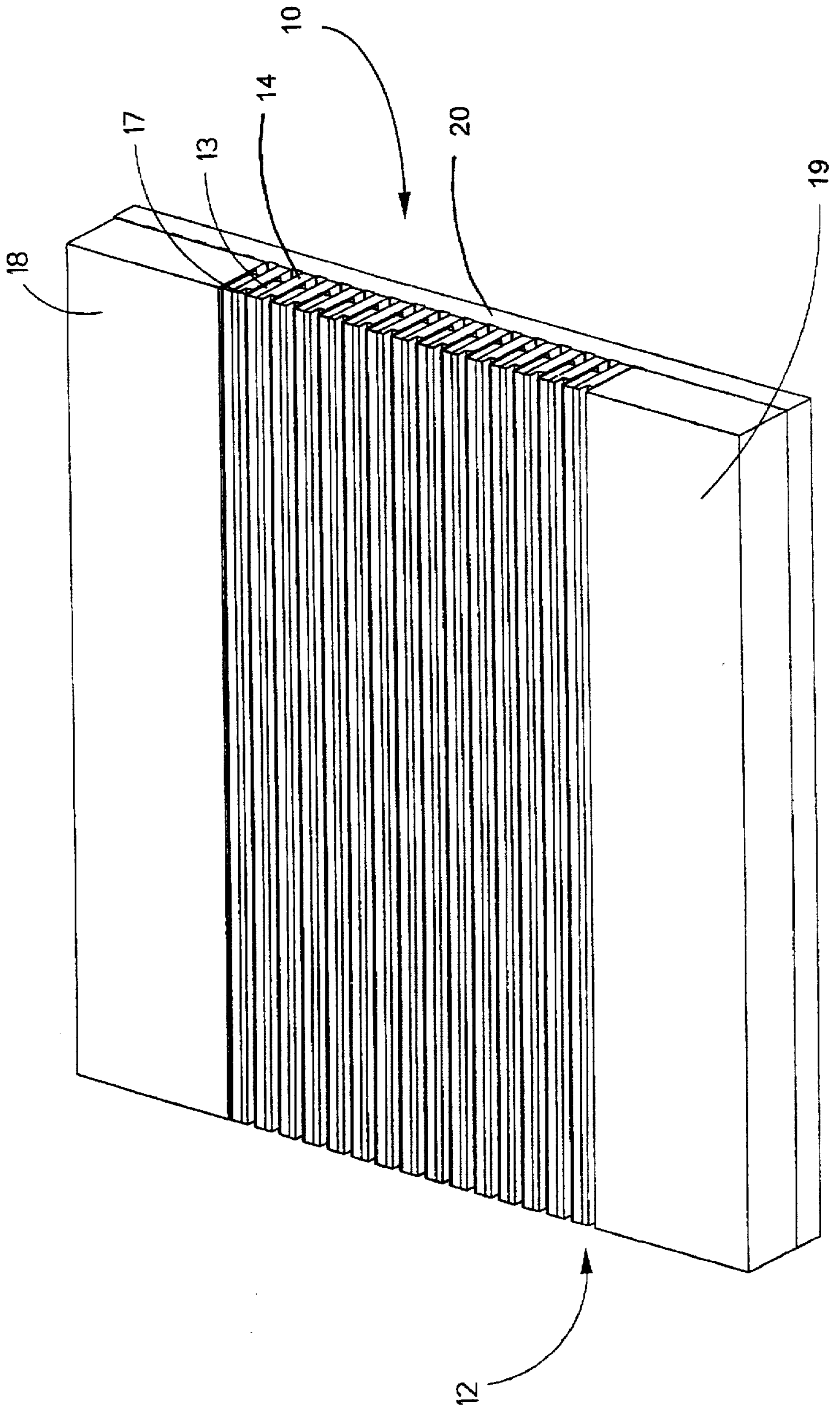
Primary Examiner—Brian Healy
Attorney, Agent, or Firm—Arnold, White & Durkee

[57] **ABSTRACT**

A laser diode array assembly includes a laser diode array and a memory device integrally packaged with the array. The memory device includes operational information concerning the array. The memory device is accessible by a host external operating system which determines the manner in which the array is to be powered based on the operational information. The memory device may have the capability to be written to such that the external operating system can record in the memory device significant events such as extreme operational conditions, operational faults, and the on-time or shot-count of the array. The assembly may include sensors to which the operating system is coupled. The assembly may further include a processing means to monitor the sensors and provide real-time updates to the external operating system such that laser diode array is continuously powered in an optimal manner.

76 Claims, 12 Drawing Sheets

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14
17
13
20
19
18
12

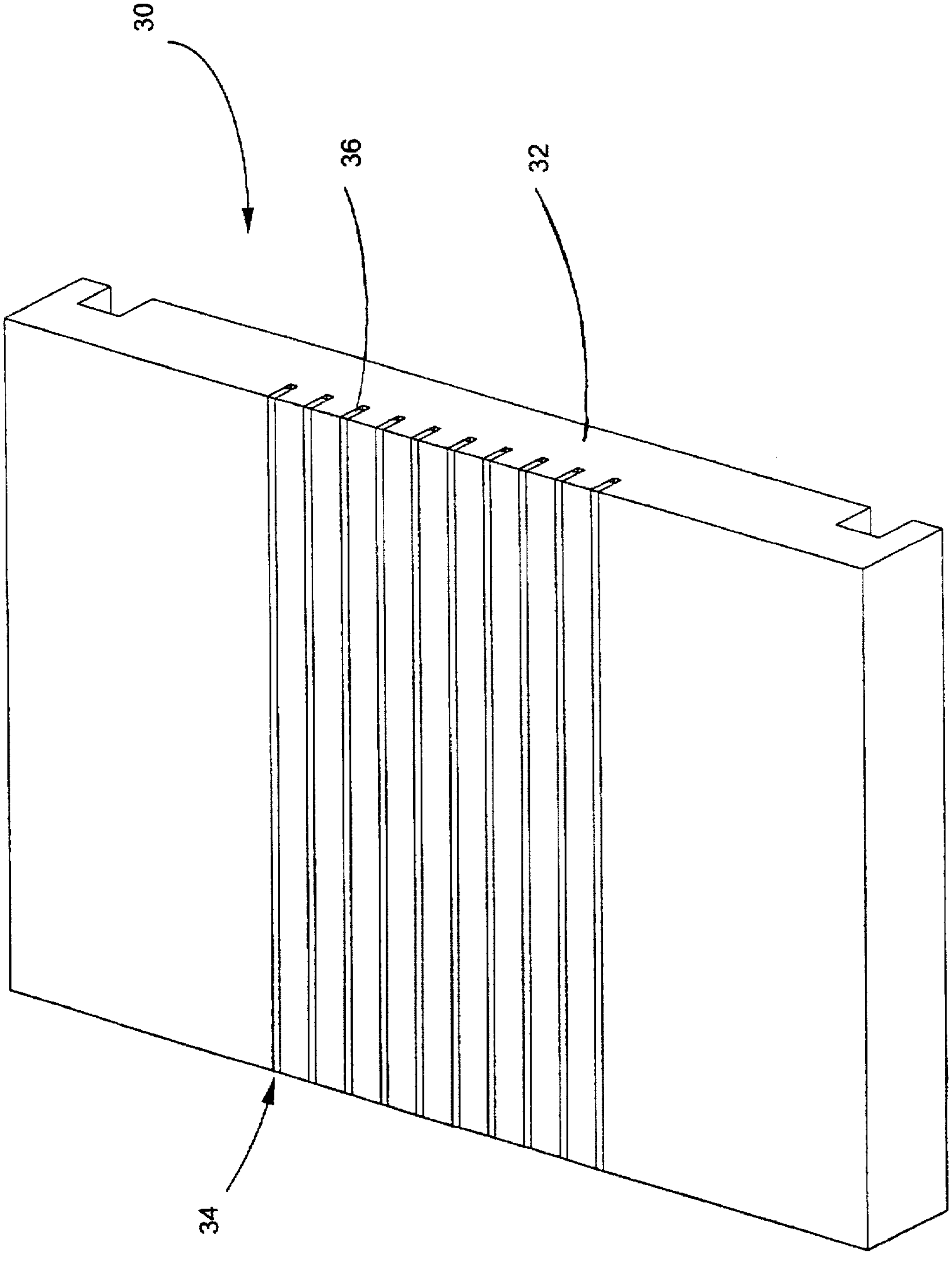


FIGURE 1B

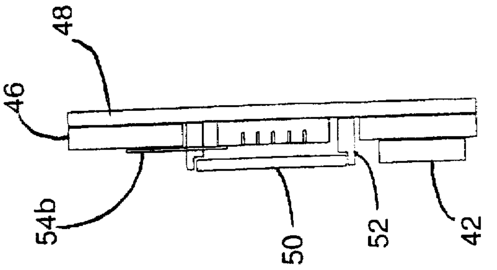


FIGURE 2C

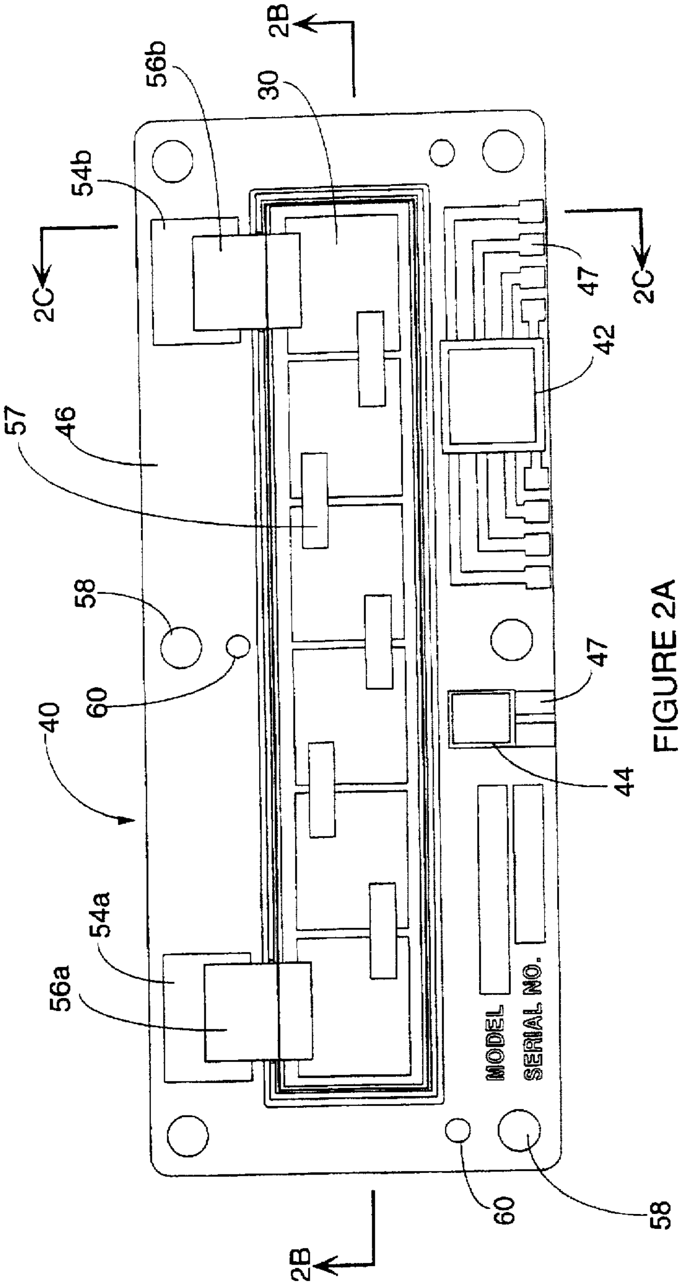


FIGURE 2A

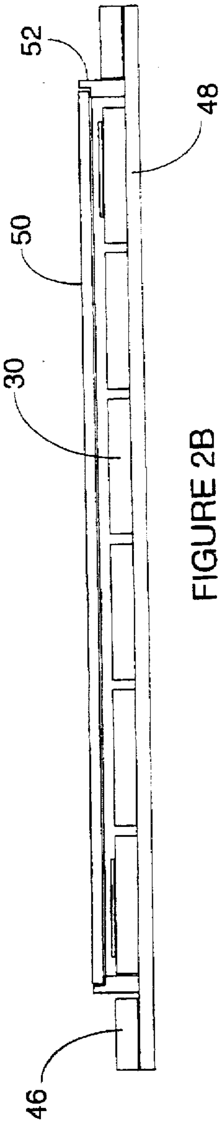
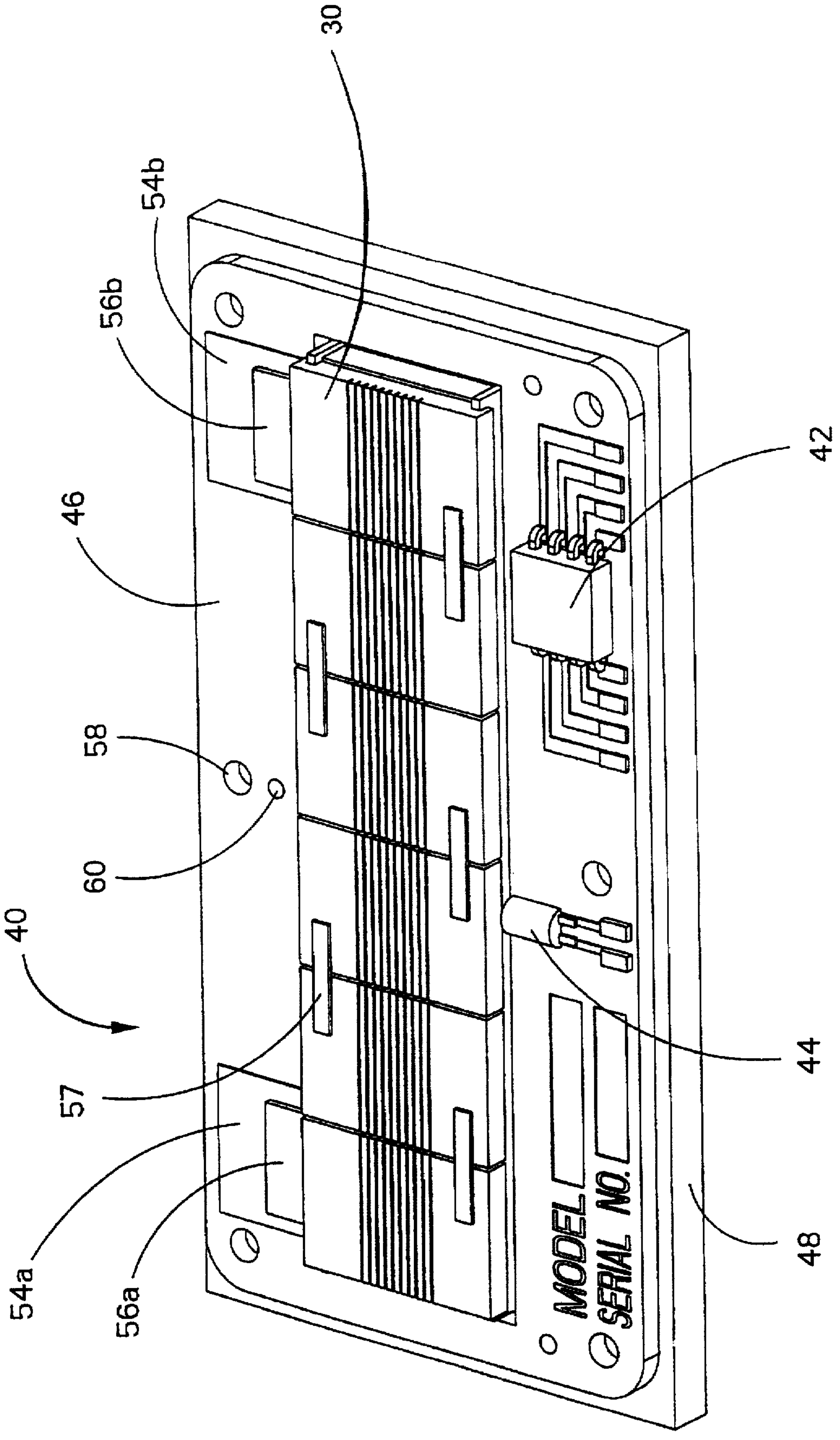


FIGURE 2B



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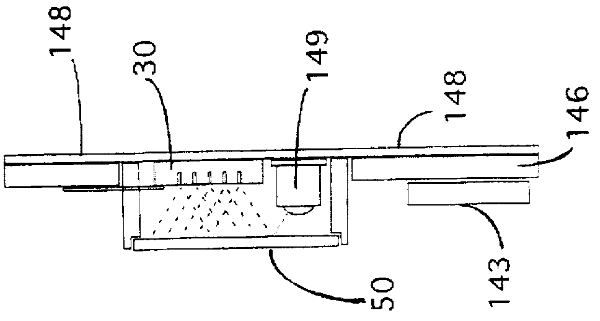


FIGURE 3C

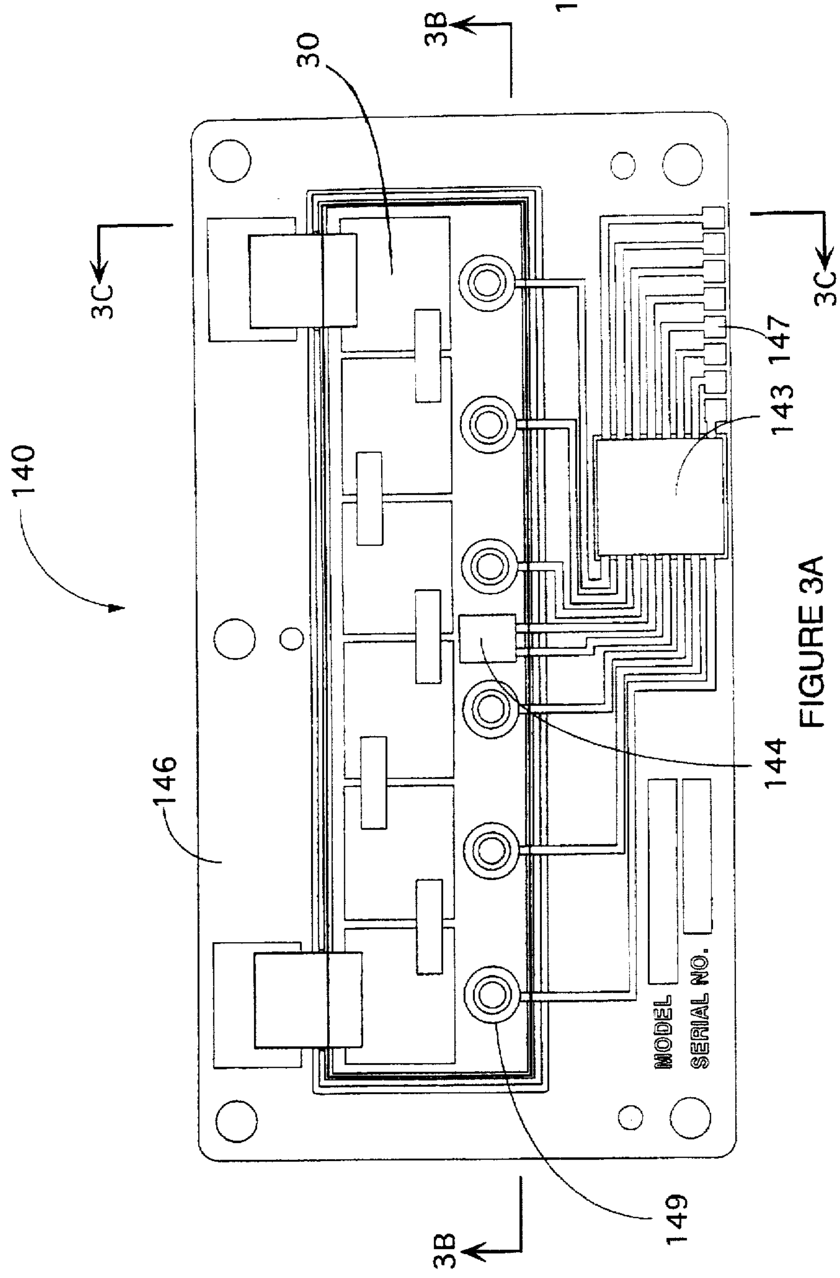


FIGURE 3A

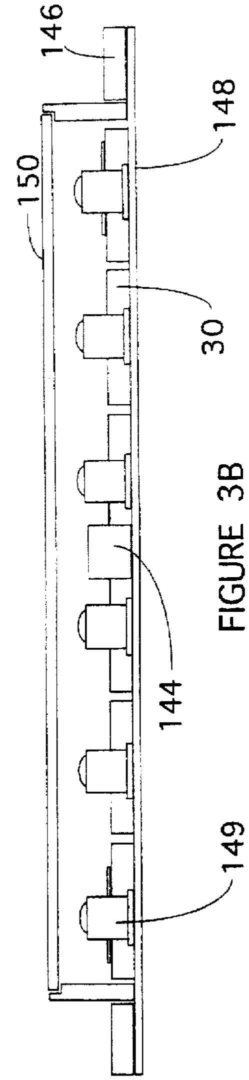


FIGURE 3B

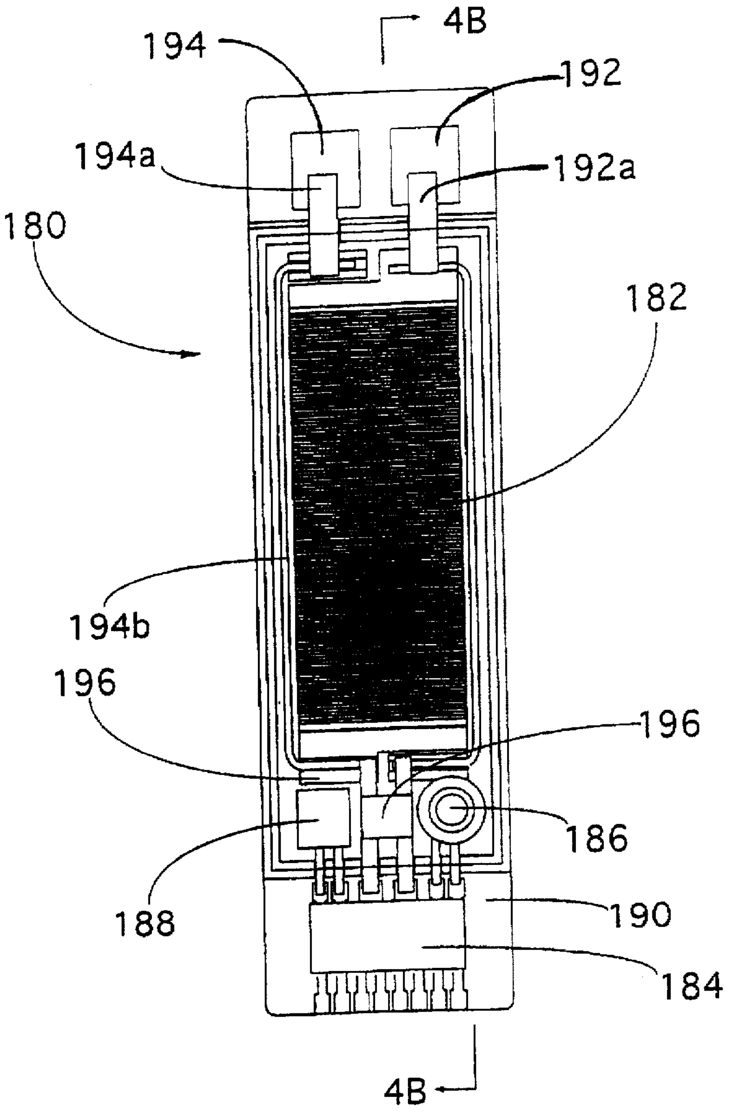
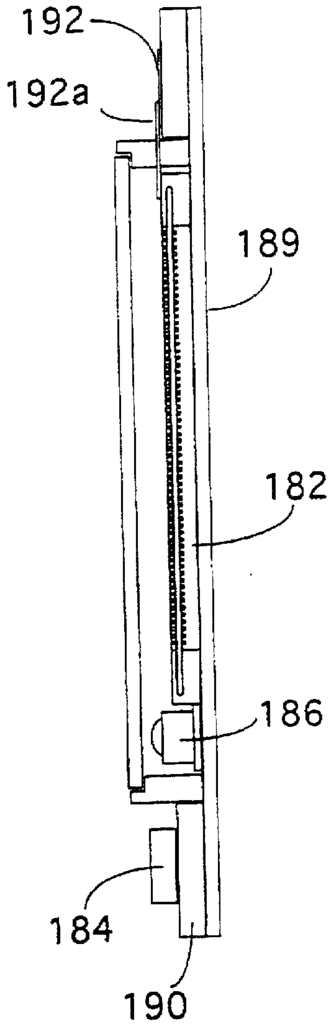


FIGURE 4A



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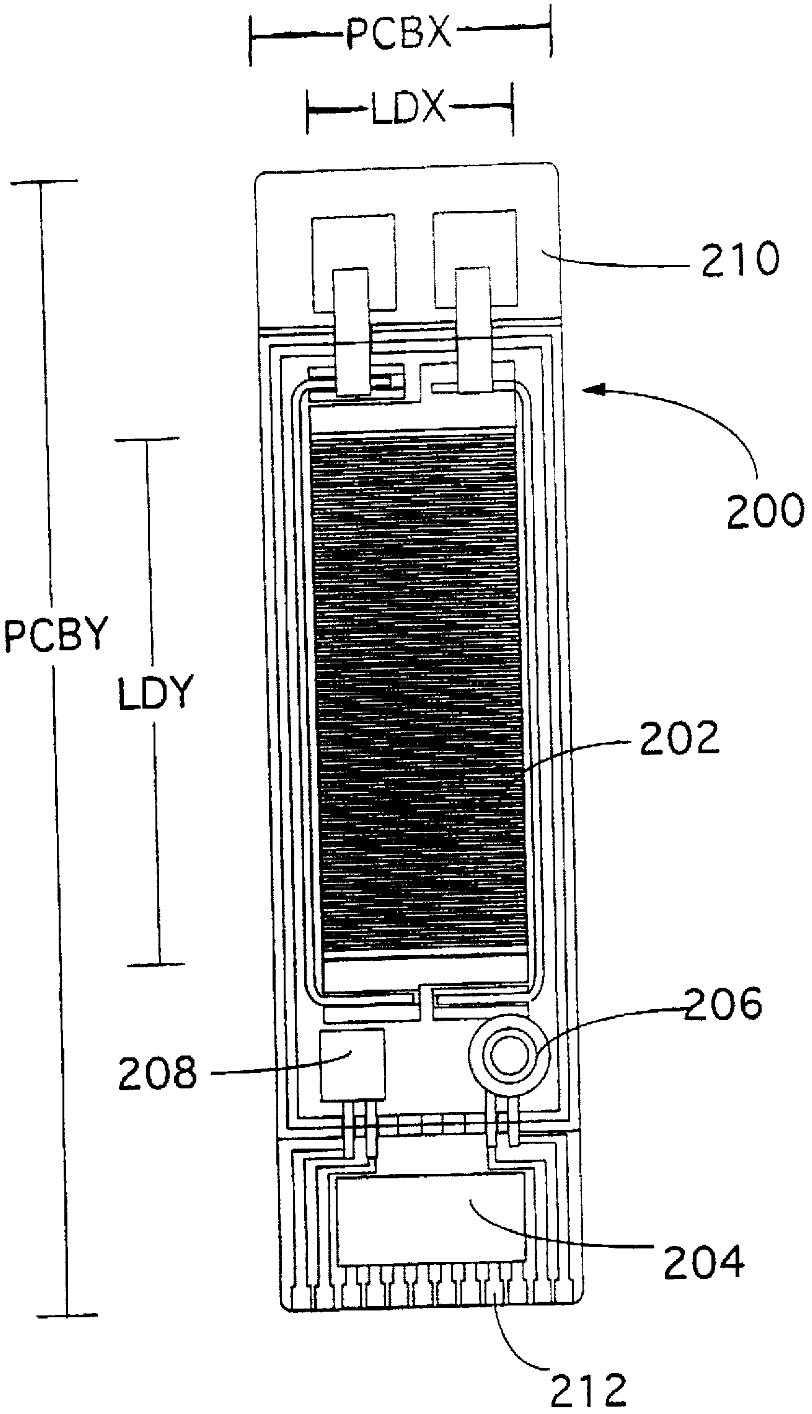


FIGURE 5

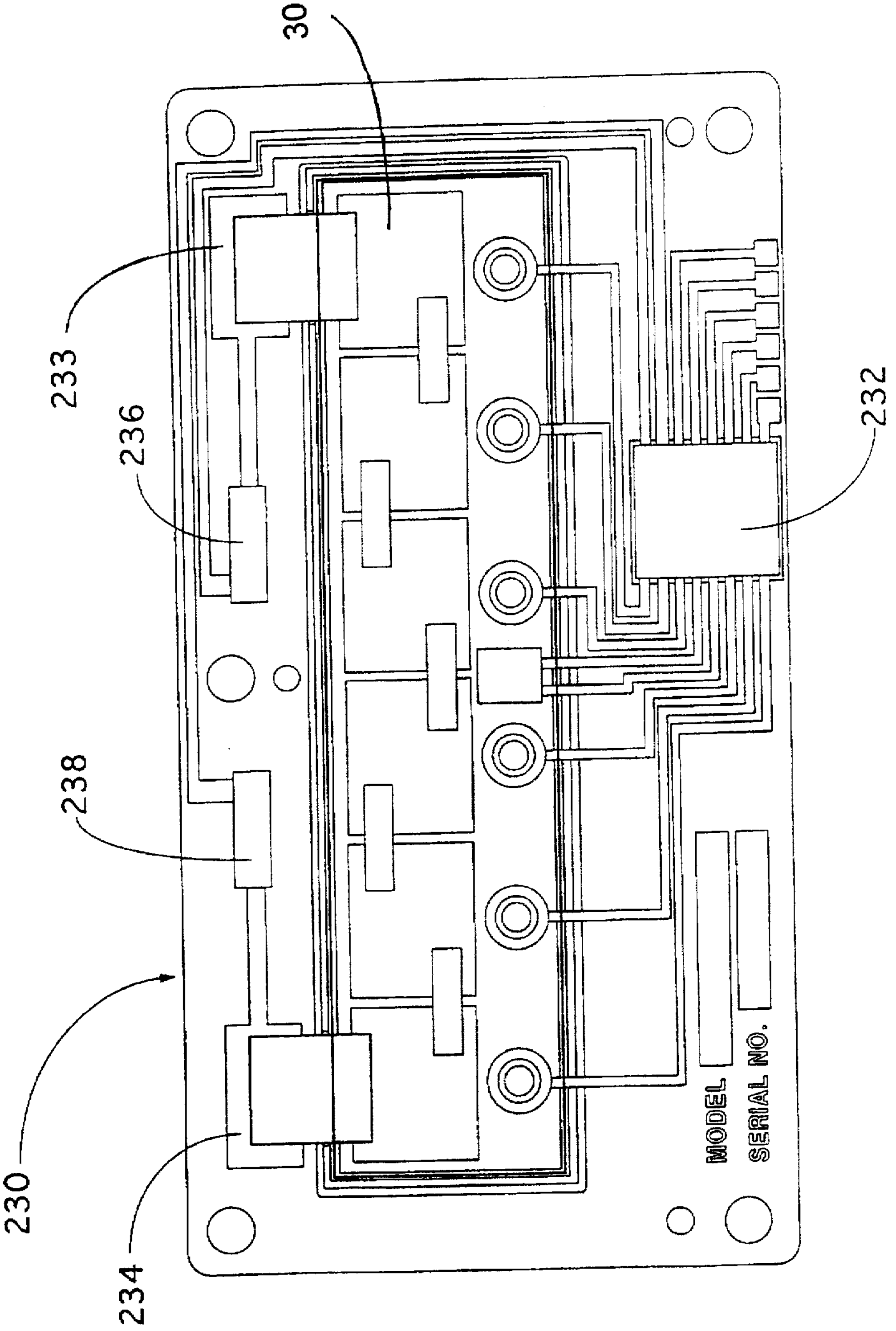
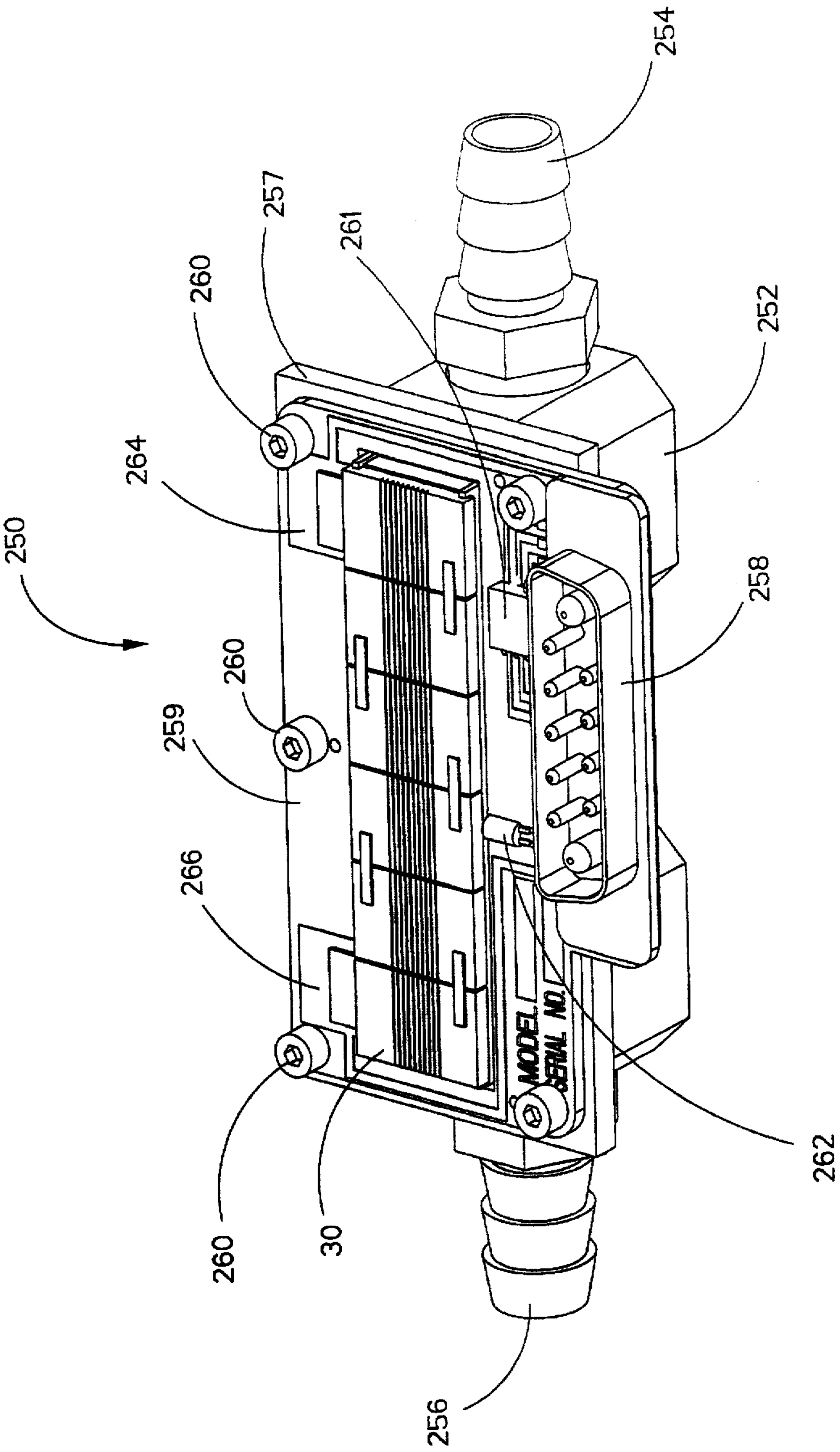


FIGURE 6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257
261
260
252
264
250
258
260
259
266
MODEL
SERIAL NO.
262
260
30
256

FIGURE 7

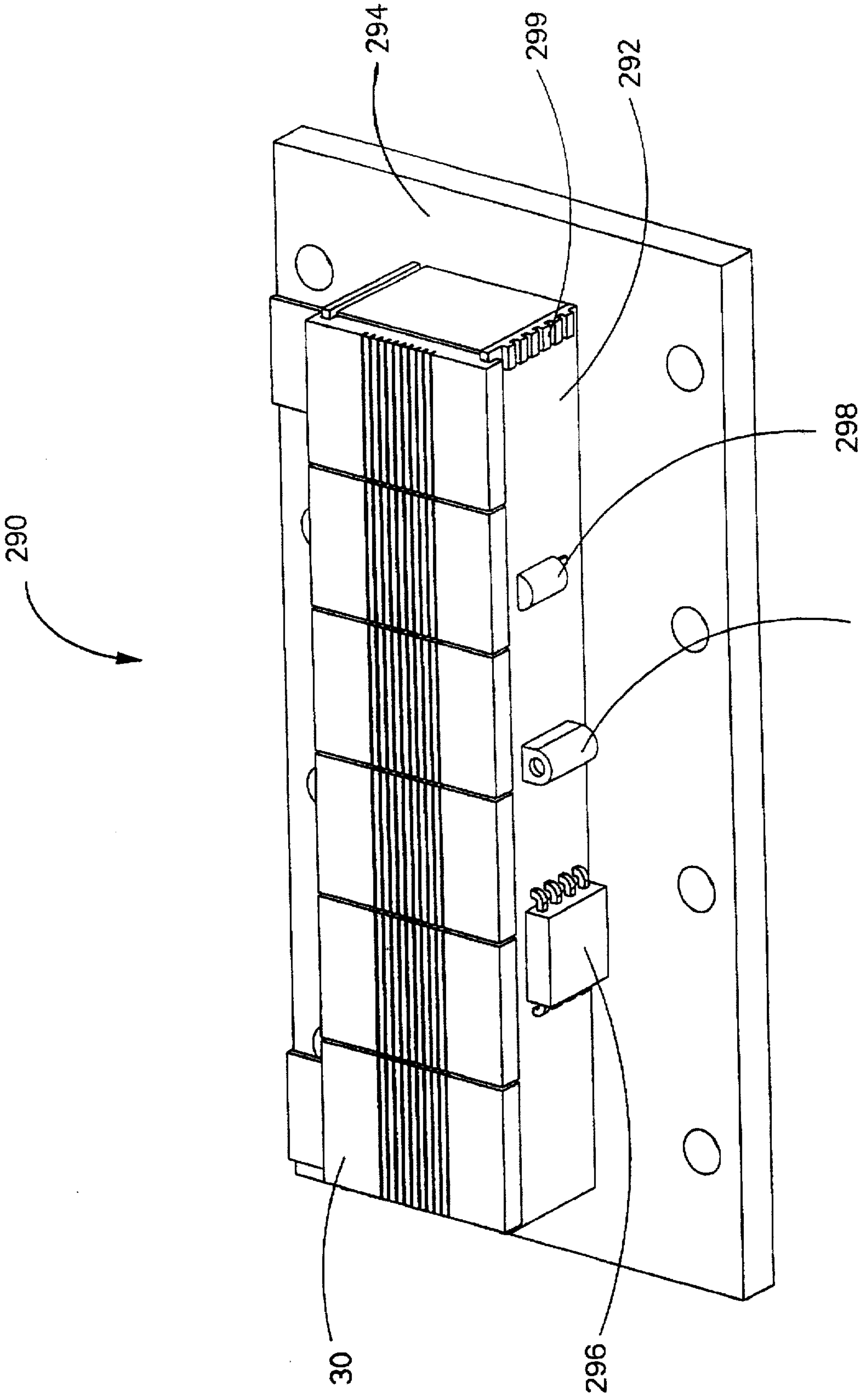
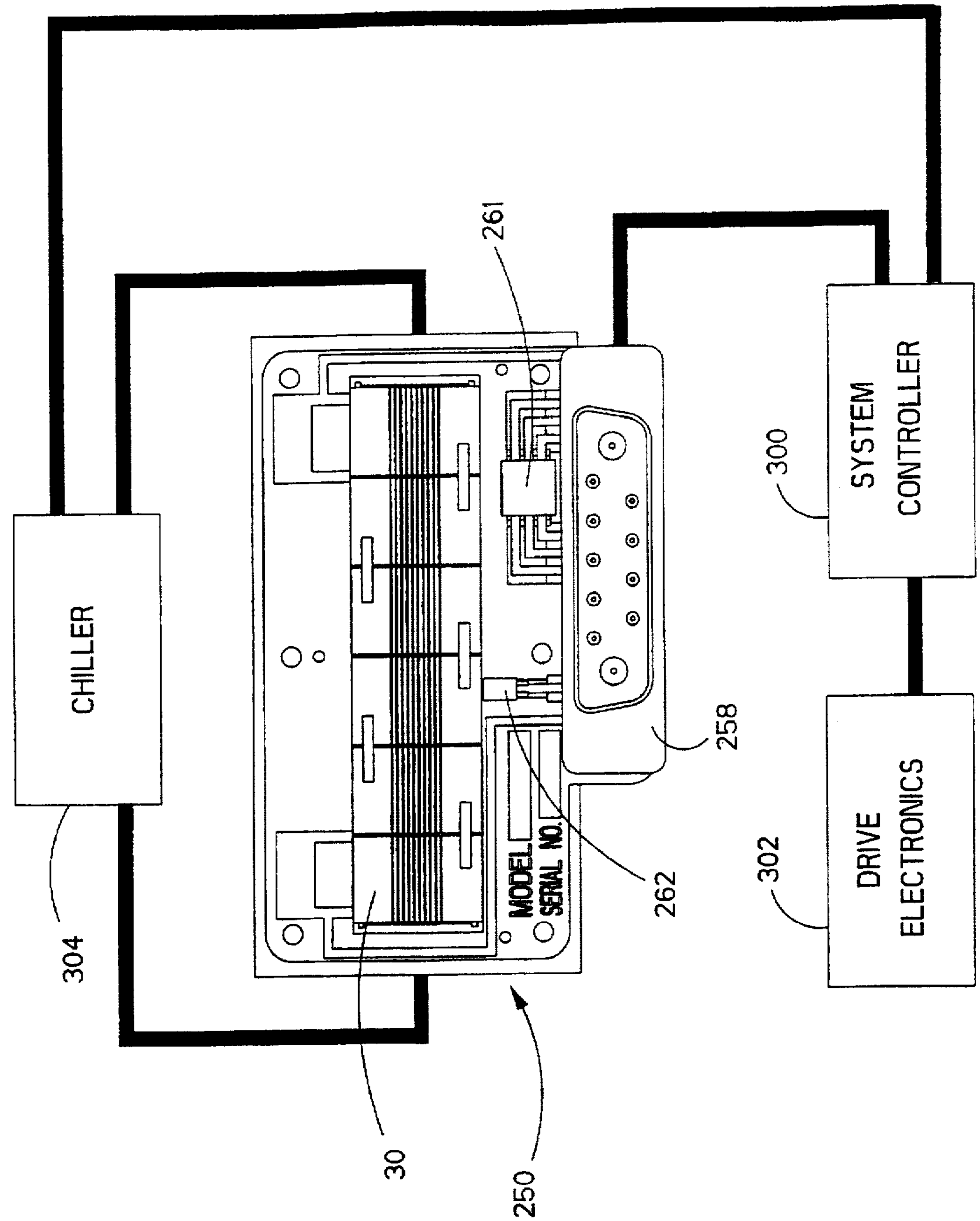


FIGURE 8


CHILLER
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30
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MODEL
SERIAL NO.
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261
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SYSTEM CONTROLLER
300
DRIVE ELECTRONICS
302

FIGURE 9

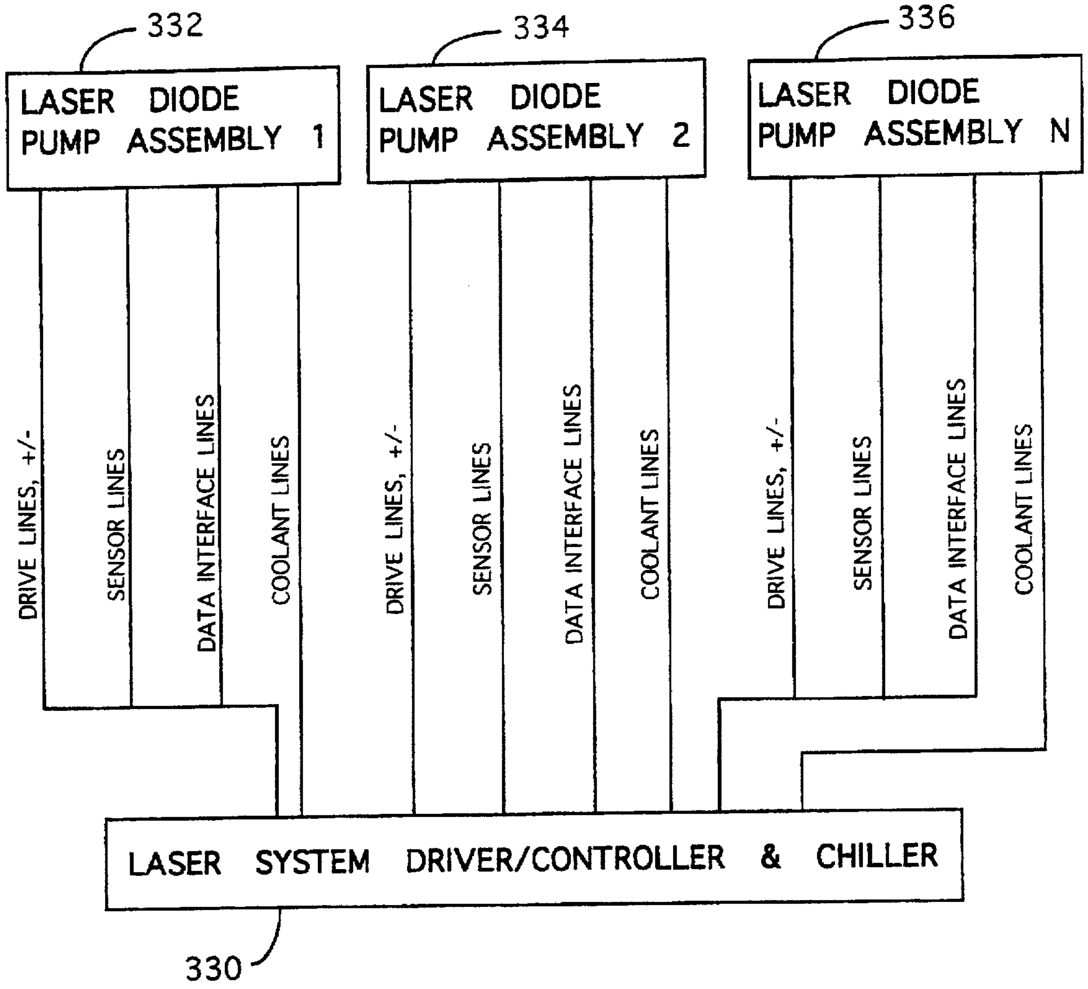
332
LASER DIODE PUMP ASSEMBLY 1
334
LASER DIODE PUMP ASSEMBLY 2
336
LASER DIODE PUMP ASSEMBLY N
DRIVE LINES, +/-
SENSOR LINES
DATA INTERFACE LINES
COOLANT LINES
DRIVE LINES, +/-
SENSOR LINES
DATA INTERFACE LINES
COOLANT LINES
DRIVE LINES, +/-
SENSOR LINES
DATA INTERFACE LINES
COOLANT LINES
LASER SYSTEM DRIVER/CONTROLLER & CHILLER
330

FIGURE 10

SMART LASER DIODE ARRAY ASSEMBLY AND OPERATING METHOD USING SAME

FIELD OF THE INVENTION

The present invention relates generally to lasers diodes and, in particular, to an assembly that includes a laser diode array, an integral memory device storing operational information about the laser diode array, and an integral processing device that records information to and retrieves information from the memory device.

BACKGROUND OF THE INVENTION

Semiconductor laser diodes have numerous advantages. They are small in that the widths of their active regions are typically submicron to a few microns and their heights are usually no more than a fraction of a millimeter. The length of their active regions is typically less than about a millimeter. The internal reflective surfaces, which are required in order to produce emission in one direction, are formed by cleaving the substrate from which the laser diodes are produced and, thus, have high mechanical stability. Additionally, high efficiencies are possible with semiconductor laser diodes with pulsed junction laser diodes having external quantum efficiencies near 50% in some cases.

The cost and packaging of laser diodes are problems that has limited their commercialization. It is only recently that both the technology and availability of laser diode bars, and a method for packaging them, has made two dimensional laser diode pump arrays a commercial reality. One technique for producing such a two dimensional laser diode array is demonstrated in the U.S. Pat. Nos. 5,040, 187 and 5,128,951 to Karpinski. Also, newer techniques have been used to make more efficient an older packaging approach whereby individual diodes are sandwiched between two metallic foils. The advent of lower cost laser diodes and efficient packaging has led to the possibility of producing very large, solid-state laser systems which use many pump arrays.

While laser diode pump arrays have a relatively long life when compared to the traditional flash-lamp or arc-lamp pump sources, they are still considered consumable items that require periodic replacement. In some cases with modularized laser diode arrays, one may even wish to replace only a portion of the array. For pulsed lasers, the number of shots which the laser diode arrays have fired is recorded. For continuous-wave (CW) lasers, the amount of time the laser diode arrays have operated (time-on) is of interest. Typically, these values are monitored and stored within the external electronic control systems which operate these laser systems. These electronic control systems must contain a shot-counter or time-on counter for each laser diode pump array to determine the relative age of each laser diode array thereby permitting the development of a replacement schedule for each laser diode array. However, when a laser diode pump array is replaced, these shot-counters or on-timers must have the ability to be reset to zero if a new laser diode array is used. If a used laser diode array is installed, then these shot-counters or on-timers must have the ability to be reset to a predetermined value. Furthermore, when a laser diode array is removed from a system for replacement, a difficulty arises in that there is no longer a shot count or on-time associated with the pump array, unless written records are meticulously kept.

In addition to the shot-count, there is other information about a diode array that is of particular interest, such as the serial number of the array, the number and frequency of over-temperature fault conditions, and the voltage drop (i.e. the resistance rise) across the array. These characteristics are useful for selecting an application for a used laser diode array, or for determining the causes of its failure. These characteristics are also important for warranty purposes. However, the operator of the system has no interest in recording these data since it may limit his or her ability to rely on the warranty when a failure arises. On the other hand, the manufacturer has a keen interest in knowing the operational history of an array for warranty purposes.

When semiconductor laser diodes are used as the optical pumping source for larger, solid-state laser systems, the emitted wavelength is critical. Laser diode pump arrays achieve efficient pumping of the laser host material (e.g. Neodymium-doped, Yttrium-Aluminum Garnet) by emitting all of their light energy in a very narrow spectral band which is matched to the absorption spectrum of the gain media (i.e. slabs, rods, crystals etc.), typically within 2–6 nanometers full-width at the half-maximum point (fwhm). The laser diode pump array emission wavelength is a function of the temperature at which the pump array is operated. The pump array temperature is a complicated function of many interrelated variables. The most important of these variables are the temperature of the coolant flowing to the diode array, the operational parameters of the diode array, and the configuration of the heat exchanger on which the laser diodes are mounted. The operational parameter of a CW driven array is simply the drive current. But for pulsed laser systems, the peak drive current, the repetition rate, and the pulse width of the drive current are all important operational parameters. Because the performance of the laser diode array changes during the service life of a laser diode array, the host external system controller has to compensate for any degradation of performance (output power or wavelength) by modifying these input operational parameters except for the heat exchanger configuration. Often, the altering of the operational parameters requires manual calibration of the arrays using external optical sensors. This is a tedious job and requires a skilled technician who understands the ramifications of modifying the interrelated variables which change the output power and wavelength. Even when the laser diode array's operational parameters are properly calibrated, rapid changes in the performance of the laser diode array may go unnoticed until the next scheduled maintenance. This manual calibration also is often required during the initial installation of the laser diode array assembly.

Therefore, a need exists for a laser diode array assembly that includes an integral means for recording operational events and maintaining this information with the assembly throughout its service life. It would also be beneficial for this laser diode array assembly to have the capability of instructing the external laser operating system on the input drive parameters that should be used to provide for optimal output of the laser diode array assembly.

SUMMARY OF THE INVENTION

A modular laser diode array assembly includes at least one laser diode array, an intermediate structure on which the array is mounted, and an integral memory device. The laser diode array has a plurality of laser diodes which are in electrical contact with at least one other of the plurality of laser diodes. The assembly further includes means for supplying external power to the laser diode array. The memory device stores operating information for the laser diode array and is mounted on the intermediate structure which may be a printed circuit board. The memory device communicates with an external operating system. After the assembly is

installed in and connected to the external operating system, a system controller accesses the memory device to obtain the operating information (temperature, input power parameters, etc.) which enables the system controller to properly apply power to, or set conditions for, the laser diode array.

In another embodiment, the assembly includes sensors for sensing the operating conditions experienced by the laser diode array. The external operating system monitors the sensors to assist in determining the operational parameters at which the system is to be operated. These sensors may be optical power sensors, optical wavelength sensors, electrical input power sensors, temperature sensors, vibration sensors, etc.

In yet another embodiment, the assembly includes processing means that communicates with the external operating system. The processing means is coupled to the sensors for directly monitoring the operating conditions of the laser diode array and is also coupled to the memory device. Based on the operating conditions monitored, the processing means instructs the external operating system to supply the optimum operating parameters. Thus, the assembly is self-calibrating in that it monitors the operating conditions and instructs the external operating system to provide input power in a manner that allows for the optimum output.

Using the integral memory device and the processing means provides numerous benefits. For example, the shot-count or on-time value becomes physically a part of the assembly as it is stored within the integral memory device. This integral memory device could then be read from and updated, as necessary, by the control electronics of the external operating system or the processing means when one is used.

There are many additional pieces of data which could be stored in this memory device, such as: the array serial number; the number and times of fault conditions such as over temperature or activation of protection circuitry; the voltage drop across the array and the time of the occurrence if it changes significantly (this may be an indication of individual laser bar failures); and the array's spectral and power response to different operational conditions. The memory device may also record the ambient environmental conditions such as the ambient temperature, the ambient shock environment, ambient humidity, or electrostatic discharge (ESD) events resulting from the environment around the array.

The above summary of the present invention is not intended to represent each embodiment, or every aspect, of the present invention. This is the purpose of the figures and the detailed description which follow.

BRIEF DESCRIPTION OF THE DRAWINGS

Other objects and advantages of the invention will become apparent upon reading the following detailed description and upon reference to the drawings in which:

FIG. 1A is a perspective view of a laser diode array used in the present invention;

FIG. 1B is a perspective view of another laser diode array used in the present invention;

FIGS. 2A–2D are views of a multiple-array assembly having an integral memory device and a sensor;

FIGS. 3A–3C are views of a multiple-array assembly having an integral processing device including a memory device, a sensor, and multiple photodetectors;

FIGS. 4A–4B are views of a single-array assembly having an integral processing device including a memory device, a sensor, and a photodetector;

FIG. 5 is a plan view of a single-array assembly having an integral memory device, a temperature sensor, and a photodetector;

FIG. 6 is a plan view of a multiple-array assembly having an integral processing device including a memory device, a temperature sensor, multiple photodetectors, and an input power sensing device;

FIG. 7 is perspective view of the multiple-array assembly of FIGS. 3A–3C including a connector and being installed on a heat exchanger;

FIG. 8 is a perspective view of a multiple-array assembly having an printed circuit board positioned at approximately 90° degrees from the plane in which the emitting surfaces reside;

FIG. 9 is a schematic view of a multiple-array assembly incorporating the present invention and being installed in an external operating system; and

FIG. 10 is a schematic view of an external operating system being coupled to multiple assemblies labeled 1-N.

While the invention is susceptible to various modifications and alternative forms, a specific embodiment thereof has been shown by way of example in the drawings and will herein be described in detail. It should be understood, however, that it is not intended to limit the invention to the particular forms disclosed. Quite to the contrary, the intent is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION OF THE INVENTION

Referring initially to FIG. 1A, a laser diode array **10** is illustrated in a perspective view. The laser diode array **10** includes a plurality of laser diodes packages **12** each of which includes a laser diode **13** sandwiched between a heat sink **14** and a lid **17**. The laser diode packages **12** are arranged in a parallel fashion commonly referred to as a stack. At the ends of the stack are endcaps **18** and **19** through which power is supplied to the stack of laser diode packages **12**. A thermal backplane **20**, usually made of an electrically insulative material, such as beryllium oxide, is the surface to which each of the packages **12** is mounted. The laser diode array **10** is one type of array that can be used in the present invention.

In FIG. 1B, a second type of laser diode array **30** is illustrated. The laser diode array **30** includes a substrate **32** made of an electrically insulative material and a plurality of grooves **34** which are cut in the substrate **32**. Within each groove **34** is a laser diode bar **36**. To conduct electricity through the plurality of laser diode bars **36**, a metallized layer is placed within each groove **34** and connects adjacent grooves **34**. The bottom of the substrate **32** is the backplane through which heat flows to the heat exchanger positioned below the bottom. Although the number of grooves **34** is shown as ten, the application of the array **30** dictates the amount laser diode bars **36** and, therefore, the number of grooves **34**. Laser diode array **30** is another type of laser diode array that can be used with the present invention.

FIGS. 2A–2D are views of an assembly **40** having six laser diode arrays **30**, an integral memory device **42**, and a sensor **44**. The memory device **42** and the sensor **44** are mounted on a printed circuit board (PCB) **46**. The information on the memory device **42** can be accessed and the sensor **44** can be monitored through contact pads **47** located on the PCB **46**. A board heat sink **48** is disposed on the back of the

PCB **46** and is the surface to which the backplanes of the laser diode arrays **30** are attached. The diode arrays **30** can be soldered to this heat sink **48** or fastened in other ways which minimize the thermal resistance across the interface of the heat sink **48** and the laser diode array **30**.

The sensor **44** can be of a type that measures output power or output wavelength (assuming it receives the emitted light). More commonly, the sensor **44** is a temperature sensor since the temperature of the arrays **30** is critical to their operation. If the sensor **44** is a temperature sensor, it could be moved to a location closer to the backplanes of the arrays **30**. The sensor **44** may also be an ESD sensor or one that measures the shot-count or on-time of the array **30**. Furthermore, the PCB **46** may contain multiple sensors although only one sensor **44** is shown.

The memory device **42** preferably is a non-volatile memory device such that the information stored therein is not altered when power is removed from the memory device **42**. An example of such a memory device **42** is the model 24632, manufactured by Microchip, of Chandler, Ariz.

To protect the emitting surfaces of the laser diode arrays **30**, a protective window **50** can be affixed to the assembly **40**. The protective window **50** is supported by a retainer frame **52**. The frame **52** and the window **50** may merely act to protect the upper emitting surfaces. Alternatively, the frame **52** and window **50** may completely seal the six laser diode arrays **30** by placing a sealing material between the frame **52** and the window **50**. The window **50** can be made of a variety of materials including acrylic with an anti-reflective coating. Besides the window **50** that is shown, the window **50** could be replaced by a diffractive, binary, or two-dimensional array of lenses to provide focusing and collimation to the beam of energy. FIG. **2D** illustrates the assembly **40** without the window **50** and retainer frame **52**.

The laser diode arrays **30** require electrical energy to produce the emitted radiation. Thus, a pair of contact pads **54*a*** and **54*b*** are located on the PCB **46**. To provide electrical energy to the laser diode arrays **30**, a pair of leads **56*a*** and **56*b*** are disposed between the endcaps of the two end arrays **30** and the pads **54*a*** and **54*b***. Adjacent arrays **30** are connected in electrical series through jumpers **57**. In the case where the window **50** and the frame **52** seal the laser diodes **30**, the leads **56*a*** and **56*b*** can be potted or bonded onto the window frame **52**. The host external operating system makes electrical contact with the assembly **40** through the contact pads **54*a*** and **54*b***.

The PCB **46** and the board heat sink **48** include holes **58** through which fasteners will pass to connect the assembly **40** to the ultimate heat sink which is typically a high efficiency heat exchanger. Also provided are indexing holes **60** which align the PCB **46** and, therefore, the array **30** on the ultimate heat sink.

Although the PCB **46** is shown as the intermediate structure between the array **30** and the memory device **42**, other structures could be used. For example, merely providing an epoxy layer which adheres the memory device **42** to the array **30** may suffice if the epoxy provides electrical insulation.

The memory device **42** contains the operating information for the laser diode arrays **30**. The types of information can range from the basic to the complex. For example, the identity of the laser diode array assembly **40** can be recorded in the memory device. This can include the wafer number of the wafers that were used to produce the laser diode bars that are contained in each array **30**. It may also include the lot number of the bars comprising the arrays **30** or the laser diode bar number. It may also include an inspector number associated with the individual who approved of the bar in the quality control department.

The memory device **42** can also be loaded with performance data on the laser diode array assembly **40**. For example, the center wavelength can be given as well as the wavelength shift as a function of temperature (i.e. Gallium Arsenide laser diodes shift at about 1 nanometer per about 3–4°C). The wavelength distribution of the arrays **30** can be stored so as to provide the full-width at half maximum value (FWHM) (i.e. the difference between the wavelengths at the point on the wavelength distribution curve where the intensity is at one-half of its maximum value). This FWHM value is critical when the assembly **40** is used for solid-state laser pumping applications. The wavelength can also be given as a function of spatial orientation along the assembly **40**.

Information related to the output power can be included as well. For example, the output power can be given as a function of the efficiency of the arrays **30**, the current and voltage at which the arrays **30** are driven, or the threshold current (i.e. the current after which lasing occurs). The output power can also be given as a function of spatial orientation along the assembly **40**. Also, the estimated output power degradation of the array **30** over its service life can be stored.

The memory device **42** can also include extreme design values for various operating conditions that should not be exceeded for a particular array. For example, the maximum or minimum design operating temperature can be recorded as can the maximum design drive parameters such as current, pulse-width, duty-cycle, voltage, etc. This allows for a real-time comparison between the actual operating conditions and the extreme design conditions to ensure that no damage will occur to the laser diode array **30**. The external operating system may use such a comparison to shut-down the system when the extreme design values are exceeded.

Although the memory device **42** has been described thus far as having operational information that has been recorded before its delivery to the customer, the memory device **42** can also be updated with information throughout its service life. Typically, the external operating system is monitoring various environmental conditions including temperature, vibration, shock, humidity, and also the input drive parameters. Since the operating system is configured to read from the memory device **42**, the only difference needed to achieve the goal of updating the memory device **42** is merely having an external operating system with the capability to write to the memory device **42**. Consequently, the memory device **42** then captures the operational history of the array **30** which is advantageous for determining the cause of failures and for warranty purposes.

The types of operational information related to the service life of the array **30** that can be recorded in the memory device **42** is quite extensive. For example, the shot-count of a pulsed laser diode array **30** or the on-time of a CW laser diode array **30** can be recorded. This is a very important value when considering the warranty of the array **30**.

The extreme operating conditions which the laser diode array **30** experiences can be recorded in the memory device **42** which is also useful for warranty purposes and for determining the cause for failures. Thus, the maximum and minimum operating temperature can be recorded in the memory device **42**. Other operating conditions such as the maximum shock, vibration, and humidity can be recorded as well. The maximum drive parameters (current, voltage, pulse width, frequency, etc.) can also be recorded in the memory device **42**. Additionally, the extreme ambient conditions of the environment surrounding the array **30** or surrounding the entire external operating system can be stored as well (nonoperational or operational).

A list of incident reports may be recorded in the memory device **42**. This may include the over-temperature failures, over-current failures, over-voltage failures, reverse-voltage failures (i.e. wrong bias across the arrays **30**), coolant-flow interrupts (to the heat exchanger), and electrostatic discharge events. These faults can be recorded as merely an affirmative response to whether the fault occurred or as the value of the condition. Additionally, a drop in the voltage across the array **30** is indicative of a single laser diode failure and may be recorded. For example, a typical voltage drop across one good laser diode is approximately 2.0 volts and about 0.5 volt after certain types of failures. The number of laser diode bar failures can be estimated by such a voltage drop. Other types of fault conditions may be included as well, including those fault conditions recorded by sensors monitoring the output of the arrays **30** (i.e. wavelength and power).

Thus far, only fault conditions, operating conditions, and non-operating conditions have been discussed as being data that are recorded in the memory device **42**. However, recording the dates and times of these conditions is also worthwhile and can be accomplished by having the external operating system write the times that these conditions occur in the memory device **42**. When the time values are recorded, the memory device **42** then can be used to store a variety of parameters as a function of time (temperature, input power, output power, output wavelength, etc. v. time).

FIGS. 3A–3C illustrate an assembly **140** having multiple arrays **30** similar to the assembly **40** of FIGS. 2A–2D. The assembly **140** includes a processor **143** and a temperature sensor **144** that are mounted on a PCB **146**. A heat sink **148** is located on the backside of the PCB **146** and is the structure to which the arrays **30** are attached. Each array **30** has a corresponding photodetector **149** which measures the output characteristics of the emitted light. As shown best in FIG. 3C, the emitted light reflects partially off the inside surface of the window **150** and then hits the photodetector **149**. The photodetector **149** may measure the power of the reflected light which corresponds to the output power of the entire array **30**. Alternatively, the photodetector **149** may be of a more advanced type that measures the output wavelength of the reflected beam which corresponds to the output wavelength of the emitted output.

The processor **143** as shown includes a memory portion which allows basic information to be stored therein (extreme operating temperatures, input powers, etc.) If a larger amount of information is to be stored, then it may be desirable to include a separate memory chip on the PCB **146**, like the memory device **42** in FIG. 2, and couple it to the processor **143** for storing the additional data. This may be required when the operational history of the laser diode array **30** is to be recorded.

The processor **143** is coupled to the temperature sensor **144** and to the photodetectors **149** through traces on the PCB **146**. The processor **143** is also coupled to an external operating system through contact pads **147**. In this way, the processor **143** determines the appropriate drive levels to be supplied by the external operating system based on the conditions it monitors through the temperature sensor **144** and the photodetectors **149**. The processor **143** also instructs the external operating system to supply the coolant at a

temperature and a rate that maintains the temperature of the temperature sensor **144** at the desired value. The processor **143**, therefore, provides a self-calibrating system in that any deviations seen in the output power and wavelength can be altered by instructing the operating system to change the input drive parameters and the coolant characteristics.

The processor **143** would typically be an Application Specific Integrated Circuit (ASIC) or a hybrid, custom-manufactured model.

FIGS. 4A and 4B illustrate an assembly **180** having a single array **182**, a processor **184**, a photodetector **186**, and a temperature sensor **188**. The array **182** holds substantially more bars than arrays **10** and **30** of FIGS. 1A and 1B. The photodetector **186** and the temperature sensor **188** are mounted on a PCB **190** and are coupled to the processor **184** which is also mounted on the PCB **190**. The array **182** is mounted to a heat sink **189** below the PCB **190**. Power is supplied to the array **182** via a pair of contacts **192** and **194** which are coupled to the array **182** via leads **192*a*** and **194*a***. A trace **194*b*** runs within the PCB **190** from the lead **194*a*** to the endcap of the array **182** adjacent the photodetector **186**.

The processor **184** has internal memory portion with enough capacity to perform the required tasks. Alternatively, a memory device can be mounted on the PCB **190** and coupled to the processor **184**.

Also connected to the processor **184** is a circuit **196** which limits high power being received by the processor **184**. This circuit **196** is coupled to the input power leads and allows the processor **184** to determine the voltage drop across the array **182** or the current therethrough. Because the array **182** is usually coupled in series with a field effect transistor (FET) and a known voltage drop occurs across the diode array **182** and the FET, the processor **184** could also monitor the voltage drop across the FET to determine the voltage drop across the array **182**. The change in the voltage drop across the array **182** is indicative of a failure of the individual laser diode bars within the array **182**. The circuit **196** may include a fuse for guarding against high voltage or high current.

The use of such a circuit **196** also permits the counting of each shot supplied to the array **182** or the amount of on-time if array **182** is a CW laser. Thus, the processor **184** would count and store these values.

Although the circuit **196** has been described as one which measures the voltage drop across the array **182** or counts shots, it could also include a reverse-bias sensor (possibly an electrical diode) that permits the flow of current in one direction. If a voltage is applied in the wrong direction, then the current will flow through the electrical diode instead of the array **182** which decreases the likelihood of any harm to the array. Thus, the processor **184** can monitor the occurrence of a reverse-bias fault.

The circuit **196** can also include components for monitoring a electrostatic discharge across the array **182**. Thus, the processor **184** could monitor this circuit **196** for such an event and record it as well.

FIG. **5** illustrates an assembly **200** having a single array **202**, a memory device **204**, a photodetector **206**, and a temperature sensor **208**. These memory device **204** and the photodetector **206** are mounted on a PCB **210** while the array is mounted on a heat sink on the bottom of the PCB **210**. Thus, this single-array assembly **200** does not have the processing capability of assembly **180** in FIG. **4**. Instead, assembly **200** supplies to the external operating system the operational information needed to operate the array **202**. Also, the memory device **204** can be configured to receive and record information (fault conditions, operating conditions, etc.) from the external operating system.

The external operating system communicates with the memory device **204** by the contact pads **212** at the edges of the PCB **210**. Likewise, the external operating system communicates with the photodetector **206** and the temperature sensor **208** via the pads **212**.

FIG. **5** also illustrates the geometrical configuration of the assembly **200**. The emitting surfaces of the laser diode array **202** are within an area defined by LDY multiplied by LDX. The area of the PCB **210** is defined PCBX multiplied by PCBY. It is desirable to keep the ratio of the PCB area to the emitting area as low as possible such that the assembly **200** having these additional components (e.g. sensors, memory devices, processors, etc.) is not much larger that just the array. This is important for retrofitting purposes. Generally, the ratio of the PCB area to the emitting area is less than approximately 10 to 1. In a preferred embodiment, the ratio is in the range from about 5 to 1 to about 7 to 1. When a connector is added to the PCB **210** (see FIGS. **7** and **9** below), the ratio is less than about 14 to 1.

FIG. **6** illustrates an assembly **230** having six arrays **30** which is very similar to the assembly **140** shown in FIGS. 3A–3C. However, the processor **232** is coupled to the contacts **233** and **234** through circuits **236** and **238**. These circuits **236** limit the high power to the processor **232** so as to allow the processor **232** to determine the voltage drop across the six arrays **30**.

Again, circuits **236** and **238** may instead, or in addition to what is described above, provide for electrostatic discharge sensing.

Circuits **236** and **238** may also be used for counting the shots of a pulsed laser or the on-time for a CW laser since the processor **232** can receive a signal from these circuit each time power is supplied to the assembly **230**. Alternatively, if circuits **236** include an electromagnetic sensor (e.g. a Hall's Effect sensor) then they just need to be in close proximity to the arrays **30** or the contact pads **233** and **234** such that each time a high-current pulse is supplied to the assembly **200**, the Hall's Effect sensor is tripped by the resultant electromagnetic field. The processor **232** then receives the signal after each shot.

The arrays **30** have a finite life which is in a large part a function of the temperature at which they are operated and the power is supplied thereto. Because the processor **232** monitors both the temperature and the input power, the processor **232** can compare these values to a range of standard, assumed, operating conditions. Then, the processor **232** modifies the estimated life at a predetermined rate programmed in the processor **232** based on the actual conditions under which the arrays **30** are being operated. In a preferred embodiment, not only would the processor **232** inform the external operating system of the amount of service that is remaining, but the processor **232** would also inform the external operating system of the amount that the estimated life has been adjusted based on the actual operating conditions.

FIG. **7** illustrates an assembly **250**, similar to the one shown in FIGS. 2A–2D, that is mounted on a heat exchanger **252** having an inlet port **254** and an outlet port **256**. The assembly **250** further includes a connector **258** to which the external operating system is coupled. The arrays **30** are connected to the heat sink **257** of the PCB **259**. The heat sink **257** of the PCB **259** is mounted on the heat exchanger **252** by a series of fasteners **260**.

The connector **258** is coupled to a memory device **261**, to a sensor **262** (i.e. one of the types discussed thus far), and to power supply contact pads **264** and **266**. Each of these devices is mounted on the PCB **259** and is coupled to the connector **258** through traces located on the PCB **259**. The connector **258** provides for an easy connection between the assembly **250** and the external operating system.

FIG. **8** illustrates an alternative embodiment in which an assembly **290** includes a PCB **292** that is located in a plane that is generally perpendicular to the emitting surfaces of arrays **30**. Consequently, the arrays **30** are elevated slightly from a base **294** which attaches the assembly **290** to a heat exchanger. Again, the assembly **290** includes a memory device **296** and two sensors **297** and **298**. Typically, sensor **298** is a temperature sensor and sensor **297** is a photodetector. Each of the sensors **297** and **298** and the memory device **296** are coupled to contact pads **299** at the end of the PCB **292** through traces (not shown) in the PCB **292**. The assembly **290** communicates with the external operating system through these contact pads **299**.

FIG. **9** illustrates the assembly **250** of FIG. **7** installed in the external operating system. Thus, a system controller **300** is coupled to drive electronics **302** which supply the electrical power needed to operate the diode arrays **30**. The system controller **300** is also coupled to a chiller **304** which supplies the cooling fluid to the heat exchanger **252** (FIG. **7**). The system controller **300** receives operational information from the memory device **261** via the connector **258**. For example, the operational information received from the memory device **261** may inform the controller **300** that to obtain X watts of output power at **808** nanometers, the temperature at the temperature sensor **262** must be 31° C. and the arrays must be driven at 110 amps with a rate of 30 Hz, and a pulse width of 220 microseconds. The system controller **300** then causes the drive electronics **302** to supply the requested input power and causes the chiller **304** to provide coolant at a rate and a temperature that will maintain sensor **262** at 31 °C.

Although the cooling system has been described as a chiller **304**, the system could also be one which utilizes solid-state thermoelectric coolers such as those manufactured by Marlow Industries of Dallas, Tex. The cooling capacity of these devices varies as a function of the input power. Thus, the system controller **300** would control the electrical power to the thermoelectric coolers such that their cooling capacity would result in the desired temperature at the arrays **30**.

The controller **300** also may store in the memory device **261** operational conditions if the configuration of the memory device **241** allows for this information. Thus, the controller **300** could record to the memory device **261** extreme operating conditions (temperature, humidity, shock, vibration, the amount of on-time or the number of shots, etc.), extreme non-operating conditions (temperature, humidity, shock, vibration), extreme input powers (current, voltage, duty cycle, etc.), and fault conditions (coolant non-flow condition, electrostatic discharge, over-temperature fault, over-power fault, reverse-bias faults). Clearly, sensors (vibration sensors, shock sensors, humidity sensors, etc.) which measure these types of operating conditions would need to be incorporated onto the PCB or be adjacent the assembly **250** and monitored by the controller **300**.

If a processor is used on the assembly **250**, then the processor may monitor these sensors instead of the controller **300** monitoring them. Additionally, a processor could monitor the output of the assembly **250** and provide real-time modifications to the instructions sent to the system controller **300**. Thus, the basic operating information stored in the memory device **261** would serve as a starting point for operation and be modified based on the conditions sensed by the sensors and monitored by the processor.

FIG. **10** is a schematic illustrating a concept similar to what is shown in FIG. **9** except that the external operating system **330** is coupled to multiple assemblies **332**, **334**, **336** to produce the desired output. For example, the desired output from each assembly may by X watts at **808** nanometers. The operating system **330** then receives information from each assembly **332**, **334**, and **336** through the data interface lines which indicates the temperature and input power require to produce this output. Each assembly **332**, **334**, and **336** will usually require slightly different operating parameters (e.g. 33° C., 36° C., and 32° C.; or **105**A, **108**A, and **101**A) to achieve the desired output. Consequently, the operating system **330** supplies coolant and input power at different levels to each assembly **332**, **334**, and **336**. The operating system **330** may monitor sensors on the assemblies **332**, **334**, **336** through the sensor lines. Alternatively, if a processor is present on each of the assemblies **332**, **334**, **336**, the processor may monitor the sensors and instruct the operating system **330** accordingly through the data interface lines.

The present invention is quite useful for numerous reasons. For example, one of the main factors affecting yield and, therefore, the cost of laser diode pump arrays, is selecting only laser diode bars within a small spectral range for incorporation into one array. There is a significant cost savings if it is possible to use pump arrays which have a larger range in their peak emission spectra, since the system control electronics will be able to compensate for the array's spectral differences by using the stored thermal and spectral (wavelength) information. Furthermore, storing the thermal/spectral data within the assembly considerably simplifies replacement of a used or damaged assembly by allowing for the automatic compensation for the new assembly by merely accessing this data within the assembly's memory device. There is no longer the need to build a replacement array that exactly matches the used or damaged array.

Because the shot count or timer is integral with the assembly, rather than with the external control system electronics, the records are accurately maintained. And, a simplified way of recording significant events (faults, extreme conditions, etc.) is provided. Consequently, the need for meticulously recording this type of information on paper is obviated and, therefore, the integrity of the operational information on the array is greatly improved. Accessing this information from the memory device of the assembly is also useful for later analyzing the problems experience by the assembly.

The safety features of the assembly are greatly improved by providing in-situ monitoring of such operating conditions such as the array's voltage, temperature, ambient humidity, and the occurrence of fault conditions. This information can be used to shut-down the assembly to avoid damage to the assembly or injury to the operator of the assembly.

Each of these embodiments and obvious variations thereof is contemplated as falling within the spirit and scope of the invention, which is set forth in the following claims.

What is claimed is:

1. A modular laser diode array assembly, comprising:

at least one laser diode array having a plurality of laser diodes, each of said plurality of laser diodes being in electrical contact with at least one other of said plurality of laser diodes;

an intermediate structure to which said at least one laser diode array is attached;

a memory device mounted on said intermediate structure for storing operating information for said at least one laser diode array, said memory device for communicating with an external operating system.

2. The modular laser diode array assembly of claim **1**, wherein said operating information includes the serialization identity of said at least one laser diode array.

3. The modular laser diode array assembly of claim **1**, wherein said operating information includes an estimate of output energy degradation over the service life of said at least one laser diode array.

4. The modular laser diode array assembly of claim **1**, wherein said operating information includes a wavelength of output energy as a function of temperature of said at least one laser diode array.

5. The modular laser diode array assembly of claim **1**, wherein said operating information includes output energy of said at least one laser diode array as a function of input power.

6. The modular laser diode array assembly of claim **1**, wherein said external operating system records in said memory device updated operating information based on the performance of said at least one laser diode array.

7. The modular laser diode array assembly of claim **1**, wherein said external operating system records in said memory device operating conditions experienced by said at least one laser diode array.

8. The modular laser diode array assembly of claim **7**, wherein said operating conditions include a maximum temperature of said at least one laser diode array.

9. The modular laser diode array assembly of claim **7**, wherein said operating conditions include a maximum power supplied to said at least one laser diode array.

10. The modular laser diode array assembly of claim **7**, wherein said operating conditions include a total on-time or shot-count of said at least one laser diode array.

11. The modular laser diode array assembly of claim **7**, wherein said operating conditions include a maximum ambient condition to which said at least one laser diode array is subjected.

12. The modular laser diode array assembly of claim **7**, wherein said operating conditions include a fault condition experienced by said at least one laser diode array, said fault condition being one of the group consisting of a reverse-bias fault, a coolant flow fault, an extreme power input fault, an extreme temperature fault, and an electrostatic discharge fault.

13. The modular laser diode array assembly of claim **7**, wherein the time that one of said operating conditions said operating conditions occurs is recorded in said memory device.

14. The modular laser diode array assembly of claim **1**, further including a temperature sensor for providing said external operating system with a temperature of said at least one laser diode array.

15. The modular laser diode array assembly of claim **14**, wherein said external operating system includes means to remove heat from said at least one laser diode array, said external operating system controlling the operation of said heat removal means in response to said temperature monitored via said temperature sensor.

16. The modular laser diode array assembly of claim **1**, further including an optical sensor for providing said external operating system with optical characteristics of said array.

17. The modular laser diode array assembly of claim **1**, wherein said intermediate structure includes a printed circuit board on which said memory device is mounted, said printed circuit board further having a surface on which said at least one laser diode array is mounted.

18. The modular laser diode array assembly of claim **17**, wherein said at least one laser diode array includes an emitting surface, said emitting surface being in a plane that is askew with said printed circuit board.

19. The modular laser diode array assembly of claim **17**, wherein said printed circuit board includes a connector to which said external operating system is coupled.

20. A modular laser diode array assembly, comprising:

at least one laser diode array having a plurality laser diodes, each of said plurality of laser diodes being in electrical contact with at least one other of said plurality of laser diodes;

an intermediate structure to which said at least one laser diode array is mounted;

at least one sensor for sensing operating conditions experienced by said at least one laser diode array;

a memory device for storing operating information of said at least one laser diode array and being mounted on said intermediate structure; and

processing means being mounted on said intermediate structure and being coupled to said at least one sensor for monitoring said operating conditions, said processing means being coupled to said memory device and to an external operating system.

21. The modular laser diode array assembly of claim **20**, wherein said operating information includes the serialization identity of said at least one laser diode array.

22. The modular laser diode array assembly of claim **20**, wherein said operating information includes an estimate of output energy degradation over the service life of said at least one laser diode array.

23. The modular laser diode array assembly of claim **20**, wherein said operating information includes a wavelength of output energy as a function of temperature of said at least one laser diode array.

24. The modular laser diode array assembly of claim **20**, wherein said operating information includes output energy of said at least one laser diode array as a function of input power.

25. The modular laser diode array assembly of claim **20**, wherein said memory device is integral with said processing means.

26. The modular laser diode array assembly of claim **20**, wherein said processing means records said operating conditions sensed by said at least one sensor in said memory device.

27. The modular laser diode array assembly of claim **26**, wherein said recorded operating conditions include a maximum temperature of said at least one laser diode array.

28. The modular laser diode array assembly of claim **26**, wherein said recorded operating conditions include a maximum power supplied to said at least one laser diode array.

29. The modular laser diode array assembly of claim **26**, wherein said recorded operating conditions include a total on-time or shot-count of said at least one laser diode array.

30. The modular laser diode array assembly of claim **26**, wherein said recorded operating conditions include a maximum ambient condition to which said at least one laser diode array is subjected.

31. The modular laser diode array assembly of claim **26**, wherein said operating conditions include a fault condition experienced by said at least one laser diode array, said fault condition being one of the group consisting of a reverse-bias fault, a coolant flow fault, an extreme power input fault, an extreme temperature fault, and an electrostatic discharge fault.

32. The modular laser diode array assembly of claim **20**, wherein said at least one sensor includes a temperature sensor measuring a temperature of said at least one laser diode array.

33. The modular laser diode array assembly of claim **20**, wherein said at least one sensor includes an optical sensor for measuring the output energy of said at least one laser diode array.

34. The modular laser diode array assembly of claim **20**, wherein said at least one sensor includes an optical sensor for measuring the output wavelength of the output energy of said at least one laser diode array.

35. The modular laser diode array assembly of claim **20**, wherein said at least one sensor includes a voltage sensor for measuring the voltage across said at least one laser diode array.

36. The modular laser diode array assembly of claim **20**, wherein said at least one sensor includes a current sensor positioned between said power contacts pads for measuring the current through said at least one laser diode array.

37. The modular laser diode array assembly of claim **35**, wherein said voltage sensor includes a fuse for relieving a high-voltage condition.

38. The modular laser diode array assembly of claim **36**, wherein said current sensor includes a fuse for relieving a high-current condition.

39. The modular laser diode array assembly of claim **20**, wherein said processing means instructs said external operating system to drive said at least one laser diode array at a power level delineated by said operating information stored in said memory device.

40. The modular laser diode array assembly of claim **39**, wherein said power level is updated based on said operating conditions monitored by said processing means via said at least one sensor.

41. The modular laser diode array assembly of claim **40**, wherein said sensor is a temperature sensor measuring a temperature of said at least one laser diode array.

42. The modular laser diode array assembly of claim **40**, wherein said sensor is an optical sensor measuring optical characteristics of said at least one laser diode array.

43. The modular laser diode array assembly of claim **20**, wherein said external operating system includes means to remove heat from said at least one laser diode array and said at least one sensor includes a temperature sensor, said processing means instructing said external operating system to operate said heat removal means at a specified level in response to a temperature monitored via said temperature sensor.

44. The modular laser diode array assembly of claim **20**, wherein said intermediate structure includes a printed circuit board on which said memory device and said processing means are mounted, said printed circuit board further having a surface on which said at least one laser diode array is mounted.

45. The modular laser diode array assembly of claim **44**, wherein said at least one laser diode array includes an emitting surface, said emitting surface being in a plane that is askew with said printed circuit board.

46. The modular laser diode array assembly of claim **44**, wherein said at least one sensor is mounted on said printed circuit board.

47. The modular laser diode array assembly of claim **44**, wherein said printed circuit board includes a connector to which said external operating system is coupled.

48. The modular laser diode array assembly of claim **44**, wherein said at least one sensor includes a temperature sensor and an optical sensor, said temperature sensor and said optical sensor being mounted on said printed circuit board.

49. The modular laser diode array assembly of claim **20**, further including a window disposed above an emitting surface of said at least one laser diode array.

50. A modular laser diode array assembly, comprising:

at least one laser diode array having a plurality laser diodes, each of said plurality of laser diodes being in electrical contact with at least one other of said plurality of laser diodes, said at least one laser diode array having an emitting region where energy is emitted from each of said laser diode arrays, said emitting region defining an emitting area;

a printed circuit board mechanically coupled to said at least one laser diode array, said printed circuit board including a plurality of contact pads and having a board area, the ratio of said board area to said emitting area being less than approximately 10.

a memory device for storing operating information on said plurality of laser diodes and being mounted on said printed circuit board, said memory device being coupled to said plurality of processing contact pads for communicating with an external operating system.

51. The modular laser diode array assembly of claim **50**, wherein said ratio is in the range from about 5 to about 7.

52. The modular laser diode array assembly of claim **50**, further including at least one sensor for monitoring an operating condition of said at least one laser diode array, said sensor being electrically coupled to said printed circuit board.

53. The modular laser diode array assembly of claim **52**, further including processing means monitoring said at least one sensor and being coupled to said external operating system.

54. The modular laser diode array assembly of claim **53**, wherein said printed circuit board includes a connector thereby increasing the area of said board to a second area, the ratio of said second area to said emitting area being increased to approximately 14.

55. A method of operating a laser diode array comprising the steps of:

providing a laser diode array having an associated memory device;

storing operating data for said laser diode array in said associated memory device;

assembling said laser diode array into an operating system having drive electronics and a controller, said drive electronics being coupled to said laser diode array, said controller being coupled to said drive electronics and to said associated memory device;

instructing said controller to retrieve said operating data from said associated memory device; and

powering said drive electronics at an electrical drive state corresponding to said operating data to produce output energy from said laser diode array.

56. The method of claim **55**, further including the steps of:

monitoring an operating condition of said laser diode array with at least one sensor;

selecting other operating data in response to said operating condition monitored by said at least one sensor; and

instructing said controller to retrieve said other operating data so as to modify said electrical drive state.

57. The method of claim **56**, wherein said at least one sensor is a temperature sensor measuring a temperature of said laser diode array.

58. The method of claim **56**, wherein said at least one sensor is an optical output sensor for monitoring the output energy of said laser diode array.

59. The method of claim **56**, wherein said at least one sensor is a wavelength sensor for monitoring a wavelength of the output energy of said laser diode array.

60. The method of claim **55**, wherein said operating data is capable of being externally altered throughout the lifetime of said laser diode array.

61. The method of claim **60**, wherein said controller of said operating system alters said operating data by recording in said memory device updated operating data.

62. The method of claim **56**, wherein said at least one sensor includes a temperature sensor and said other operating data includes output energy as a function of temperature.

63. The method of claim **55**, wherein said associated memory device is integral with said laser diode array.

64. A method of determining an operating history of a laser diode array comprising the steps of:

providing a laser diode array assembly having an integral memory device;

assembling said laser diode array into an operating system having drive electronics and a controller, said drive electronics being coupled to said laser diode array, said controller being coupled to said drive electronics and to said integral memory device;

powering said drive electronics to produce output energy from said laser diode array;

monitoring operating conditions of said laser diode array; and

recording said operating conditions in said integral memory device.

65. The method of claim **64**, further including a step recording a serialization identity of said laser diode array assembly in said memory device.

66. The method of claim **64**, wherein said step of monitoring said operating conditions includes the step of sensing said operating conditions with at least one sensor integrally packaged with said laser diode array assembly.

67. The method of claim **66**, wherein said laser diode assembly further includes processing means coupled to said memory device and to said sensor, said processing means monitoring said operating conditions via said sensor and recording said operating conditions in said integral memory device.

68. The method of claim **66**, wherein step of recording said operating conditions includes the step of said controller monitoring said at least one sensor and said step of recording said operating conditions is accomplished by said controller.

69. The method of claim **64**, wherein said step of monitoring said operating conditions includes the step of sensing said operating conditions with a sensor positioned adjacent to said laser diode array.

70. The method of claim **64**, wherein said step of monitoring and recording said operating parameters further includes the step of monitoring and recording an amount of total on-time or shot-count of said laser diode array.

71. A method of predicting an operating life of a laser diode array comprising the steps of:

(a) providing a laser diode array having an integral memory device;

(b) recording in said memory device an estimated life based on a standard operating temperature and a standard input power;

(c) assembling said laser diode array into an operating system having drive electronics and a controller, said drive electronics being coupled to said laser diode array, said controller being coupled to said drive electronics and to said integral memory device;

(d) powering said drive electronics to produce output energy from said laser diode array;

(e) monitoring an actual operating temperature and an actual input power;

(f) comparing said actual input power to said standard input power;

(g) comparing said actual operating temperature to said standard operating temperature; and

(h) adjusting said estimated life to an adjusted estimated life based on steps (f) and (g).

72. The method of claim **71**, wherein said estimated life is given in a value of number of shots.

73. The method of claim **71**, wherein said steps (e) though (h) are repeated when at least one of said actual input power

and said actual operating temperature is outside a predetermined range, said standard input power and said standard operating temperature being within said predetermined range.

74. The method of claim **71**, further including the step of instructing said controller of operating system of said adjusted estimated life.

75. The method of claim **71**, further including the steps of:

monitoring an amount of total on-time or shot-count of said laser diode array;

periodically instructing said controller of operating system of the difference between said amount of total on-time or shot-count and said adjusted estimated life.

76. The method of claim **71**, wherein said steps (b), (e), and (g) further include, respectively, the steps of:

recording in said memory device an estimated life based on standard ambient condition;

monitoring an actual ambient condition; and

comparing said actual ambient condition to said standard ambient condition.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 5,734,672

DATED : March 31, 1998

INVENTOR(S) : Theodore S. McMinn, Dana A. Marshall, Michael A. Hope, Georffrey O. Heberle

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Claim 13, column 12, lines 49-50, delete "said operating conditions"; (2nd occur.)

Claim 20, column 13, line 12, after "plurality" insert --of--;

Claim 65, column 16, line 41, after "step" insert --of--.

Signed and Sealed this

Twelfth Day of January, 1999

Attest:

Q. Todd Dickinson

Attesting Officer

Acting Commissioner of Patents and Trademarks

US005844928A

United States Patent [19]

Shastri et al.

[11] **Patent Number: 5,844,928**

[45] **Date of Patent: Dec. 1, 1998**

[54] **LASER DRIVER WITH TEMPERATURE SENSOR ON AN INTEGRATED CIRCUIT**

[75] Inventors: **Kalpendu Ranjitrai Shastri**, Allentown; **David Alan Snyder**, Springfield Township, Bucks County, both of Pa.

[73] Assignee: **Lucent Technologies, Inc.**, Murray Hill, N.J.

[21] Appl. No.: **803,405**

[22] Filed: **Feb. 20, 1997**

Related U.S. Application Data

[60] Provisional application No. 60/012,378 Feb. 27, 1996.

[51] **Int. Cl.**^{6} **H01S 3/102**

[52] **U.S. Cl.** **372/38**; 372/34

[58] **Field of Search** 372/9, 29, 31–34, 372/38

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Primary Examiner—John D. Lee

[57] **ABSTRACT**

There is disclosed a laser driver or transmitter in which a drive current is generated by monitoring the temperature of an integrated circuit that generates drive current for the laser. The temperature sensed at the integrated circuit is transformed to a corresponding temperature at the laser. A drive current is generated for the laser that is dependent on the corresponding temperature at the laser.

8 Claims, 2 Drawing Sheets

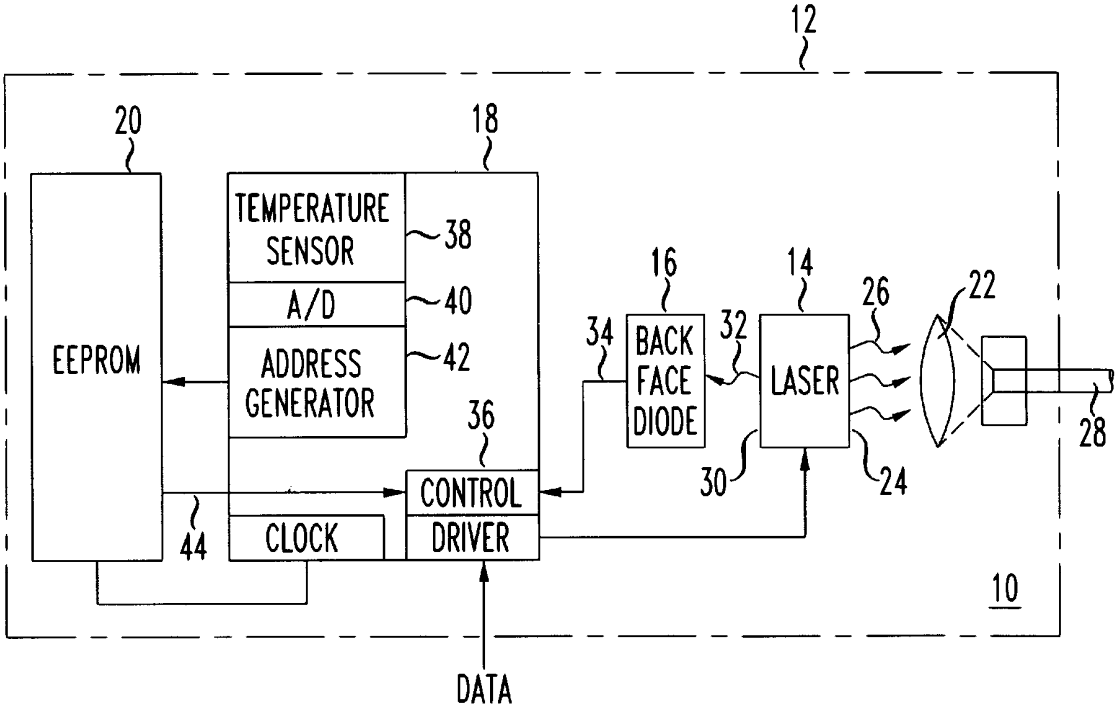


FIG. 1

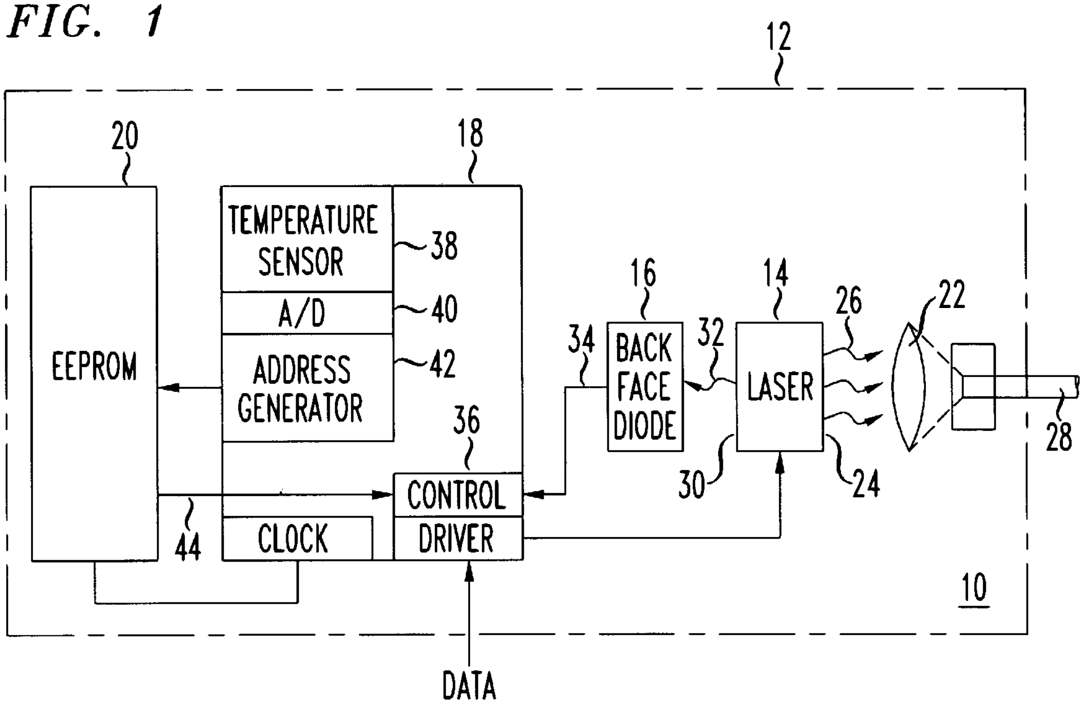

12
20
18
TEMPERATURE SENSOR
38
A/D
40
ADDRESS GENERATOR
42
EEPROM
16
14
26
22
34
BACK FACE DIODE
32
LASER
28
36
30
24
CONTROL
44
CLOCK
DRIVER
10
DATA

FIG. 2

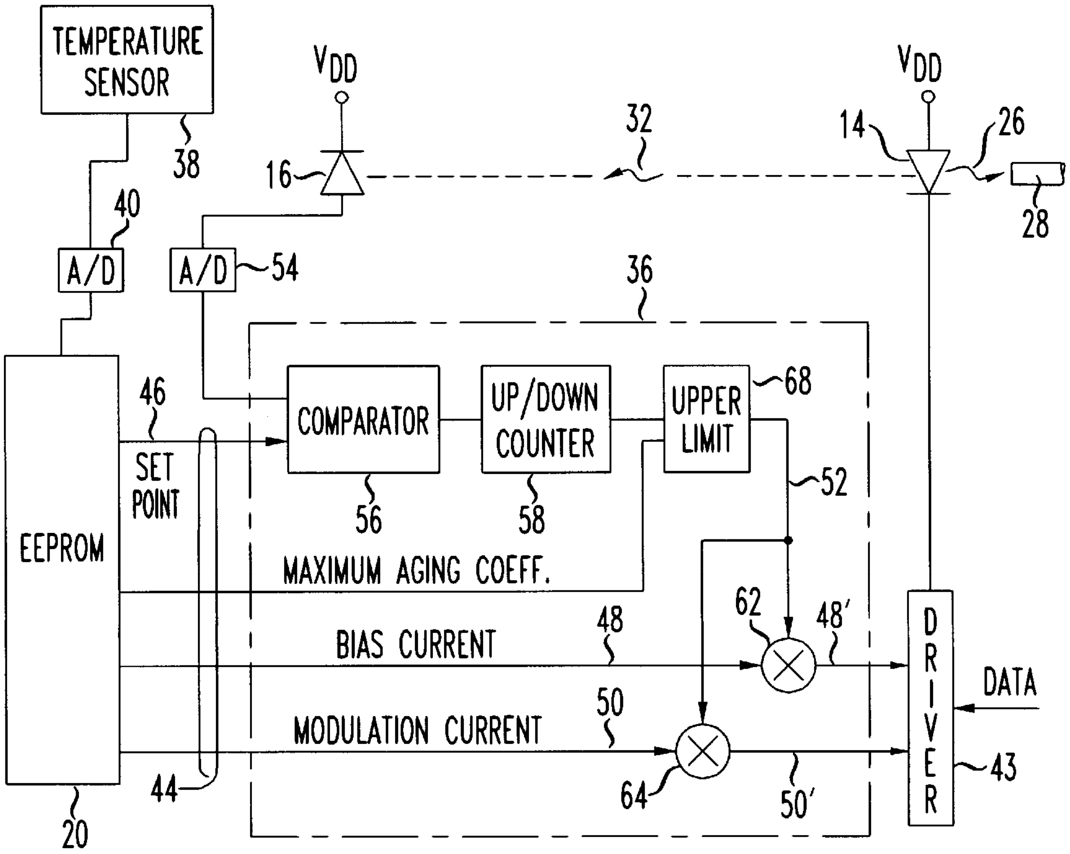

TEMPERATURE SENSOR
38
VDD
VDD
16
32
14
26
28
40
A/D
A/D
54
36
EEPROM
46
SET POINT
COMPARATOR
UP/DOWN COUNTER
UPPER LIMIT
68
56
58
52
MAXIMUM AGING COEFF.
62
48′
48
BIAS CURRENT
DRIVER
DATA
50
MODULATION CURRENT
43
44
64
50′
20

FIG. 3

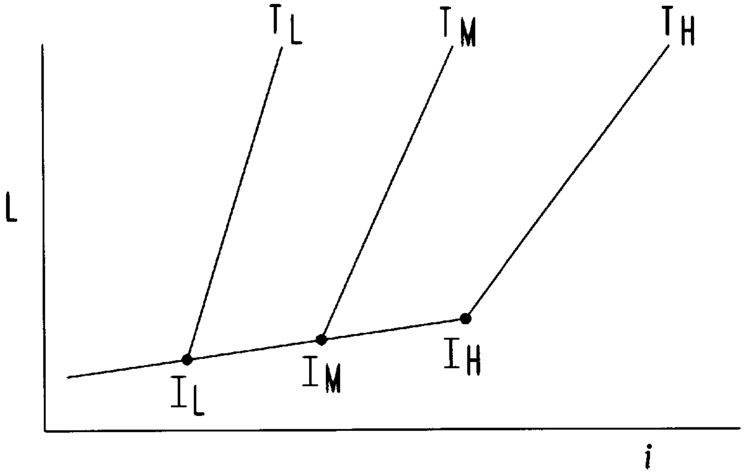
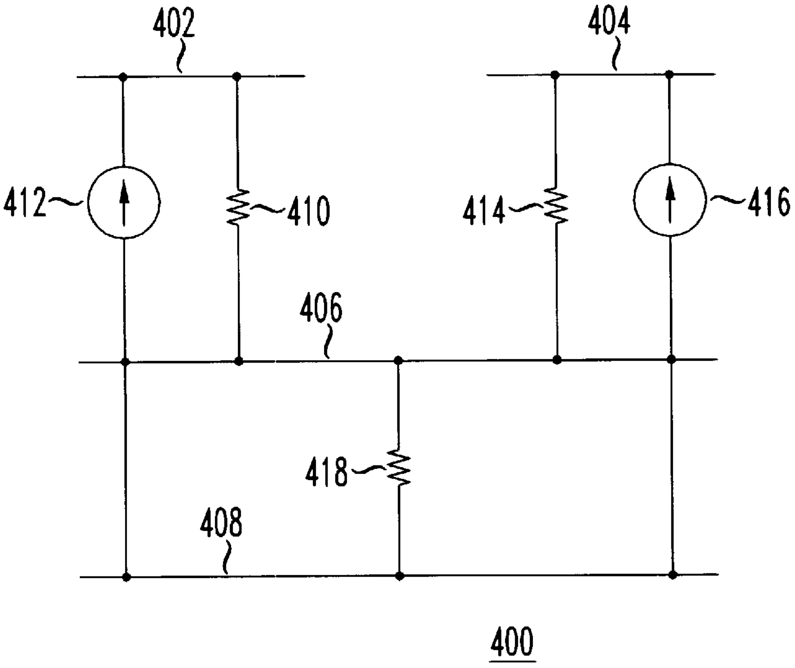


FIG. 4



LASER DRIVER WITH TEMPERATURE SENSOR ON AN INTEGRATED CIRCUIT

This application claims benefit of Provisional application Ser. No. 60,012,378 filed Feb. 27, 1996.

TECHNICAL FIELD

This invention relates generally to laser drivers or transmitters, and particularly to laser drivers having temperature compensation.

BACKGROUND OF THE INVENTION

The optical output (light) of a laser diode or laser is a nonlinear function of the current driving the laser. The light-current characteristic of a laser is also temperature dependent. The minimum driving current that causes the laser to operate in a lasing mode is known as the threshold current. Over the temperature operating range of a laser, higher operating temperatures require higher threshold currents to cause the laser to operate in a lasing mode. Correspondingly, lower operating temperatures require smaller threshold currents to cause the laser to operate in a lasing mode. The threshold current is a function of the operating temperature of the laser and may vary as much as an order of magnitude over the temperature operating range of the laser.

Integrated circuits are employed to modulate data onto the laser output. The laser is turned on and off by a driving current commensurate with the data to be modulated. The driving current is generally comprised of two components, a bias current that maintains the laser at the edge of operating in the lasing mode and a modulation current. The bias current has been controlled to be the threshold current of the laser. Since a laser will not operate in the lasing mode until the threshold current has been reached (or exceeded) it is important that the bias current be controlled precisely to be the threshold current at the temperature at which the laser is operating. Should the bias current fall below the threshold current, an unacceptable laser turn-on delay occurs. A turn-on delay is particularly undesirable when the laser operates at high switching speeds. A bias current higher than the threshold current is also undesirable because an extinction ratio problem is introduced into the laser output. An extinction ratio problem occurs when the light emitted by the laser should decrease to zero, and not be offset from zero, when the modulation current component of the laser drive circuit is zero, however the light emitted by the laser does not decrease to zero due to the bias current being higher than the threshold current. It is thus desirable to maintain the bias current precisely at the threshold current level for the temperature at which the laser is operating.

In one known bias current control technique, such as disclosed in U.S. Pat. No. 5,019,769, a laser and backface diode are mounted on a thermoelectric cooler. The thermoelectric cooler maintains the laser operating temperature at a controlled set point. A laser temperature sensor, also mounted on the thermoelectric cooler, senses the temperature of the thermoelectric cooler which is the same temperature as the operating temperature of the laser. A laser controller employs a programmed microcontroller to sense the laser temperature, control the thermoelectric cooler (and hence the laser temperature), and control the process of turning on and selecting the operating point of the laser. Using a thermoelectric coder introduces additional cost and requires more complex controls.

In another known technique, a temperature compensating circuit is mounted in thermal contact with the laser. A temperature compensating circuit produces a current component for driving the laser that is proportional to the operating temperature of the laser. This technique varies the laser drive current to compensate for temperature variations, without the need for a thermoelectric cooler.

SUMMARY OF THE INVENTION

In accordance with the present invention, a drive current for a laser driver is generated by monitoring the temperature of an integrated circuit that generates drive current for the laser. The temperature sensed at the integrated circuit is transformed to a corresponding temperature at the laser. A drive current is generated for the laser that is dependent on the corresponding temperature at the laser.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be described by way of example in which:

FIG. **1** is a block diagram illustration of a laser package, including control electronics, in accordance with the present invention;

FIG. **2** is a schematic diagram of a portion of the control electronics in the block diagram of FIG. **1**;

FIG. **3** is a graphical illustration of the optical output of a laser, L, for a given drive current, i, at three temperatures over the operating temperature range of a laser; and

FIG. **4** is a electrical representation of a thermodynamic model of a laser transmitter package that may be used to analytically determine, from a temperature at the integrated circuit, a corresponding temperature at the laser over the operating temperature range of the laser.

DETAILED DESCRIPTION

An illustrative embodiment of a laser driver **10** in accordance with the present invention is shown in FIG. **1**. Laser driver **10** is enclosed in a package **12** which is represented symbolically. Laser driver **10** includes a laser **14**, a backface diode **16**, an integrated circuit **18** providing a multiplicity of functions, and a look-up table **20** such as an electrically erasable programmable read only memory (EEPROM). A remotely sensed temperature at integrated circuit **18** is translated through data stored in look-up table **20** to a corresponding temperature at laser **14**, and laser **14** is controlled in response to the corresponding temperature at the laser. Laser driver **10** may also include a lens **22** for focusing light emitted by laser **14**.

Laser **14** has a front facet **24** from which coherent light **26** is emitted. The coherent light, which may be passed through lens **22**, is passed into a fiber **28** for transmission. A small portion of the light emitted from laser **14** is emitted from rear facet **30**. A portion **32** of the light emitted from rear facet **30** impinges on backface diode **16**. Since the optical power output from front facet **24** of laser **14** is proportional to the optical power output from rear facet **30**, backface diode **16** continuously monitors the optical power output by laser **14**. The optical power output by laser **14** can be correlated to heat generated by laser **14**. Backface diode **16** provides a signal, such as a current, over a conductor **34** to the control portion **36** of integrated circuit **18**.

The temperature within package **12** has local variations. There is not a single temperature within package **12**. Some components generate or dissipate more heat than other components, and some regions of the package may dissipate heat transferred to it from heat generating components more readily than other regions of the package. In accordance with the present invention, a temperature is measured on an integrated circuit **18** within package **12** of laser driver **10**, remotely relative to laser **14**. Thus, the temperature of laser **14** is not measured. The measured temperature may be less than or greater than the temperature of laser **14**. Typically, the measured temperature will be lower than the temperature of laser **14**. The temperature is measured by a temperature sensor **38** on integrated circuit **18**, such as a temperature sensitive circuit, varying a temperature sensitive parameter. The temperature sensitive parameter either is or creates a temperature sensitive signal. In the illustrative embodiment, the temperature sensitive signal is converted from an analog form to a digital form in analog-to-digital converter **40** on integrated circuit **18**, which in turn is converted by address generator **42** to a corresponding address. The address so generated is used to access look-up table **20** to retrieve data stored at that address relative to operation of laser driver **10** at a corresponding temperature. Also retrieved may be other data such as back face monitor setpoint, the value at which to limit current to the laser should it fail which is the extremum aging coefficient or current. The aging coefficient is ratio of the actual laser threshold current, at a given temperature, to the beginning-of-life threshold current at the same temperature. This data may represent multiple channels **44** of data. The data stored in look-up table **20** is predetermined from a model described below with respect to FIG. **4**. The measured temperature is a temperature on integrated circuit **18** that corresponds to an operating temperature of laser **14**. The data predetermined and stored in look-up table **20** is based on the temperature at the laser corresponding to the measured temperature.

The data retrieved from look-up table **20** over channels **44** is provided to control **36** and may include a digital representation of the backface diode current set point **46**, a digital representation of the desired bias and modulation currents **48** and **50** at the measured temperature, and maximum allowed aging coefficient **52**. The current signal generated by backface diode **16** is digitized by analog-to-digital converter **54** for comparison in comparator **56** to the digital representation of the backface diode current set point **46** retrieved from look-up table **20**. If the digital representation of the current signal is greater than the backface diode set point **46**, a feedback loop operates in that up-down counter **58** counts down. This correction is used to multiply, in multipliers **62** and **64**, the bias current **48** and modulation current **50** retrieved from look-up table **20**. This reduces the drive current to laser **14**, interalia, reducing the portion of light **32** emitted from rear facet **30**. This feedback loop eliminates the difference between set point **46** and the digital representation of the backface diode output. The counter output, when multiplied with the digital representation of the bias current, results in a modified bias current **48'** that is provided to driver **43**, which in turn generates the drive current to drive laser **14**. If the digital representation of the current signal from backface diode **16** is less than the backface diode set point **46**, the feedback loop operates in that up-down counter **58** counts up, as limited by maximum aging coefficient **52** in upper limit **68**, increasing its output to driver **43**, which increases the drive current to laser **14** and in turn increases the portion of light **32** emitted from rear facet **30**. Again, operation of the feedback loop eliminates the difference between set point **46** and the digital representation of the backface diode output.

If appropriate, modulation current **50** for the sensed temperature is also retrieved from look-up table **20**. As shown in FIG. **2**, either or both of the bias current **48** and modulation current **50** can be modified, such as by multiplication factors M1 and M2 respectively, in multipliers **62** and **64**. The age compensated digital representation of bias current is designated **48'**. The age compensated digital representation of modulation current is designated **50'**. Note that when factors M1 and M2 are set to 1, unmodified bias current **48** and modulation current **50** are provided to driver **43**. The digital representations of bias current **48'** and the digital representation of modulation current **50'** are provided driver **43** to be converted to an analog current signal to drive laser **14**. Data to modulate the operation of laser **14** is also provided to driver **43**. The data is used by driver **43** to switch on and off the modulation current.

Upon power-up of laser driver **10**, with the feedback loop turned off, configuration information is downloaded from look-up table **20**. This is done since the same integrated circuit and look-up table can be used for various configurations in the physical packaging of laser driver **10**. The predetermined digital representations of drive current stored in the look-up table are unique to the package and components in the package. The temperature is sensed by temperature sensor **38** and once the temperature is sensed and the various analog-to-digital and digital-to-analog converters settle, the feedback loop is turned on to control operation of laser driver **10**.

The optical output, L, of a laser is a nonlinear function of the forward bias and modulation currents, or drive current, of the laser as shown in FIG. **3**. When drive current is applied to a laser, the laser does not commence lasing operation until the drive current reaches a minimum, known as the threshold current. The threshold current varies among lasers, with laser aging, and as seen in FIG. **3**, also varies with temperature. FIG. **3** illustrates graphically the threshold current variation with temperature of the laser being driven, as well as how the drive current is temperature dependent. The drive current is illustrated for three temperatures, a low temperature T_L, medium temperature T_M and high temperature T_H, over the operating range of the laser. The threshold current for each of the low, medium, and high temperature ranges is shown as I_L, I_M, and I_H, respectively.

A thermal model is shown in FIG. **4** that may be used to analytically evaluate the temperature of the laser based on the temperature sensed by temperature sensor **38** on integrated circuit **18**. FIG. **4** represents a thermal model **400** of laser driver **10**. Node **402** represents the temperature measured at the integrated circuit **18**, temperature sensor **38**. Node **404** represents the temperature at laser **14**. Node **406** represents the temperature at the housing or case in which the laser and integrated circuit are packaged. Node **408** represents the ambient, an infinite reservoir for heat dissipation. Thermal resistance **410** represents the thermal resistance between heat generated in integrated circuit **18** and the housing or case in which the laser and integrated circuit are packaged. Current generator **412** represents the heat generated by the drive circuit, which is a function of the drive current provided to the laser. Thermal resistance **414** represents the thermal resistance between heat generated in the laser and the housing or case in which the laser and integrated circuit are packaged. Current generator **416** represents heat generated at laser **14**, which is a function of the laser drive current. Thermal resistance **418** represents a thermal resistance between the case or housing and the surrounding ambient.

By varying parameters in model **400**, the thermal characteristics of laser driver **10** can be modeled to determine the appropriate laser drive current for measured temperatures at integrated circuit **18** under the modeled conditions. While a more complex thermal model could be employed, applicants have found this model to suffice. Model **400** is versatile and can accommodate many variations in locating the integrated circuit and laser relative to each other, various packaging materials and shapes, as well as environmental factors such as ambient air or forced air environment.

The model equations may be solved in any known manner by one skilled in the art. Solving the model equations may be recursive until a solution converges, as is known in the art.

While the invention has been described as measuring the temperature of an integrated circuit that generates drive current for a laser and converting the temperature of the integrated circuit to a corresponding temperature at the laser and generating a drive current for the laser that is a function of the corresponding temperature at the laser, it should be readily recognized that once the relationship between the temperature of the integrated circuit and the corresponding temperature at the laser is determined, it is not necessary to generate the actual temperature at the laser. In this manner, it is contemplated that it is not necessary to generate the actual temperature at the laser but rather be able to generate a drive current for the laser that is a function of the temperature at the laser.

While the invention has been described as predetermining a plurality of discrete drive currents over a range of corresponding laser temperatures, which suggests a digital implementation, it is recognized that the invention could be implemented in a total analog capability.

While the invention has been described as predetermining digital representations of the bias and modulation current data for the look-up table using a thermal model, alternatively the digital representations of the bias and modulation current data could be determined by empirical testing.

While the maximum aging current has been disclosed as limiting the output of an up-down counter when counting up, the invention is not limited thereto. Other techniques of implementing the aging coefficient are contemplated within the scope of the invention.

The invention claimed is:

1. A method of generating a drive current for a laser, comprising the steps of:

monitoring the temperature of an integrated circuit that generates drive current for a laser, the integrated circuit remotely located with respect to said laser;

converting the temperature of the integrated circuit to a corresponding temperature at the laser; and

generating a drive current for the laser that is a function of the corresponding temperature at the laser.

2. The method as recited in claim **1**, wherein the converting step comprises entering a look-up table with a representation of the integrated circuit temperature to obtain the corresponding temperature at the laser.

3. The method as recited in claim **1**, wherein the generating step comprises:

predetermining a plurality of discrete drive currents over a range of corresponding laser temperatures; and

storing a digital representation of the plurality of discrete drive currents in a look-up table.

4. The method as recited in claim **3**, further comprising the steps of:

entering the look-up table based on a temperature of the integrated circuit; and

retrieving from the look-up table a digital representation of one of the plurality of drive currents that correlates to the temperature of the integrated circuit.

5. A laser transmitter, comprising

a laser for receiving a drive current and for emitting light in response thereto;

an integrated circuit for generating the drive current for the laser and remotely located with respect to said laser, the integrated circuit comprising a temperature sensing circuit that senses the temperature of the integrated circuit, the integrated circuit converting the temperature at the integrated circuit to a representation corresponding to the temperature at the laser;

a look-up table for receiving the representation corresponding to the temperature at the laser and for generating a representation of a corresponding drive current; and

a driver for converting the representation of the drive current into a drive current, the drive current provided to the laser.

6. The laser transmitter as recited in claim **5**, wherein the look-up table is stored in an electrically erasable programmable read only memory.

7. The laser transmitter as recited in claim **5**, wherein the representation of the corresponding drive current is a digital representation.

8. The laser transmitter as recited in claim **7**, wherein the driver is a digital-to-analog converter.

* * * * *

US006195370B1

(12) **United States Patent**
Haneda et al.

(10) **Patent No.: US 6,195,370 B1**
(45) **Date of Patent: Feb. 27, 2001**

(54) OPTICAL TRANSMISSION DEVICE AND METHOD FOR DRIVING LASER DIODE

(75) Inventors: **Makoto Haneda**, Takasaki; **Hiroaki Hanawa**, Hino, both of (JP)

(73) Assignees: **Hitachi, Ltd.**; **Hitachi ULSI Systems Co., Ltd.**, both of Tokyo (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/462,992**

(22) PCT Filed: **Sep. 16, 1997**

(86) PCT No.: **PCT/JP97/03260**

§ 371 Date: **Jan. 18, 2000**

§ 102(e) Date: **Jan. 18, 2000**

(87) PCT Pub. No.: **WO99/14832**

PCT Pub. Date: **Mar. 25, 1999**

(51) **Int. Cl.**^{7} **H01S 3/13**
(52) **U.S. Cl.** **372/29**; 372/38; 372/34
(58) **Field of Search** 372/29, 38, 34; 359/189; 250/205

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6-61555	3/1994	(JP) .
7-147443	6/1995	(JP) .
7-221369	8/1995	(JP) .
8-204268	8/1996	(JP) .
9-214043	8/1997	(JP) .

* cited by examiner

Primary Examiner—Leon Scott, Jr.
(74) *Attorney, Agent, or Firm*—Mattingly, Stanger & Malur, P.C.

(57) ABSTRACT

An optical transmission device obtains driving control data corresponding to a temperature detected by a temperature detection circuit (**112**) from memory means (**173**), controls a driving current to be supplied to a laser diode (**100**) based on the driving control data, and measures a driving current to be actually supplied to the laser diode whose emission power is held constant by an automatic optical output control circuit (**115**, **113**). Further, when the difference between the measured driving current and a driving current determined by the driving control data corresponding to the detected temperature at that time exceeds an allowable range, the optical transmission device updates the driving control data. Upon determination of the deterioration of the laser diode, the progress of the deterioration of the laser diode is determined based on the difference between a driving current defined by driving control data corresponding to a newly measured temperature and an actual driving current formed by automatic optical output control. Therefore, a distinction between whether an increase in driving current due to the automatic optical output control results from the deterioration of the laser diode and whether it results from a variation in ambient temperature is reliably made.

5 Claims, 9 Drawing Sheets

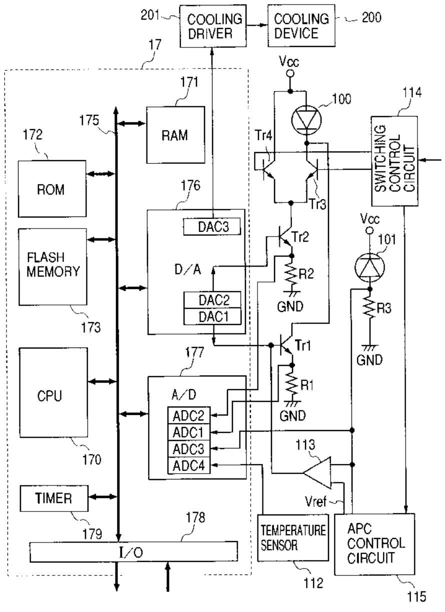


FIG. 1

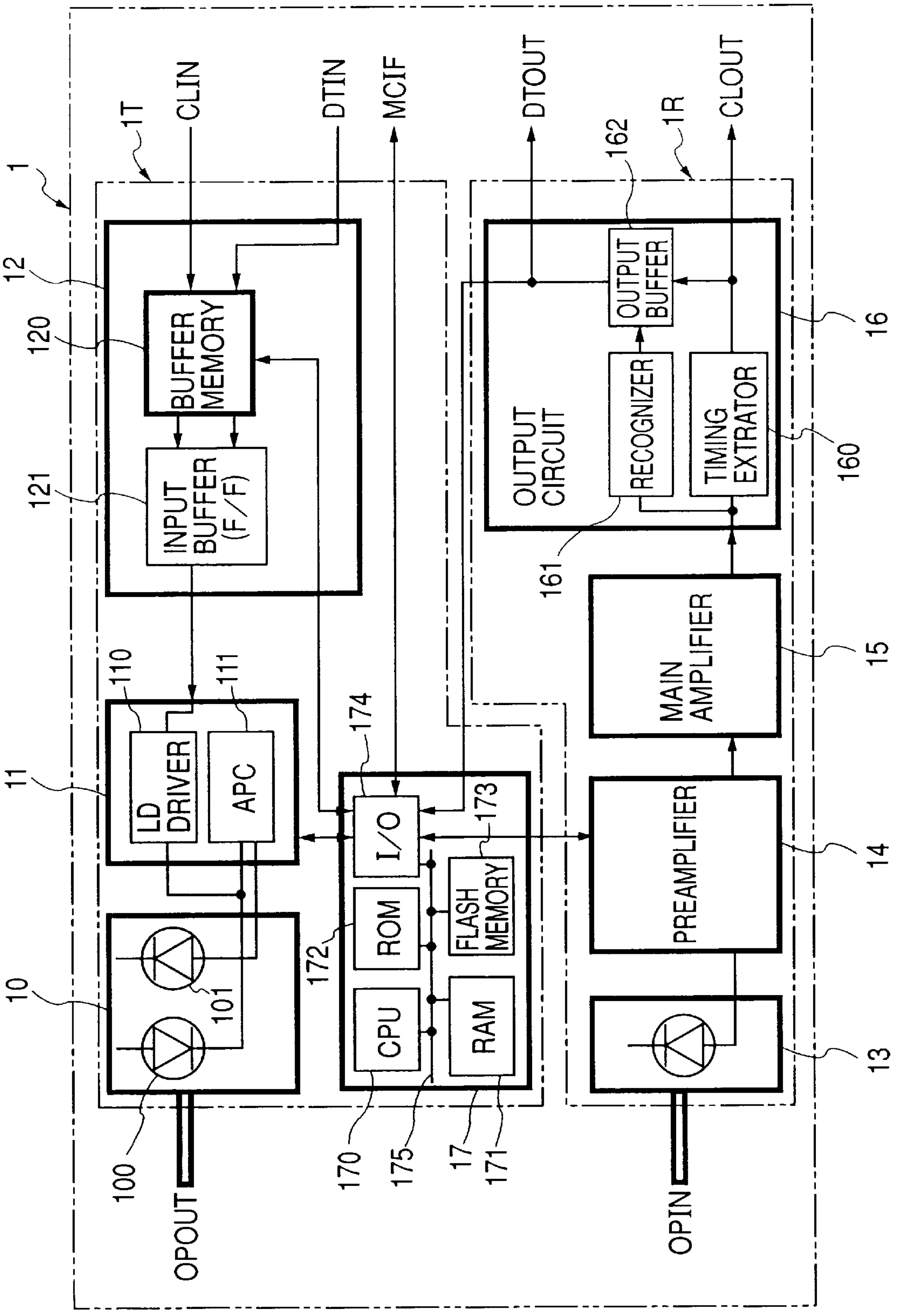

1
1T
CLIN
DTIN
MCIF
DTOUT
1R
CLOUT
12
120
121
BUFFER MEMORY
INPUT BUFFER (F/F)
162
OUTPUT BUFFER
RECOGNIZER
TIMING EXTRATOR
OUTPUT CIRCUIT
16
160
161
11
110
111
LD DRIVER
APC
174
173
I/O
ROM
FLASH MEMORY
CPU
RAM
172
MAIN AMPLIFIER
15
PREAMPLIFIER
14
10
101
100
13
OPOUT
170
175
17
171
OPIN

FIG. 2

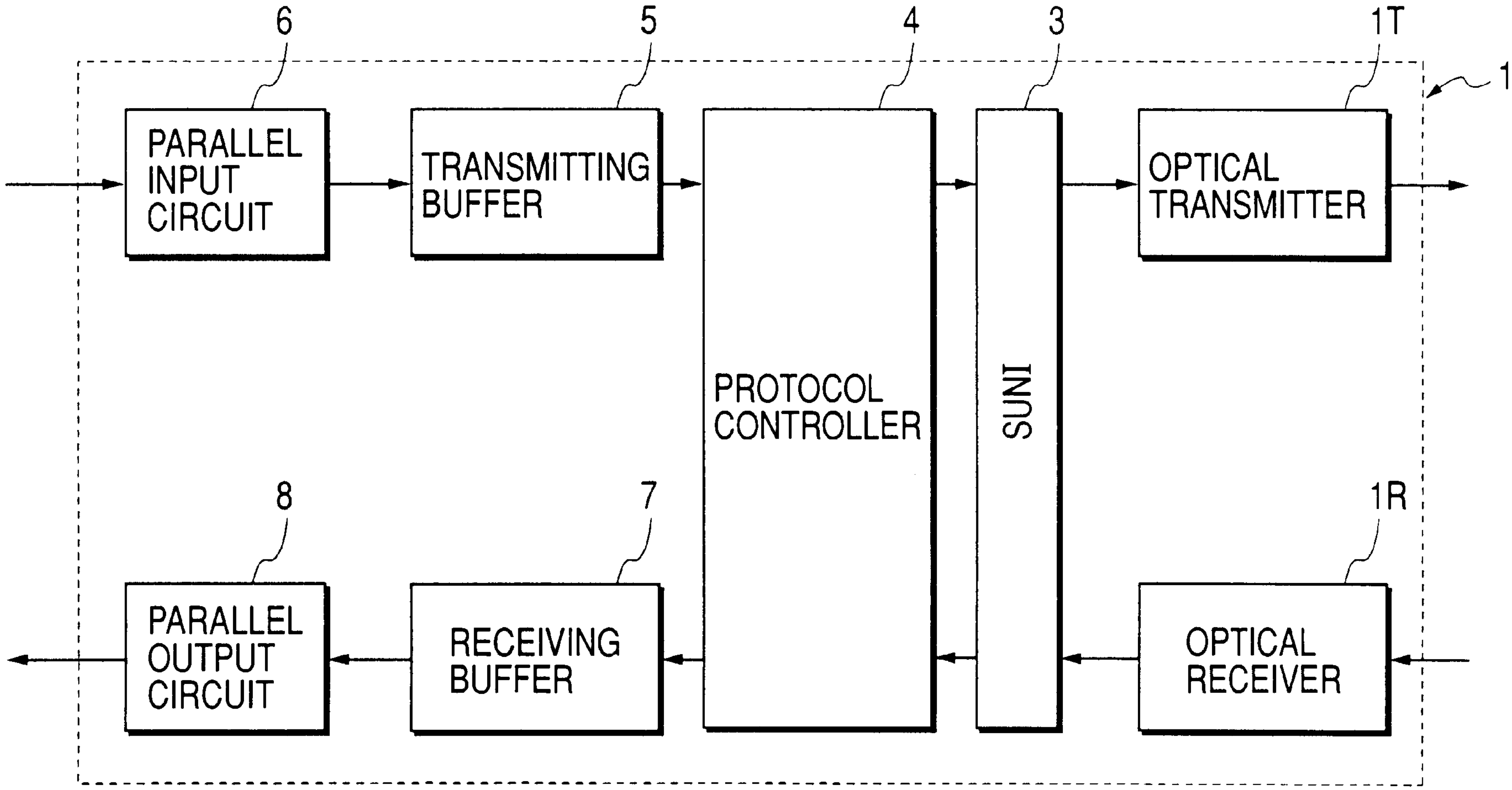

6
5
4
3
1T
1
PARALLEL INPUT CIRCUIT
TRANSMITTING BUFFER
PROTOCOL CONTROLLER
SUNI
OPTICAL TRANSMITTER
8
7
1R
PARALLEL OUTPUT CIRCUIT
RECEIVING BUFFER
OPTICAL RECEIVER

FIG. 3

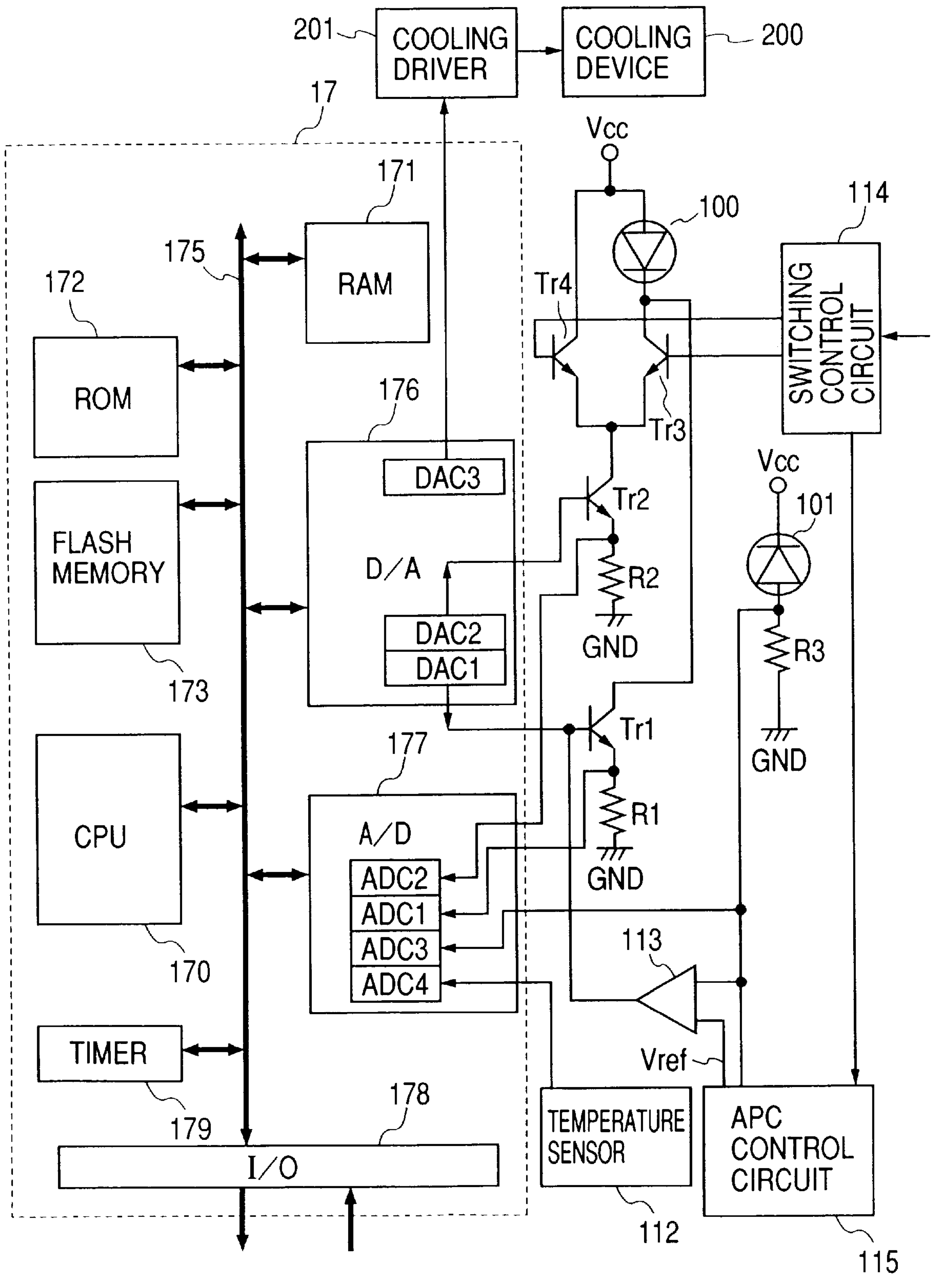

201
COOLING DRIVER
COOLING DEVICE
200
17
Vcc
171
100
114
175
RAM
172
Tr4
SWITCHING CONTROL CIRCUIT
ROM
176
Tr3
DAC3
Tr2
Vcc
FLASH MEMORY
D/A
101
R2
DAC2
DAC1
R3
GND
173
Tr1
GND
177
CPU
R1
A/D
ADC2
GND
ADC1
ADC3
113
ADC4
170
Vref
TIMER
TEMPERATURE SENSOR
APC CONTROL CIRCUIT
179
178
I/O
112
115

FIG. 4

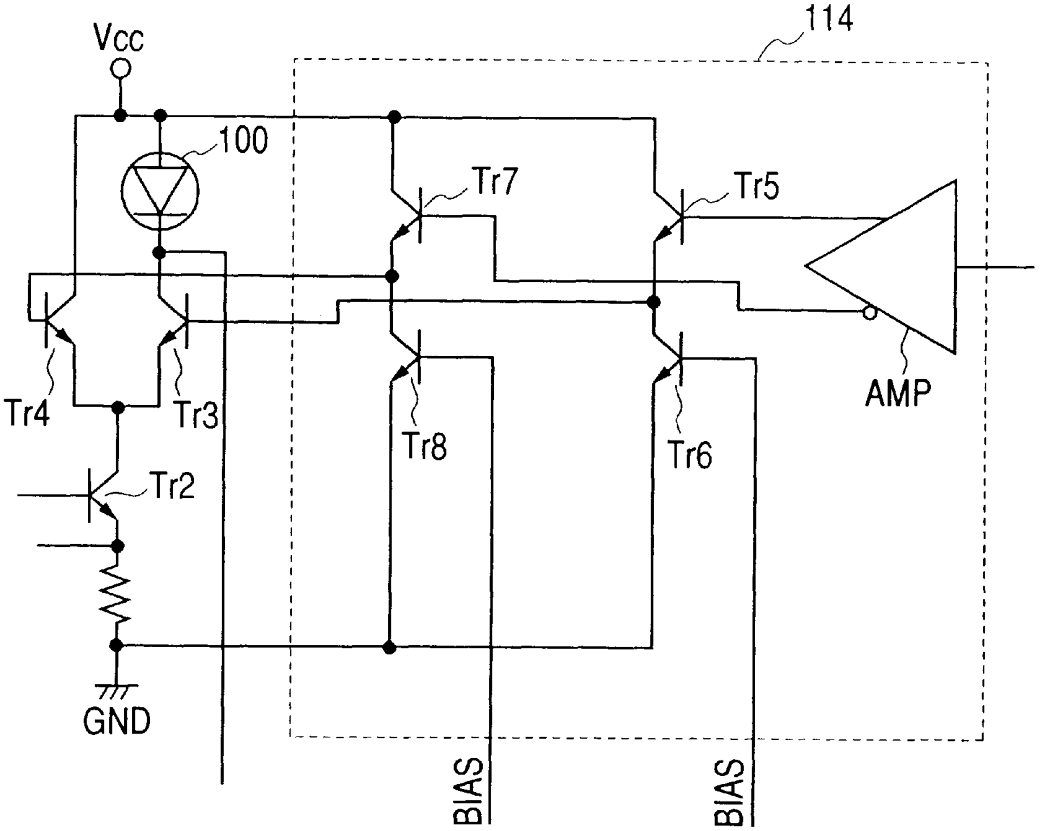


FIG. 5

	Eini			Ecor		
TEMPERATURE (˚C)	Ib(0) (mA)	Imod(0) (mA)	Id(0) (mA)	Id(t) (mA)	δId (mA)	δIb (mA)
70	25.0	19.5	44.5			
71	25.5	19.7	45.2			
72	26.0	20.1	46.1			
73	26.6	20.4	47.0	55.6	8.6	6.0
74	27.2	20.7	47.9			
⋮	⋮	⋮	48.9			
			⋮			

TBL

FIG. 6

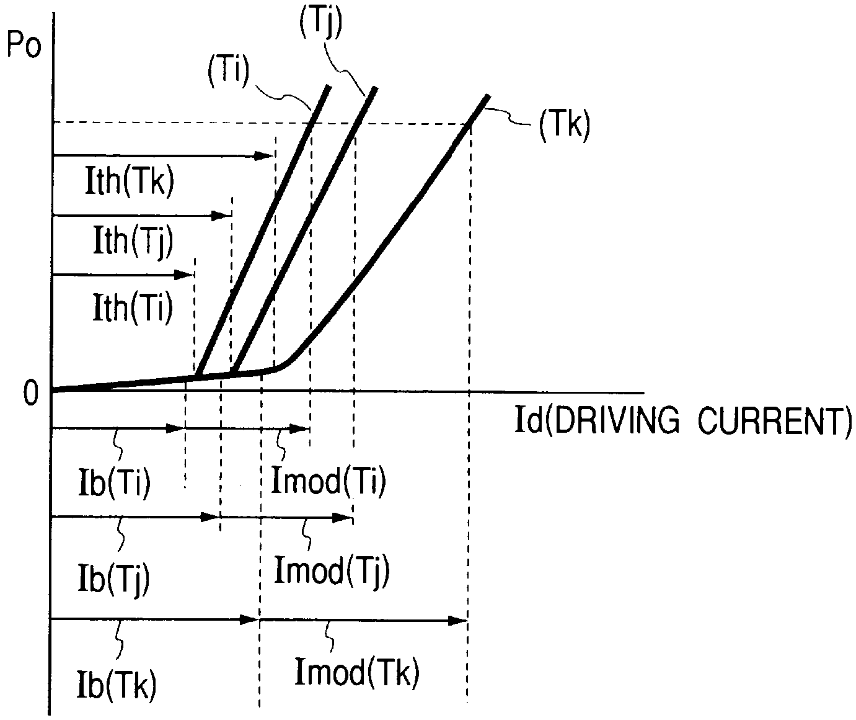

Po
(Ti)
(Tj)
(Tk)
Ith(Tk)
Ith(Tj)
Ith(Ti)
0
Id(DRIVING CURRENT)
Ib(Ti)
Imod(Ti)
Ib(Tj)
Imod(Tj)
Ib(Tk)
Imod(Tk)

FIG. 7

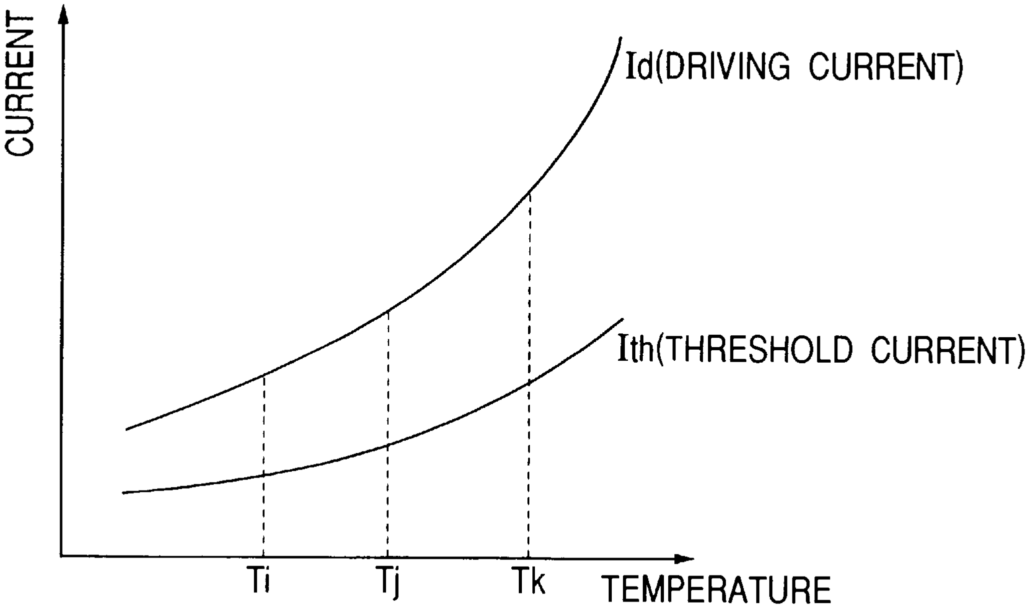

CURRENT
Id(DRIVING CURRENT)
Ith(THRESHOLD CURRENT)
Ti
Tj
Tk
TEMPERATURE

FIG. 8

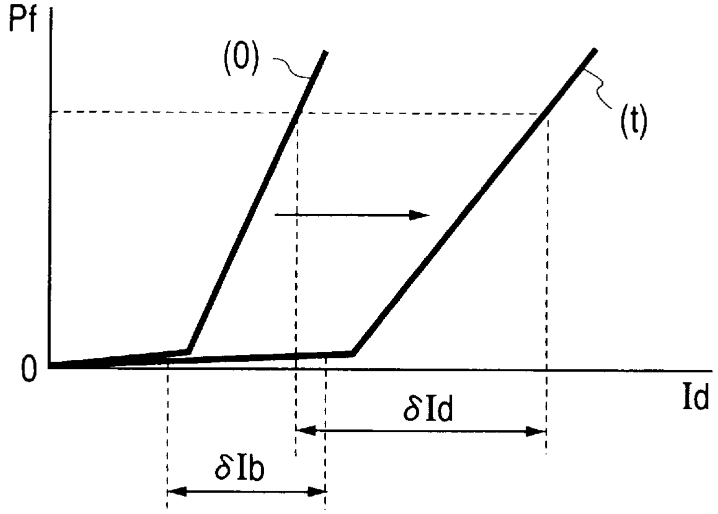


FIG. 10

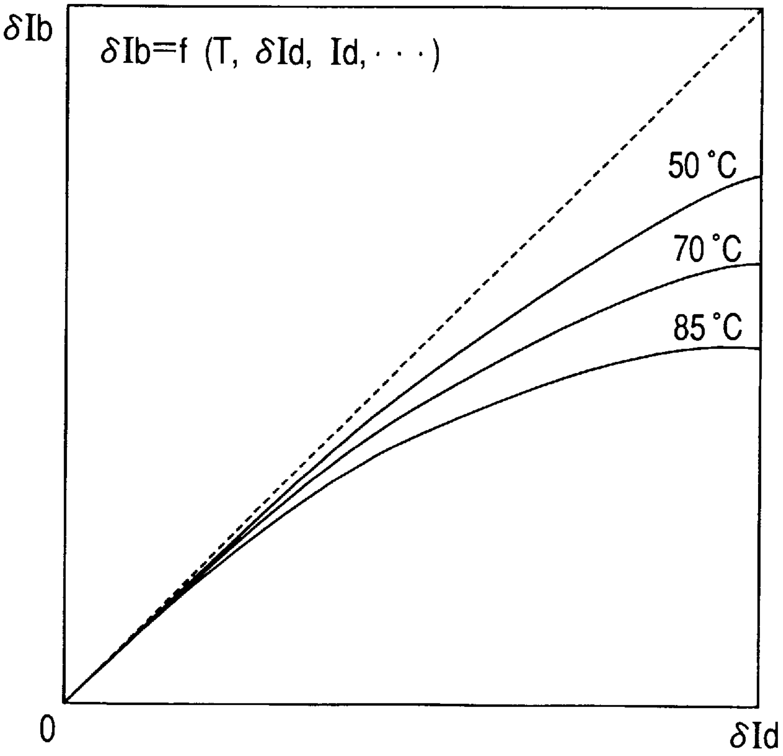


FIG. 9

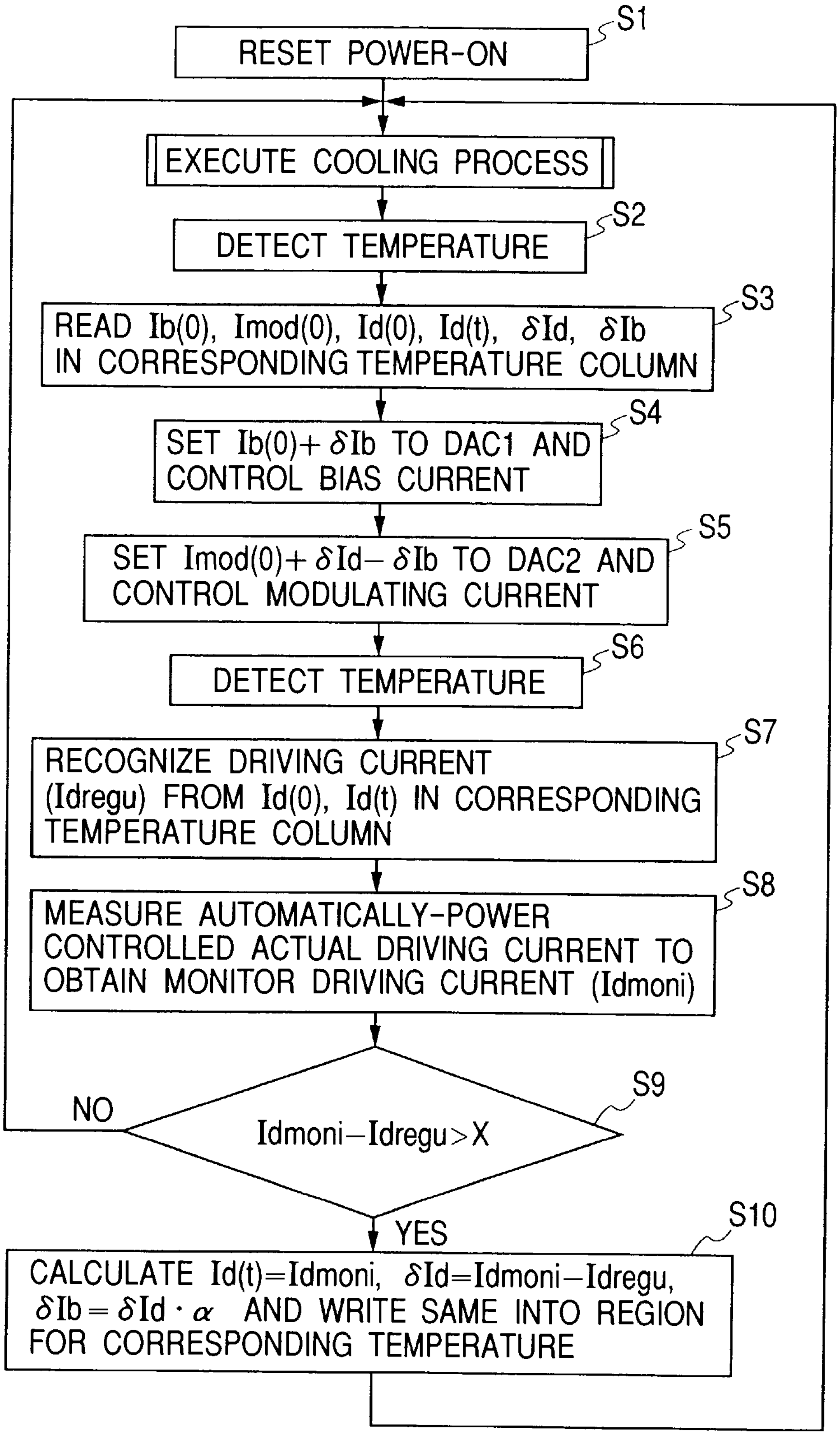

S1
RESET POWER-ON
EXECUTE COOLING PROCESS
S2
DETECT TEMPERATURE
S3
READ Ib(0), Imod(0), Id(0), Id(t), δId, δIb IN CORRESPONDING TEMPERATURE COLUMN
S4
SET Ib(0)+δIb TO DAC1 AND CONTROL BIAS CURRENT
S5
SET Imod(0)+δId−δIb TO DAC2 AND CONTROL MODULATING CURRENT
S6
DETECT TEMPERATURE
S7
RECOGNIZE DRIVING CURRENT (Idregu) FROM Id(0), Id(t) IN CORRESPONDING TEMPERATURE COLUMN
S8
MEASURE AUTOMATICALLY-POWER CONTROLLED ACTUAL DRIVING CURRENT TO OBTAIN MONITOR DRIVING CURRENT (Idmoni)
S9
Idmoni−Idregu>X
NO
YES
S10
CALCULATE Id(t)=Idmoni, δId=Idmoni−Idregu, δIb=δId·α AND WRITE SAME INTO REGION FOR CORRESPONDING TEMPERATURE

FIG. 11

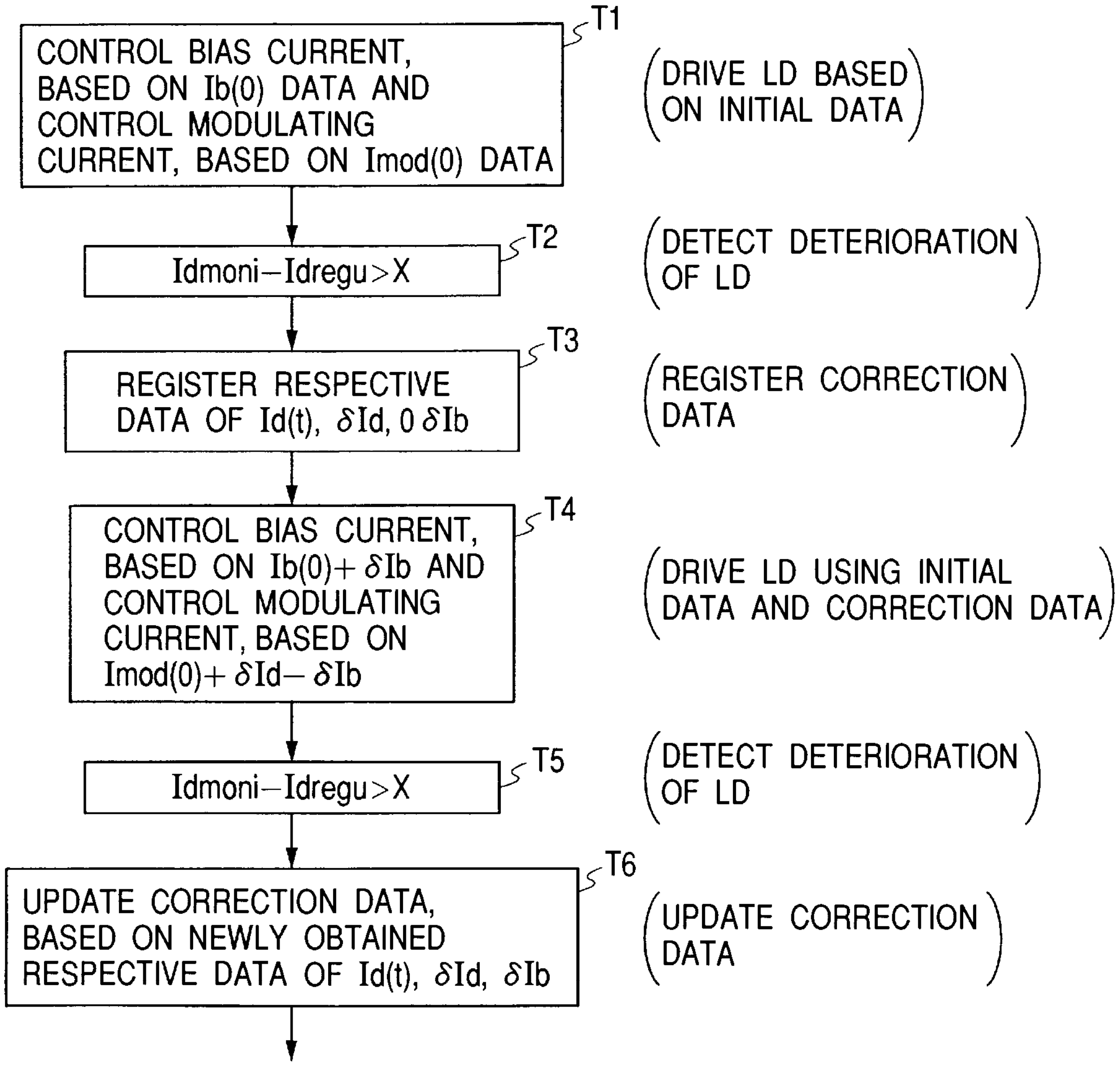
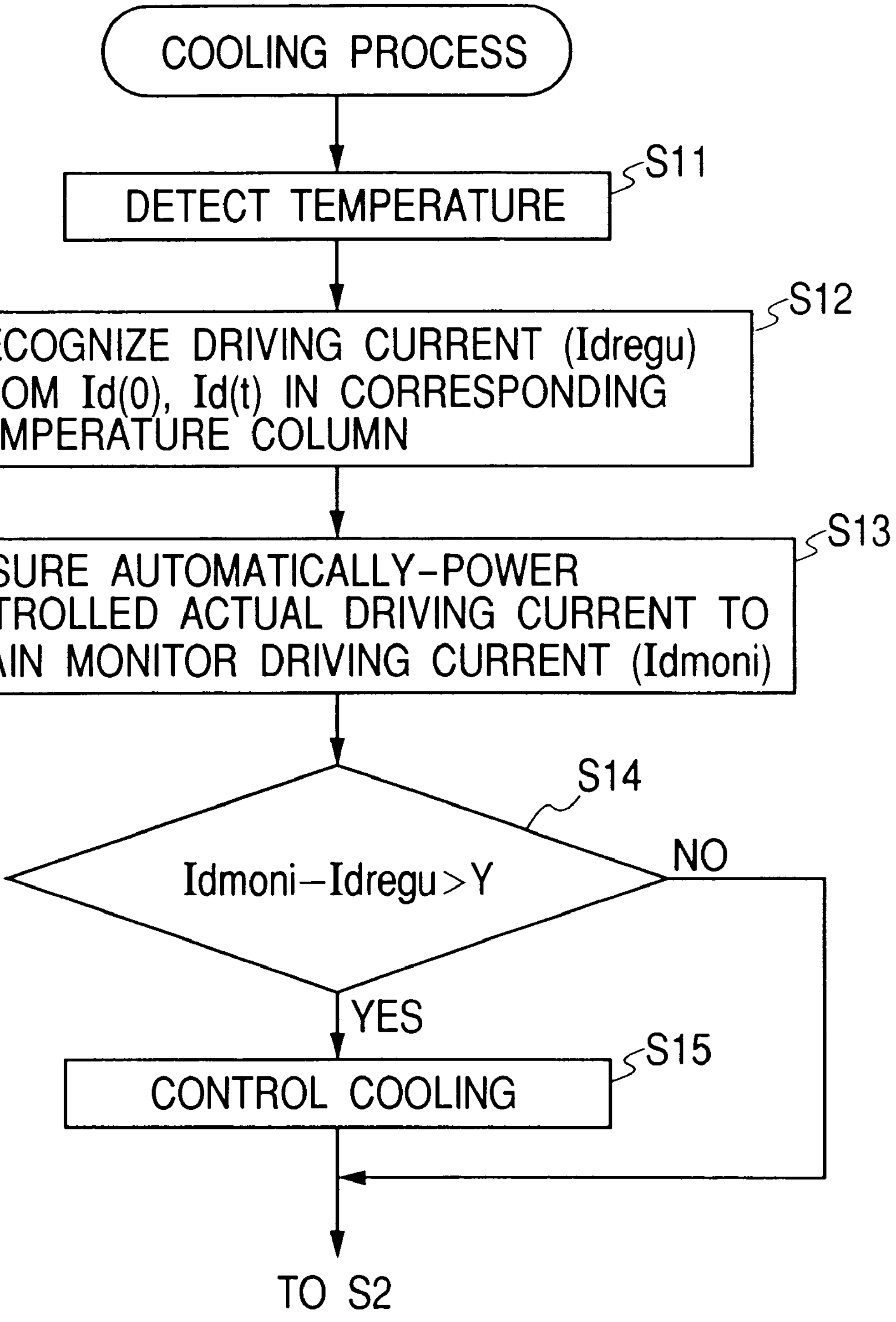

T1
CONTROL BIAS CURRENT, BASED ON Ib(0) DATA AND CONTROL MODULATING CURRENT, BASED ON Imod(0) DATA
(DRIVE LD BASED ON INITIAL DATA)
T2
Idmoni−Idregu>X
(DETECT DETERIORATION OF LD)
T3
REGISTER RESPECTIVE DATA OF Id(t), δId, 0 δIb
(REGISTER CORRECTION DATA)
T4
CONTROL BIAS CURRENT, BASED ON Ib(0)+δIb AND CONTROL MODULATING CURRENT, BASED ON Imod(0)+δId−δIb
(DRIVE LD USING INITIAL DATA AND CORRECTION DATA)
T5
Idmoni−Idregu>X
(DETECT DETERIORATION OF LD)
T6
UPDATE CORRECTION DATA, BASED ON NEWLY OBTAINED RESPECTIVE DATA OF Id(t), δId, δIb
(UPDATE CORRECTION DATA)

FIG. 12


COOLING PROCESS
S11
DETECT TEMPERATURE
S12
RECOGNIZE DRIVING CURRENT (Idregu) FROM Id(0), Id(t) IN CORRESPONDING TEMPERATURE COLUMN
S13
MEASURE AUTOMATICALLY-POWER CONTROLLED ACTUAL DRIVING CURRENT TO OBTAIN MONITOR DRIVING CURRENT (Idmoni)
S14
Idmoni−Idregu>Y
NO
YES
S15
CONTROL COOLING
TO S2

OPTICAL TRANSMISSION DEVICE AND METHOD FOR DRIVING LASER DIODE

TECHNICAL FIELD

The present invention relates to an optical transmission device having a laser diode and a method for driving the laser diode, and specifically to a technique for optimizing a driving current of a laser diode even with respect to deterioration in characteristic of the laser diode due to secular changes, e.g., a technique effective for application to a digital optical communication system.

BACKGROUND ART

A laser diode emits light when a driving current thereof exceeds an oscillating threshold current (called simply threshold current). The intensity or power of emission thereof is proportional to a modulating current corresponding to the current exceeding the threshold current. In order to make fast the speed of response of an emitting operation of the laser diode, the threshold current or a neighboring current thereof is caused to flow at all times, and the modulating current is allowed to flow as a pulse current corresponding to a data signal in form superimposed on the bias current. As a result, an optical pulse can be generated.

The stable execution of optical communications needs to hold the intensity of light at its emission constant. At this time, the emission characteristic of the laser diode greatly depends on the temperature. Namely, the threshold current becomes great as the temperature rises. Further, the modulating current necessary to obtain predetermined emission power becomes also great as the temperature rises. The emission characteristic of the laser diode is deteriorated due to secular changes, and the threshold current becomes great as its using period becomes long. The modulating current necessary to obtain the predetermined emission power is also made great. Further, the characteristic change corresponding to the temperature and secular changes differs between the threshold current and the modulating current.

In order to cope with such a characteristic change, an auto power control technique has heretofore been adopted wherein the mean level of emission power of a laser diode is detected from a current flowing in a photodiode provided so as to be opposed to the laser diode and a bias current is increased by the amount equivalent to a reduction in the detected level, whereby fixed emission power can be obtained. Japanese Patent Application Laid-Open No. Hei 8-204268 is known as an example of a reference in which the present technique has been described.

In the above-described prior art, however, only the bias current is changed and no modulating current is controlled. Therefore, if the bias current exceeds the threshold current, then a quenching failure occurs. If the bias current is excessively smaller than the threshold current in reverse, then a quenching delay occurs. In a word, the prior art merely controls the sum of the bias current and the modulating current with respect to changes in threshold current of the laser diode and modulating current for obtaining fixed emission power of the laser diode due to a change in temperature and secular changes.

On the other hand, a technique for controlling a driving current of a laser diode while paying attention to both changes in threshold current corresponding to the temperature and modulating current for obtaining fixed emission power has been described in Japanese Patent Application Laid-Open No. Hei 6-61555. Namely, current ratio control data defining the ratio between the optimum bias current and modulating current for each operating temperature of the laser diode is prepared in a ROM or the like. The current ratio control data is read from the ROM in accordance with the result of detection of the operating temperatures of the laser diode, and reference is made to the driving current of the laser diode subjected to auto power control, whereby the bias current and modulating current are determined according to the current ratio control data with respect to the driving current.

However, the aforementioned prior art has no taken into consideration the deterioration in characteristic of the laser diode due to the secular changes. According to the discussions of the present inventors, it was revealed that if a distinction between whether an increase in driving current by the auto power control results from a change in ambient temperature and whether it results from deterioration in characteristic of the laser diode due to the secular changes would not be done, it was difficult to optimize both the bias current and the modulating current.

Further, the wavelength of output light also varies with the deterioration of the laser diode. This occurs because the laser diode is deteriorated and the driving current for obtaining the required optical output increases to thereby increase the temperature of an active layer of the laser diode and shift the output wavelength to the long-wave side. If the temperature of the active layer is lowered, then the wavelength of the optical output is shifted to the short-wave side. Such changes in wavelength cause a recognition error of a transmission signal in, for example, a system for performing wavelength-division multiplexing transmission.

An object of the present invention is to provide an optical transmission device capable of improving the reliability of light-based information transmission.

Another object of the present invention is to provide an optical transmission device which reduces a quenching failure and an emission delay to the minimum with respect to deterioration in characteristic of a laser diode due to a change in ambient temperature and secular changes to thereby make it possible to hold an optical output constant.

A further object of the present invention is to provide a method of reducing a quenching failure and an emission delay to the minimum with respect to deterioration in characteristic of a laser diode due to a change in ambient temperature and secular changes to thereby drive the laser diode.

A still further object of the present invention is to provide an optical transmission device capable of relaxing a change in the wavelength of an emission output.

DISCLOSURE OF THE INVENTION

An optical transmission device according to the present invention comprises a laser diode, a current supply circuit for supplying a bias current and a modulating current superimposed on the bias current to the laser diode as driving currents, an automatic optical output control circuit for supplementing the shortage of the driving currents so that emission power of the laser diode is held constant, a temperature detection circuit for detecting an ambient temperature of the laser diode, memory means storing driving control data for determining a modulating current and a bias current necessary to obtain predetermined emission power therein for each predetermined temperature, and control means for obtaining driving control data corresponding to the temperature detected by the temperature detection circuit from the memory means, controlling each driving current to be supplied from the current supply circuit to the laser diode, based on the obtained driving control data, measuring each driving current actually supplied to the laser diode whose emission power is held constant by the automatic optical output control circuit, detecting whether the difference between the measured driving current and a driving current determined according to the driving control data corresponding to the detected temperature at that time exceeds an allowable range, and updating the driving control data related to the corresponding temperature, on the memory means so that the difference between the driving currents is defined as each of increases in bias current and modulating current.

The range allowable for the increase in driving current is a range in which a quenching failure and an emission delay substantially show no problem when automatic optical output control is effected on a driving current formed by driving control data at a given temperature, for example. This can be defined as a current corresponding to about a few % of the driving current, for example.

According to the above-described means, the driving control data corresponding to the detected temperature is used to control the driving current of the laser diode. Upon determination of the deterioration of the laser diode, the ambient temperature of the laser diode is further measured and a decision is made as to whether the difference between a driving current defined by driving control data corresponding to the newly measured temperature and an actual driving current formed by the automatic optical output control exceeds an allowable value. When the difference is found to exceed the allowable value, it is determined that the deterioration of the laser diode has been advanced. Thus, a distinction between whether the increase in driving current due to the automatic optical output control results from the deterioration of the laser diode and whether it results from a variation in ambient temperature is reliably done. The driving control data corresponding to the corresponding temperature is updated based on the difference between the driving currents used to determine the deterioration of the laser diode. After the renewal of the driving control data, the driving current for the laser diode is controlled using the corresponding updated driving control data. Thus, a quenching failure and an emission delay are limited to the minimum with respect to both the change in ambient temperature and the characteristic deterioration of the laser diode due to secular changes, whereby an optical output can be held constant.

Once the driving control data is updated, the driving currents under the corresponding temperature are set as a bias current and a modulating current determined by the updated driving control data. The subsequent detection of the deterioration in the laser diode is carried out by determining whether the difference between the driving current determined by the corresponding updated driving control data and the driving current subjected to the automatic optical output control exceeds the allowable value. Thus, when the progress of the deterioration of the laser diode is detected, the previously-stored driving control data is renewed into driving control data including information for defining the newly-acquired amount of correction. Thereafter, the driving current of the laser diode is determined according to the updated correction driving control data.

The driving control data comprises initial data for initially determining the bias current and the modulating current for each predetermined temperature, and correction data subsequently added to the initial data. At this time, the correction data can be set as data for defining the difference between the driving currents as each of the increases in bias current and modulating current. Described more specifically, the control means can include data about the difference between the driving currents and a value obtained by increasing the difference between the driving currents by a factor of a constant ratio smaller than 1 in the correction data as data about an increase in bias current. At this time, the control means determines a bias current by the sum of the initial bias current data included in the initial data and the data about the increase in bias current included in the correction data when the driving current for the laser diode is determined based on the initial data and the correction data, and adds the initial modulating current data included in the initial data to the difference between the data about the difference between the driving currents and the data about the increase in bias current respectively included in the correction data, thereby making it possible to determine a modulating current.

In order to relax a change in wavelength incident to a rise in the temperature of the laser diode, a cooling device capable of selectively cooling the laser diode is further provided. The control means is capable of lowering an ambient temperature of the laser diode by a predetermined temperature by the cooling device each time the difference between the measured driving currents reaches a predetermined value with respect to a driving current defined by initial driving control data or a driving current defined by correction driving control data and the initial driving control data.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram showing one example of an optical transmission device according to the present invention with an optical transceiver as the core;

FIG. **2** is a block diagram schematically illustrating the entire optical transmission device constructed as an interface board.

FIG. **3** is a circuit diagram depicting one detailed example of the optical transceiver;

FIG. **4** is a circuit diagram showing one example of a switching control circuit for allowing a modulating current to flow in a diode in pulse form;

FIG. **5** is an explanatory view illustrating one example of a driving control data table;

FIG. **6** is an explanatory view depicting the relationship between a driving current and emission power of an LD;

FIG. **7** is an explanatory view showing a temperature characteristic of the LD;

FIG. **8** is an explanatory view illustrating deterioration-life relationship between a driving current Id and emission power Pf of the LD under a fixed temperature environment;

FIG. **9** is a flowchart depicting a procedure for generating data for driving control of the LD using the driving control data table and correction driving control data therefor;

FIG. **10** is an explanatory view showing, as an example, the relationship between an increase δId in driving current and an increase δIb in bias current by auto power control;

FIG. **11** is a flowchart illustrating the transition of the driving control of the LD according to a progress in characteristic deterioration of the LD; and

FIG. **12** is a flowchart showing one detailed example of a cooling process.

BEST MODE FOR CARRYING OUT THE INVENTION

<<Optical Transmission Device>>

One embodiment of an optical transmission device is illustrated in FIG. **1** with an optical transceiver as the core. An optical transceiver 1T and an optical receiver 1R are typically illustrated in the optical transmission device **1** shown in the same drawing. Although not restricted in particular, the optical transceiver 1T is provided with a laser diode module **10**, a driver circuit **11**, an input circuit **12**, and a microcomputer **17** respectively individually brought into semiconductor integrated circuits. The optical receiver 1R includes a pin photodiode **13**, a pre-amplifier **14**, a main amplifier **15** and an output circuit **16** respectively individually brought into semiconductor integrated circuits.

The laser diode module **10** has a laser diode (also described as LD) **100** and a photodiode (also described as PD) **101** for monitoring. An optical output of the laser diode **100** is outputted to an optical output terminal OPOUT. The pin photodiode **13** receives a light or lightwave signal from an optical input terminal OPIN. The input circuit **12** is connected to a data input terminal DTIN and a clock input terminal CLIN, whereas the output circuit **16** is connected to a data output terminal DTOUT and a clock output terminal CLOUT.

The input circuit **12** has a buffer memory **120** and an input buffer **121** such as a D type flip flop (F/F) or the like. The buffer memory **120** successively stores data signals sent from the data input terminal DTIN in synchronism with a clock signal inputted from the terminal CLIN. The data stored in the buffer memory **120** is supplied to the input buffer **121** in synchronism with the clock signal supplied from the clock input terminal CLIN, where it is waveform shaped, followed by supply to the driver circuit **11**.

The driver circuit **11** has an LD driver **110** and an auto power controller (APC) **111**. The LD driver **110** allows a bias current corresponding to a threshold current of the LD**100** to flow in the LD**100** and selectively supplies a modulating current for on/off-controlling the LD**100** to the LD**100** in response to each data signal supplied from the input buffer **120**.

The PD**101** effects photoelectric conversion on light outputted from the LD**100** to form or produce a current corresponding to the intensity or power of emission of the LD**100**. The APC**111** auxiliarily controls a driving current supplied to the LD**100**, based on the current flowing in the PD**101** so that the emission power of the LD**100** becomes constant. The microcomputer **17** performs basic control related to the bias current and modulating current on the LD driver **110**. The details thereof will be described later. The optical output of the LD**100** is supplied from the optical output terminal OPOUT to a transmission line such as an optical fiber or the like.

The pin photodiode **13** detects the light signal supplied to the optical input terminal OPIN from the transmission line and converts or transforms it to a received signal current. The received signal current is converted into a voltage signal by the pre-amplifier **14**. The converted voltage signal is supplied to the main amplifier **15**. The main amplifier **15** amplifies the input voltage signal up to an ECL level. The output circuit **16**, which receives the output of the main amplifier **15** therein, has a timing extractor **160**, a recognizer or identifier **161** and an output buffer **162** like a flip-flop. The timing extractor **160** divides the input signal into two systems. Further, the timing extractor **10** delays one of them and ANDs it and the other thereof to thereby produce a pulse containing a clock component of, for example, 155.52 MHz.

Only the clock component of 155.52 MHz is extracted from the pulse by an unillustrated SAW (Surface Acoustic Wave) filter and limit-amplified to produce a clock signal. The identifier **161** sufficiently amplifies the input signal supplied from the main amplifier **15** and waveshapes it into a signal whose waveform's upper and lower portions are sliced. The output buffer **162** performs waveform shaping (suppression on pulse-width distortion) on the so-sliced signal, using the clock signal. The output of the output buffer **162** is supplied to the data output terminal DTOUT and the clock signal produced by the timing extractor **160** is supplied to the clock output terminal CLOUT.

The optical transceiver 1T shown in FIG. **1** is provided with the microcomputer **17**. Although not restricted in particular, the microcomputer **17** is used even for control of the optical receiver 1R.

Although not restricted in particular, the microcomputer **17** has a CPU (Central Processing Unit) **170**, a RAM (Random Access Memory) **171**, a ROM (Read Only Memory) **172**, a flash memory **173** illustrative of one example of an electrically erasable and programmable nonvolatile memory device, an input/output (I/O) circuit **174**, etc. They are connected to an internal bus **175**. Although not restricted in particular, the ROM**172** is a mask ROM which stores constant data or the like therein, whereas the RAM**171** is defined as a work area or region of the CPU**170**. Further, the flash memory **173** holds an operating program, driving control data, etc. for the CPU**170** therein so that they are programmable.

The microcomputer **17** is a circuit for controlling the optical transmission device **1** over its entirety. The driving control data for the LD**100** is stored in the flash memory **173**. When the LD**100** is driven to transmit light, the CPU**170** reads driving control data corresponding to a temperature detected by a temperature sensor **112** to be described later from the flash memory **173** and performs driving control of the LD**100** by the LD driver **110**, based on the read data. Namely, a data table (driving control data table) created based on a temperature characteristic of the LD**100** is prepared in the flash memory **173**. Thereafter, the CPU**170** controls a driving current flowing in the LD**100** in conformity with the temperature characteristic of the LD**100** according to the optical output, temperature, etc. necessary for the LD**100**. The contents of control on the driving current will be described later. In addition to the above, the microcomputer **17** controls the gain of the pre-amplifier **14** by switching.

The microcomputer **17** is connected to an unillustrated protocol controller or the like lying within the optical transmission device through a microcomputer interface terminal (also called micon interface terminal) MCIF so as to be supplied with instructions for transmission and reception control, etc. The micon interface terminal MCIF is connected to a mode terminal of the microcomputer **17** and a predetermined port of the input/output circuit.

The microcomputer **17** has, for example, a boot mode in addition to a user program mode. When the user program mode is set to the microcomputer **17**, the CPU**170** executes the operating program stored in the flash memory **173**. The boot mode is an operation mode for allowing the flash memory **173** to be rewritten or programmed directly from outside the microcomputer **17**. When the boot mode is set to the microcomputer **17**, the input/output circuit **174** is brought to a signal input/output state capable of externally directly programming or rewriting the flash memory **173**. Namely, when the boot mode is set, a rewriting high voltage, a program signal, addresses and data can be transferred to and from the flash memory **173** through the micon interface terminal MCIF. By using the boot mode, the driving control data can initially be written into the flash memory **173** and the operating program for the CPU**170** can be written into the flash memory **173**. It is also possible to rewrite the flash memory **173**. The writing and rewriting of data into the flash memory **173** can be carried out even by the user program mode of the microcomputer **17**. The driving control data written into the flash memory **173** can be reprogrammed under the control of the CPU**170**.

FIG. **2** is an overall block diagram of the optical transmission device. Although not restricted in particular, the optical transmission device shown in the same drawing constitutes one of a large number of interface boards which make up of an ATM switch or the like. The optical transceiver **1**T and the optical receiver **1**R are connected to an optical trunk network by an optical fiber. A SUNI (Serial User Network Interface) **3** is provided at a stage subsequent to the optical transceiver **1**T and the optical receiver **1**R. Deserialization or serial-parallel conversion of data is done at a portion of the SUNI**3**, which is connected to the optical transceiver **1**T, whereas serialization or parallel-serial conversion of data is carried out at a portion of the SUNI**3**, which is connected to the optical receiver **1**R. When the protocol controller **4** supports an ATM (Asynchronous Transfer Mode), it performs assembly/de-assembly of each data cell and multiplexing/de-multiplexing thereof. A transmit signal is supplied to the protocol controller **4** through a parallel input circuit **6** and a transmitting buffer **5**. A receive signal is supplied from the protocol controller **4** to a parallel output circuit **8** through a receiving buffer **7**. The parallel input circuit **6** and the parallel output circuit **8** are connected to another switch through, for example, an unillustrated interface cable or the like.

<<Optical Transceiver>>

FIG. **3** shows one detailed example of the optical transceiver **1**T. The LD driver **110** has a transistor Tr**1** for determining a bias current fed through the LD**100** and a transistor Tr**2** for determining a modulating current to be supplied to the LD**100**, as current source transistors. Transistors Tr**3** and Tr**4** are switching transistors for controlling on and off of the modulating current fed through the LD**100**. The transistors Tr**1** through Tr**4** are constructed as npn type bipolar transistors.

The transistors Tr**3** and Tr**4** are electrically connected in parallel. A common emitter thereof is electrically connected to the collector of the transistor Tr**2**. The emitter of the transistor Tr**2** is coupled to a ground voltage GND through a resistor R**2**. The cathode of the LD**100** is electrically connected to the collector of the transistor Tr**3**. The anode of the LD**100** and the collector of the transistor Tr**4** are commonly connected to a source voltage Vcc.

As one detailed example of a switching control circuit **114** for the transistors Tr**3** and Tr**4** is illustrated in FIG. **4**, a series circuit of transistors Tr**5** and Tr**6** and a series circuit of transistors Tr**7** and Tr**8** are placed between the source voltage Vcc and the ground voltage GND. The transistors Tr**5** through Tr**8** are constructed as npn bipolar transistors. The bases of the transistors Tr**6** and Tr**8** are biased by a predetermined voltage and serve as load resistors for the transistors Tr**5** and Tr**7**. In other words, the series circuit of the transistors Tr**5** and Tr**6** and the series circuit of the transistors Tr**7** and Tr**8** respectively constitute emitter follower circuits. The emitter of the transistor Tr**5** is electrically connected to the base of the transistor Tr**3**, and the emitter of the transistor Tr**7** is electrically connected to the base of the transistor Tr**4**.

The bases of the transistors Tr**5** and Tr**7** are supplied with a differential output produced from a differential output amplifier AMP. When their inputs are reversed, the states of potentials applied to the bases of the transistors Tr**3** and Tr**4** are inverted. The amplifier AMP is supplied with the output of the selector **121**.

When the potential applied to the base of the transistor Tr**3** is brought to a high level, the transistor Tr**3** is shifted to a saturated state. When the base of the transistor Tr**4** is brought to the high level, the transistor Tr**4** is shifted to the saturated state. The transition of the transistors Tr**3** and Tr**4** to the saturated states is complementarily carried out so that the transistors Tr**3** and Tr**4** are complementarily switched, thus causing a pulse-shaped modulating current to flow in the LD**100** through the current source transistor Tr**2**.

As shown in FIG. **3**, the collector of the transistor Tr**1** is electrically connected to the collector of the transistor Tr**3**, whereas the emitter thereof is electrically connected to the ground voltage GND through a resistor R**1**. The transistor Tr**1** allows a bias current equivalent to a threshold current to flow in the LD**100** according to the base voltage applied thereto.

The PD**101** is electrically series-connected to a resistor R**3** and placed in a backward connected state between the source voltage Vcc and the ground voltage GND. The PD**101** supplies a current corresponding to emission intensity or power outputted from the LD**100**.

Referring to FIG. **3**, the input/output circuit **174** of the microcomputer **17** is illustrated in form divided into a digital-analog converter (D/A) **176** for converting a digital signal into an analog signal, an analog-digital converter (A/D) **177** for converting an analog signal to a digital signal, a timer **179** and another input/output circuit **178**. The D/A**176** has three D/A conversion channels DAC**1** through DAC**3**, and the A/D**177** has four A/D conversion channels ADC**1** though ADC**4**.

The D/A conversion channel DAC**3** has an intrinsic register accessed by the CPU**7** and output a signal for driving a cooling driver **201** to be described later. The D/A conversion channels DAC**1** and DAC**2** respectively have intrinsic registers accessed by the CPU**170**. Further, the D/A conversion channels DAC**1** and DAC**2** convert values of the corresponding registers into D/A form and outputs base bias voltages for the transistors Tr**1** and Tr**2**. Although not restricted in particular, each of the D/A conversion channels DAC**1**, DAC**2** and DAC**3** converts a 8-bit digital signal to an analog signal in a 256-step gradation.

As described above, the modulating current to be fed through the transistor Tr**3** in accordance with on/off-control of the optical output is determined according to driving control data set to the D/A conversion channel DAC**2** by the CPU**170**. The bias current to be fed through the LD**100** is determined according to driving control data set to the D/A conversion channel DAC**1** by the CPU**170**.

Thus, the CPU**170** is capable of individually and arbitrarily controlling the modulating current and bias current capable of being supplied to the LD**100** in accordance with the driving control data set to the D/A conversion channels DAC**1** and DAC**2**. Thus, the CPU**170** sets data corresponding to the temperature characteristic of the LD**100** or the like with respect to a use condition (use atmospheric temperature) of the optical transmission module **1** to the D/A conversion channels DAC**1** and DAC**2**, in other words, the CPU**170** sets data corresponding to a bias current equivalent to the threshold current of the LD**100** at a use ambient or environmental temperature at that time to the D/A conversion channel DAC**1** and sets data corresponding to a modulating current to be added to the bias current to the D/A conversion channel DAC**2** to obtain necessary emission intensity or power under the temperature thereof, thereby making it possible to light-produce and drive the LD**100** without a quenching error and an emission delay.

The A/D conversion channels ADC**1** through ADC**4** are successively assigned to their corresponding inputs of an emitter voltage of the transistor Tr**1**, an emitter voltage of the transistor Tr**2**, an anode voltage of the PD**101** and an output voltage of the temperature sensor **112**, and have registers inherent in them, for holding the results of A/D conversion of the assigned input voltages therein so as to be accessible by the CPU**170**. Although not restricted in particular, the A/D conversion channels ADC**1** through ADC**4** respectively have 10-bit conversion accuracy.

Thus, the CPU**170** is capable of monitoring a bias current fed through or flowing in the transistor Tr**1**, a modulating current flowing in the transistor Tr**2**, a current flowing in the PD**201**, and the output of the temperature sensor **10** through the A/D converter **177** as needed. Although not restricted in particular, the operation of the CPU**170** for monitoring their information can be carried out each time the CPU**170** receives a timer interrupt given from the timer **179**.

The output of the monitor PD**101** is made available even to auto power control (automatic optical output control). The APC**111** shown in FIG. **1** is comprised of, for example, a comparator **113** and an APC control circuit **115** shown in FIG. **3**. Namely, the comparator **113** receives an anode voltage corresponding to a current fed through the PD**101** according to actual emission power of the LD**100**, determines whether the input voltage is smaller than a reference potential Vref corresponding to predetermined emission power, superimposes a signal corresponding to the result of determination over the signal outputted from the D/A conversion channel DAC**1** and supplies it to a base electrode of the transistor Tr**1**, and increases or decreases a bias current fed through the LD**100** through the transistor Tr**1**. The APC control circuit **115** is a circuit for forming the reference potential Vref, which forms the reference potential Vref, based on the mean value of current fed through the PD**101** according to the emission power of the LD**100** and the mean value (mark rate) relative to the input signal of the amplifier AMP at that time. Although not restricted in particular, the auto power control is supplementary to bias current control based on the output of the D/A conversion channel DAC**1**. Namely, it supplements an error unable to be followed up by the bias current and modulating current based on the output of the D/A**176**.

The CPU**170** can monitor the anode voltage of the PD**101** through the A/D conversion channel ADC**3**, recognize the actual emission intensity or power of the LD**100**, and detect, for example, a state in which the actual emission power is reduced with respect to target emission power. The CPU**170** is capable of monitoring the emitter voltage of the transistor Tr**1** through the A/D conversion channel ADC**1**, converting the monitored voltage to a current, comparing the value of the converted current and a bias current to be fed through the transistor Tr**1** via the D/A conversion channel DAC**1**, and detecting an abnormal variation in bias current, based on the difference therebetween. Similarly, the CPU**170** is capable of monitoring the emitter voltage of the transistor Tr**2** through the A/D conversion channel ADC**2**, converting the monitored emitter voltage to a current, comparing the value of the converted current and a modulating current to be fed through the transistor Tr**2** via the D/A conversion channel DAC**2**, and detecting an abnormal variation in modulating current, based on the difference therebetween.

Further, the CPU**1710** monitors the emitter voltages of the transistors Tr**1** and Tr**2** through the A/D conversion channels ADC**1** and ADC**2** respectively and converts the monitored voltages to their corresponding currents, thereby making it possible to measure a driving current (corresponding to the sum of the bias current and the modulating current) fed through the LD**100** in practice. The measured current also includes an increase in bias current by the auto power control. Accordingly, the CPU**170** is capable of grasping or keeping track of the difference between the driving current measured in this way and the driving current to be supplied to each of the transistors Tr**1** and Tr**2** through each of the D/A conversion channels DAC**1** and DAC**2**.

<<Driving Control Data for LD>>

The driving control data for determining the modulating current and the bias current to be supplied to the LD**100** is stored in a driving control data table. The driving control data table includes data to be set to the D/A conversion channels DAC**1** and DAC**2** for each use environmental temperature in order to obtain a predetermined target optical output and is formed in the flash memory **173** of the microcomputer **170**.

FIG. **5** shows one example of the driving control data table TBL. The driving control data table TBL has an initial data region Eini and a correction data region Ecor. The respective regions Eini and Ecor are associated with each other every temperatures.

Initial data corresponding to an initial temperature characteristic of the LD**100** is stored in the initial data region Eini. The initial data is data for determining a bias current and a modulating current for obtaining the intended emission intensity or power every temperatures. For example, data about an initial bias current Ib(0), data about an initial modulating current Imod(0) and data about their total current (driving current) Id(0) necessary to obtain a fixed emission power like 0.8 mW are held in the initial data region for each predetermined temperature.

The relationship between the driving current (Id) and emission power (P**0**) of the LD**100** is shown in FIG. **6**, for example. Bias currents Ib(Ti), Ib(Tj) and Ib(Tk), threshold currents Ith(Ti), Ith(Tj) and Ith(Tk), and modulating currents Imod(Ti), Imod(Tj) and Imod(Tk) at typically-illustrated temperatures Ti, Tj and Tk are shown in the same drawing. Each bias current referred to above is set to a current corresponding to about 90% of its corresponding threshold current, for example. As is apparent from FIG. **6**, if the temperature rises when attempt is made to obtain the fixed emission power, then both the threshold and modulating currents must be made great according to its rise. On the other hand, a temperature characteristic of the LD**100** is shown in FIG. **7**. Since the threshold current Ith and the driving current Id respectively show a characteristic nonlinear with respect to the temperature as is apparent from the same drawing, it is necessary to control even the bias current Ib and the modulating current Imod non-linearly with respect to the temperature (T) in a manner similar to the above. Particularly, since the threshold current Ith increases suddenly as the temperature rises, a control method for varying the bias current Ib simply linearly with respect to the temperature encounters difficulties in most suitably setting the bias current Ib. Namely, when the temperature varies during the execution of the auto power control, the driving current of the LD**100** increases or decreases so that the intensity of light becomes constant. However, the setting of the bias current cannot follow a variation in threshold current Ith and hence the modulating current Imod cannot be set to the optimum value either in a manner similar to the above. In the optical transceiver **1**T, data about the optimum bias current Ib(0) and modulating current Imod(0) corresponding to the temperature characteristics related to the initial threshold current Ith and driving current Id of the LD**100** are stored in the initial data region Eini for each predetermined temperature. Thus, if the LD**100** is driven using the data about the initial bias current Ib(0) and initial modulating current Imod(0) of the LD**100**, corresponding to the respective temperatures, then an emission delay and a quenching failure can substantially be solved.

The correction data region Ecor shown in FIG. **5** includes data about a difference bias current δIb and data about a difference driving current δId as correction data for defining each current superimposed on a bias current and a modulating current defined by the initial data. Data about a driving current Id(t) stored in the correction data region Ecor is data which means a current obtained by superimposing a current defined based on the data about the difference driving current δId on a driving current Id(0) defined based on the data about the initial bias current Ib(0) and the data about the initial modulating current Imod (0). Incidentally, while the driving control data shown in FIG. **5** are illustrated as data expressed in mA units for convenience, the driving control data are actually defined as digital data set every temperatures for defining such current values.

FIG. **8** shows the fore-and-aft relationship of life and degradation between a driving current Id and emission power Pf of the LD**100** under a fixed temperature environment. In FIG. **8**, (0) shows one example of an initial Id-Pf characteristic of the LD**100**, and (t) indicates one example of an Id-Pf characteristic of the LD**100** after the elapse of a predetermined period. The characteristic indicated by (t) is a characteristic deteriorated due to secular changes. Both the bias current and modulating current must be increased to obtain the same emission power. When the characteristic changes from (0) to (t) due to the secular changes, the whole driving current must be increased by δId with respect to the characteristic indicated by (0) to obtain the same emission power. The driving current with respect to the initial characteristic indicated by (0) can be determined based on the initial data. When the characteristic is deteriorated, the CPU**170** controls the driving current of the LD**100** so that the bias current is increased by δIb and the modulating current is increased by δId−δIb. Data for determining increases in bias current and modulating current due to the deterioration of the characteristic of the LD respectively correspond to the data about the difference currents δIb and δId. When the LD**100** deteriorated in characteristic is driven using data at a temperature of 73° C. shown in FIG. **5** when the temperature of the LD**100** is 73° C., for example, the bias current is determined based on the value of Ib(0)+δIb and the modulating current is determined based on the value of Imod(0)+δId−δIb.

Data about currents Ib(0), Imod(0) and Id(0) for each predetermined temperature, each of which corresponds to the intended emission power, are initially stored in the initial data region Eini shown in FIG. **5**. The data about those currents Ib(0), Imod(0) and Id(0) are externally downloaded through the micon interface MCIF, for example. The down-loaded data can be written into the flash memory **173** under the control of the CPU**170**. Alternatively, the data can also be written therein in a boot program mode in a microcomputer manufacturing process.

The correction data region Ecor shown in FIG. **5** is first initially set to a value like "0". The CPU**170** calculates correction driving control data according to the degree of deterioration of the LD**100** and stores it therein. The once-stored correction driving control data is updated each time the deterioration of the LD increases or develops.

<<Driving Control of LD>>

A procedure for generating data for driving control of the LD**100** and correction driving control data therefor, using the driving control data table will be explained based on FIG. **9**.

After power-on has been reset (S**1**), the CPU**170** detects the temperature through a cooling process to be described later (S**2**). The temperature detection is carried out by obtaining data detected by the temperature sensor **112** through the A/D conversion channel ADC**4**. The CPU**170** reads initial driving control data and correction driving control data corresponding to the detected temperature from the driving control data table TBL (S**3**). The read data are defined as the data about the initial bias current Ib(0), the data about the initial modulating current Imod(0), the data about the driving current Id(0) obtained by summing up them, the data about the difference bias current δIb, the data about the difference driving current δId and the data about the driving current Id(t). The CPU**170** sets data of Ib(0)+δIb to the D/A conversion channel DAC**1** based on the read data and controls a bias current to be supplied to the LD**100** through the transistor Tr**1** (S**4**). Further, the CPU**170** sets data of Imod(0)+δId−δIb to the D/A conversion channel DAC**2** and controls a modulating current to be supplied to the LD**100** through the transistor Tr**2** (S**5**). Since the correction data region Ecor of the driving control data table TBL is filled with such a predetermined initializing code that all the bits are "0", δId=0 and δIb=0 when the optical transmission control device **1** is in first use. The emission intensity or power is controlled fixedly by starting bias current control and modulating current control and executing the auto power control by the APC**111**.

When a predetermined interval has elapsed, the CPU**170** detects the temperature in a manner similar to the above according to a timer interrupt or the like (S**6**) and reads data about Id(0) and Id(t) in the column corresponding to the detected temperature. If Id(t)=0, then the CPU**170** recognizes Id(0) as a driving current corresponding to the detected temperature. If Id(t)≠0, then the CPU**170** recognizes Id(t) as a driving current corresponding to the detected temperature at that time (S**7**) Since the so-recognized driving currents (also called simply regulated driving currents Idregu) are based on the temperature detected in the temperature detection Step S**6** different from Step S**2**, the driving currents might be different from the driving currents set in Steps S**4** and S**5** if an atmosphere temperature changes.

Next, the CPU**170** obtains the values of voltages applied to the emitters of the transistors Tr**1** and Tr**2** through the A/D conversion channels ADC**1** and ADC**2** to thereby measure a driving current subjected to auto power control under the driving current control in Steps S**4** and S**5** and actually supplied to the LD**100** (S**8**). The so-measured actual driving current is simply called monitor driving current Idmoni.

The CPU**170** determines whether the measured monitor driving current Idmoni exceeds a range X allowable for the regulated driving current Idregu and increases (S**9**) The allowable range X is a range in which a quenching failure and an emission delay due to an increase in bias current under the auto power control substantially show no problem in the regulated driving current Idregu at the temperature at that time, for example. This is equivalent to a current corresponding to a few % or so of the regulated driving current Iregu, for example. Namely, whether the monitor driving current Idmoni exceeds the range X allowable for the regulated driving current Idregu will be defined as a