Optical Phased Array Technology

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Optical phased arrays represent an enabling new technology that makes possible simple, affordable, lightweight, optical sensors offering very precise stabilization, random-access pointing, programmable multiple simultaneous beams, a dynamic focus/defocus capability, and moderate to excellent optical power handling capability. These new arrays steer or otherwise operate on an already formed beam, as compared to modern microwave phased arrays which both generate a beam and direct it in a specific direction. A phase profile is imposed on an optical beam as it is either transmitted through or reflected from the phase shifter array. The imposed phase profile steers, focuses, fans out, or corrects phase aberrations on the beam. The array of optical phase shifters is realized through lithographic patterning of an electrical addressing network on the superstrate of a liquid crystal waveplate. Refractive index changes sufficiently large to realize full-wave differential phase shifts can be effected using low (<10 V) voltages applied to the liquid crystal phase plate electrodes. High efficiency large-angle steering with phased arrays requires phase shifter spacing on the order of a wavelength or less; consequently addressing issues make 1-D optical arrays much more practical than 2-D arrays. Orthogonal oriented 1-D phased arrays are used to deflect a beam in both dimensions. Optical phased arrays with apertures on the order of 4 cm by 4 cm have been fabricated for steering green, red, 1.06 μm, and 10.6 μm radiation. Steering efficiencies of about 60% at 4° and 85% at about 2° have been achieved to date with switching times as short as a few milliseconds in the visible. Fluences of several hundred W/cm^2 have been demonstrated at 10.6 μm with nonoptimally engineered devices. Higher fluences can be handled at shorter wavelengths. Larger apertures are feasible, as is operation at other wavelengths and significantly faster switching times. System concepts that include a passive acquisition sensor as well as a laser radar are presented.

I. INTRODUCTION

Currently optical sensor systems, including laser radar, are often limited in performance and cost by mechanical beam directing and stabilization mechanisms. The requisite pointing and stabilization usually requires precise, rapid, mechanical motion, and is often associated with substantial masses. Submicroradian steering precisions are often desired, but are usually impractical for available, affordable, mechanical beam directing systems. Most mechanical systems do not facilitate rapid random pointing. Furthermore, the rapid steering of a large aperture optical sensor often requires a prohibitive amount of power. Despite the considerable accumulated manufacturing experience in this field, mechanical beam steering for optical sensors remains complex, precise, and expensive.

Optical phased arrays appear to have the potential to overcome many of the limitations of mechanical beam steering. Liquid-crystal-based phased arrays require very little prime power, even for large apertures, thereby opening up application areas such as missile interceptors, satellite communications, and portable sensors of all types. Phased arrays are inherently random-access devices, a distinct advantage when regions of interest are distributed widely across a sensor field of regard (FOR). Unlike mechanical systems, liquid crystal devices are generally insensitive to accelerations, and their costs can drop rapidly with volume production, as is the general case for the electronic devices they resemble. Flat panel displays, fabricated using technologies that are similar to those required for liquid-crystal optical phased arrays, are now inexpensive enough to be in every notebook computer.

In the related microwave radar arena, phased arrays are rapidly displacing conventional horn antennas. The clear benefits of random-access, rapid beam pointing with no moving parts have made phased arrays the technology of choice, despite their high cost. Fortunately, cost trades for optical radars using optical phased arrays promise to be more favorable since the optical arrays are monolithically fabricated with no discrete elements, consist of an array of phase shifters rather than individual transmit/receive

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modules, and are designed to use low-cost addressing electronics. The optical phased arrays discussed here are passive arrays, consisting soley of phase shifters, and are operated as space-fed arrays, meaning that an already formed beam is fed to the array of phase shifters, which then effects steering of that beam. This contrasts to an active phased array in which individual transmit modules form a beam as it exits a large array of transmitters.

There are many application areas that can benefit from the performance/cost benefits made possible by optical phased arrays. Inexpensive, reliable laser radar for target detection, wind profiling, and gas cloud identification are examples of high interest. Laser communication, whether effected with directed beams in free space or by switching of guided beams within fiber links, is another application area. Defense against infrared guided missiles benefits from directed laser energy, and is another potential optical phased array application area. Later in the paper issues associated with steering broadband optical energy are addressed. Passive infrared sensors for imaging or point detection applications can also benefit from phased array optical beam steering, but to a more limited degree at this time; however, future applications are expected to expand as techniques for reducing the influence of dispersion are developed.

Optical beam steering by means of phased elements is a rich area heavily researched by prior workers. As early as 1971, Meyer [1] had developed a 1-D optical phased array using bulk, lithium tantalate phase shifters. The array comprised 46 phase shifters on one-half millimeter spacings. The number of addressable beam positions, beam widths, scan angles, and beam spacings all were shown to agree with theory as developed for microwave phased array antennas. Shortly thereafter Ninomiya [2] demonstrated a 1-D array of lithium niobate electrooptic prism deflectors. The resolving power of the array was shown to be N times that of a single prism, where N is number of arrayed prisms. The array successfully demonstrated 50 resolvable spots with 600 V applied. Both discrete and continuous steering were demonstrated. The power required was noted to be similar to that for acousto-optic deflectors. Although these early phased arrays clearly demonstrated the concept, they were neither developed for high performance nor were intended for practical application. Large phase shifter spacings of hundreds of wavelengths were unavoidable, given the state of the technology, and precluded achieving efficient large angle beam steering. The small aperture fill factors also guaranteed large insertion losses. However, many of the key advantages of the phased array approach to beam steering were well appreciated by these early workers. Ninomiya pointed out that a phased array offers random access, that the resolving power of a phased array is high, that the steering angle is very accurate, and that there is no shift of optical frequency as with acousto-optic deflectors.

Beam steering of visible light has recently been reported using a liquid crystal television panel as an elementary phased array [3]. Although liquid crystal displays are usually configured to effect intensity modulation, when the polarizers are removed the accompanying phase shift becomes observable. The display pixels are programmed to effect a discrete blazed-grating phase ramp across the aperture. However, the relatively large pixel spacing (several hundred waves), the nonunity array fill factor, and the limited available phase modulation depth (1.3π) have severely limited the achievable steering efficiency and angle ($<0.1°$).

Other workers in the field have attempted to develop higher performance optical phased arrays by greatly reducing the phase shifter spacings. Vasey *et al.* [4] have developed an integrated optics approach comprising a 1-D phased array based on a linear array of closely spaced AlGaAs waveguides, the relative phases of which can be electrically adjusted using the electrooptic effect in the waveguiding material itself. Beams are coupled into the guided structure and launched into free space using grating couplers. Continuous steering is achieved by electrically imposing a linear phase ramp of adjustable slope across the aperture. Addressing is accomplished via a fine/coarse architecture, somewhat similar to the approach discussed in Section IV. Continuous steering of a 900 nm beam over a ±7.5 mrad field has been reported. Element spacings are orders of magnitude less than those in earlier bulk demonstrations, but remain multiple (13–14) wavelengths. Consequently, maximum steering angles are limited and efficiencies are low due to the large number of radiated diffraction orders (so-called grating lobes). Although the electrooptic effect used in this approach is inherently fast (ns), achieving the steering angles and efficiency levels required for laser radar is expected to be difficult, as is scaling to required aperture sizes and obtaining steering in two-dimensions.

Another approach reported recently [5] uses a thin, 2-D array of liquid crystal phase shifting elements configured to operate as coherent microprisms with a relatively high fill factor. The individual elements are multiple wavelengths in extent and spacing, but are constructed to produce a linear phase ramp of adjustable slope across each element face, thereby simulating a discrete blazed grating with programmable blaze angle. The current device steers in one dimension only, although in principal two devices could be cascaded to steer in both dimensions. Unlike most preceding optical arrays, this device was specifically designed for laser radar application and is, in principle, capable of high efficiency at large angles (20°) and of being fabricated with large apertures. However, to date, only small apertures (2 mm square), moderate steering angles (5°), and low efficiencies (1%–9%) have been achieved owing to fabrication difficulties inherent to the approach. One of the difficulties is that this approach requires using only the linear portion of the liquid crystal versus voltage curve, resulting in a limited use of available birefringence.

A more classic approach to optical phased arrays has been under development by the authors. This work has resulted in development of a true optical phased array with 1-D phase shifter spacings smaller than a single free-space wavelength, 100% aperture fill factors over significant apertures, and performance approaching theoretical predictions for small to moderate angles. The unity fill factor, small phase shifter spacings, and careful fabrication techniques used result in very low sidelobe levels. These are the first optical phased arrays which are capable of redirecting a single input beam into essentially a single, diffraction limited, output beam with negligible sidelobes. Using this approach, high performance optical phased array based steering of carbon dioxide laser beams (10.6 μm) was first demonstrated in 1989, with demonstrations of Nd:YAG steering (1.06 μm) following soon thereafter [6], [7]. That work will soon appear in the open, reviewed, literature [8], [9].

These new optical phased arrays are direct functional analogs of the well known microwave phased array antennas [10] that make possible the agile, inertialess steering of microwave beams. The underlying fundamental concepts are identical to those for a microwave array. However, due to the orders-of-magnitude difference in wavelengths between the microwave and optical worlds, these new optical phased arrays have been implemented quite differently. The current optical devices are 1-D, space-fed, passive, phase-only, apertures. This differs from modern microwave phased arrays with which a beam is usually both formed and steered in two dimensions by a 2-D array of active elements. The field intensity across the aperture of an active microwave array is generally tapered at the edges in order to achieve low sidelobe levels. This is not an option with a passive, phase-only array. However, being space-fed, if the input optical beam is Gaussian in spatial profile, as is the usual case, additional tapering is not needed. The 1-D phase-only array steers an optical beam in one dimension only. Unlike modern microwave arrays, and most other optical phased arrays to date, these new arrays are designed to be easily cascaded. This allows simple mounting of orthogonal 1-D arrays to steer the beam in two dimensions. Microwave arrays are built using discrete phase shifters, as have been most early optical phased arrays. However, since a vast number of phase shifters is needed to realize a high performance optical array, distributed liquid crystal phase shifters have been implemented, as described by Huignard *et al.* [11]; however, it has proven essential to implement additional innovative addressing means to avoid the otherwise impractical numbers of interconnects.

The organization of this paper is as follows. In Section II liquid crystal optical phased array technology is summarized. In Section III we briefly discuss alternative candidates to optical phased arrays for eliminating complex and expensive mechanical motion from laser radar optical systems. A more detailed description is presented in section IV. Section V summarizes performance levels achieved and predicted performance potential. Section VI considers the pointing of an acquisition sensor, often a passive infrared (IR) sensor. Section VII discusses laser radar system concepts that incorporate target acquisition and tracking capabilities. Section VIII contains conclusions.

II. Overview of Liquid Crystal Optical Phased Array Concepts

A prism inserted into the aperture of an optical system introduces a linear gradient of optical path delay (OPD) across the aperture which tilts the phase front and thereby steers the optical beam. For a given wavelength a phase shift of 2π (corresponding to an OPD of one wavelength) can be subtracted periodically from the phase front without influencing the far-field pattern produced by the phase front [12]. The "folded" phase profile represents a blazed grating. The phase ramp, or its equivalent modulo-2π sawtooth phase profile, further can be approximated by a series of discrete phase steps, as long as the steps are small.

Fig. 1 illustrates the use of nematic liquid crystal cells as phase shifters. With no applied fields, the liquid crystal molecules align with an average orientation parallel to the substrates, according to the liquid crystal alignment layer applied at the substrate interface. Application of a relatively low voltage, on the order of 1–10 V, reorients the liquid crystal molecules and changes the effective index of refraction as seen by light polarized along the direction of quiescent molecular orientation. The maximum phase shift available is proportional to the thickness of the liquid crystal layer. The case of a 2π phase retarder is illustrated. The switching speed of a nematic liquid crystal phase shifter is generally inversely proportional to the square of the thickness of the nematic liquid crystal layer [13]. For steering angle/aperture size combinations that require phase resets, the minimum thickness of the liquid crystal layer to produce efficient steering requires a liquid crystal layer sufficiently thick to produce a full wavelength of OPD and allow modulo 2π operation. Only a combination of very small angles, or very small aperture size, allows practical beam steering without the use of resets. The liquid crystal layer thickness, t, for a 2π phase shift is given by

$$t \geq \lambda / \Delta n \tag{1}$$

where $\Delta n = (n_e - n_o)$ is the birefringence of the material and λ is the free space wavelength. As an example, the nematic liquid crystal E7 has a birefringence of approximately 0.2 in the visible and near infrared spectrum. It requires a 5 μm layer thickness to achieve a relative phase delay of 2π radians at a 1 μm wavelength. If a reflective-mode design is used, allowing two passes through the liquid crystal layer, a full wave OPD is created using only half that thickness, or 2.5 μm.

The diffraction efficiency, η, of a grating with a stair-step blaze designed to maximize energy in the first order is given by [23]:

$$\eta = \left(\frac{\sin(\pi/q)}{\pi/q} \right)^2 \tag{2}$$

where q is the number of steps in the blaze profile. From (2) it can be seen that an eight-step approximation gives a theoretical efficiency of approximately 95%. Fig. 2 shows a step approximation to the wavefront deflected by a prism, including the 2π phase resets. Note that a 2π phase reset has that value only for the design wavelength. Fig. 3 shows the deviation from a straight line in the unfolded phase profile when a wavelength other than the design wavelength is used. This variation in phase reset values causes dispersion

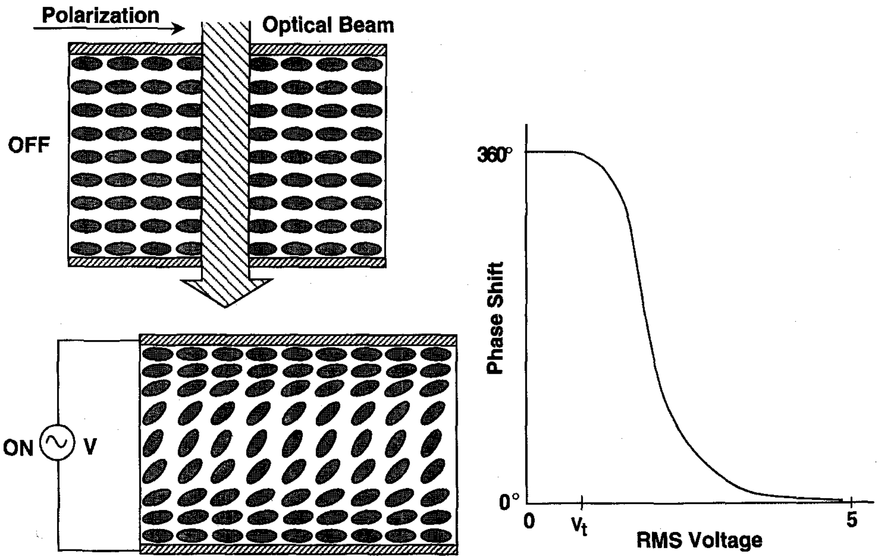

Fig. 1. Nematic liquid crystal phase shifters. The liquid crystal molecules are birefringent. Light polarized along the long axis of the molecule will experience a different index of refraction than light polarized along the short axis of the crystal. The molecules will rotate when a voltage is applied, producing an effective index change for light polarized perpendicular to the long axis of the crystal.

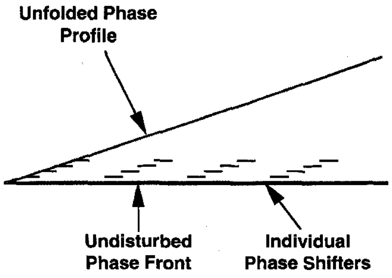

Fig. 2. *Optical phased array agile beam steering*. The optical phase delay introduced by a prism in an aperture can be approximated by a series of stair-step ramp phase delays. When a ramp has an optical path difference equal to or larger than the design wavelength one design wavelength of optical path difference is subtracted from the ramp. At the design wavelength, the phased array effectively reproduces the steering caused by a prism.

[14], which will be discussed further in Section VI. As shown in Fig. 3, the unfolded OPD is in error by $(\lambda - \lambda_d)$ after each reset, and the unfolded phase is in error by $2\pi(\lambda - \lambda_d)/\lambda$ after each reset, where λ is the actual wavelength and λ_d is the design wavelength.

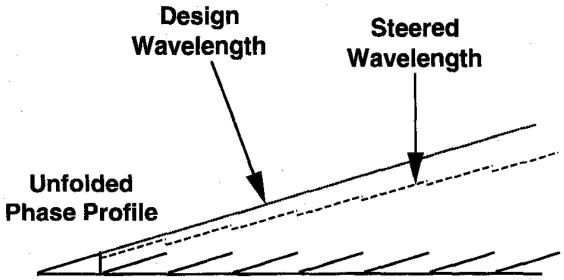

Fig. 3. *Unfolded phase profile*. This figure shows the influence on the unfolded phase profile of operation at a wavelength other than the design wavelength.

Practical factors can cause the measured efficiency of an actual phased array beam steerer to deviate from the theoretical value given by (2). One such factor, evident in liquid crystal phased arrays currently being developed, is a spatial "flyback" in the molecular orientation of the liquid crystals which results from the minimum spatial extent required to change from the orientation for a phase shift of 2π to that for a phase shift of zero. The actual flyback transition is a complex function of device design and liquid crystal visco-mechanical properties. Fig. 4 depicts phase versus position for a simple flyback model. As a result of flyback, only a portion of the grating imposes the correct phase distribution to steer a beam in the design direction. That portion of the grating over which flyback occurs can be thought of as steering the beam in a different direction. The resulting diffraction efficiency η into the desired grating order can be approximated by [15]

$$\eta = \left(1 - \frac{\Lambda_F}{\Lambda}\right)^2 \tag{3}$$

where Λ_F is the width of the flyback region and Λ is the period of the programmed grating. The energy that is not directed into the desired grating order is distributed among numerous other grating orders, causing a loss in efficiency for the primary order. The overall steering efficiency is given by the product of (2) and (3). Depending on the grating period (which affects both the number of steps in the blaze profile as well as the relative size of the flyback),

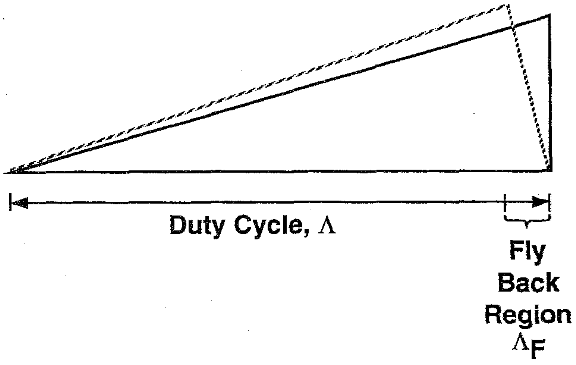

Fig. 4. *Flyback.* When one design wavelength of optical path difference is subtracted it requires finite spatial extent. This region is referred to as the flyback region. The steering efficiency into a given order is influenced by the relative size of the flyback region with respect to the grating period.

either (2) or (3) may dominate the overall steering efficiency of an optical phased array beam steerer.

For a normally incident input beam the steered angle is given by [16]

$$\sin\theta = \frac{\lambda_o}{\Lambda} \tag{4}$$

where λ_o is the design wavelength for the beam steerer, $\Lambda = qd$ is the period of the staircase ramp, q is the number of phase shifters between resets, and d is the center-to-center spacing between phase shifters, which is assumed to equal the width of the phase shifter as well. Large steering angles correspond to high spatial frequencies (small periods) and vice versa. From (3) and (4) it can be seen that the steering efficiency decreases monotonically with steering angle, for fixed flyback.

Two-dimensional beam steering can be achieved using two orthogonally oriented 1-D liquid crystal phase gratings. In addition, any optical distortion that is separable in Cartesian coordinates can be fully compensated, modulo 2π. Spherical aberrations can be fully compensated with a crossed grating system. For a full adaptive optics capability, a third layer, with a 2-D array of phase shifters, would be required. This would add the ability to clean up an arbitrarily aberrated beam and adapt for atmospheric turbulence. Such a liquid crystal adaptive optics layer has recently been discussed [17]. The spacing of elements on such an adaptive optics layer would be orders of magnitude courser than the spacing required for large angle beam steering. Current adaptive optics mirror systems have on the order of 50–400 elements correcting for turbulence while using apertures up to a few meters [18]. However, the adaptive optic element is usually used prior to final beam expansion and is much smaller in aperture. Pixelated phase shifters of about 1 mm square would probably suffice for most applications and could be readily fabricated with the current technology. Thus liquid crystal phase shifter technology could replace the current piezoelectrically driven adaptive optic components, resulting in a single three-layer component that both deflects and phase compensates a beam. If operated modulo 2π, such adaptive optic elements would be dispersion limited to narrow band applications.

III. BEAM STEERING APPROACHES USING LIMITED MECHANICAL MOTION

An optical phased array is not the only approach to realizing rapid beam steering without the use of conventional mechanical systems. Some of the more viable alternate options are briefly reviewed here. All of the options discussed here potentially allow the redirection of the field-of-view of an optical sensor without the use of complex, costly, mechanical mechanisms. Unlike the optical phased array, most of these alternate options do not eliminate mechanical motion, but instead minimize the degree of mechanical motion required. To date, none of these alternate approaches have demonstrated the scope of performance characteristics desired for laser radar and most other optical sensors.

One such option is the use of cascaded microlens arrays [19], [20] an example of which is shown in Fig. 5. Each microlens array consists of a (generally) close packed, periodic array of miniature lenses which can be fabricated in either diffractive or refractive forms. Beam steering is effected by translating one microlens array with respect to the other. The concept can be understood by first considering a single microlens pair from a set of aligned afocal arrays. A collimated input beam is focused to the back focal point of the first microlens, which is also the front focal point of the second microlens, resulting in an unsteered, collimated output beam. However, if the second microlens is offset, then the back focal point of the first microlens appears as an off-axis point to the second microlens. The point remains in the front focal plane of the second microlens, so the second microlens still recollimates the light, but the beam is redirected to a nonzero field angle. A paraxial ray trace shows that the tangent of this field angle is equal to the amount of offset divided by the focal length of the second microlens. Maximum useful steering occurs with an offset equal to the radius of a microlens. It may be noted that it does not matter if the second microlens has a positive or negative focal length so long as the condition of overlapping focal planes is met. If the individual microlenses of the arrays are aligned, periodically spaced, and designed to fill the aperture, the output beam replicates the input beam. If the offset is small, the steered beam approximates a simple redirection of the input beam.

However, if the offset is large, significant fractions of the input beam are coupled into other grating modes. This can be appreciated by noting that phased arrays and microlens arrays both approximate blazed gratings [21]. If the periodic quadratic phase profiles of two offset microlens arrays are superimposed, the result is a (generally asymmetric) triangular waveform, which approximates a blazed grating. If the composite phase profile were a sawtooth, the approximation would be exact. Motion of the lenses alters the slope(s) of the phase profile, thereby changing the blaze

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