1 kW of continuous-wave output power

Y. Jeong, J.K. Sahu, D.N. Payne and J. Nilsson

A ytterbium-doped fibre laser with up to 1 kW of continuous-wave output power at 1.09 µm with a slope efficiency of 80% and a good beam quality ($M^2 = 3.4$) is reported. The fibre was pumped by two diode-stack sources launched through opposite ends. No undesirable roll-over was observed in output power with increasing pump power.

Introduction: In recent years the output powers of ytterbium (Yb^{3+}) doped fibre lasers have grown dramatically and they are now competing with conventional bulk solid-state lasers (e.g. Nd:YAG lasers) in high-power application areas such as material processing, medicine, and range finding. The technique of cladding-pumping combines the attractions of fibre lasers with high-power, low-cost, multimode-diode pumping and leads to fibre lasers with high-brightness, even diffraction-limited, output, even when low-brightness diode lasers are used as pump sources. An excellent conversion efficiency (>80%) and a broad tunability of Yb-doped fibre lasers make them exceptional high-power sources in the 1–1.1 µm wavelength range, e.g. 10 kW of output power has been reached from highly multimoded devices that combined the output power from several fibre lasers [1]. The power achieved in high-brightness output beams from single-fibre configurations is lower, but has nevertheless reached 500 W in 30–40 m-long fibre devices [1, 2].

In this Letter, we describe further power-scaling of the single-fibre laser configuration to an output power of 1 kW. For this to be possible, we used a higher pump power, a larger inner cladding, and a larger core than before.

A large inner cladding is necessary to accommodate the large pump beams required for a kW fibre laser in our end-pumped configuration. A large core is also required for many reasons: with a thick inner cladding, a conventional core diameter of e.g. 10 µm or less would lead to excessively long fibres in which background loss would degrade the output power. Therefore, a large core is needed to reach sufficient pump absorption with an acceptable Yb-concentration. Another reason is the suppression of nonlinear-scattering [2–4], achieved with the lower power density and shorter fibre possible with a larger core. There is also the possibility of fibre facet damage: in the case of pure silica the damage threshold intensity is $\sim 10\ \mathrm{GW/cm^2}$, i.e. $\sim 100\ \mathrm{W/\mu m^2}$ in pulsed operation [5]; however, this value is likely to be lower in continuous-wave (CW) operation and even for a rare-earth-doped core, because the impurities and inhomogeneities caused by dopant molecules are likely to increase the susceptibility to damage. As a conservative estimate, we may want to keep power density at the facet below $1\ \mathrm{W/\mu m^2}$ for reliable operation. With this value, the modefield area needs to be as large as $\sim 10^3\ \mathrm{\mu m^2}$ if we aim for a 1 kW output power from a single-fibre laser, though further power scaling may well be possible with this core size in view of our conservative estimate of the damage threshold.

Experiments and results: A double-clad Yb-doped large-core fibre was designed to meet the requirements for power-scaling to the kW level. It was pulled from a preform that was fabricated in-house by the modified chemical-vapour deposition (MCVD) and solution doping technique. The fibre had a 43 µm-diameter Yb-doped core with a numerical aperture (NA) of 0.09, centred in the preform. With this design, the modefield area for the fundamental mode becomes $\sim 1100\ \mathrm{\mu m^2}$, which should allow for reliable operation with kW level output power. The D-shaped inner cladding had a 650/600 µm diameter for the longer/shorter axis after being milled. This diameter was chosen to enable efficient coupling of the high power pump sources. The fibre was coated with a low-refractive-index polymer outer cladding which provided a nominal inner-cladding NA of 0.48. The small-signal absorption rates in the inner cladding were ~1.5 and ~3 dB/m at 972 and 975 nm, respectively. This corresponds to a Yb^{3+}-concentration of ~4500 ppm by weight. The fibre length used in the laser experiments was 8 m.

The experimental setup is shown in Fig. 1. We used a double-sided end-pumping scheme, with two pump sources launched into opposite ends of the fibre. Two diode-laser-stack-based pump sources were used, emitting at 972/975 nm, respectively. The pump beams were could launch a combined maximum pump power of 1.3 kW, corresponding to ~85% of the power incident on the fibre. In one end of the laser cavity, high-reflectivity feedback was provided by a pair of dichroic mirrors, with high transmission at the pump wavelength and high reflection at the signal wavelength. The mirrors were external to the fibre and coupled to it via a lens. The laser output coupler was formed by a 4% reflecting flat perpendicular cleave in the other end of the fibre. The signal was separated from the pump beam with another dichroic mirror. Both ends of the fibre were held in temperature-controlled metallic V-grooves designed to prevent thermal damage to the fibre coating by any non-guided pump or signal power, or by the heat generated in the laser cycle itself.

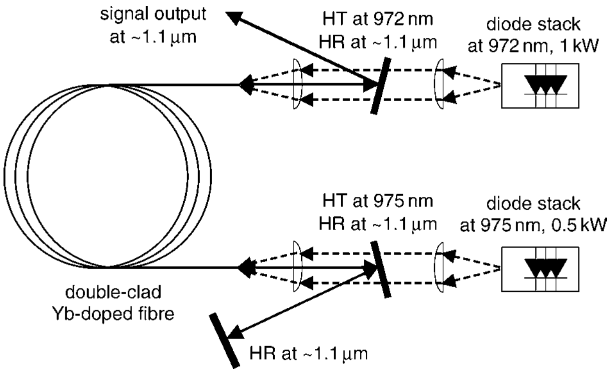

Fig. 1 *Yb-doped fibre laser arrangement used with two diode-stack pump sources*

HR: high reflectivity; HT: high transmission

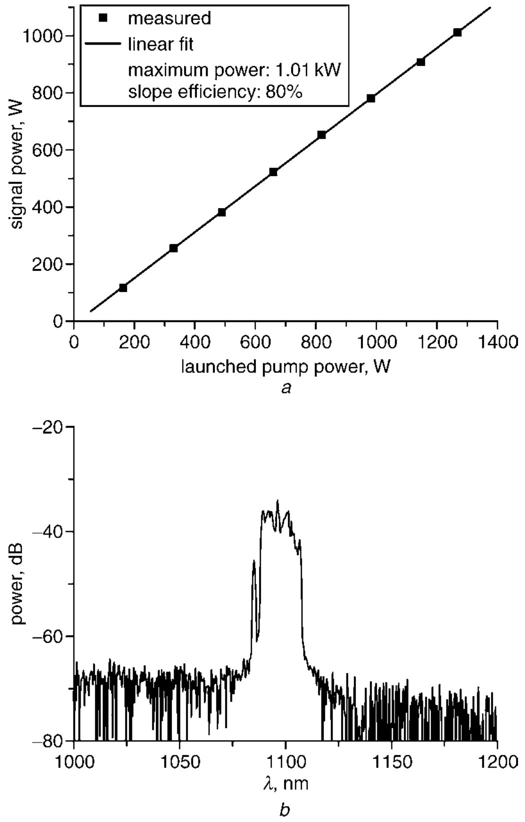

Fig. 2 *Fibre laser output power against launched pump power, and laser output spectrum at full power*

a Output power against launched pump power
b Output spectrum

The laser output power characteristics are shown in Fig. 2, together with the output spectrum at full output power. The maximum laser output power was 1.01 kW and the slope efficiency with respect to the launched pump power was 80%. The pump leakage was estimated to be below 1.7%. The standard deviation of the temporal power was <1.2%, oscilloscope. The output power increased linearly with launched pump power. There was no evidence of any power limitation due to nonlinear scattering, nor was any stimulated Raman scattering observed. Compared to previous results generating up to 500 W from 30–40 m-long fibres with 12 and 24.5 µm core diameters [1, 2], our fibre was significantly shorter (8 m) and had a bigger core (43 µm diameter). This suggests a very high threshold for undesirable nonlinear scattering for our Yb-doped fibre laser, and thus, nonlinear scattering was completely suppressed. We measured the beam quality factor (M^2) of 3.4. This must be considered to be a good result, bearing in mind the relatively high V-parameter of 11.2 of the core at 1.09 µm, and given that no special measures were taken to suppress operation on higher-order modes. Given that we may be relatively far from the damage threshold, one could consider making the core smaller (provided acceptable pump absorption can be maintained). This would allow for an improved beam quality. The core-NA could also be reduced to improve the beam quality. There are also mode-selecting techniques such as a fibre taper and bend-loss filtering that can be used to improve the beam quality further in the multimode core [6, 7].

Conclusion: We have demonstrated a highly efficient, high Yb concentration, double-clad Yb-doped large-core fibre laser with a CW output power of 1.01 kW at 1.09 µm based on an 8 m single fibre. No evidence of roll-over in laser output power at the highest launched pump powers (∼1.3 kW) was observed, suggesting that our laser could be scaled to even higher powers using a more powerful pump source or, for example, with additional multiplexed-pump sources.

Acknowledgment: This work was supported in part by DARPA under contract MDA972-02-C-0049.

28 January 2004
Electronics Letters online no: 20040298
doi: 10.1049/el:20040298

Research Centre, University of Southampton, SO17 1BJ, United Kingdom)

E-mail: yoj@orc.soton.ac.uk

References

1 Gapontsev, V.P., Platonov, N.S., Shkurihin, O., and Zaitsev, I.: ‘400 W low-noise single-mode cw ytterbium fiber laser with an integrated fiber delivery’. Proc. Conf. on Lasers and Electro-Optics, Baltimore, MD, USA, June 2003 (postdeadline paper CThPDB9)

2 Limpert, J., Liem, A., Zellmer, H., and Tünnermann, A.: ‘500 W continuous-wave fibre laser with excellent beam quality’, *Electron. Lett.*, 2003, **39**, pp. 645–647

3 Jeong, Y., Sahu, J.K., Williams, R.B., Richardson, D.J., Furusawa, K., and Nilsson, J.: ‘Ytterbium-doped large-core fibre laser with 272 W output power’, *Electron. Lett.*, 2003, **39**, pp. 977–978

4 Platonov, N.S., Gapontsev, D.V., Gapontsev, V.P., and Shumilin, V.: ‘135 W CW fiber laser with perfect single mode output’ . Proc. Conf. on Lasers and Electro-Optics, Long Beach, CA, USA, May 2002 (postdeadline paper CPDC3)

5 Said, A.A., Xia, T., Dogariu, A., Hagan, D.J., Soileau, M.J., Van Stryland, E.W., and Mohebi, M.: ‘Measurement of the optical damage threshold in fused quartz’, *Appl. Opt.*, 1995, **34**, pp. 3374–3376

6 Alvarez-Chavez, J.A., Grudinin, A.B., Nilsson, J., Turner, P.W., and Clarkson, W.A.: ‘Mode selection in high power cladding pumped fibre lasers with tapered section’. Proc. Conf. on Lasers and Electro-Optics, *OSA Tech. Dig.* Washington, DC, USA, 1999, pp. 247–248

7 Koplow, J.P., Kliner, D.A.V., and Goldberg, L.: ‘Single-mode operation of a coiled multimode fiber amplifier’, *Opt. Lett.*, 2000, **25**, pp. 442–444