810 W continuous-wave and single-transverse-mode fibre laser using 20 μm core Yb-doped double-clad fibre

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It is shown that continuous-wave kW-power fibre lasers can be built using double-clad fibres with relatively small cores. 810 W in a single-transverse-mode output ($M^2 = 1.27$) is demonstrated experimentally with 20 μm core low-NA (NA = 0.06) Yb-doped double-clad fibre. A laser numerical model matches experimental results and predicts scalability of achievable powers into a multi-kW range.

Introduction: Use of large mode area (LMA) fibres has led to a recent increase in continuous-wave fibre laser powers to a kW level [1–3] produced in a single-transverse-mode. LMA fibres allow significant reduction of signal nonlinear distortions in a fibre core and facilitate high power pumping. So far, however, high powers were predominantly achieved using LMA fibres with core sizes from 25 to 50 μm. Furthermore, a number of advanced fibre designs, such as multicore structures [4, 5], have been suggested to reach kW power levels. Such large cores and complex structures are inherently associated with complex techniques to suppress higher-order mode lasing.

In this Letter we demonstrate that relatively small core fibres are suitable for reaching kW and even higher single-transverse-mode powers. Using 20 μm diameter low-NA ($NA = 0.06$) core Yb-doped double-clad (DC) fibre, we demonstrate experimentally 810 W in a single-transverse-mode output with $M^2 = 1.27$. Numerical simulations indicate that further power scaling into a multi-kW range is also possible with these fibres. The particular practical advantage of the 20 μm core fibres used is that they support only two transverse modes, thus making higher-order mode suppression relatively easy and splicing relatively straightforward, compared to larger cores. Owing to this practical advantage, a number of standard fibre components, such as monolithic pump combiners [6] and fibre Bragg gratings are becoming technologically available, thus facilitating development of all-fibre kW-level lasers.

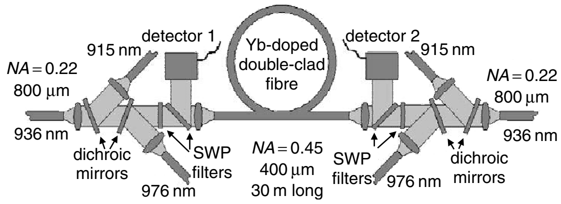

Fig. 1 *Experimental setup*

Experiment: Configuration of an 810 W single-transverse-mode fibre laser is shown in Fig. 1. The fibre laser was built using 30 m of low NA ($NA = 0.06$) 20 μm core double-clad fibre with 400 μm diameter and $NA = 0.46$ hexagonal cladding. The pump absorption in the cladding at 915 nm is 0.66 dB/m. One version of a fibre laser cavity (shown in Fig. 1) was formed by 3.5% Fresnel reflections from each straight-cleaved fibre end, which produced two equal-power beams emitted from both ends of the laser. This fibre laser was end-pumped from both sides using six diode-bar lasers operating at three different wavelengths of 915, 936 and 976 nm and producing total of 1.6 kW of combined pump power. Each diode pump was coupled separately into 800 μm diameter, 0.22 NA delivery fibres, and each set of three different wavelength diodes were wavelength combined using dichroic mirrors and coupled into 400 μm cladding at each fibre laser end using 2:1 imaging optics. The total coupled pump power into double-clad fibre was 1.16 kW, resulting in a total signal power of 810 W, shown in Fig. 2, with 70% slope efficiency and 3 W lasing threshold. The laser spectrum is shown in the inset of the Figure, indicating a rather broad band (>10 nm), which suppresses completely Brillouin scattering. We also used another version (not shown in the Figure) of the laser cavity, with an HR mirror at one end to produce one-side output. In this configuration only three diodes were used for one-side pumping with the maximum coupled pump power of 700 W and the resulting maximum output power of 500 W. It is interesting to note that no end caps were needed to protect fibre ends from surface damage at all power levels.

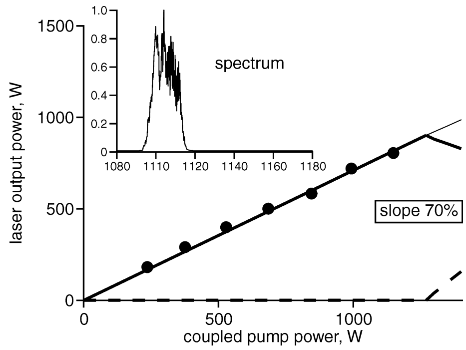

Fig. 2 *Laser power and spectrum*
● measured laser power
Lines represent calculated results:
— signal – – – – Raman — total power

Owing to the fact that the fibre used supports only two modes, it is relatively easy to suppress the single higher-order mode by appropriate fibre coiling [7]. Fig. 3 shows the high-power output beam profile and M^2 value measurement for a coiling diameter of 15 cm. The measured $M^2 = 1.27$ indicates a high degree of LP_{11}-mode suppression.

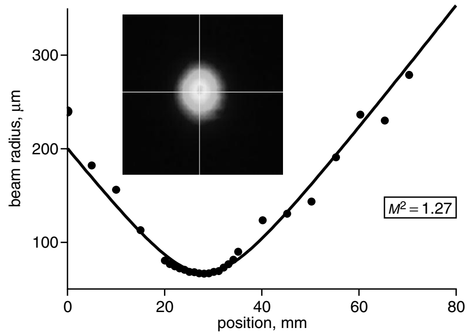

Fig. 3 *M^2 measurement and beam profile*

Thermal dissipation, due to high pump power used, is an important issue and must be considered carefully. Our calculation for 1 kW pumped fibre in the experimental setup of Fig. 1 revealed that if heat from the fibre is removed only through air convection at the fibre surface, the thermal equilibrium is expected to occur at an unacceptably high fibre-surface temperature (~800°C) at each pumped end. Therefore, for more efficient (~100 times) heat removal we used water immersion of fibres. Both calculation and measurement indicated a negligibly low fibre-surface temperature increase of ~10°C at fibre ends, thus eliminating all thermal issues. For the sake of evaluating the limits of such thermal management we also calculated the temperature rise in the same water-immersed fibre for the hypothetical case of ~10 kW pumping. The calculation predicted a fibre-surface temperature increase of merely ~80°C, indicating that multi-kW pumping powers could be potentially feasible.

Therefore, stimulated Raman scattering (SRS) is expected to be the principal factor limiting the achievable fibre-laser power. In order to explore this SRS limit, we developed a laser model, which includes spectral dependence of emission and absorption cross-sections, background and bending losses, amplified spontaneous emission and Raman scattering. Fig. 2 compares experimental and modelling results for the dual output configuration, indicating good agreement between the two. The model predicts 900 W of Raman-free maximum signal power in this particular experimental configuration, which is slightly above the highest achieved laser power of 810 W (pump-power limited) and is consistent with the experimentally observed absence of SRS.

Further numerical studies revealed that much higher SRS thresholds are possible by using more sophisticated laser system configurations. Indeed, a simple calculation shows that in a single-pass amplifier the SRS threshold for the same fibre should exceed 10 kW of signal power. This indicates that suppressing feedback at Raman wavelength in a CW fibre laser should raise significantly the SRS threshold. This, as one example, could be implemented by forming a fibre laser cavity between two narrowband Bragg gratings instead of mirrors, thus providing optical feedback at only the selected signal wavelength. The resulting increase in SRS threshold is illustrated in Fig. 4, where a numerical model prediction for a 30 m-long laser cavity formed by 3.5% and 99% reflections at the signal wavelength and pumped equally from both ends is shown. In this Figure laser power at SRS threshold is plotted against Raman feedback suppression. If we assume that 30 to 60 dB feedback suppression is practically achievable (from residual splice, fibre grating, etc., reflections) then CW fibre lasers, of the order of a few kW, using 20 µm core fibres are, in principle, feasible.

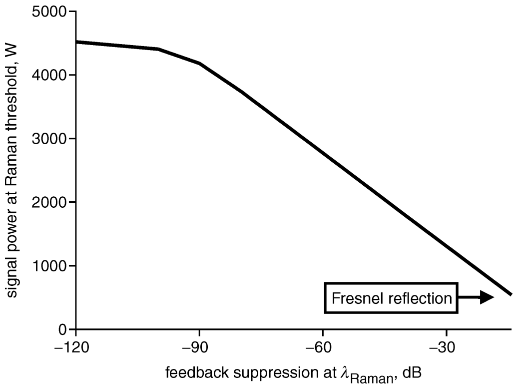

Fig. 4 *Theoretical Raman threshold against feedback suppression at* λ_{Raman} *in 30 m-long 20 µm core Yb-doped fibre laser*

Conclusion: We have demonstrated 810 W in a single-transverse-mode ($M^2 = 1.27$) from a CW fibre laser using a 20 µm core double-clad Yb-doped fibre. We also demonstrated that effective thermal management is possible at kW pump powers by using a suitable method for heat removal from a fibre (e.g. water immersion). Our numerical model predicts that, although the SRS is limiting the maximum achievable CW fibre laser power, optimisation is possible with a potential of reaching multi-kW Raman-free laser powers from 20 µm core LMA fibres. The practical significance of the reported demonstration and analysis is that, owing to the relative maturity of 20 µm LMA fibres and fibre components, all-monolithic fibre lasers with single-transverse-mode outputs at multi-kW power levels are feasible.

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