Ytterbium-doped large-core fibre laser with 610 W of nearly diffraction-limited output power

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

Abstract

We report a cladding-pumped ytterbium-doped fibre laser, generating up to 610 W of continuous-wave (cw) output power at 1.1 μm with slope efficiency of 80% and near diffraction-limited beam quality (M^2 = 1.3). No undesirable roll-over was observed in output power with increasing pump power.

Subject categories and indexing terms*:* *Lasers (Fibre lasers), Optics (Optical pumping)*

Introduction:

In recent years, the dramatically increased output power from high-power rare-earth-doped silica fibre lasers has made them interesting for high-power applications in science and industry in areas such as material processing, marking, medicine, and range finding. The rise in power is due mainly to improvements in fibre design and fabrication and in the performance of pump diode sources including multi-emitter lasers diodes, diode bars, and diode stacks. In the high power regime, ytterbium (Yb^{3+})-doped fibres (YDFs) make exceptional sources in the 1 – 1.1 μm wavelength range because of excellent power conversion efficiency of over 80% and broad tuning range over several tens of nanometers. A highly multi-mode device that combined the output power from several fibre lasers reached an output power of 10 kW [1]. A single-fibre device has reached 1 kW of output power at 1.1 μm, with high, but not diffraction-limited, beam quality (M^2 = 3.4) [2]. Though a diffraction-limited single-mode output beam is often required, a large core diameter (43 μm) and a relatively high numerical aperture (NA, 0.09) lead to a high V-value of 11, which precluded single-mode operation [2], [3]. A nearly diffraction-limited (M^2 = 1.42) output power of 810 W was also reported [4]; however, the output was double-ended, i.e., the actual power emitted by a single-fibre end was a half of the total out power. In this symmetric cavity laser with 4% feedback in both ends, a Raman gain seems to be relatively high because it used a 30-m long fibre with a relatively small core of a 20-μm diameter and 0.06 NA. More recently, a single-ended high-brightness output of 1.3 kW was reported; however, the output beam was slightly multi-moded (M^2 ~ 3) [5].

The beam quality can be improved with a smaller core, e.g., a conventional single-mode cores of diameters of ~9 μm or less, i.e., that can be strictly single-moded if $V < 2.405$; however, there exits a limit to further power scaling with a smaller core. The parasitic lasing by stimulated Raman scattering (SRS) and facet damage threshold can be potential problems due to the extremely high intensity as the output power grows. In addition, the smaller core has a lower pump absorption rate in a cladding pumping scheme that the device length becomes longer which also ramp up the undesirable Raman gain.

Thus, further power-scaling of single-ended, single-mode fibre lasers requires careful attention to fibre design via optimising fibre parameters including core/cladding dimension, refractive index profile, and doping level as well as laser configurations [6]. In this letter, we further discuss details of a YDFL that established a single-fibre / single-ended output power of over 600 W with a near diffraction-limited beam quality in comparison to our previous results [2], [3].

Experiments and Results:

We used two diode-stack pump sources at 972 – 975 nm in a so-called end-pumping scheme which is a simple and efficient way to pump a double-clad fibre. These diode-stack pump sources produce high-power beams, but with poor beam quality, which means that we have to use a fibre with a large inner-cladding diameter. With a sufficiently thick inner cladding, a conventional core diameter of, e.g., 9 µm or less would lead to a small pump absorption and therefore excessively long fibres, because of the small overlap of the pump with the core. The Raman gain would be high, and SRS would be difficult to suppress. Therefore, a large core is preferable in a single-fibre laser configuration. A large core can also mitigate the facet damage of fibres. For reliable cw operation we target a signal power density of no more than ~1 $W/\mu m^2$ [2], though considerably higher power densities may well be allowable [7]. Considering these constraints, we designed and fabricated a YDF and arranged the experimental setup with the fibre and appropriate diode-stack-based pump lasers to investigate possibilities of realising a fibre laser that can emit a nearly diffraction-limited beam from a multi-moded large-core fibre in a high-power regime, resolving the poor beam quality obtained from our previous work [2], [3].

The double-clad YDF used in this experiment was designed and pulled from a preform that was fabricated in-house by the modified chemical-vapour deposition (MCVD) and solution doping technique. The fibre had a 28-µm diameter Yb^{3+}-doped core with an NA of 0.09, centred in the preform. Before being drawn to fibre, the preform was milled to have a D-shape so as to improve the cladding-mode overlap with the Yb^{3+}-doped core. As a result, the inner cladding had a 400/350-µm diameter for the longer/shorter axis. 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 dB/m and ~3 dB/m at 972 nm and 975 nm, respectively. This corresponds to an Yb^{3+}-concentration of ~4500 ppm by weight. The fibre length used in the laser experiments was 7 m.

Two diode-laser-stack-based pump sources emitting at 972 nm and 975 nm, respectively, were coupled to either end of the active fibre via collimating and focusing lenses in a double-sided end-coupling scheme: A similar experimental setup can be found in Fig. 1 in Ref. [6]. It is noteworthy that we used an additional pump source at 975 nm in extension to a single-end pumping configuration that had been employed in our previous experiment to achieve 610W of multi-mode output (M^2 = 2.7) in Ref. [3]. We could launch a combined maximum pump power of 760 W. The coupling efficiency was ~60%, worse than those obtained in Refs. [2], [3] (>80%) because of the smaller diameter of the fibre. A pair of dichroic mirrors, with high transmission at the pump wavelength and high reflection at the signal wavelength, provided a high, external, feedback in one end of the fibre. In the other end of the fibre, an output coupler was formed by a 4% reflecting flat perpendicular cleave. The signal was then deflected, and separated from the pump-beam path, 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.

The laser output power characteristics are shown in Fig. 1. The maximum laser output power was 610 W which was limited by the available pump power. The slope efficiency with respect to the launched pump power was 80%. We estimate the pump leakage through the fibre to <2%. The standard deviation of the temporal power was <1.5%, measured with a photo-detector of 3.5-ns rise/fall time and a 400 MHz oscilloscope. The output power increased linearly with launched pump power, without any evidence of any power limiting effects. The laser output spectrum measured at the maximum output is shown in Fig. 2 together with its beam profile in the inset. We measured a nearly diffraction-limited beam of the quality factor (M^2) of 1.3. This must be considered to be a good result, bearing in mind a relatively high V-parameter of 7.3 for the core at 1.1 µm, and given that no special measures were taken to suppress operation on higher-order modes except the core design. No stimulated Raman scattering was observed. We estimate the un-polarised Raman gain in our fibre to be no more than 1 dB.

For further power-scaling, optical damage must be controlled, as well. The maximum power density in our fibre becomes 1.2 $W/\mu m^2$, based on a mode area of 512 μm^2. No damage was observed. The power density was significantly higher in other work, e.g., ~2 $W/\mu m^2$ in a

YDF and ~6 W/μm^2 in a passive fibre in [1], and still higher in bulk silica in a pulsed regime [7]. This shows that our fibre is far from the damage threshold at 610 W as well as the SRS threshold, and that it can be power-scaled even higher.

Conclusions: We have demonstrated a highly efficient, high concentration, double-clad YDFL with a cw output power of 610 W at 1.1 μm and near diffraction-limited beam quality based on a 7-m single fibre. No fibre damage and no evidence of roll-over in laser output power at the highest launched pump power (760 W) indicate that our fibre design of having the V-parameter of ~7 can be kept for further kW-level power-scaling with combining more pump power.

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Fig. 1 Fibre laser output power vs. launched pump power.

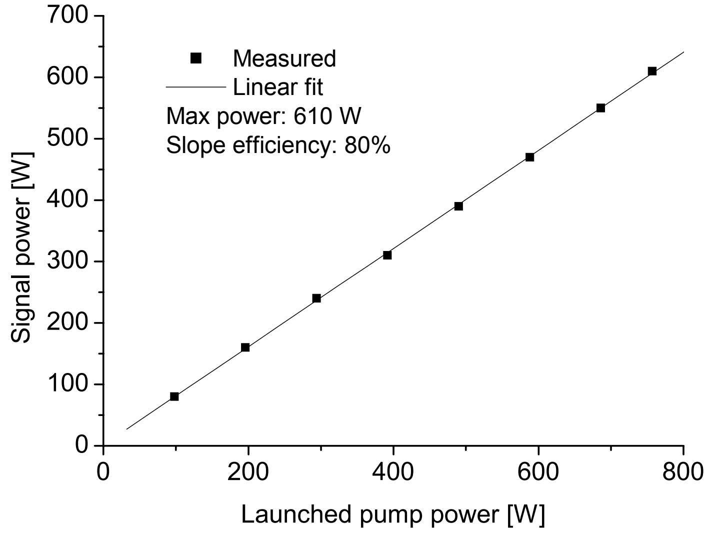

Fig. 2 Laser output spectrum at full power (resolution: 2 nm). Inset: a relay-image of output beam profile.