Power-scaling of a 2 µm ytterbium-sensitized thulium-doped silica fibre laser diode-pumped at 975 nm

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An ytterbium-sensitized thulium-doped silica fibre laser that generates up to 75 W of output power in the 2 µm wavelength range when cladding-pumped by a 975-nm diode stack is reported. The slope efficiency is 32% with respect to the launched pump power and the beam quality factor (M^2) is 1.3.

Introduction: Thulium (Tm^{3+})-doped fibre lasers are of great interest for generating coherent emission in the "eye-safe" wavelength range. Their emission band extends over a wide range from 1.6 µm to over 2 µm, and they can be efficiently pumped at ~790 nm, ~1200 nm, or ~1600 nm [1-3]. These features make Tm^{3+}-doped fibre lasers attractive for a variety of applications in medicine and spectroscopy, and potentially attractive for applications such as material processing. For high power operation, pumping at 790 nm is attractive since with the appropriate core composition one can exploit the "two-for-one" cross-relaxation process with the result that very high efficiency can be achieved [4]. However, the availability of high-power diodes in this wavelength range at >100-W level from commercial supplies is relatively poor. Pumping Tm^{3+}-doped fibres at 1200 nm or 1600 nm is complicated by the need for an intermediate laser source, since high-power laser diode are not commercially available at this wavelength.

An alternative approach is to cod-dope with Yb^{3+} and pump at 910–980 nm. Tm^{3+} has a level ($^3H_5$), which is (quasi-) resonant with the excited Yb^{3+}-level ($^2F_{5/2}$), allowing for the possibility of sensitization of Tm^{3+}-doped fibres with Yb^{3+}, similar to the case of Yb^{3+}-sensitized Er^{3+}-doped fibres [5]. Sensitization of Tm^{3+}-doped fibres has long been used for upconversion systems [6], but only more recently used for the more conventional 2-µm fibre laser [7]. In such an Yb^{3+}-sensitized Tm^{3+}-doped fibre (YTDF), pump energy is absorbed by the Yb^{3+}-ions and is then transferred non-radiatively to the Tm^{3+}-ions, which emit in the 2-µm wavelength range. This makes possible the use of commercially available high-power pump diodes in the 910–980 nm wavelength regime. The fibre in ref. [7] had equal Tm^{3+}- and Yb^{3+}-concentrations, however, because of the high absorption cross-section of Yb^{3+}, the fibre length required to absorb 975 nm pump light was only one third of that required for effective 805 nm absorption. In this letter, we explore the limits of power scaling the cladding-pumped YTDF laser (YTDFL) using single wavelength pumping at 975 nm using a diode-stack-based pump source.

Experiments and Results: A new double-clad YTDF was pulled from the same preform (made by standard modified chemical-vapour deposition and solution doping) as described in ref. [7]. The core of the fibre had a 23-µm diameter, 0.22 NA (numerical aperture) aluminosilicate core doped with Tm^{3+} and Yb^{3+} in equal 2 wt.% concentrations. The pump core had a 400-µm diameter D-shaped geometry. The pump core was coated with a low-index polymer that provided an NA of 0.48. The small-signal absorption coefficient at 975 nm was ~4 dB/m.

The experimental set-up is shown in Fig. 1. A 2.5 m long YTDF was pumped with a diode-stack-based pump source emitting at 975 nm. A focusing lens with a focal length of 25 mm coupled the pump light into the pump core of the YTDF with coupling efficiency of >80% with respect to incident pump power. Both ends of the fibre were cleaved perpendicularly to the fibre axis. The far end of the fibre, as seen from the pump source, was butt-coupled to a broadband dichroic mirror that was highly reflecting at ~2 μm and highly transmitting at ~1 μm, covering both the pump and Yb^{3+} emission wavelengths. The laser cavity was formed between this dichroic mirror and the perpendicularly cleaved fibre facet at the pump launch end. The laser output was taken from the pump launch end via another dichroic mirror which was also highly reflecting at ~2 μm and highly transmitting at 975 nm and ~1 μm. An additional dichroic mirror was employed to reject any emission from Yb^{3+}-ions at ~1 μm. Both ends of the fibre were held in 20-cm long, temperature-controlled metallic V-grooves and the intermediate part of the fibre (between the two V-grooves) was sandwiched between water-cooled metal plates in order to remove heat generated from the fibre.

The resulting power characteristic is shown in Fig. 2, together with the output spectrum measured with a monochromator as the inset. The operating wavelength was centred at 2038.5 nm and the linewidth of the laser was ~5 nm (full width at half maximum). The slope efficiency was 32% and the threshold was ~7 W, with respect to the launched pump power. The slope efficiency with respect to absorbed pump power (39%) was only ~20% smaller than the Stokes limit, indicating that the Yb^{3+} to Tm^{3+} energy transfer was very efficient. The maximum output power of 75 W was reached with a launched pump power of 240 W and was limited by fibre failure due to overheating of the output fibre end. Spurious lasing at ~1 μm was not detected and emission in this band was negligible. The short-term fluctuation in output power has a standard deviation of <1.4% when measured with a 5 GHz photo-detector and a 400 MHz bandwidth oscilloscope. The beam quality factor (M^2) was 1.3, measured with a commercial moving slit-based beam-scanner with an indium-arsenide detector, indicating that the laser output was nearly diffraction limited, despite the large diameter and NA of the core ($V = 8$ at 2 μm) and no attempts to improve the beam quality.

Initially, we had observed thermally induced coating damage at output powers approaching 32 W when the fibre used in ref. [7] was held in air and cooled by unforced convection. We estimated, based on the parameters of the fibre and the pump power, that the coating temperature approached ~230°C at this damage point. To reduce the temperature rise, the new fibre was actively cooled the fibre using additional temperature-controlled metallic holders. In this way we reached the current 75 W of output power without coating failure. Beyond this power level, however, we observed that the pump launch end failed either because of a high temperature or because of stress-induced fracture caused by a high temperature gradient. Although the coated part of the fibre was adequately cooled by the water-cooled metallic holder, the last ~5 mm of each fibre end was stripped of coating material and left protruding from the holder to prevent pump light directly damaging the coating. The fibre end melted from the core region, indicating that the local temperature reached well over 1000°C. Since most of the pump power is converted into heat inside the fibre, the YTDFL generates over five times more heat than a comparable Yb^{3+}-doped fibre laser at the same output power. The high absorption coefficient is a further concern. Based on the pump absorption of ~4 dB/m, the heat generated reaches 130 W/m at the tip of the fibre when pumped with 240 W of pump power which is clearly high enough to cause catastrophic fibre damage. To resolve the thermal management problems, we may consider reducing the pump absorption by using an off-peak pump wavelength, e.g., 915 nm or 940 nm, reducing the doping concentration, or by making the active core to pump core ratio smaller. The range of doping concentrations has not been explored, and thus, it is currently unclear if the Yb^{3+}-concentration can be reduced.

Conclusion: We have demonstrated a YTDFL generating up to 75 W of output power with a nearly diffraction-limited beam ($M^2 = 1.3$) at a wavelength of 2.04 µm, which we believe is a record for a directly diode-pumped YTDFL. The absence of rollover in the power characteristic suggests that higher powers should be possible if thermally induced fibre damage can be avoided.

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FIGURES

Fig. 1. Schematic of the YTDFL experimental arrangement with a diode-stack pump source at 975 nm. HR: high reflection, HT: high transmission.

Fig. 2. YTDF laser output power vs. launched pump power. Inset: YTDF laser output spectrum measured with a monochromator (resolution: 1.5 nm).

Fig. 1

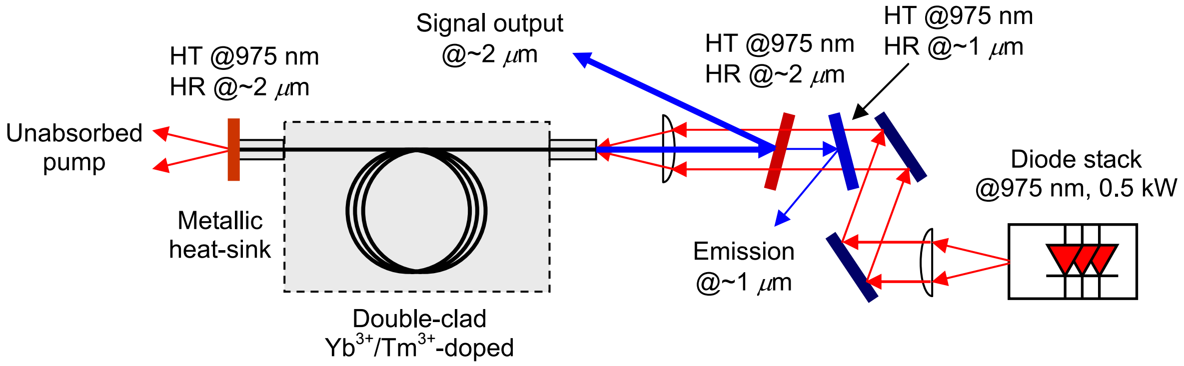

Fig. 2