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# LD-pumped 6 W cw $Tm^{3+}$-Doped Silica Double-Cladding Fibre Laser *

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*We report a thulium-doped silica fibre laser that generates a maximum cw output power of 6 W in a 2 μm wavelength range when cladding-pumped by a laser diode (LD) operating at approximately 791 nm at room temperature. The slope efficiency with respect to the launched pump power is 50% and 38.4%, with and without an output coupler mirror, respectively. The corresponding thresholds are 2.8 W and 4.8 W, respectively. The beam qualities $M_x^2$ and $M_y^2$ are 1.26 and 1.32, respectively. The experimental results are also analysed.*

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$Tm^{3+}$-doped fibre lasers, which operate at wavelength of approximately 2 μm, make compact and efficient high power laser sources for applications such as microsurgery because the strong water absorption that is present in this spectral range leads to short penetration depths into bodily tissues and hemostasis. $Tm^{3+}$-doped fibre lasers are also attractive for other applications such as lidar, remote sensing of gases and spectroscopy. Laser action in thulium-doped glass was first reported by Gandy *et al.* in 1967.[1] The first operation of a Tm-doped fibre laser was reported by Hanna *et al.* in 1988.[2] Ten years later, a cladding-pumped Tm-doped silica fibre laser was reported by Jackson and King. The maximum output power of 5.4 W at a sloped efficiency of 31% with respect to the launched pump power was obtained.[3] The lasers also provide an ideal starting wavelength for efficient nonlinear frequency conversions to the mid-infrared (3–5 μm) spectral range.[4] Clarkson *et al.*[5] demonstrated the ability to tune the output wavelength from 1860 nm to 2090 nm by using a diffraction grating in Littrow configuration. King *et al.*[6] showed a short Q-switched pulse duration of 25 ns and a peak pulse power of about 2.7 kW using a rotating mirror mounted at an asymmetric angle. Jackson[7] reported to date the highest slope efficiency of 74% relative to absorbed pump. A few works have been carried out with Tm-doped silica fibres. Wang *et al.*[8] reported a Tm-doped large mode area fibre laser cooled by water. Zhang *et al.*[9] reported a Tm-doped silica double-cladding fibre laser with the maximum output of 2.2 W. Du *et al.*[10] reported a wide band thulium-doped silica fibre amplifier operating at the *S* band.

In this Letter, we report a $Tm^{3+}$-doped double-cladding silica fibre laser operating at a wavelength of 2.027 μm and at a maximum output power of 6 W and at a slope efficiency of 50% with respect to the launched pump power. The beam quality $M_x^2$ and $M_y^2$ are 1.26 and 1.32, respectively.

The pump source is lasing at the central wavelength of 791 nm and with a 400 μm-diameter-core pigtail fibre output. The double-cladding fibre has a $Tm^{3+}$ concentration of 1.846 wt%, a core diameter of 20 μm with a numerical aperture (NA) of 0.17. The inner cladding has a 300 μm-diameter D-shaped geometry and NA of 0.4. The absorption coefficient is 2.2 dB/m at a wavelength of 793 nm, thus the length of 5 m is enough to absorb sufficient pump energy. The inner cladding of the fibre is approximately matched with the pump pigtail fibre. The fibre was codoped with $Al^{3+}/Tm^{3+}$ ratios of about 18:1 to decrease the energy transfer upconversion loss caused by clustering of the active ions.[11]

Figure 1 schematically shows the experimental setup. A 5-m-long fibre is pumped with an LD pump source. A coupler system is used to couple the pump light into the pump core. The pumping end of the fibre is butt-coupled to the broadband dichroic mirror that is highly reflecting at 1.8–2.1 μm and highly transmitting at 780–800 nm. An additional dichroic mirror (high reflection at 780–800 nm and transmission at 1.8–2.1 μm) at the fibre output end is used for laser feedback and for reflecting the unabsorbed pump light into the fibre. The laser cavity is formed between the two dichroic mirrors. The output power can be measured with a surface absorbing power meter (Spectra Physics, model 407A) with the maximum measurement range up to 30 W. The output wavelength is measured using the manually operated monochromator (WDG30) with 300 lines per mm grating blazed at 2 μm. Before measuring wavelength, the output beam is collimated into the monochromator.

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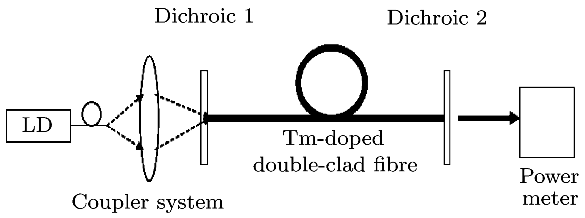


**Fig. 1.** Schematic diagram of the Tm-doped fibre laser experimental setup.

Figure 2 shows the variations of the laser output power with the launched pump power. Without the dichroic coupler mirror at the fibre output end, the laser has an output power of 4.02 W. The slope efficiency is approximately 38.4%, and the threshold is 4.8 W. With the mirror the maximum output power increases from 4.02 W to 6 W and the slope efficiency from 38% to 50%. Furthermore, the lasing threshold falls from 4.8 W to 2.8 W. Without the dichroic coupler mirror, the reflectivity of the fibre end owing to Fresnel's reflection is only about 4%, thus results in higher threshold and lower output and efficiency.

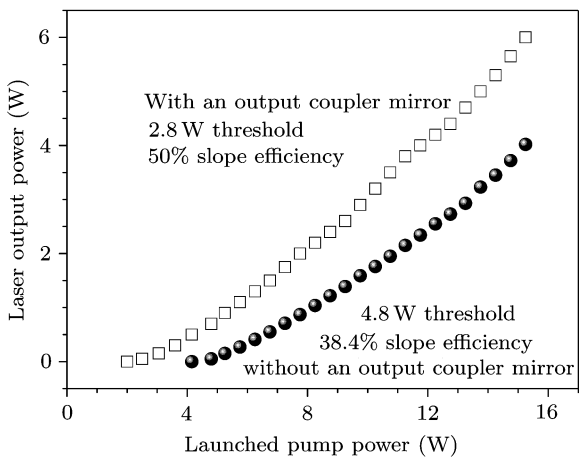


**Fig. 2.** Output power against launched pump power.

The laser output spectra at two different pump powers are shown in Fig. 3. We can observe a red shift in the wavelength of the output as the pump power is increased. The operating wavelength is centred at 2027 nm when pump power is 14 W and the full width at half maximum (FWHM) is about 20 nm. The $Tm^{3+}$-doped silica fibre has broad band fluorescent spectra at approximately 2 $\mu$m, and the cavity in the experiment have also broad band reflectors, thus we obtain wide band spectra. If the reflectors in the cavity are narrowed or the fibre Bragg grating (FBG) is used, there is no doubt that a narrow laser spectrum could be acquired.

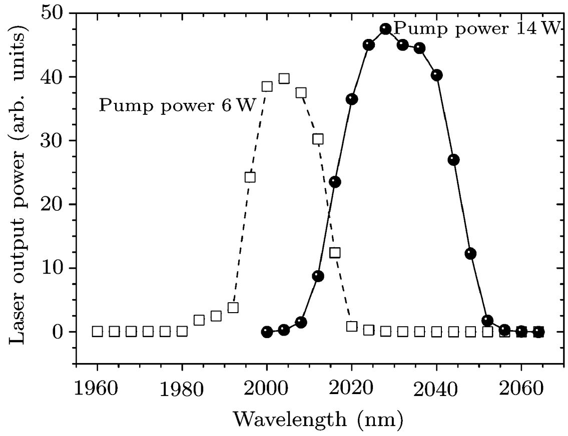


**Fig. 3.** Laser output spectra.

We also measured the changes of the central wavelength with pump powers as shown in Fig. 4. The red shift phenomenon is approved again. As the pump power is increased, the heat generated in the core of the fibre increases the Boltzmann population in the upper Stark levels of the ground state and reduces the population inversion, thus the emission extends to longer wavelengths. This effect is consistent with the result reported in Ref. [12].

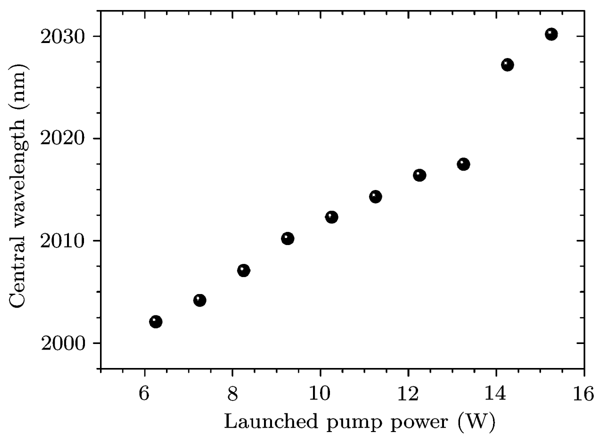


**Fig. 4.** Changes of the central wavelength with the increase of launched pump power.

The pyroelectric array camera has been selected to measure the output laser beam quality. The measured beam quality of $M_x^2$ and $M_y^2$ are 1.26 and 1.32, respectively, when the output laser power is 3.3 W at 2.02 $\mu$m for 19.7 W of incident diode power.

In summary, we have demonstrated a $Tm^{3+}$-doped double-cladding fibre laser with a maximum cw output power of 6 W and slope efficiency of 50% at approximately 2 $\mu$m with good beam quality. The results here cannot be compared with the results reported in Ref. [8] because the heavily $Tm^{3+}$-doped large-mode area double-cladding fibre was cooled by water. For uncooled condition, our results are comparable (the slope efficiency was 43.6% and the threshold was 4.9 W in Ref. [8]). We believe that the output power and the slope efficiency of $Tm^{3+}$-doped silica fibre lasers will still have the capability to increase with further research.

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