Short Tm^{3+}-doped fiber lasers with watt-level output near 2 μm

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High-power operation of diode-pumped fiber lasers at wavelength near 2 μm are demonstrated with short length of heavily Tm^{3+}-doped silica glass fibers. With 7-cm long fiber, a laser at near 2 μm is obtained with the threshold of 135 mW, maximum output power of 1.09 W, and slope efficiency of 9.6% with respect to the launched power from a laser diode at 790 nm. The output stability of this fiber laser is within 5%. The dependence of the performance of fiber lasers on the operation temperature and cavity configuration parameters is also investigated.

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The developments of solid-state laser operating around 2 μm wavelength have attracted great interest due to its wide applications in remote sensing, lidar, and medicine[1−3]. The Tm^{3+} ion is an excellent candidate because of its high quantum efficiency, broad emission band, and strong absorption band at $\sim$ 800 nm that perfectly overlaps with the emission band of the commercially available AlGaAs laser diodes. By incorporating the Tm^{3+} ion into the core of an optical fiber, 'eye-safe' wavelength lasers with low threshold and high efficiency can be constructed, providing other advantages such as reliability, ruggedness and compactness. The quantum efficiency of Tm^{3+}-doped fiber lasers can be close to 200% due to the cross relaxation energy transfer ($^3H_6$, $^3H_4 \rightarrow ^3F_4$, $^3F_4$) between Tm^{3+} ions[4]. With Tm^{3+}-doped silica glass fiber, a slope efficiency of 61% with respect to the launched power was reported by Shen *et al.*[5]. When germanate glass fiber was adopted as the host, a slope efficiency of 68% and a quantum efficiency of 180% have been achieved by Wu *et al.*[6].

Short fiber lasers have many advantages over long fiber lasers. Firstly, short fiber lasers can provide narrow-linewidth laser emission due to large axial mode spacing. Secondly, when Q switching is used, short fiber lasers are preferable to produce short pulse-width emission with high peak power. In addition, short fiber lasers are free from the undesired nonlinear effects such as stimulated Raman and Brillouin scattering effects. Many short Tm^{3+}-doped fiber lasers have been constructed to achieve single frequency output in mid-infrared region[7−9]. However, the highest output power was only tens milliwatts. Even with a master-oscillator power amplifier configuration, the maximum output power was 345 mW[10].

In this paper, we developed short Tm^{3+}-doped fiber lasers with high power output, and analyzed their performance dependence on temperature and some other configuration parameters.

The double-cladding Tm^{3+}-doped fiber has a 30 μm diameter, 0.22 N.A. core doped with $\sim$ 2 wt.-% Tm^{3+}. The pure-silica cladding, coated with a low-index polymer, has a $\sim$ 410 μm diameter and a N.A. of 0.46. The cladding absorption coefficient at the pump wavelength (790 nm) is $\sim$ 7 dB/m. These fiber specifications of large fiber cross section, large ratio of core diameter to cladding diameter, high N.A. and high doping concentration make it possible to achieve high output power from short length fibers. The pump source for the experiment was a single high-power LD bar (Nlight Co.), operating TM mode centered at 790 nm, shifting to $\sim$ 793 nm at comparatively higher operating temperature. With this pump source, the maximum power launched into the fiber was near 12 W.

The laser cavity configuration is shown in Fig. 1. The laser pumping beam was reshaped first by a micro-prism stack, and then focused into a circular spot of $\sim 0.5 \times 0.5$ (mm) diameter with a cylindrical lens and an aspheric lens. The focused pump beam was launched into the Tm^{3+}-doped fiber through a dielectric mirror. The pump end of the fiber was butted directly to the dielectric mirror with high reflectivity ($> 99\%$) at $1850-2100$ nm and high transmission ($> 97\%$) at $760-900$ nm. The distal end of the fiber was directly butted to the output coupler with $\sim$ 90% reflectivity at $1800-2000$ nm to build a Fabry-Perot laser resonator. During the experiments, the fiber was clipped between two copper sheets, which were closely fixed onto a water-cooling heat sink. Laser output power was measured by a thermal power meter (LP-102A). The combination of a dielectric mirror ($R > 99\%$ at $1850-2100$ nm, $T > 99\%$ at 790 nm) and a Ge filter was used to block the unabsorbed pump light in front of the power meter.

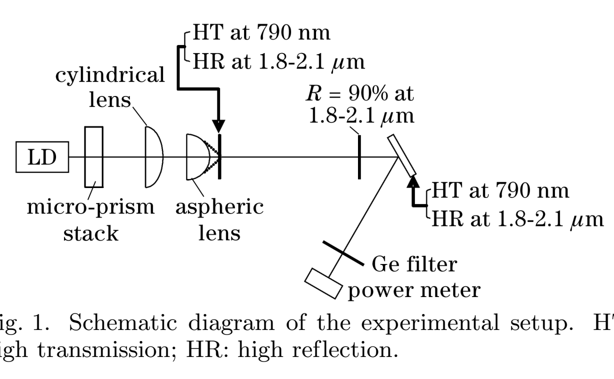

Fig. 1. Schematic diagram of the experimental setup. HT: high transmission; HR: high reflection.

Pumping Tm^{3+} ion at 790 nm excites population from the ground state $^3H_6$ to $^3H_4$, followed by rapid nonradiative decay to the upper laser level $^3F_4$, which has a lifetime of 340 μs[11]. The lower laser level $^3H_6$ is a Stark component of the ground state manifold. The stimulated emission on the $^3F_4 \rightarrow {}^3H_6$ transition will be the dominant mechanism, leading to a lasing wavelength near 2 μm.

The experiments were carried out with 7, 6, and 5.5-cm length of fibers, respectively. The operation temperature of the fiber laser was controlled by changing the temperature of circulating water through the heat sink. Without water-cooling, the operation temperature was detected to be around 40 °C. With water-cooling, the operation temperature could be adjusted at 20, 15, and 10 °C, respectively.

Figure 2 shows the output power of the 7-cm-long fiber laser as a function of launched pump power without water-cooling. When the cavity is constructed with an output coupler of 10% transmission, the laser has a threshold pump power of 135 mW and a maximum output power of 1.09 W. When the pump power is over 10 W, rollover of the output power occurred, which probably stemmed from large amount of heat generated in the fiber due to over pumping or large quantum defect. The slope efficiency of the fiber laser is about 9.6% with respect to launched pump power, which is much higher than that of those silica based distributed-feedback (DFB) fiber lasers[7,10], but lower than that from a heavily Tm^{3+}-doped germinate glass fiber laser[9]. The comparatively low slope efficiency can be accounted for by poor pump absorption due to relatively low doping concentration and short fiber length. Another alternative explanation can be related to the background loss of the silica-based fiber at wavelengths longer than 1.8 μm[12]. When the output coupler mirror is removed and only the 4% Fresnel reflection of the fiber end is used to complete the laser cavity, the maximum output power and slope efficiency decrease to 0.96 W and 8.7%, respectively. However, when the pump power is below 2.3 W, the fiber-end output coupler leads to slightly higher output power. Different output coupling seems to have little influence on the threshold pump power, which remains around 135 mW.

The output laser emission had only a few longitudinal modes due to short fiber length of several centimeters, and a narrow spectral bandwidth $\sim$ 3 nm centered at 1997 nm. Compared with long fiber lasers with a several tens of nanometers linewidth, it is much easier to obtain single frequency laser emission with the short length fiber laser. High power single-frequency laser emission from short Tm^{3+}-doped fibers will be our subsequent work.

In order to find out the influence of the spacing between the rear fiber end and the output coupler, a 6-cm-long fiber was used. The air spacing is denoted by L_s. This fiber laser was still operated with only air convectional cooling. The output characteristics are shown in Fig. 3. When $L_s = 0$, a maximum output power of 496 mW and a slope efficiency of 4.6% are obtained. When $L_s = 0.5$ and 1 mm, the laser operation efficiency greatly decrease: the maximum output power reduces to 328 mW, and the slope efficiency decreases to 2.95%. This can be accounted by large reduction of the cavity Q factor by strong fiber-end diffraction loss. Comparing $L_s = 0.5$ mm with $L_s = 1$ mm, no significant different performance can be observed.

The output characteristic of the 5.5-cm-long fiber laser with different operation temperatures is plotted in Fig. 4. Both the maximum output power and slope efficiency exhibit a notable increase as the operation temperature of the fiber laser decrease from 40 to 10 °C. The maximum output grow from 345 to 531 mW, and the slope efficiency rise from 4% to 5.8%. When the fiber laser

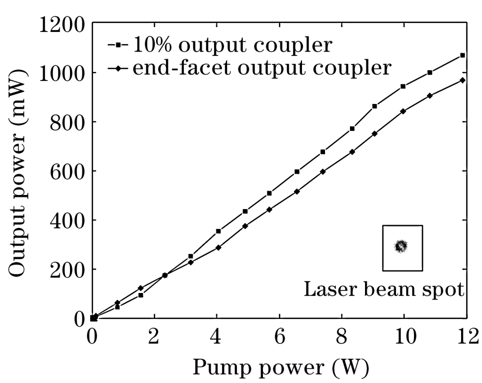

Fig. 2. Output characteristics of a 7-cm-length fiber laser with 10% output coupler and fiber-end-face coupler ($R \sim$ 4%). Inset is the laser beam spot.

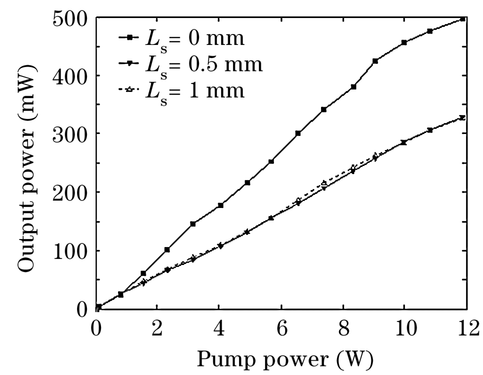

Fig. 3. Output characteristics of a 6-cm-length fiber laser with different air spacing between distal fiber end and output mirror.

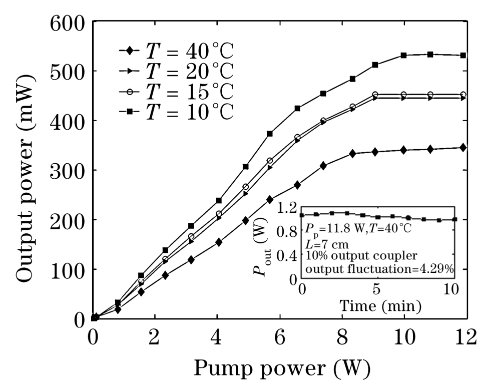

Fig. 4. Output characteristics of a 5.5-cm-length fiber laser with different operation temperatures; inset is the output power versus time (minute) at constant pump (11.8 W) and operation temperature (40 °C).

operats at 10 °C, the threshold pump power drops to 85 mW. At high pump level, a rollover of the output is observed for all operation temperatures, which can be accounted by saturation of pump absorption and distortion of the fiber end (the fiber end exposed in air).

The stability of the short fiber laser was detected by using the 7-cm-long fiber. The pump power was kept at 11.8 W. The operation temperature was ~ 40 °C with only air cooling. During ten-minutes operation, output power was recorded every minute. As shown in the inset of Fig. 4, the output stability is 4.29% rms with the maximum and minimum value of 1.09 W and 0.96 W, respectively. Considering the output power fluctuation of the pump diode laser, the fiber laser is very stable.

In conclusion, short high-power Tm^{3+}-doped fiber lasers have been demonstrated with different lengths of fibers. A maximum output power of 1.09 W and slope efficiency of 9.6% are obtained from a 7-cm-long fiber laser with output coupling of 10%. The fiber laser is very stable with an output power fluctuation of only 4.29% rms. At high pump level, rollover of the output power occurres due to saturation of pump absorption.

The performance of the short Tm^{3+}-doped fiber laser has a notable dependence on configuration parameters and operation temperature. When the air spacing L_s increases to 1 mm, the output power and the slope efficiency are decreased by 34% and 36%, respectively. Decreasing the operation temperature by 30 °C improves the output power and slope efficiency by 54% and 45%, respectively. At low operation temperature (10 °C), the threshold pump power decreases to 85 mW.

The performance of the short Tm^{3+}-doped fiber laser still has great potential to be explored. Improvement of the slope efficiency and output power can be achieved by increasing the ion doping concentration and optimizing the cavity configurations, which will be our subsequent works. Future efforts also include using Q-switching elements to achieve high-energy pulse output, and application of Bragg grating to tuning the emission wavelength.

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References

1. L. Esterowitz, Opt. Eng. **29,** 676 (1990).
2. R. C. Stoneman and L. Esterowitz, Opt. Lett. **15,** 486 (1990).
3. S. W. Henderson, P. J. M. Suni, C. P. Hale, S. M. Hannon, J. R. Magee, D. L. Bruns, and E. H. Yuen, IEEE Trans. Geosci. Remote Sens. **31,** 4 (1993).
4. S. D. Jackson, Opt. Commun. **230,** 197 (2004).
5. D. Y. Shen, J. I. Mackenize, J. K. Sahu, W. A. Clarkson, and S. D. Jackson, in *Proceedings of Advanced Solid-State Photonics* **98,** 516 (2005).
6. J. Wu, Z. Yao, J. Zong, and S. Jiang, Opt. Lett. **32,** 638 (2007).
7. S. Agger, J. H. Povlsen, and P. Varming, Opt. Lett. **29,** 1503 (2004).
8. J. Wu, S. Jiang, T. Luo, J. Geng, N. Peyghambarian, and N. P. Barnes, IEEE Photon. Technol. Lett. **18,** 334 (2006).
9. J. Geng, J. Wu, and S. Jiang, Opt. Lett. **32,** 355 (2007).
10. N. Y. Voo, J. K. Sahu, and M. Ibsen, IEEE Photon. Technol. Lett. **17,** 2550 (2005).
11. J. Xu, M. Prabhu, J. Lu, K.-I. Ueda, and D. Xing, Appl. Opt. **40,** 1983 (2001).
12. S. D. Jackson and S. Mossman, Appl. Opt. **42,** 2702 (2003).