150-W Tm^{3+}-Doped Fiber Lasers With Different Cooling Techniques and Output Couplings *

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A home-made double-clad Tm^{3+}-doped silica fiber laser with over 150-W output power is reported. Pumped with a diode bar at 793 nm, the fiber laser is operated at 2.04 μm with a slope efficiency of 56.3%. A quantum efficiency of > 140% is achieved owing to the efficient cross-relaxation process in heavily Tm^{3+}-doped fibers. By using different fiber-cooling techniques, the slope efficiency shows a deviation over 10%. The influence of output coupling on the laser characteristics is also investigated.

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Owing to the advantageous operating wavelength at about 2 μm, Tm^{3+}-doped fiber lasers have attracted much attention in recent years. The combination of double-clad pumping with particular fiber configuration has explored multi-kilowatt-level output power from Yb^{3+}-doped fiber lasers.[1,2] Engrafting the same techniques into Tm^{3+}-doped fiber lasers, it will be possible to scale the 2-μm output beyond kilowatt level due to efficient pump absorption, relatively large transverse fiber-core area and high numerical aperture of inner cladding. Since the first reported high-power double-clad Tm^{3+}-doped silica fiber laser,[3] power scaling of about 2-μm fiber lasers has achieved great progress recently.[4–7]

There are two important processes relevant to the operating efficiency of a Tm^{3+}-doped fiber laser.[8] One is the cross relaxation (CR) process and the other is the energy transfer up-conversion (ETU) process. CR can improve the performance of high power Tm^{3+}-doped fiber lasers by providing 'two-for-one' excitation of the upper laser level, while ETU is effective in reducing the population inversion. Hence, the beneficial effects of CR are competed with the ETU when the degree of clustering is high.[9] It has been shown that increasing the concentration of Tm^{3+} ions and minimizing the detrimental effects of ETU are paramount to the maximization of the slope efficiency.[10]

In this Letter, we report a high power 2-μm fiber laser with home-made double-clad highly doped Tm^{3+}-doped fiber, which is operated at a maximum output power of 153 W and a slope efficiency of 56.3%. Influence of different cooling techniques and various output couplings on the laser characteristics are also investigated.

The double-clad Tm^{3+}-doped silica fibers used in the experiment were provided by the Fiberhome Co., China. The fiber had a ∼ 30-μm diameter, 0.09 NA (numerical aperture) core doped with Tm^{3+} of ∼ 2 wt% concentration. The pure-silica inner cladding, coated with a low-index polymer, had a 400-μm diameter and an NA of 0.46. The fiber had a D-shape inner cladding, which helps to improve the pump absorption. The absorption coefficient at the pump wavelength (∼ 793 nm) was measured with the cut-back method to be ∼ 3 dB/m.

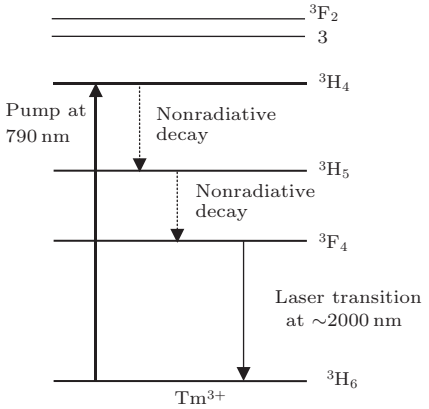

Fig. 1. Schematic of several lowest energy levels of Tm^{3+} ion in silica fiber.

The several lowest energy levels for Tm^{3+} ion in silica fiber are shown in Fig. 1. Pumping 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 measured lifetime of

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$\sim$ 340 μs.[11] The lower laser level is a Stark component of the ground-state manifold with a thermal population of the order of $\sim$ 1% of the total ground state population, so that the transition is quasi-three-level in nature.

The experimental setup for the double-clad Tm^{3+}-doped fiber laser is shown in Fig. 2. The pump sources were two high-power laser diode modules operated at 793 nm with the total output power of $\sim$ 310 W. Two aspheric lenses were used to couple the pump light into the fiber, with a coupling efficiency of $\sim$ 90%. A dichroic mirror (T = 97%@793 nm and R = 99.5%@2 μm) was right butted to the pump-end fiber as the in-put cavity mirror, which together with the far-end fiber facet (provides $\sim$ 3.55% of the Fresnel reflection for laser oscillation) completed the laser cavity. The 4-m long Tm^{3+}-fiber was wrapped on a copper drum or emerged in water for cooling. At the output end of the fiber, a double-convex lens was used to collimate the $\sim$ 2 μm laser beam, and a 3-mm thick high-reflection ($R > 99.9\%$@793 nm) mirror was used to filter un-absorbed 793-nm pump light. Both fiber ends were cleaved perpendicularly to the axis and clipped in two copper heat sinks. Due to quasi-three-level nature of the laser, cooling the fiber was critical for achieving high slop efficiency. The laser output power was measured with a thermal power meter and the laser spectrum was tested with a spectrometer.

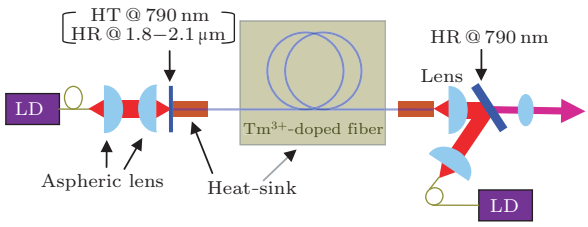

Fig. 2. Experimental setup of the self-pulsing Tm^{3+}-doped fiber laser.

In experiment, two cooling techniques were used to dissipate the heat load in the Tm^{3+}-doped fiber laser. One method was wrapping the fiber around a copper drum, and the other was emerging the fiber in stationary water. In the former, the temperature of the fiber was about 26°C at stable operation, and in the latter the temperature of the operating fiber was about 35°C. With these two cooling methods, output characteristics of the Tm^{3+}-doped fiber laser are shown in Fig. 3. These two cooling methods give out nearly the same laser pump threshold of $\sim$ 6 W. In both cases, the laser output increases linearly with the launched pump power, showing power scalability can be easily achieved only by improving pump power. The copper cooling technique provides a better laser performance: a maximum output of 153 W and a slope efficiency of 56.3% with respect to the launched pump power (corresponding to a quantum efficiency of $\sim$ 1.45). On the contrary, the stationary water cooling method provides a maximum output of 136 W and a slope efficiency of 49.3%. Owing to the quasi-three-level features of the Tm^{3+}-doped fiber, efficient cooling is very crucial in improving the laser performance. These laser efficiencies obtained by us are somewhat lower than that achieved by Moulton *et al.*,[7] which may be due to comparatively lower Tm^{3+}-doping level and different fiber structure in our experiments. In Tm^{3+}-doped fibers, high doping level is beneficial to facilitate the cross-relaxation process, which can greatly improve the laser efficiency of the fiber laser. A quantum efficiency of $\sim$ 2 for the Tm^{3+}-doped fiber laser is possible by optimization of doping level and fiber structure, combined with efficient fiber cooling. The fiber core had a normalized frequency (V number) of 8.31 at the laser wavelength of $\sim$ 2.04 μm, so the laser output must be multimode (without mode control). The M^2 factor of the laser beam at $\sim$ 150-W level was measured with the scanning-knife-edge method to be $\sim$ 3.5.

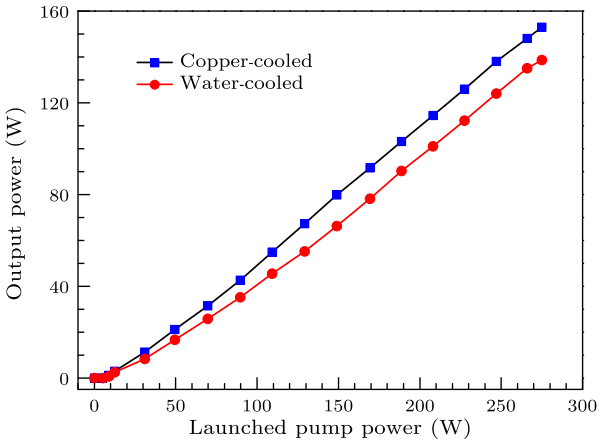

Fig. 3. Output performance of the 4-m-long Tm^{3+}-doped fiber laser with different cooling techniques.

Laser spectra recorded at different power levels are shown in Fig. 4. Due to multi-stark splitting of energy-level manifolds, the operation temperature of Tm^{3+} fibers has an important impact on the laser spectrum. With increasing laser output power, the laser spectrum red-shifted from $\sim$ 2020 nm at 20 W to $\sim$ 2040 nm at 100 W. At 100-W level, the full bandwidth of the laser spectrum is $\sim$ 20 nm, much broader than that achieved in our short Tm^{3+}-doped fiber lasers ($\sim$ 3 nm with the 5-cm long fiber). The broad spectral width was caused by high gain in the fiber, with which many longitudinal modes could oscillate by surpassing the cavity loss. The broad-spectrum feature of the Tm^{3+}-doped fiber laser facilitate its achieving narrow pulse width in the pulsed regime.

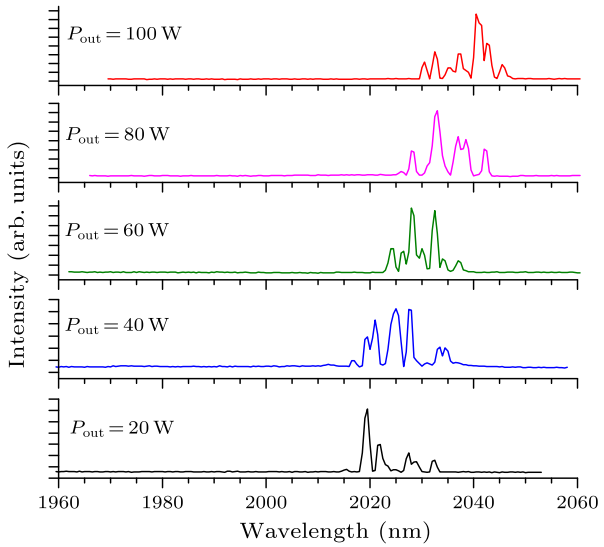

Fig. 4. Spectra of the Tm^{3+}-doped fiber laser at various output levels.

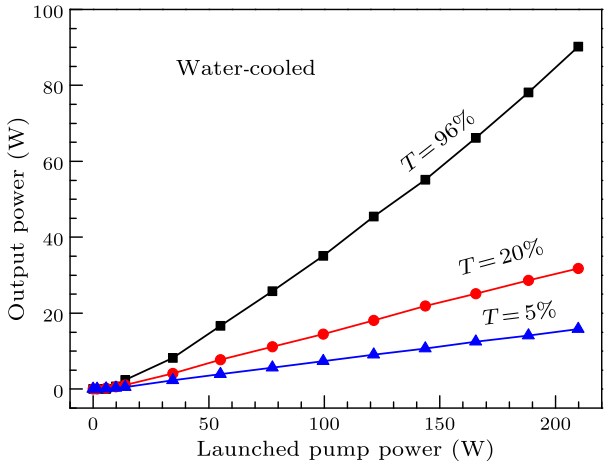

Fig. 5. Laser output of the 4-m Tm^{3+}-doped fiber laser with different output couplings under water cooling.

In order to further understand the laser characteristics of the Tm^{3+}-doped fiber laser, output coupling was changed in the experiments. In these cases, the fiber was pumped with only one LD module and water-cooled at temperature of $\sim 35°C$. The output results are shown in Fig. 5. Compared with the fiber-end-facet output coupler ($T = 96\%$), the $T = 20\%$ and $T = 5\%$ couplers provided much lower laser outputs and slope efficiencies. With the $T = 20\%$ coupler, the maximum output was 31.8 W and the slope efficiency was 15.3%; with the $T = 5\%$ coupler, the maximum output was 15.8 W and the slope efficiency was 7.6%. Due to high gain and strong re-absorption of signal light in the Tm^{3+}-doped fiber laser, decreasing output coupling will deteriorate the laser performance. Therefore, high output couplings should be adopted for the aim of achieving high CW (continuous-wave) laser output in 2-μm Tm^{3+}-doped fiber lasers.

In conclusion, over 150-W 2-μm laser output has been achieved with home-made double-clad Tm^{3+}-doped fibers. The copper-cooling method can improve laser performance by more than 10% than the non-circulating water-cooling technique. Ideal operation efficiency can only be achieved through the combination of efficient fiber cooling with optimization of Tm^{3+} doping concentration and fiber structure. Higher output coupling will be beneficial for achieving high-power 2-μm laser output in CW Tm^{3+}-doped fiber lasers. Complete-fiber high-power (over 500 W) Tm^{3+}-doped fiber lasers will be our subsequent work.

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