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Research Letter

High Power Tm^{3+}-Doped Fiber Lasers Tuned by a Variable Reflective Output Coupler

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Wide wavelength tuning by a variable reflective output coupler is demonstrated in high-power double-clad Tm^{3+}-doped silica fiber lasers diode-pumped at ~790 nm. Varying the output coupling from 96% to 5%, the laser wavelength is tuned over a range of 106 nm from 1949 to 2055 nm. The output power exceeds 20 W over 90-nm range and the maximum output power is 32 W at 1949 nm for 51-W launched pump power, corresponding to a slope efficiency of ~70%. Assisted with different fiber lengths, the tuning range is expanded to 240 nm from 1866 to 2107 nm with the output power larger than 10 W.

1. Introduction

Cladding-pumped Tm^{3+}-doped fiber lasers operating in the eye-safe ~2 μm spectral region have attracted much attention in recent years, owing to their wide applications in areas such as remote sensing and biomedicine [1]. Benefiting from the large surface to volume ratio, fiber-based laser sources suffer less thermal management problems, and hence offer the prospect of higher output power and improved beam quality. Direct pumping of double-clad Tm^{3+}-doped fiber lasers with diode lasers at ~790 nm has achieved output power up to 85 W [2] and 120 W [3] with slope efficiencies of around 57% with respect to the launched pump power. A slope efficiency of 74% has also been obtained at 10-Watt level [4]. Due to the well-known "two-for-one" cross relaxation (CR) energy transfer ($^3H_6$, $^3H_4 \rightarrow {}^3F_4$, $^3F_4$) process [2], the theoretical quantum efficiency of Tm^{3+}-doped fiber lasers approaches 200%.

A particular attraction of thulium-doped fiber lasers is the widely tunable region over ~1700–2100 nm due to their very broad transition linewidth. Many wavelength tuning methods, such as birefringent tuning plate [5], diffraction grating [6–8], fiber length [7, 9], and Peltier plate [10] have been used to exploit the tuning capability of thulium-doped fiber lasers. By using an external cavity containing a diffraction grating, wavelength tuning ranges of 230 nm (1860–2090 nm) [7] and 250 nm (1723–1973 nm) [8] have been demonstrated at multiwatt levels. The highest output power was around 15 W over a 140-nm tuning range, and the longest wavelength was not longer than 2090 nm.

In this study, we report efficient operation of Tm^{3+}-doped double-clad silica fiber lasers, pumped by high-power diode lasers at 790 nm, with the maximum output power over 30 W and a slope efficiency of ~70% with respect to launched pump power. In addition, by using a variable reflective mirror (VRM) as the output coupler, the fiber laser was tuned over a range of 106 nm from 1949 nm to 2055 nm with the output power over 20 W in the range of 90 nm. Combined with fiber-length-tuning method, the laser wavelength can be tuned from 1866 to 2107 nm, resulting in a tuning range over 240 nm.

2. Experiment and Results

In the experiment, the double-clad Tm^{3+}-doped silica fiber has a doped core with the N.A. of 0.20 and diameter of 27.5 μm. High Tm^{3+} ions doping concentration of 2.5 wt% is essential to facilitate the CR energy transfer process. A small portion of Al^{3+} ions was also doped into the fiber to suppress the energy transfer upconversion (ETU) processes, which may cause the quenching of the $^3F_4$ multiplet lifetime. The pure silica inner cladding, coated with a low-index polymer, has a 400-μm diameter and the N.A. of 0.46. The

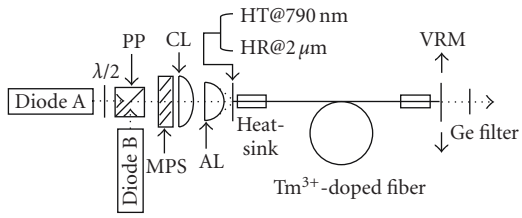

Figure 1: Schematic of the experimental setup. PP: polarizing plate; MPS: micro-prism stack; CL: cylindrical lens; AL: aspheric lens; HT: high transmission; HR: high reflection; VRM: variable reflective mirror.

hexagonal cross section of the inner clad helps to improve pump absorption. The absorption coefficient at the pump wavelength (790 nm) is ~2.8 dB/m.

Figure 1 shows the experimental setup. High-power LD arrays operating at 790 nm and TM mode were used as the pump source. The outputs from two LD arrays were polarizedly combined to form a single pump beam. This pump beam was reshaped by a microprism stack at first, and then focused into a circular spot using a cylindrical lens and an aspheric lens. Through a dichroic mirror, the pump light was launched into the fiber. The launched efficiency was measured through a 4-cm-long Tm-doped fiber. The largest pump power of 51 W can be launched into the fiber. The pump end of the fiber was butted directly to the dichroic mirror with high reflectivity (>99.7%) at 2.0 μm and high transmission (>97%) at 790 nm. Both fiber ends were cleaved perpendicularly to the axis and polished carefully. The output coupler was formed by a VRM or the bare fiber-end facet. The transmission of the VRM can be changed continuously from 5% to 80% (the reflection R is changed from ~94.8% to 18.4%) at 2 μm by simply horizontally displacing the VRM with a one-dimensional stage. The ends of the fiber were clamped tightly in water-cooled copper heatsinks, and the remaining fiber was immersed into water to achieve maximum efficiency. During the experiment, both cavity mirrors were carefully adjusted with five-dimensional holders.

Laser output power was measured with a thermal power meter after unabsorbed pump light blocked by a Ge filter. Laser spectra were measured by an InAs PIN photodiode combined with a midinfrared spectrograph with a resolution of 0.2 nm.

The lasing characteristics obtained with relative higher output couplings in a 4-m long fiber laser are shown in Figure 2. When the VRM was moved away from the fiber end, and the bare fiber-end facet was used as the output coupler ($T \approx 96\%$), the laser reached threshold at a launched pump power of 5.9 W and produced a maximum output power of 32 W at 1949 nm for 51-W launched pump power, corresponding to a slope efficiency of 69% and a quantum efficiency of 170%. The high efficiency was attributed to high Tm^{3+}-doping concentration, suppression of ETU with Al^{3+} ions [4], and efficient fiber cooling. With T = 80% output coupling, a slightly lower output power of 29.8 W was generated at 1970 nm, and the slope efficiency with respect

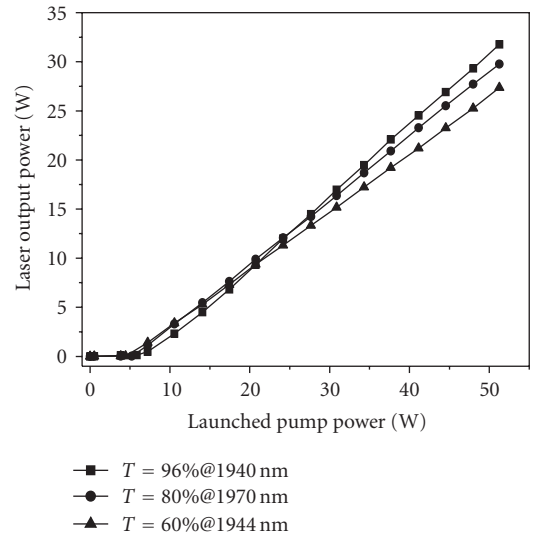

Figure 2: Laser output power versus launched pump power with three high output couplings.

to launched pump power was ~65%. When the output coupling decreased to 60%, the output power dropped to 27.4 W at 1994 nm with a slope efficiency of ~58%. In all these cases, the output power increased linearly with the launched pump power, suggesting that the laser can be power scaled further by increasing the pump power. The power stability of the laser output, monitored by an InAs PIN photodiode and a 100 MHz digital oscilloscope, was less than 1% (RMS) at ~30 W power levels.

After carefully optimization the position of the coupler, the fiber laser was wavelength tuned by simply horizontally moving the VRM coupler. In this paper, the peak wavelength of the laser spectrum is taken as the laser wavelength. Figure 3 shows the dependence of the laser wavelength on the output coupling. When the output coupling decreased from ~96% to 5% in the 4-m long fiber laser, the laser wavelength was tuned from 1949 to 2055 nm with the tuning range of 106 nm. The nearly linear dependence provides a basic knowledge to choose the wavelength from Tm^{3+}-doped silica fiber lasers. The phenomenon can be explained by the enhanced reabsorption of laser in the high-Q cavity. Since the photon lifetime in the cavity is increased with higher reflective mirrors, the photon travels more round trips and undergoes more reabsorption before escapes from the cavity.

Employing different fiber lengths from 0.5 m to 10 m, as shown in Figure 3, the laser can be tuned from 1866 to 2107 nm. The total tuning range is over 240 nm at above ten-watt levels. This is the first demonstration of laser wavelength longer than 2100 nm from Tm^{3+}-doped silica fiber lasers. A typical laser spectrum obtained with the 4-m fiber at coupling of T = 15% and 16-W output power is shown as inset in Figure 3. The laser spectra under different couplings and fiber lengths hold nearly identical features. The spectrum has a bandwidth (FWHM) of ~15 nm and several lasing peaks. The multipeak spectrum indicates the laser operated in multiple longitudinal modes.

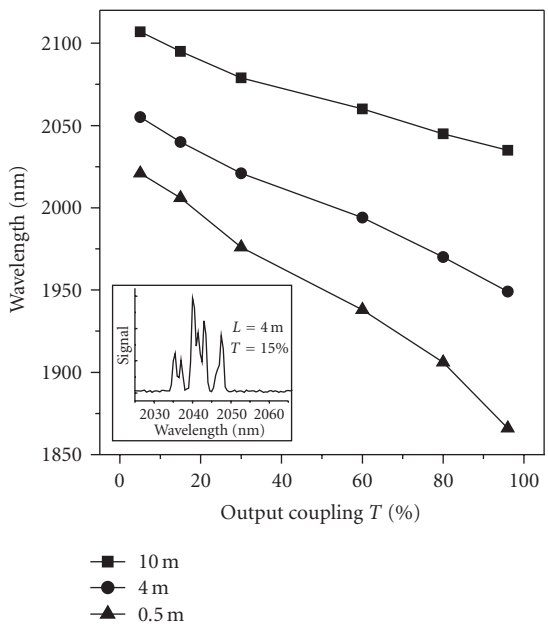

Figure 3: Laser peak wavelength as a function of output coupling; inset is the laser spectrum obtained with the 4-m fiber at coupling of T = 15%.

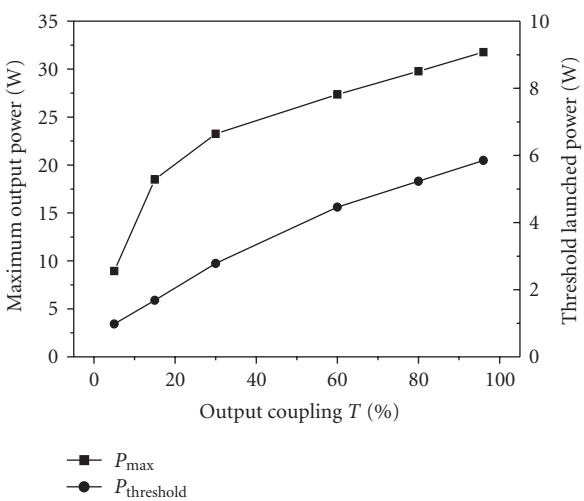

Figure 4: Maximum laser output power and threshold launched power as functions of the output coupling.

The maximum output power and launched threshold pump power as functions of the output coupling are shown in Figure 4. When the output coupling decreased from ~96% to 5%, the threshold pump power reduced almost linearly from 5.9 to 1.0 W, and the maximum output power dropped from 32 W to 9.0 W. The sharp decreasing of the output power with <15% output coupling was mainly due to low-output transmission and increased reabsorption of laser light. Between the output coupling of 20% and 96%, the laser output power exceeded 20 W over a tuning range of 90 nm from 1949 to 2040 nm (see Figure 3). This presents the potential of Tm^{3+}-doped silica fiber lasers to generate multiten watts output over a hundred nanometers tuning range.

3. Conclusion

Pumped by diode lasers at 790 nm, high-power widely tunable Tm^{3+}-doped silica fiber lasers have been demonstrated. The wavelength tuning has been achieved by changing the output coupling with a variable reflective mirror. The fiber laser can be tuned from 1949 to 2055 nm at multiten watts levels. The maximum output power is 32 W at 1949 nm with a slope efficiency of ~70% relative to the launched pump power. Using different length of fibers, the wavelength tuning range can be extended over 240 nm from 1866 to 2107 nm. The combination of high power, high efficiency, and wide tunability of Tm^{3+}-doped fiber lasers provides a great opportunity for applications of eye-safe lasers.

Acknowledgment

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