High-power and widely tunable Tm-doped fiber laser at 2 μm

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Efficient, high-power, and widely tunable Tm-doped fiber lasers cladding-pumped by diode lasers at 791 nm are demonstrated by use of an external cavity containing a diffraction grating. A maximum output power of 62 W is obtained at 2 004 nm for 140 W of launched pump power, corresponding to a slope efficiency of 48% with respect to launched pump power. The operating wavelength is tunable over 200 nm (1 895 to 2 109 nm), with >52 W of output power over a tuning range of 140 nm (1 926 to 2 070 nm). Prospects for further improvement in output power, lasing efficiency, and tuning range are considered.

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High-power solid-state lasers operating in the eye-safe 2 μm spectral region are of great interest for numerous applications, such as atmospheric monitoring, remote sensing, lidar, and medicine[1−3]. Owing to the great advantages of Tm-doped fiber lasers (TDFLs)[4−6] over conventional "bulk" solid-state lasers, cladding-pumped TDFLs are becoming potential replacements in many applications. Fiber-based sources have a larger surface-area-to-volume ratio than that of conventional "bulk" solid-state lasers (by virtue of their geometry), which benefits effective heat dissipation[7]. As a result, fiber lasers only need very simple thermal management. Furthermore, the laser modes are determined by the waveguide properties of the active-ion-doped core, which can be controlled by designing the fiber properly. These features of cladding-pumped fiber lasers offer a promising route to higher output power without decreasing efficiency or degrading beam quality. A particular attraction of TDFLs is the potential for broad wavelength tunability owing to the broad transition linewidths typical in glass hosts[8]. For many applications, a high degree of spectral control (in terms of both tunability and linewidth) of the TDFL is also required[9]. One popular approach for wavelength selection is to use an in-fiber Bragg-grating (FBG)[10]. However, FBGs are not very effective for wavelength selection in large-mode-area (LMA) fibers that sustain multi-mode operation[11]. Moreover, the tuning range of FBGs is quite limited[12]. Diffraction gratings and volume Bragg gratings (VBGs) are used to control the output spectrum of high-power fiber lasers[13−15]. TDFLs using VBG for wavelength selecting have been reported[16−18] with 1, 48, and 53 W of continuous wave (CW) output power and corresponding tuning range of >50, >100, and >50 nm, respectively. When diffraction gratings are used as wavelength selecting elements, output power over 5 and 17.4 W have been reported[19,20] for tunable operation.

In this letter, we report a high-power and widely tunable TDFL cladding-pumped by 791-nm diode lasers (DLs) and using a diffraction grating for wavelength selection, with a much-improved output power level than that previously reported using this configuration. We achieved a maximum output power of 62 W at 2 004 nm for a launched pump power of ∼140 W and with a slope efficiency of 48%. The operating wavelength could be tuned over 200 nm, from 1 895 to 2 109 nm, with >52 W output power over a tuning range of 140 nm, from 1 926 to 2 070 nm, and a spectral linewidth of ∼1 nm.

Tunable operation of the TDFL was demonstrated by employing a simple external cavity design, as shown in Fig. 1(a). The double-clad Tm-doped fiber (Nufern Inc.) used in our experiments had a 0.09 NA, 25-μm-diameter core and a 0.46 NA, 400-μm octagonal cladding, which improved the absorption of helical cladding mode. The absorption coefficient was approximately 2.7 dB/m at 791 nm. A relatively short fiber with a length of ∼4 m was selected for our experiments in order to avoid re-absorption which might limit the short end of the tuning range. Pump power was provided by 791-nm DLs. Pump light was launched into opposite ends of the fiber through a plano-convex lens of 26-mm focal length and a dichroic mirror with high transmission (>96%) at the pump wavelength and high reflection (HR, >99.5% at 45°) over the wavelength range (1 850 to 2 150 nm) to allow extraction of the TDFL output beam. With this pumping arrangement, the launching efficiency into the fiber was estimated to be ∼80%.

Feedback for lasing was provided by the 4% Fresnel reflection from the perpendicularly cleaved fiber end facet on one side, and by the combination of an antireflection coated collimating lens of 150-mm focal length and a simple replica diffraction grating (600 lines/mm) on the other side. The blaze angle of the gold-coated grating was 34°, and the grating was blazed at wavelength of ∼2 μm with reflectivities of ∼65% (polarized parallel to the grooves) and ∼90% (polarized in the orthogonal direction). The grating was placed in the Littrow configuration to provide wavelength selective feedback.

The collimating lens selected in the external feedback

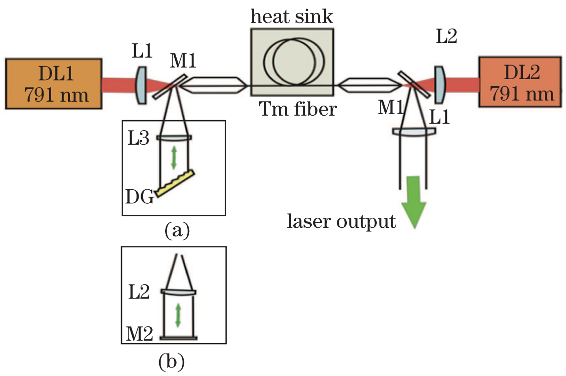

Fig. 1. Schematic of the double-clad TDFL configuration for (a) tunable operation and (b) free running operation. M1: 45° HT@780 to 810 nm, 45° HR@1 850 to 2 150 nm; M2: 0° HR@1 850 to 2 150 nm; L1: f=26 mm, HT@780 to 810 nm; L2: f=40 mm, HT@1 850 to 2 150 nm; L3: f=150 mm, HT@1 850 to 2 150 nm; DG: Diffraction grating.

cavity had a relatively long focal length. As a result, the laser beam was distributed over a large area on the grating, thereby reducing the risk of damage due to effective heat dissipation. In addition, the collimating beam divergence was reduced with a long-focal-length collimating lens, which effectively increased the spectral selectivity of the grating feedback cavity. The fiber end facet adjacent to the grating was angle-polished at ~10° to suppress parasitic lasing between the two fiber end facets. Otherwise, the parasitic lasing might compete with the wavelength-selective feedback provided by the grating and restrict the tuning range.

Owing to the quasi-three-level features of the Tm^{3+} ions, laser performance is highly dependent on temperature; therefore, thermal management is very crucial in improving the laser efficiency of the TDFL. In our experiments, the central section of the fiber was immersed in water for cooling. Both fiber ends were mounted in water-cooled V-groove heat sinks to prevent possible damage to the fiber coating due to the unlaunched pump power and heat generated in the core due to quantum defect heating.

Using this configuration, the threshold for lasing was reached at a launched pump power of ~10 W. The laser generated a maximum output power of 62 W (see Fig. 2) at 2 004 nm for a total launched pump power of ~140 W, corresponding to a slope efficiency of ~48% with respect to launched pump power.

Wavelength tuning was achieved by adjusting the incident angle of the diffraction grating. The lasing wavelength could be tuned over 200 nm, from 1 895 to 2 109 nm, at multi-watt power levels, and over 140 nm, from 1 926 to 2 070 nm, at output levels in excess of 52 W (see Fig. 3) with an output linewidth (FWHM) of ~1 nm. The output powers at 1 930 and 1 990 nm versus launched pump power are shown in inset of Fig. 3.

Parasitic lasing became noticeable when operating at wavelengths longer than 2 070 nm, especially at output power in excess of 10 W. This phenomenon may be attributed to the reduction in effective reflectivity of the diffraction grating at these wavelengths. Increase in the cleaved/polished angle at the fiber end facet nearest the diffraction grating may, to some extent, further reduce the broad reflectivity at the fiber end and effectively suppressed parasitic oscillation. When operating at wavelengths shorter than 1 920 nm, output power decreased quickly with the change of operating wavelength because of the severe re-absorption of the fiber. A very simple experiment was carried to examine the re-absorption of the fiber around this wavelength. When a laser at 1 910 nm was injected into the Tm-doped fiber used in our experiments, >50% of the laser was absorbed. We believe that a short length of fiber should benefit minimizing the re-absorption effect and extend the tuning range to the short wavelength side.

When operating at wavelengths shorter than 1 920 nm, a very interesting phenomenon was observed. When the operating wavelength was fixed by the external cavity, laser operation was observed only at low pump power. Laser output decreased with the increase of the pump power beyond a certain power, and the laser stopped lasing at a certain power point. A similar phenomenon was also observed in Er:ZBLAN[21]. We attribute this behavior to the more three-level nature of the transitions at short wavelength, where the lasing threshold at these transitions is very sensitive to the temperature of the fiber core.

To compare the performance of the grating-based laser with that of a free-running TDFL (i.e., without wavelength selection), the grating was replaced by a dielectric mirror with HR (>99.5%) at 1 850–2 150 nm

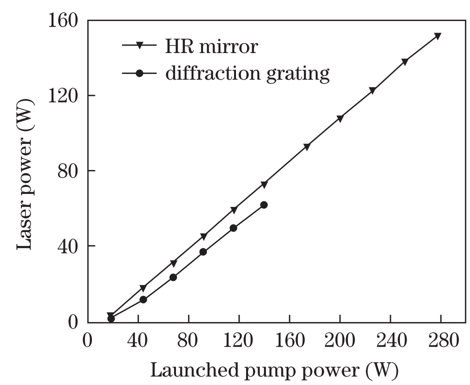

Fig. 2. Laser output power versus launched pump power for the grating-based laser and the free-running TDFL.

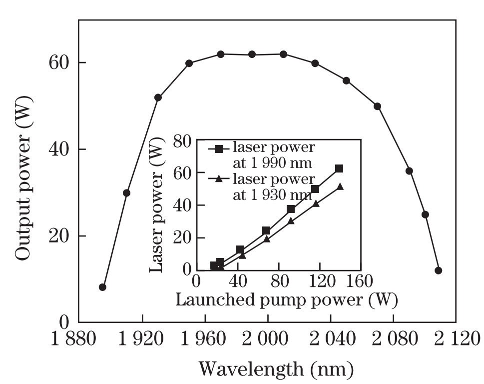

Fig. 3. Output power of the tunable TDFL versus operating wavelength for a launched pump power of ~140 W. Inset: Output power at 1 930 and 1 990 nm versus launched pump power.

(see Fig. 1(b)). With this set-up, the laser reached threshold at a launched pump power of 7 W and generated a maximum output power of 73 W centered at 2015 nm for a total launched pump power of ~140 W, corresponding to a slope efficiency of ~56% with respect to launched pump power. When pump power was further increased, a maximum output power of 152 W (see Fig. 2) centered at 2035 nm was generated, corresponding to an overall slope efficiency of ~54% with respect to launched pump power of ~280 W.

In both cases, lasing efficiency was well above the Stokes limit (~39%), which indicated the presence of the cross-relaxation phenomenon. Higher operation efficiency should be attainable by optimization of doping level and fiber structure, because cross-relaxation is highly dependent on the doping concentration. The grating-based laser had a slightly lower slope efficiency compared with the free-running TDFL, which was mainly due to the difference in the reflectivities between the grating and the HR mirror. The output spectra of the grating-based laser and the free-running TDFL are shown in Fig. 4. The free-running TDFL had a quite broad emission spectrum (~20 nm) centered at 2015 nm, whereas the spectrum of the grating-based laser was much narrower (~1 nm).

Notably, the spectrum of the free-running TDFL was not stable, and a red-shift of the centered wavelength could be observed with the increase of the output power. These phenomena were mainly due to the fact that the Boltzmann factor of the Stark energy levels in both the upper and lower laser manifolds ($^3F_4$, $^3H_6$) changed with the fiber core temperature[22,23], whereas the spectrum of the grating-based laser was quite stable. The output power level of the grating-based laser should be further improved by simply increasing the launched pump power because no sign of injury to the grating was evident and the output power is linear variation as a function of pump power.

In conclusion, we demonstrate the high-power and widely tunable operation of a TDFL by use of an external cavity containing a diffraction grating. A maximum output power of 62 W at 2004 nm is generated for a launched pump power of 140 W, corresponding to a slope efficiency of ~48%. By adjusting the angle of the grating, the operating wavelength can be tuned over 200 nm (from 1895 to 2109 nm), with >52 W output power over a tuning range of 140 nm (from 1926 to 2070 nm) and an output linewidth of ~1 nm. Further extension of the tuning range should be achievable by using shorter-length fibers and suppressing parasitic lasing more effectively, as long as sufficient pump absorption is maintained. Further increase of the output power should be possible for both the free-running and tunable cavity configuration by simply increasing the launched pump power because of the linearity of output power as a function of pump power.

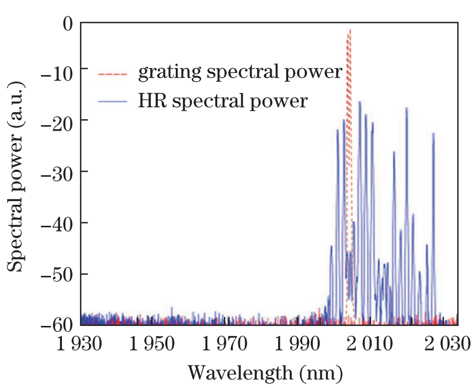

Fig. 4. Spectral output of the grating-based laser and the free-running TDFL.

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