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Communication

All-Fiber Wavelength-Tunable Narrow-Linewidth Polarization-Maintaining Tm-Doped Fiber MOPA System

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Abstract: An all-fiber wavelength-tunable narrow-linewidth polarization-maintaining (PM) Tm-doped fiber master oscillator power amplifier (MOPA) system is presented. We demonstrate an all-fiber ring cavity Tm-doped fiber master-oscillator (MO) with a tuning range of 110 nm (from 1925 to 2034 nm). The maximum output power of 459 mW is obtained at 1992.9 nm for 16 W of launched pump power at 793 nm, corresponding to a slope efficiency of 5.6% concerning launched pump power. By using a one-stage Tm-doped fiber amplifier combined with a high gain of >10 dB, the maximum slope efficiency is 12.6% and the output power is 5.65 W at 1993 nm. The 3 dB linewidth is less than 0.5 nm, $M^2 \approx 1.25$, and the polarization extinction ratio (PER) reaches 21.4 dB. The influence of different active fiber lengths on laser amplification is also studied.

Keywords: tunable; all-fiber; polarization-maintaining; Tm-doped fiber; master oscillator power amplifier (MOPA); optimal fiber length

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1. Introduction

In recent years, cladding-pumped Tm-doped fiber laser sources operating in the eye-safe 2 μm spectral region have attracted increasing interest due to their numerous applications in medical, remote sensing, and eye-safety lidar [1–3]. With these applications in demand, broadband tunability is crucial, as it allows controlling the depth of laser penetration in the tissue [4] and obtaining the absorption spectrum of atmospheric gases [5]. The Tm-doped fiber owns an emission spectrum of more than 300 nm in the 2 μm band. At the same time, thanks to the geometry of thulium-doped fiber with thermal management and the quantum efficiencies approaching two brought by the fortuitous "two-for-one" cross-relaxation process when a 790 nm high-power diode laser is used as a pump source [6,7], it provides the potential for power scaling while maintaining good beam quality [8].

To meet the above conditions, a tunable thulium-doped fiber laser system with a ring cavity structure is essential. Its advantage is that it does not need bulk-optic components, so its structure is compact, reliable, and flexible [9]. However, as the emission cross-section area of Tm ions decreases sharply in the long wavelength part, the gain competition of the emission spectrum in this region is strengthened. In comparison with the shorter wavelength, Tm-doped fiber laser (TDFL) operating in long-wavelength will produce significantly amplified spontaneous emission (ASE), which will reduce the output signal-to-noise ratio (SNR) and increase the sensitivity to the parasitic laser. Highly wavelength-selective elements, such as fiber Bragg grating (FBG) [9,10], diffraction gratings [11–13], and volume Bragg grating (VBG) [14], need to be placed in the laser cavity to eliminate parasitic laser so that Tm-doped fiber laser can produce stable laser output at long wavelength [12,15]. For large mode area (LMA) fiber, FBG is not very effective for wavelength selection, because LMA fiber maintains both fundamental mode and higher transverse mode. In addition, it is difficult for FBG to be tuned in a large range by either thermal tuning or mechanical stress. By using a diffraction grating, VBG and other free space elements, a widely tunable range can be obtained. However, these needs depend on complex external cavities containing free space components, which is not ideal in view of reliability.

In order to obtain a wide tunable laser, we build up the main oscillation stage in a ring cavity structure and use a packaged fiber-coupled tunable filter composed of a diffraction grating, coupling lens, and reflector, which not only avoids the disadvantage of narrow FBG tunability but also combines and fixes the complex components required by the diffraction grating through packaging, to ensure the simplicity and reliability of the laser system. We also have built up a one-stage amplifier with a tunable range of 110 nm (1925 to 2034 nm). The maximum output power of 459 mW is obtained in the oscillator at 1992.9 nm for 16 W launched pump power at 793 nm, corresponding to a slope efficiency of 5.6% corresponding to the launched pump power. The 3 dB linewidth is less than 0.5 nm, and the polarization extinction ratio (PER) reaches 21.4 dB. By using a one-stage Tm-doped fiber amplifier, combined with a high gain of >10 dB, the maximum slope efficiency is 12.6% and the output power is 5.65 W at 1993 nm ($M^2 \approx 1.25$), by providing a stable pump source and stable temperature control, a laser system with stable output power can be obtained. The instability of the laser is measured to be 0.0307 dB. The influence of different lengths of Tm-doped fiber on laser amplification is also studied through experiments and theoretical simulation to find the optimal fiber length of the amplifier, and the phenomena encountered in the experiment are also explained through theoretical study.

2. Experimental Setup

The main oscillation power amplification (MOPA) is to couple the signal laser with high beam quality generated by the main oscillator (MO) into the double-clad fiber in a certain way and combine the power of the pump laser to achieve high power amplification of the signal laser. Its outstanding characteristics are that the MO is mainly used to generate a high-quality signal laser, and the output power can be small, so the output signal laser maintains good beam quality and stability. The main function of the power amplifier (PA) is to amplify the signal laser, which not only ensures the high beam quality of the output signal laser but also achieves high power and high energy output.

Figure 1 describes the experimental setup of an all-fiber single-mode wavelength-tunable narrow-linewidth polarization-maintaining (PM) Tm-doped fiber master oscillator. A 793 nm laser diode (LD) with a maximum power of 16 W is used as a pump source for the master oscillator. A 3 m Tm-doped fiber (Nufern, PM-TDF-10P/130-HE) is used as the gain media with a 10 μm core diameter and a numerical aperture (NA) of 0.15. The cladding absorption of this Tm-doped fiber is 4.7 dB/m at 793 nm. The oscillator also consists of a PM isolator (ISO) to ensure the unidirectional propagation of light, a fused fiber optical coupler (OC) to extract the seed laser, and a tunable band-pass filter (TBF) as the wavelength selective element. The ISO is a two-stage isolator with an isolation of 35 dB. The tunable filter uses diffraction grating as a wavelength selector and it has a tunable width of 248 nm (1877–2125 nm), 3 dB bandwidth of 1.38 nm, and an insertion loss of 3.5 dB near the 2 μm.

The signal laser power from the oscillator is then used as the seed the power amplifier, which is a single-mode polarization-maintaining power amplifier (Figure 2). A high-power broadband PM ISO is inserted to protect the master oscillator and the PM Tm-doped fiber amplifier from the backward traveling light. A 793 nm laser diode (LD) with a maximum power of 50 W is used as a pump for the power amplifier. The length of Tm-doped fiber (Nufern, PM-TDF-10P/130HE) is 2 m with a numerical aperture (NA) of 0.15.

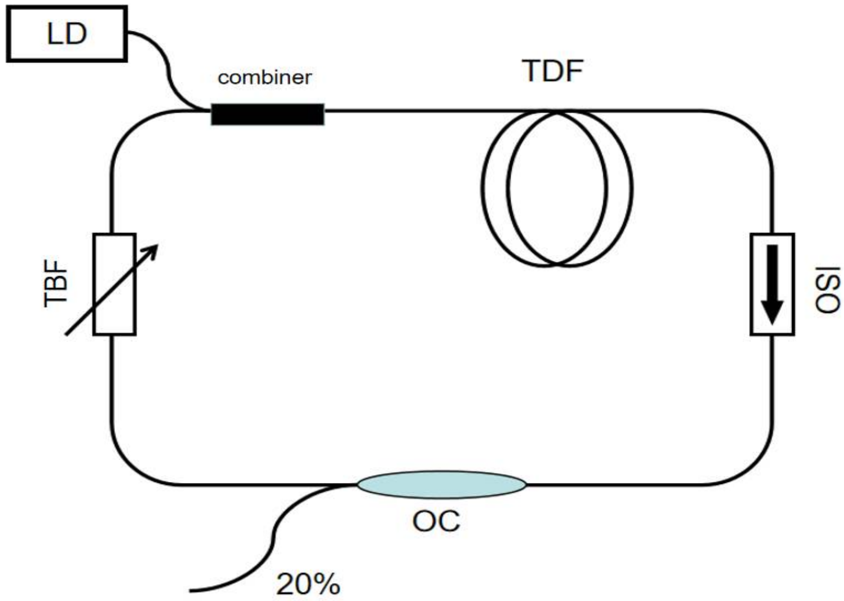

Figure 1. Layout of the all-fiber single-mode wavelength-tunable narrow-linewidth polarization-maintaining (PM) Tm-doped fiber master oscillator. LD: laser diode; TDF: Tm-doped fiber. ISO: isolator; OC: optical coupler; TBF: tunable band-pass filter.

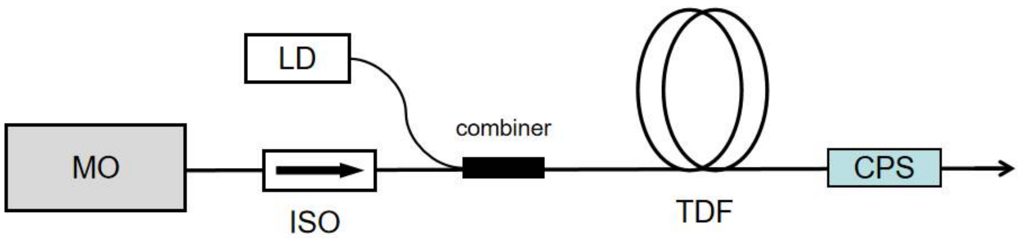

Figure 2. Layout of the all-fiber single-mode wavelength-tunable narrow-linewidth polarization-maintaining (PM) Tm-doped fiber power amplifier. MO: master-oscillator; LD: laser diode; TDF: Tm-doped fiber; ISO: isolator; CPS: cladding power stripper.

3. Experiment and Simulation Results

In the experiment, the PM thulium-doped fiber master oscillator produce an average output power of 459 mW when the pump power is increased to 16 W. The slope efficiencies of the master oscillator are calculated with the highest value of 5.6% at 1993 nm. Next, the master oscillator is injected into the power amplifier for further power scaling. When the pump power increased to its maximum, the output signal power is amplified to ~5.65 W, M^2 value is measured to be 1.25, and the polarization extinction ratio (PER) is 21.4 dB. Figure 3 shows the measured output power at a spectral interval of ~3.5 nm spanning from 1925 to 2034 nm. The slope efficiencies of the master oscillator are calculated with the highest value of 13% at 1993 nm. Since the absorption coefficient of PM fiber (4.7 dB/m @ 793 nm) is larger than that of the same type of non-PM fiber (3 dB/m @ 793 nm) [16], a shorter active PM fiber (no longer than 4.5 m) is used in the experiment.

Figure 4 shows the measured spectra at different lasing wavelengths. The output spectral linewidth is about 0.5 nm. When the pump power is increased to the maximum, the output wavelength can be tuned from 1925 nm to 2034 nm, and the wavelength tunable range is close to 110 nm.

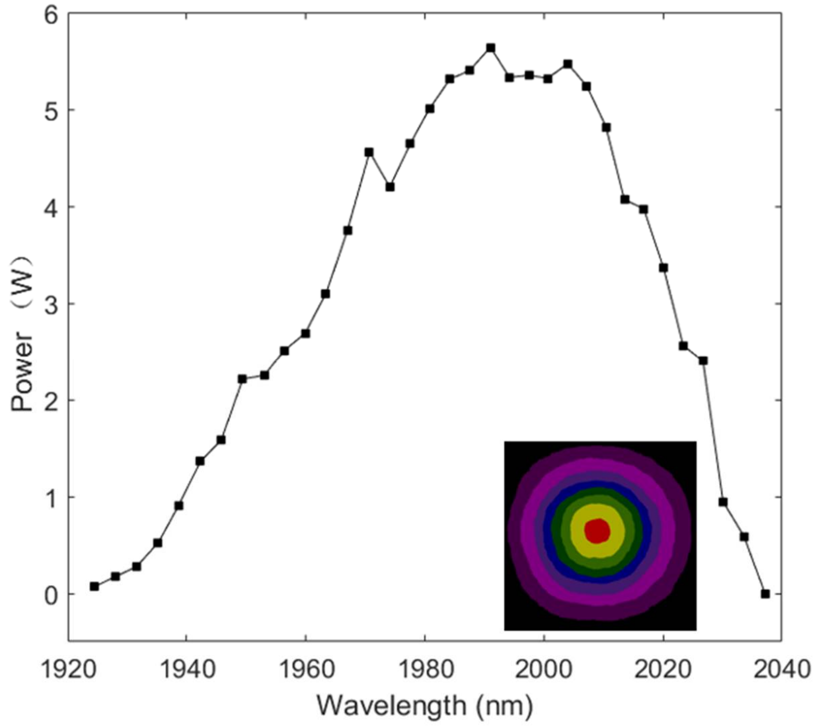

Figure 3. The output power of the MOPA system.

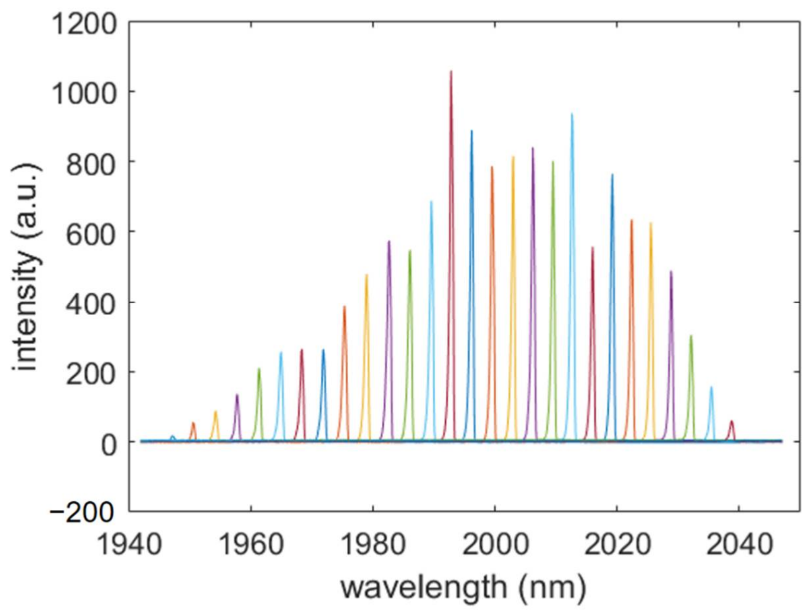

Figure 4. The spectrogram of the MOPA system.

By providing a stable pump source and stable temperature control, a laser system with stable output power can be obtained. The instability of the laser is measured to be 0.0307 dB, showing excellent power stability of the MOPA system (Figure 5).

We compare the effect of the PA system with different length gain fibers. The MO is set to the highest power, and the central wavelength of the MO is set to 1993 nm. The variation of output power with pump power under different lengths of gain fiber of the power amplifier (PA) system is shown in Figure 6.

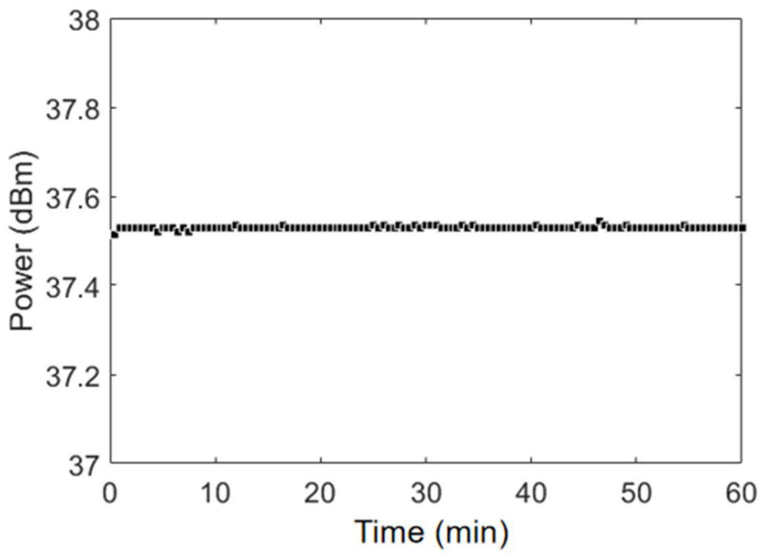

Figure 5. The spectrogram of the MOPA system.

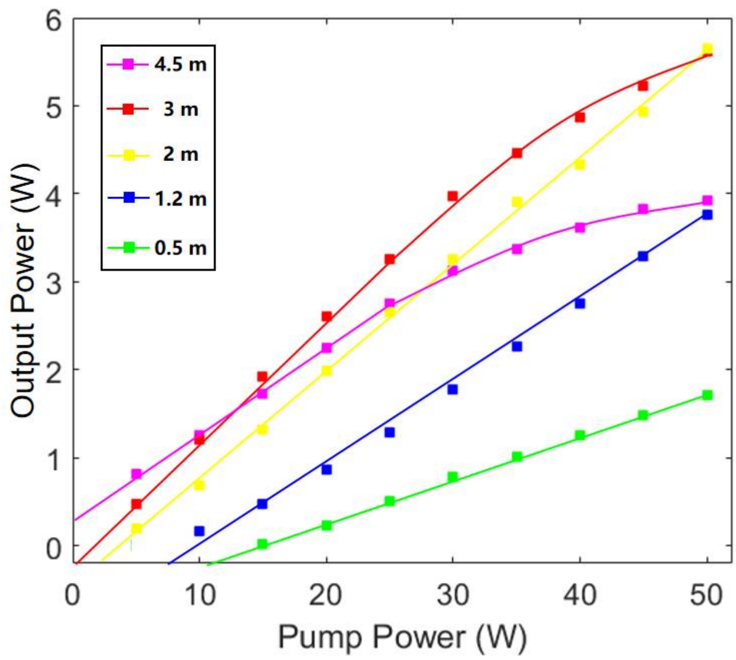

Figure 6. Variation of output power with pump power under different fiber lengths in the PA system.

It can be seen from the above figure that when the active fiber is 0.5 m, 1.2 m, 2 m,3 m, and 4.5 m the slope efficiency is 9.75%, 14.2%, 12.5%, 7.1%, and 5.0%, respectively. When the gain fiber length is shorter, the threshold power is lower. At 0.5 m, even if the pump power of the amplification stage is zero, the signal laser is greater than zero. This is because the gain fiber is too short, and the seed of MO directly transmits through the gain fiber. However, in the experiment with higher power output, it is found that the gain saturation phenomenon occurs because the 0.5 m and 1.2 m fiber is too short, and the power scalability is not as good as the active fiber with a length of 2 m. When the length of the active fiber is 3 m and 4.5 m, the slope efficiency is the lowest, which is mainly due to the reabsorption effect [17]. Currently, the highest output power we have achieved in this system is 5.65 W.

We simulate our experiment with the model from the reference [18,19]. Figure 7 shows the propagation process of pump laser, signal laser and ASE in the Tm-doped fiber core. Pump laser and signal laser are injected into the Tm-doped fiber core and transmitted through all the fiber. In this process, part of the energy of the pump laser is transferred to the signal laser, causing the power of the signal laser to increase.

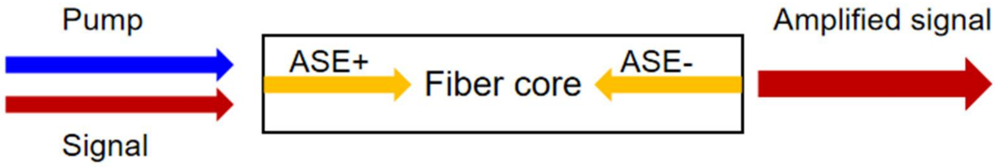

Figure 7. Propagation of the pump laser, signal laser and ASE in the Tm-doped fiber core.

The 793 nm laser is used as the pump, the seed is injected into the thulium-doped fiber amplifier. The pump power starts at 10 W and increases to 50 W with a step length of 10 W. The relationship between the output power and the fiber length under different pump powers is shown in Figure 8.

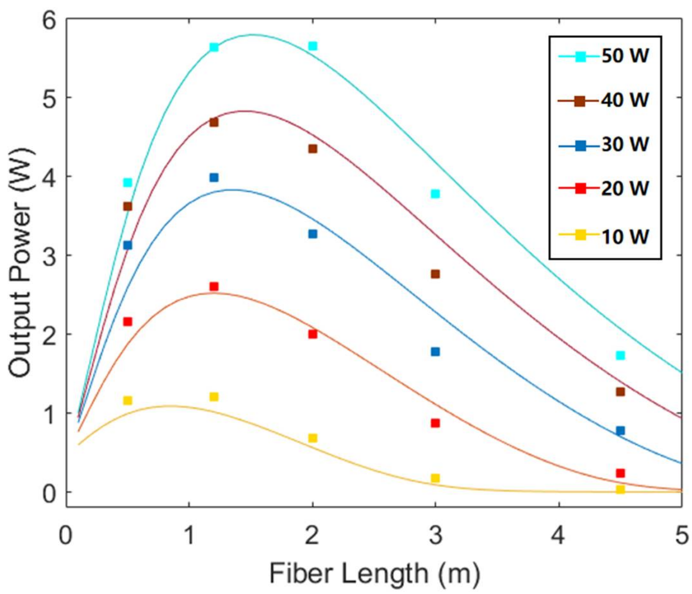

Figure 8. Relationship between amplified signal power and fiber length under different pump power. The solid line is calculated theoretically, and the square point is the experimental data.

From the theoretical simulation, it can be seen that the optimal fiber length will become longer with the increase of pump power. This explains that the slope efficiency under 0.5 m and 1.2 m gain fiber in Figure 6 will decrease with the increase of pump power. When the low-power pump laser is transmitted into the fiber, the optimal fiber length is short, so the short fiber can obtain the optimal gain. As the pump power increases, the optimal fiber length also increases, so the short fiber cannot obtain the optimal gain, which leads to a decrease of slope efficiency.

We also simulated the change of signal laser spectrum under different pump powers at 2 m fiber (Figure 9). It can be seen from the above figure that under this condition, the influence of the amplifier on the spectral shape can be almost ignored. This is also consistent with the experimental fact that the central wavelength and spectral linewidth of the amplified seed spectrum have not changed significantly.

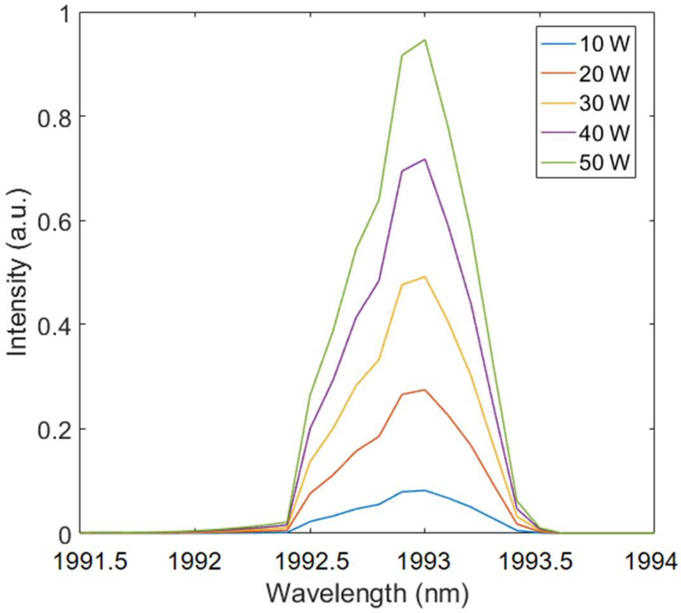

Figure 9. The change of signal laser spectrum under different pump power in 2 m optical fiber.

4. Conclusions

To sum up, we have built up an all-fiber wavelength-tunable narrow-linewidth high stability polarization-maintaining MOPA structure thulium-doped laser. The effects of different fiber lengths on the slope efficiency and output power in the power amplifier stage are also tested and calculated. By using the grating-based packaged tunable filter, we can obtain a wide wavelength tunable range, a narrow linewidth output of the fiber laser, and ensure an all-fiberized structure. The wavelength tunable range is 110 nm (from 1925 to 2034 nm), the linewidth is 0.5 nm, the polarization extinction ratio is 21.4 dB, $M^2 \approx 1.25$, the maximum output power is 5.65 W at 1993 nm, and the power stability is 0.0307 dB, which provides a solid foundation for further power amplification in the future.

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