

# Switchable dual-wavelength thulium-doped fiber laser based on all fiber Mach-Zehnder interferometer

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A stable and tunable dual-wavelength thulium-doped fiber laser based on a dual-pass Mach-Zehnder interferometer (MZI) filter is proposed and experimentally demonstrated. The designed MZI is composed of two 3-dB couplers and one broadband reflection mirror used as a wavelength reflector, and the filter is connected to a ring cavity by one circulator. A 0.8-m-long gain medium fiber is used in the experimental demonstration, and the working threshold is 182 mW. By adjusting the polarization controller (PC), tunable single-wavelength lasing lines with 3-nm intervals can be obtained within the 1851–1866-nm range, while the wavelength tuning interval and peak power shifts are less than 3.3 nm and 2.3 dB, respectively. When lasing is realized at 1863.5 nm, the wavelength and power variations are less than 1.3 nm and 0.45 dB, respectively, for a 30-min scanning period at room temperature, and the side-mode suppression ratio (SMSR) is larger than 37.5 dB. By changing the polarization condition, tunable dual-wavelength lasing can be achieved. Dual-wavelength lasing lines are realized at 1864 and 1875 nm and the stability is monitored; the respective power fluctuations are less than 1.6 and 1.8 dB for the 1864- and 1875-nm lines, respectively, the wavelength shifts are less than 0.98 and 1.73 nm, respectively, and the SMSR is larger than 31.2 dB. In the experiment, triple-wavelength lasing is also obtained by adjusting the polarization controller.

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*Keywords:* Dual-wavelength, Thulium-doped fiber laser, Mach-Zehnder interferometer, Ring cavity

## 1. Introduction

Tunable multi-wavelength thulium-doped fiber lasers (TDFL) have attracted considerable attention in fields such as dense wavelength division multiplexing (DWDM), communications, sensors, and spectrum analysis, because of their various advantages, which include a low risk of damage to eyesight, a narrow linewidth, the capacity for flexible tuning, a long work life, and a compact structure [1-6].

In recent years, some techniques to realize a tunable thulium-doped fiber laser have been reported. For example, in 2015, Yang et al. [7] reported a switchable and tunable dual-wavelength TDFL based on parallel cavities using a  $3 \times 3$  coupler. In the proposed TDFL, two fiber Bragg gratings (FBGs) with different reflection center wavelengths were spliced with two coupler beams as wavelength selectors, and a 2- $\mu\text{m}$  switchable single- or dual-wavelength fiber laser was obtained. In the same year, Soltanian et al. [8] reported a stable dual-wavelength TDFL obtained using a photonic crystal fiber (PCF). In the designed laser, a 10-cm-long PCF was inserted into the ring cavity to yield a Mach-Zehnder interferometer (MZI); the laser could produce two lines simultaneously and the power fluctuation was almost less than 1 dB. Also in 2015, Wang et al. [9] proposed a tunable multi-wavelength ring cavity TDFL using a Sagnac filter, and tunable single-wavelength lasing from 1955 to 1962 nm was

realized by adjusting a polarization controller (PC). Previously, in 2014, Liu et al. [10] reported a multiwavelength TDFL incorporating a highly nonlinear fiber. For the proposed TDFL, it was possible to achieve 15 output channels within a 10-dB bandwidth and with 1.22-nm wavelength spacing. In the same year, a tunable dual-wavelength TDFL was demonstrated by Liu et al. [11]. For the designed laser, one high-birefringence FBG (HB-FBG) was adopted as a wavelength selector, and a 6.93-nm wavelength tuning scope was realized for dual-wavelength lasing. Also in 2014, a tunable TDFL based on a multimode interference (MMI) fiber filter was realized by Ma et al. [12]. For the proposed fiber laser, the MMI was composed of a no-core fiber and a 45.18-nm tuning range was achieved. Finally, in 2013, Peng et al. [13] reported a multi-wavelength TDFL using a nonlinear amplifier loop mirror, in which 42 lines were realized simultaneously.

As shown above, a tunable multi-wavelength TDFL can be realized using a nonlinear amplifier loop, Sagnac loop, nonlinear optical element, or special structure fibers. However, as the proposed designs are very complex, the development of simple and efficient methods for realizing wavelength tuning would be valuable to research. The use of all fiber Mach-Zehnder interferometer (MZI) and broadband reflection mirror in the TDFL is novel compared with other researchers. In this paper, a tunable and stable dual-wavelength TDFL based on a dual-pass

MZI is achieved. Using the proposed laser design, it is possible to achieve tunable single- and dual-wavelength lasers. Further, a tunable triple-wavelength laser is also obtained in experiment.

## 2. Experimental setup

A schematic of the proposed TDFL setup is presented in Fig. 1. The TDFL is composed of a pump source, TDF, 973/2000 wavelength division multiplexer (WDM), optical couplers (OC1–OC3), circulator, PC, and broadband reflection mirror (BRM). The pump wavelength is 793 nm and the pump light is coupled into a 0.8-m-long TDF by the WDM. Two 3-dB couplers are connected to form a single-pass MZI, and the comb-spectrum wavelength spacing can be calculated from

$$\Delta\lambda = \frac{\lambda^2}{n\Delta L}, \quad (1)$$

where  $\lambda$  is wavelength,  $n$  is birefringence, and  $\Delta L$  represents the difference in length between the two beams. For the proposed TDFL, a BRM with a pigtail fiber is spliced with an optical coupler (OC2 in Fig. 1) to yield a dual-pass MZI configuration. Compared with single-pass MZI, dual-pass MZI can exhibit half wavelength spacing and has a superior filtering effect [14]. In the proposed TDFL, the ring cavity is composed of a pump source, gain medium, PC, WDM, and OC3, and the MZI filter is connected to the cavity by one circulator.

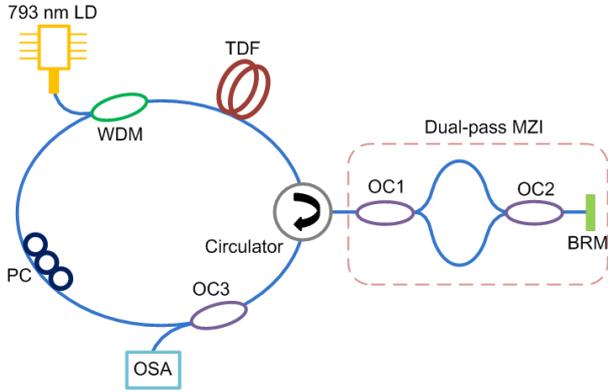


Fig. 1. Schematic diagram of TDFL

In the experiment, the maximum pump-laser (Lumics) output power was 250 mW. The TDF (SM-TSF-9/125, Nufern) absorption coefficient was 27 dB/m at 793 nm. The circulator, WDM, and OC were manufactured by Advanced Fiber Resources (AFR) Co.

## 3. Experimental results and discussion

Firstly, the comb filter spectra for the single- and dual-pass MZI cases were measured. A 2- $\mu\text{m}$  broadband light was injected into the MZI filter and the amplified spontaneous emission (ASE) light and comb spectra for wavelengths of 1700 to 2100 nm were obtained, as shown in Fig. 2(a). In Fig. 2(b), a detail of the spectrum from 1830 to 1890 nm is shown. Hence, the wavelength intervals of the single- and dual-pass MZI transmission spectra were 6 and 12 nm, respectively, and it is apparent that the designed dual-pass MZI exhibits superior filtering ability to the single-channel MZI.

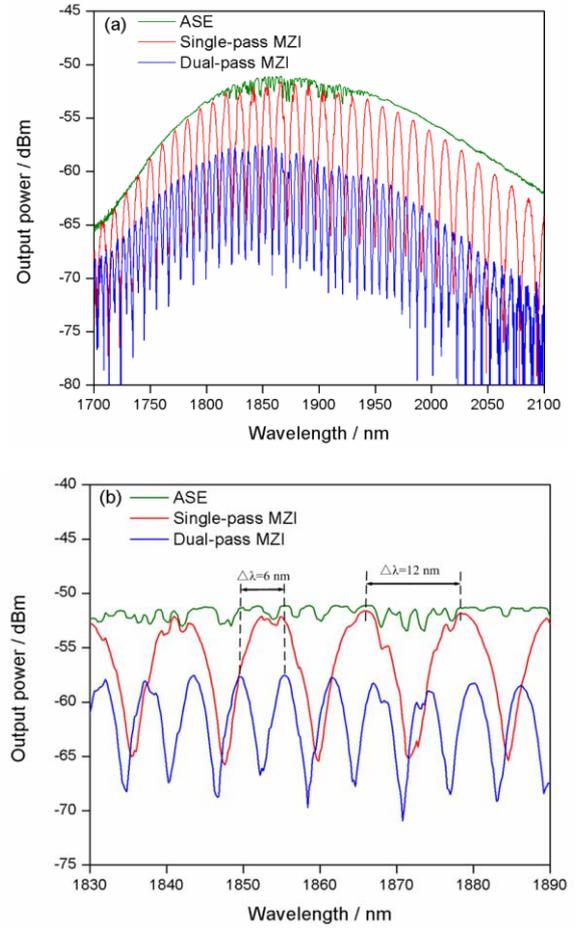


Fig. 2. Comb spectra of single- and dual-pass MZI within (a) 1700–2100- and (b) 1830–1890-nm wavelength range

Then, the proposed MZI filter was employed. For 182-mW pump power, single lines were emitted at 1855.6 nm. Fig. 3 shows the laser spectrum obtained when the pump power was set to 200 mW and the side-mode suppression ratio (SMSR) was 31.6 dB. In the experiment, tunable single-wavelength lasing lines with a 3-nm interval could be obtained within the 1851–1866-nm range by adjusting the PC, as shown in Fig. 4(a). Fig. 4(b) shows that the wavelength tuning fluctuations and peak power

shifts were less than 3.3 nm and 2.3 dB, respectively.

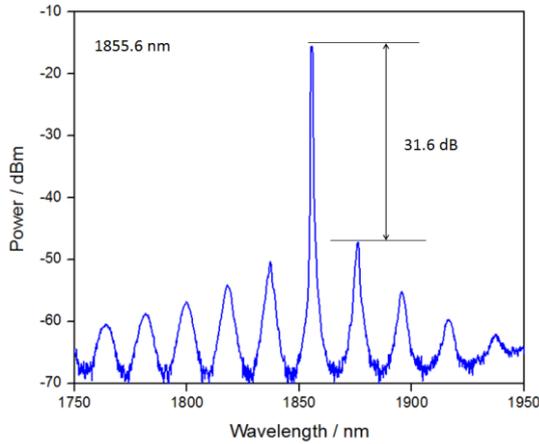


Fig. 3. Laser spectrum for 200-mW pump power

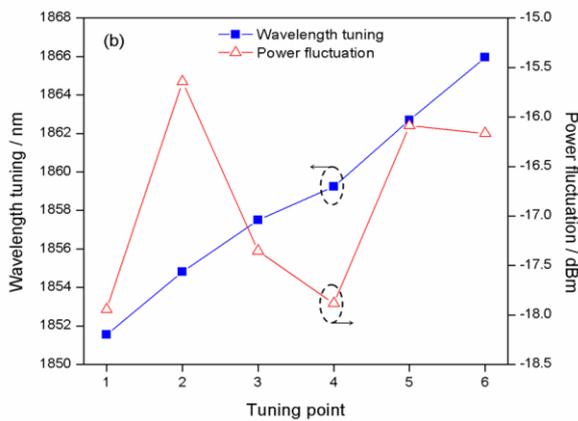
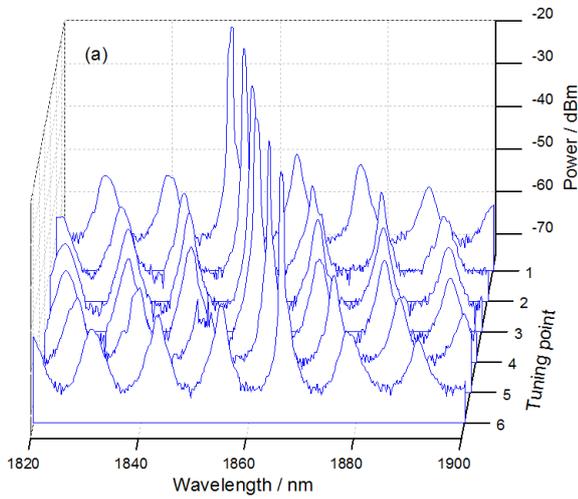


Fig. 4. Single-wavelength tuning results. (a) Tuning results. (b) Power and wavelength fluctuations

When the pump power was increased to 250 mW, tunable single-wavelength lasing was realized at 1863.5 nm by adjusting the PC, and the wavelength and peak power stability of the single-wavelength case were monitored at room temperature. As shown in Fig. 5(a),

mode jumping was not observed over a 30-min scanning period and the SMSR was larger than 37.5 dB. Fig. 5(b) shows that the wavelength and power variation were less than 1.3 nm and 0.45 dB, respectively.

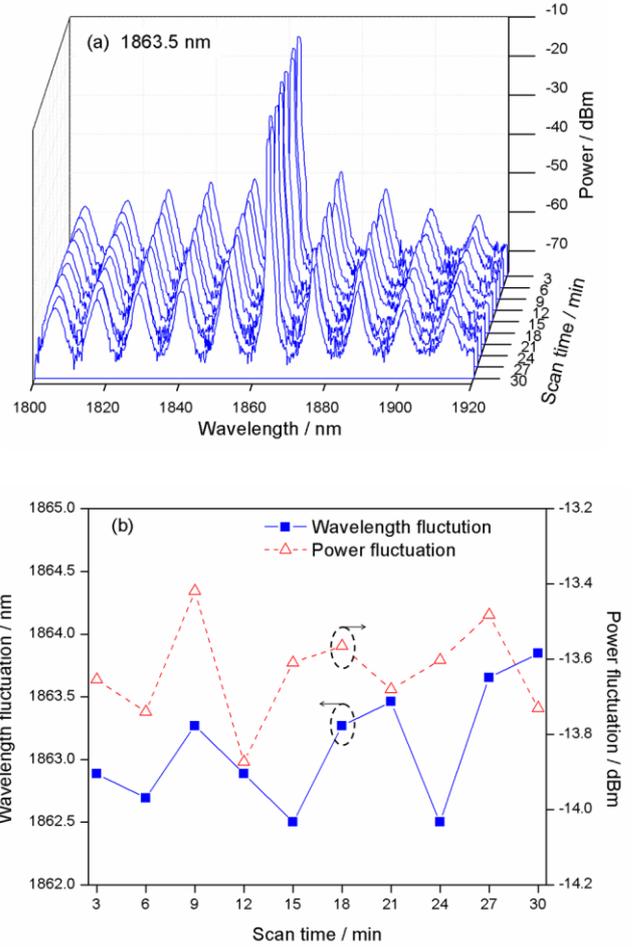


Fig. 5. Stability measurement for 1863.5-nm laser. (a) Spectrum stability and (b) peak power and wavelength variations

By changing the polarization conditions, tunable dual-wavelength lasing could be achieved. Dual-wavelength lasing lines were realized at 1864 and 1875 nm and the stability was tested, as shown in Fig. 6(a). The power fluctuations and wavelength shifts of both lines are shown in Fig. 6(b); hence, it is apparent that the power fluctuations were less than 1.6 and 1.8 dB for the 1864- and 1875-nm lines, respectively, whereas the wavelength shifts were less than 0.98 and 1.73 nm, respectively. The spectrum stability was not good, so in the next research, we plan to use two 793 nm LDs as pump source simultaneously to improve spectrum stability. We also plan to improve power stability by self-feedback light injection, thin-core fiber or fiber ring filter methods at 2 $\mu$ m band respectively. In the experiment, tunable dual-wavelength lines could be realized under the same pump conditions by changing the PC. The tuning results are shown in Fig. 7(a)–(f), where the SMSR was larger than 31.2 dB.

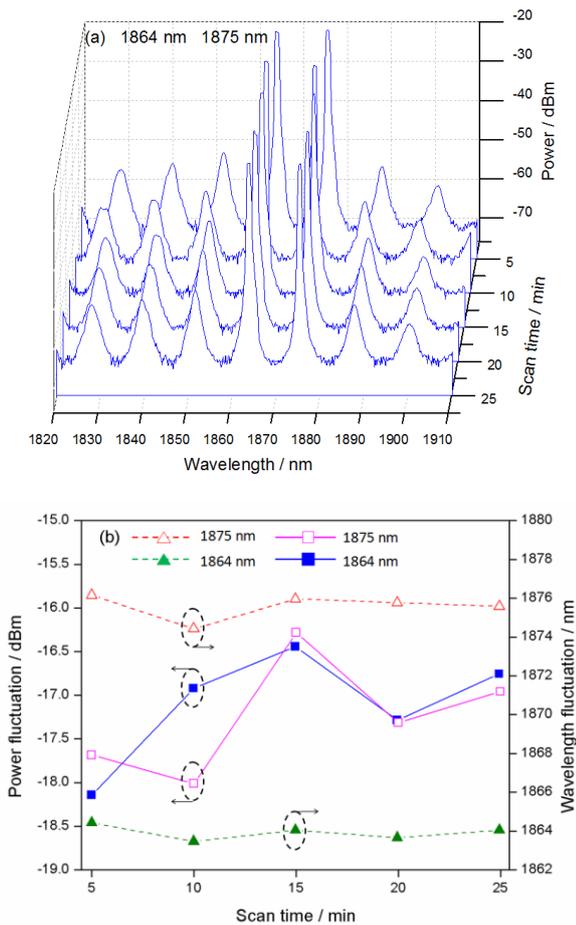


Fig. 6. Stability measurement for 1864- and 1875-nm dual-wavelength lasing. (a) Spectrum stability. (b) Spectrum stability and power fluctuation

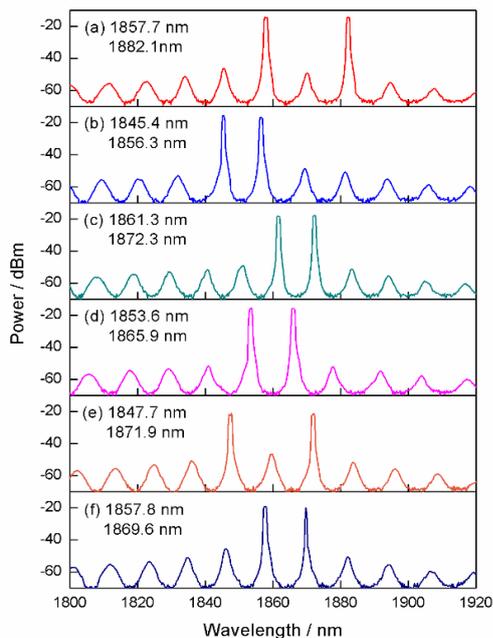


Fig. 7. Dual-wavelength tuning results

In addition, triple-wavelength lasing could be obtained by adjusting the PC during the experiment, as shown in Fig. 8. For a pump power of 250 mW, 1845.2-, 1857.5-, and 1869.8-nm lines could be emitted simultaneously, where the maximum peak power difference of each line was 4.9 dB and the SMSR was 28.6 dB. Because the maximum pump power was used in the experiment, it was not possible to achieve a greater number of emitted lines by increasing the pump power supplied to the proposed TDFL.

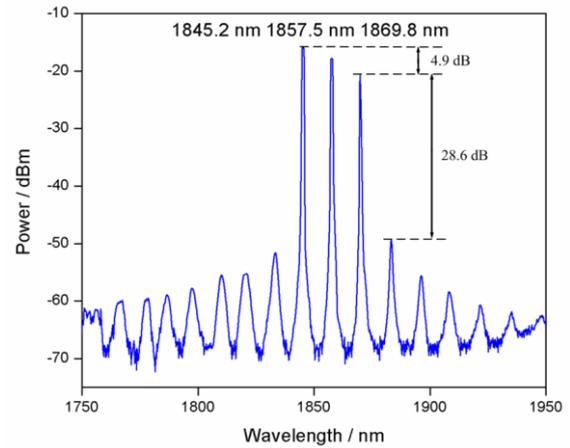


Fig. 8. Triple-wavelength laser output spectrum

In the experiment described above, the designed dual-wavelength TDFL successfully generated a stable and tunable single- and dual-wavelength laser output. It was also possible to achieve triple-wavelength lines using the proposed TDFL.

#### 4. Conclusion

In this paper, a stable and tunable single- and dual-wavelength TDFL based on a dual-pass MZI was proposed and realized experimentally. The single-wavelength laser tuning interval was less than 3 nm within a 1851–1866-nm tuning scope, while the peak power difference of each line was less than 3.3 dB. In experiment, the wavelength and power variations of the 1863.5-nm single-line were found to be less than 1.3 nm and 0.45 dB, respectively, for a 30-min monitoring period at room temperature. In addition, 1864- and 1875-nm dual-wavelength lasers were produced; the power fluctuations were less than 1.6 and 1.8 dB for the 1864- and 1875-nm lasers, respectively, and the wavelength shifts were less than 0.98 and 1.73 nm, respectively. The SMSR was larger than 31.2 dB when single- or dual-wavelength lasing was achieved. Using the proposed TDFL, a triple-wavelength laser could also be realized in experiment. The designed TDFL exhibits flexible tuning capability and high stability, and has a variety of potential applications in optical sensors, fiber communication, and spectrum analysis.

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