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WAVELENGTH SWITCHABLE THULIUM-DOPED FIBER LASER BASED ON FIBER-CORE MISMATCHED MACH–ZEHNDER FILTER

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Abstract

In this study, we propose a wavelength-switchable Thulium-doped fiber laser (TDFL) based on an all-fiber Mach–Zehnder (MZ) filter. The MZ comb interferometer is designed and manufactured by welding two mismatched fiber cores. The proposed ring-cavity TDFL has a working threshold of 140 mW. Single-wavelength switchable laser emission is achieved in the range of 1841.5 to 1892.36 nm, with a minimum wavelength spacing of 3.66 nm and a side-mode suppression ratio (SMSR) of over 32.41 dB. In the experiment, four different dual-wavelength switchable and stable lasers are generated within a 44.56 nm range with 7.12 dB power shifts. Additionally, a triple-wavelength laser at 1864.77, 1888.1, and 1896.76 nm is obtained, with an SMSR of over 30.06 dB. The designed TDFL successfully achieves stable single, dual, and triple-wavelength laser emissions with power fluctuations smaller than 0.51, 1.22, and 1.32 dB, respectively.

Keywords: Thulium-doped fiber, Mach–Zehnder filter, wavelength switchable laser, mismatched fiber.

1. Introduction

Thulium-doped fiber laser (TDFL) offers several advantages, including infrared laser emissions, narrow line width, high side-mode suppression ratio (SMSR), excellent stability, and wavelength flexibility [1–3]. Therefore, TDFLs are widely used as light sources or measurement equipment in the fields of fiber sensing, optical detection, and biomedicine [4, 5]. In comparison to traditional Erbium-doped fiber lasers, TDFL has a broader wavelength tuning range and longer wavelength. Various methods have been proposed in recent years to the achieve wavelength-switchable and stable TDFL output [6, 7].

Ibarra-Escamilla et al. reported a tunable dual-wavelength TDFL based on two fiber Bragg gratings (FBGs), and laser wavelength space could be tuned from 0.54 to 9 nm [8]. Ismail et al. reported a tunable dual-wavelength TDFL using spatial-mode beating; the interferometer structure was fabricated by multi-mode non-adiabatic taper fiber, and dual-wavelength spacings was tuned from 5 to 24.8 nm [9]. Liu et al. designed a ring cavity multi-wavelength TDFL based on nonlinear polarization rotation; the wavelength spacing was 6.75 nm, and its tuning range was 33 nm [10]. Zhang et al. reported a sampled FBG-based wavelength-tunable TDFL; for the proposed fiber laser, wavelength tuning range was 14.44 nm, and power fluctuation was smaller than 0.46 dB [11]. Jia et al. reported a single and dual-wavelength tunable ring-cavity TDFL based on Sagnac loop; the tunable operation was 70 nm [12]. Ahmad et al. reported a tunable dual-wavelength TDFL based on two tunable bandpass filters; the widest channel

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spacing obtained was 183.6 nm [13]. An individually switchable and tunable multi-wavelength TDFL based on two fiber tapers was proposed by Li et al., who combined it with nonlinear loop mirror; the tuning range was from 1952.06 to 1975.62 nm [14]. Chen et al. designed a wavelength tunable TDFL based on Sagnac loop with two segments of polarization maintaining fiber (PMF); the 40 nm tuning range was obtained [15].

As we already mentioned, various methods have been used to realize wavelength-switchable Thulium-doped fiber lasers (TDFLs), such as Sagnac loop, Fabry–Pérot interferometer, Mach–Zehnder interferometer (MZI), polarization-maintaining fiber (PMF), fiber tapers, fiber gratings, nonlinear loops, and optical components. However, these filters are complex to produce, fragile, and do not provide strong intensity. Furthermore, achieving a wide tuning range has been challenging. Therefore, it is important to propose an efficient method for achieving stable and switchable emissions of Thulium-doped fiber lasers.

In this study, we propose a multi-wavelength switchable TDFL based on an MZ filter and experimentally demonstrate stable single, dual, and triple-wavelength lasers. The designed TDFL system, which has not been reported before, exhibits improved tuning range and stability.

2. Experimental Setup

In Fig. 1, we show the scheme of proposed TDFL, where a 793 nm laser diode (LD), connected with a 793/2000 nm wavelength division multiplexer (WDM), is employed as the pump power, then a 4 m single-mode TDF (9/125 μm) is used as the gain medium. Also, an optical coupler (OC) with 30 : 70 splitting ratio (SR) is inserted into the cavity, and the output mirror with 30% SR is connected with an optical spectrum analyzer (OSA). One polarization controller (PC) is used to adjust intra-cavity losses. The proposed all-fiber MZI is used to generate comb filter; see Fig. 1, where the MZI is composed of three-segment single-mode fibers (SMFs) with the same core and cladding size, with SMF1 and SMF3 being horizontal, while SMF2 is mismatched with them. The input light is split in two paths at fiber core mismatched point; here, path 1 is transmitted into the SMF2 cladding part, path 2 is transmitted into the SMF2 core part, and finally, two parts are focused into the SMF3. In described procedure, the optical path differences in path 1 and path 2 are generated; thus, an MZI structure is realized. The free spectrum range of MZI comb filter can be expressed as follows:

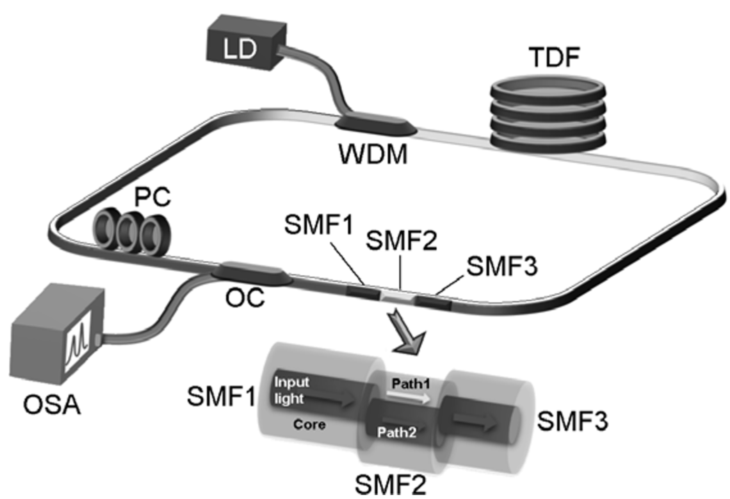

Fig. 1. Schematic of the TDFL.

$$\Delta\lambda = \frac{\lambda^2}{\Delta n L}\,, \tag{1}$$

where Δn means the refractive index difference, L is the length of the two paths, and the wavelength interval $\Delta\lambda$ is inversely proportional to L.

In Fig. 2, we demonstrate the MZI based on fiber core mismatched welding fabrication procedure. In step 1, SMF1 and SMF2 are processed by end surface cutting and alignment, being fixtured by fusion

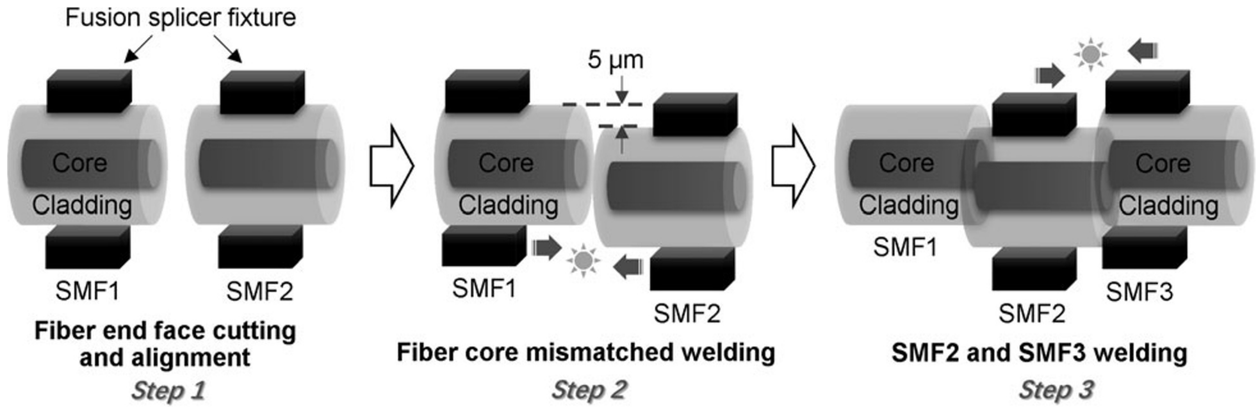

Fig. 2. MZI fabrication procedure principle.

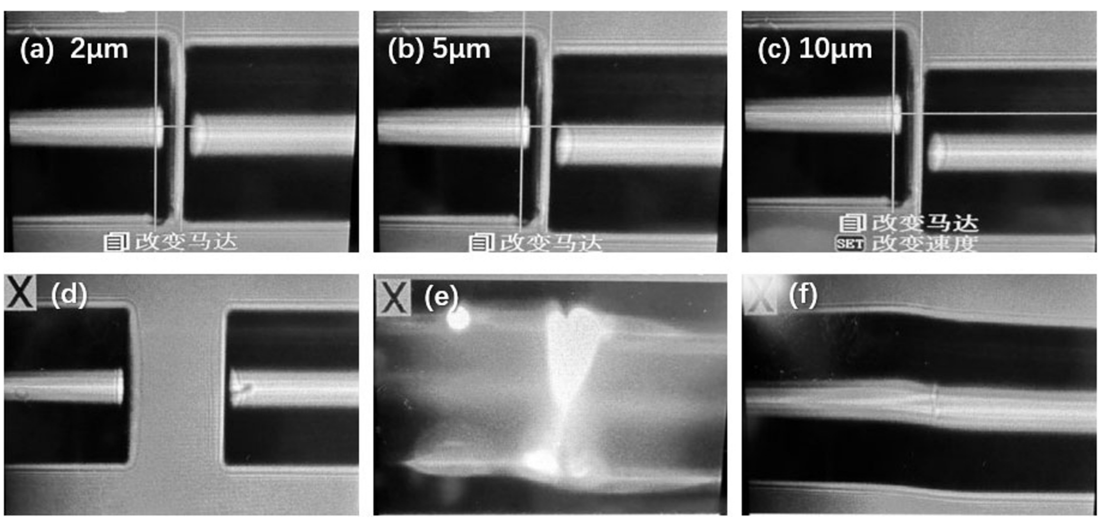

Fig. 3. Mismatch welding fabrication procedure. Here, 2 μm mismatch length (a), 5 μm mismatch length (b), 10 μm mismatch length (c), two-fiber alignment (d), mismatch welding image (e), and final fusion image (f).

splicer. In step 2, SMF2 moves 5 μm, while SMF1 is not moving, and in the next moment, SMF1 and SMF2 are welded. In step 3, SMF2 and SMF3 are welded to ultimately generate the MZI structure.

In Fig. 3, we present the mismatch welding fabrication procedure.

3. Experimental Results and Discussion

The experimental mismatch structure welding image includes the mismatch displacement images at 2, 5, and 10 μm shown in Fig. 3 a–c, where we see that, with increase in the misalignment distance, the alignment of the optical fiber core becomes impossible. In the experiment, we create a mismatch point by welding two single-mode fibers, with a 5 μm displacement. When the mismatch length between the two fibers is too short, the MZI interference phenomenon cannot be observed in the experiment. In contrast, if the mismatch length is too long, the optical fiber transmission loss increases, and the interference phenomenon becomes less apparent. The alignment image of the two optical fibers is shown in Fig. 3 d, the electric welding image, in Fig. 3 e, and the final fusion image, in Fig. 3 f.

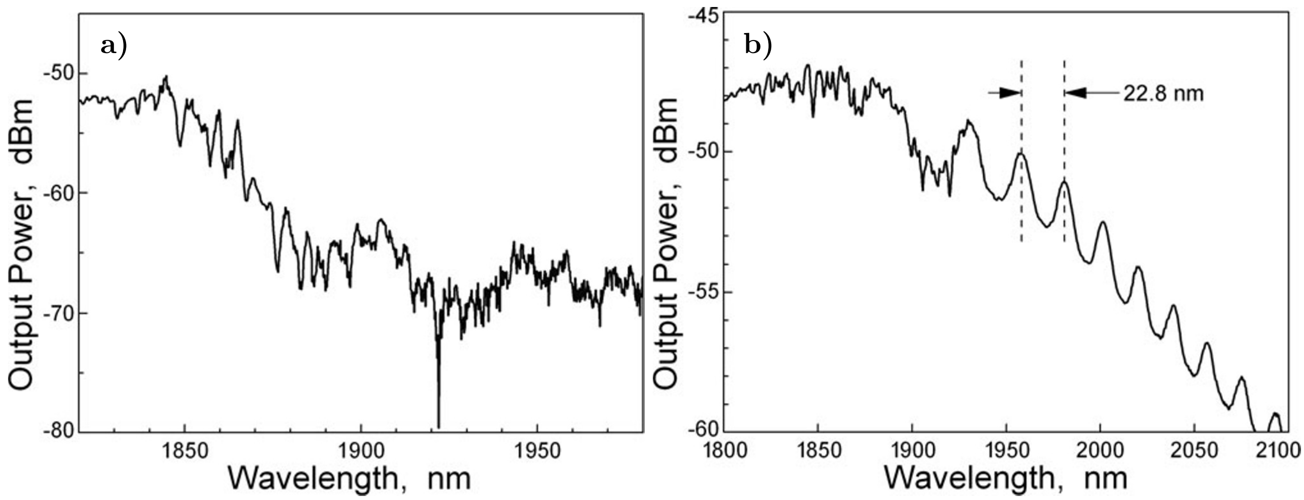

Fig. 4. MZI spectrum with 8 μm (a) and 5 μm (b) mismatch lengths.

In the experiment, first MZI is fabricated, with 0.3 m long SMF2 being used and connected with SMF1 and SMF3. When the mismatch displacement length of two fibers is short, the MZI interference phenomenon cannot be formed in the experiment; however, when the mismatch length is long, the optical fiber transmission loss is improved, and the interference phenomenon is no longer visible. Comparing the 8 μm mismatch length shown in Fig. 4 a with the 5 μm mismatch length shown in Fig. 4 b, we see that the comb spectrum is realized, with the wavelength interval equal to 22.8 nm, and this demonstrates that designed MZI based on fiber core mismatched welding method is realized. Also, we can use a filter to obtain a better filtering effect in TDFL.

Then, we insert the MZI elaborated into the TDFL ring cavity. The experimentally measured TDFL laser threshold is 140 mW. The pump power is gradually improved, and a stable single-wavelength laser emission is realized. Switchable single-wavelength laser can be obtained though adjusting PC; see Fig. 5 a, where the tuning range is from 1841.5 to 1892.36 nm, and the wavelength span is 50.86 nm. During the single-wavelength laser tuning process, the minimum wavelength space is 3.66 nm, the side-mode suppression ratio (SMSR) is larger than 32.41 dB, and there is no mode jumping. As shown in Fig. 5 b, the power shift is smaller than 8.46 dB.

The elaborated TDFL based on MZI had excellent single-wavelength tunability. We tested the single-wavelength laser stability in the experiment; within 30 min., the spectrum was collected every 5 min. by OSA. For 1867.2 nm laser output, the spectrum stability is shown in Fig. 5 c, and its power fluctuation is smaller than 0.14 dB; see Fig. 5 d. For 1878.9 nm single-wavelength laser, the wavelength stability is excellent, and power fluctuation is smaller than 0.51 dB; see Figs. 5 e, f.

For the elaborated TDFL, we could experimentally realize multi-wavelength laser emissions. Through adjusting PC, we can realize four different dual-wavelength laser emissions of 1848.8 and 1866.05 nm, 1860.51 and 1877.03 nm, 1870.49 and 1885.49 nm, and 1875.03 and 1893.16 nm; see Fig. 6 a, during the 44.56 nm tuning range, and intensity difference smaller than 7.12 dB. For dual-wavelength laser emissions, the SMSR is higher than 30.5 dB. Also, in Fig. 6 b, we show the spectrum of 1864.77, 1881, and 11896.76 nm triple-wavelength laser operated by tuning PC with a laser intensity difference smaller than 8.27 dB and SMSR larger than 30.06 dB.

Also we experimentally study the stability of the multi-wavelength laser output. For 1870.49 and

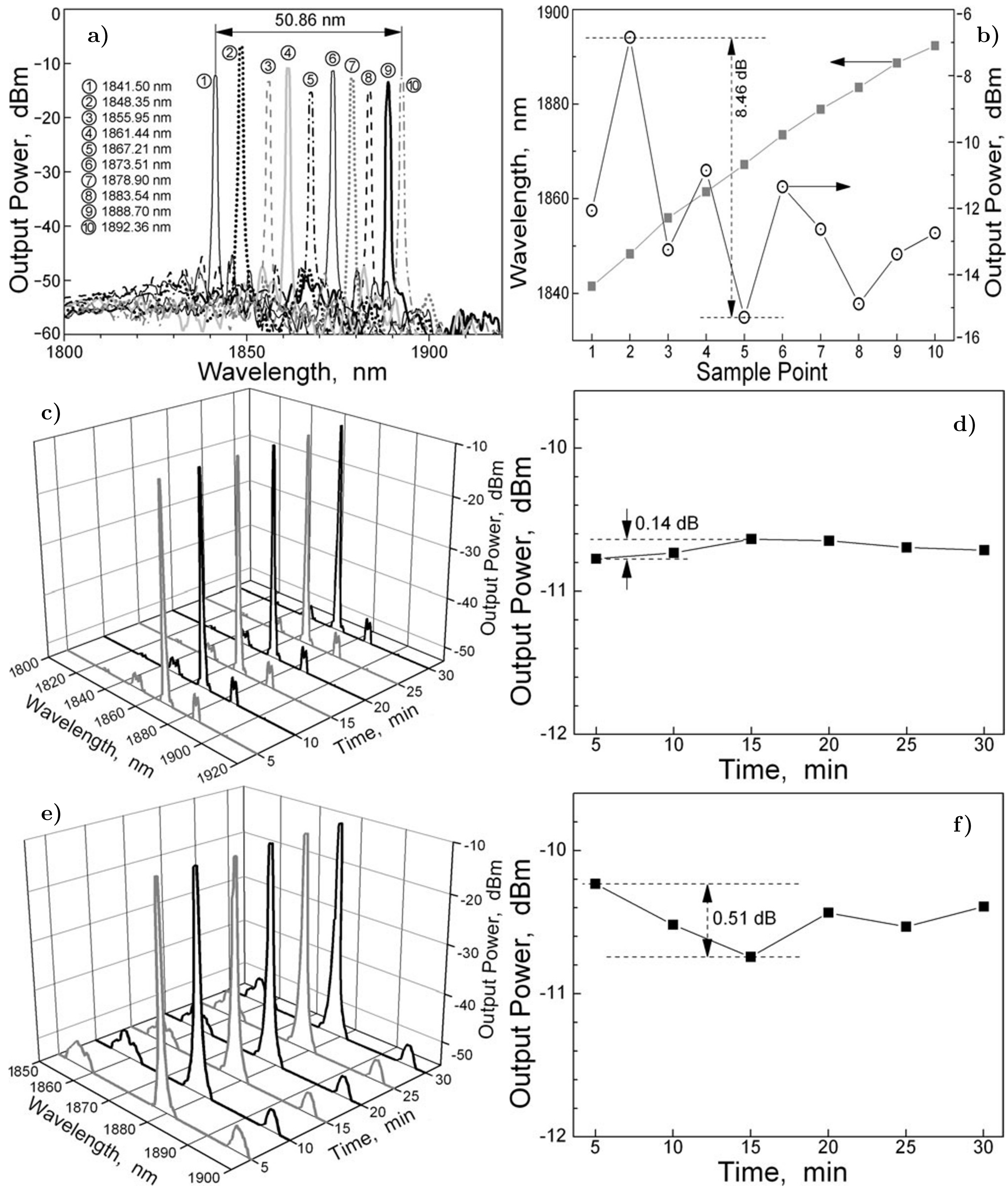

Fig. 5. Single-wavelength tunability and stability. Here, the switchable laser spectrum (a), laser tunability (b), 1867.2 nm laser stability (c), 1867.2 nm power fluctuation (d), 1878.9 nm laser stability (e), and 1878.9 nm power fluctuation (f).

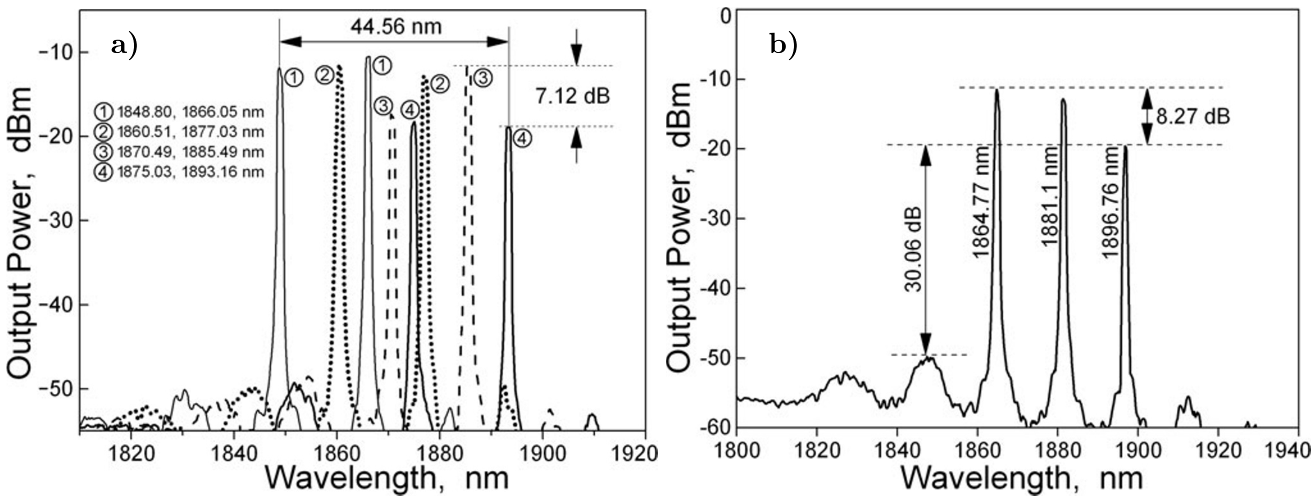

Fig. 6. Multi-wavelength tuning capability. Here, dual-wavelength (a) and triple-wavelength (b) laser emissions.

1885.49 nm dual-wavelength laser, we measure its stability within 30 min.; see Fig. 7 a, where one can observe that the dual-wavelength laser expresses good stability, without serious mode jumping. The power fluctuation is smaller than 1.22 and 0.23 dB for 1870.49 and 1885.49 nm laser, respectively; see Fig. 6 b. In addition, we also tested the triple-wavelength laser stability. As shown in Fig. 7 c, 1864.77, 1881.1, and 1896.76 nm triple-wavelength laser stably operates, the mode hopping is not exhibited, and power fluctuations of each laser is smaller than 0.25, 1.05, and 1.32 dB, respectively; see Fig. 7 d. The dual and triple-wavelength lasers, using fiber core mismatched MZI filter, exhibit excellent stability.

In our experimental demonstration, the proposed TDFL employing MZI based on mismatch welding method could realize tunable and stable single, dual, and triple-wavelength laser outputs. The single-wavelength laser output power fluctuation is lower than 0.51 dB. For dual and triple-wavelength laser output, the power fluctuations are smaller than 1.22 and 1.32 dB, respectively, during 30 min. The TDFL durability is shown in Table 1.

Table 1. Durability Characteristics of Elaborated TDFL Lasers.

Laser:	Single-wavelength	Dual-wavelength	Triple-wavelength
This work	0.51 dB	1.22 dB	1.32 dB
[3]	0.93 dB	2.04 dB	NA
[6]	0.76 dB	NA	NA
[9]	0.1 dB	0.5 dB	NA
[10]	1 dB	0.5 dB	2 dB
[11]	0.46 dB	NA	NA
[12]	0.7 dB	NA	NA

We proposed, elaborated, experimentally realized the TDFL based on all-fiber MZI comb filter and demonstrated the wavelength-switchable and stable lasers.

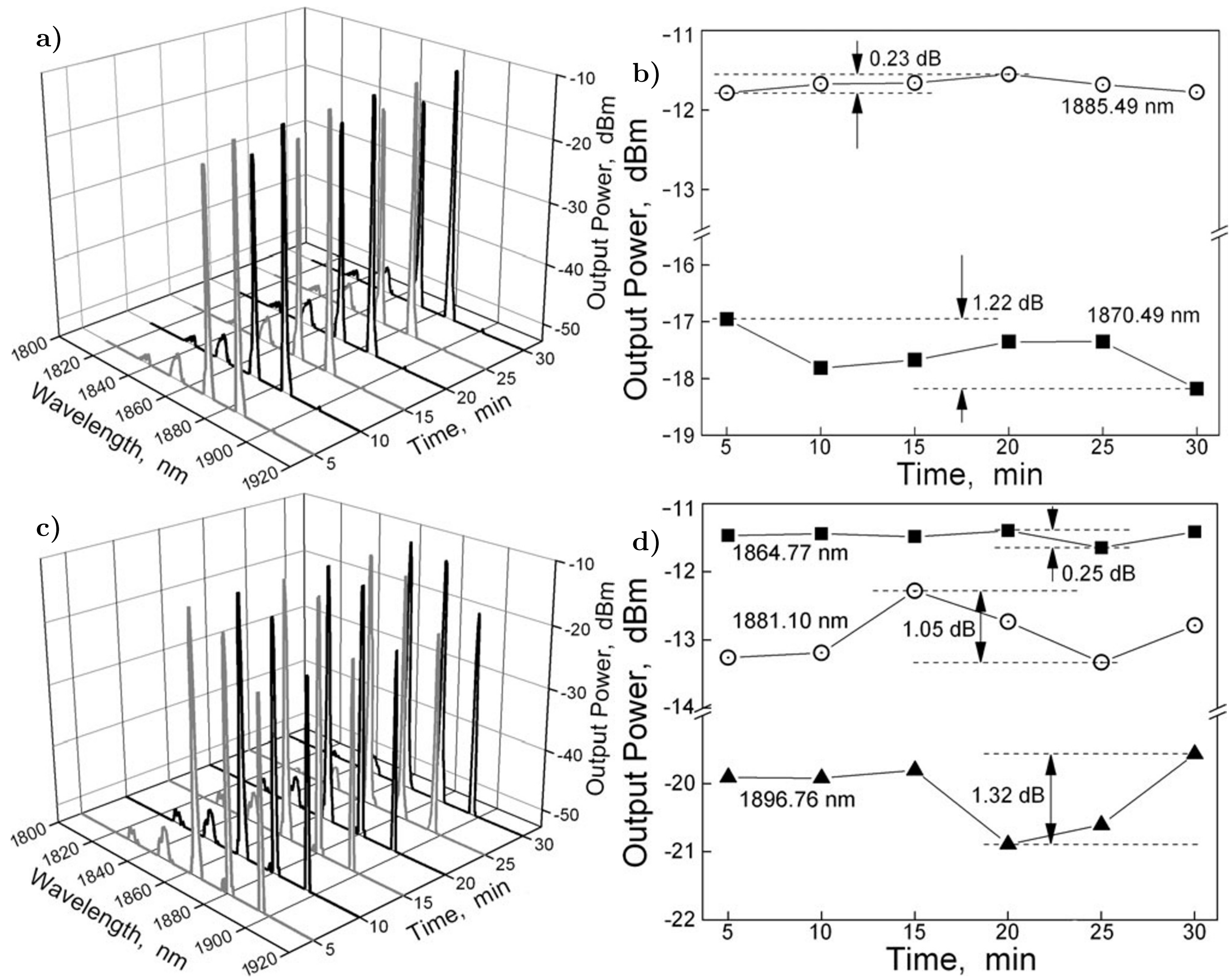

Fig. 7. Stability of multi-wavelength lasers. Here, the stability of dual-wavelength laser (a), the power fluctuation of dual-wavelength laser (b), the stability of triple-wavelength laser (c), and the power fluctuation of triple-wavelength laser (d).

4. Summary

In this study, we elaborated the wavelength switchable and stable single, dual, and triple-wavelength TDFLs. The MZI comb filer was manufactured by fiber core mismatched welding method. The single-wavelength laser tuning range was 50.86 nm with a minimum wavelength space of 3.66 nm, while the SMSR was larger than 32.41 dB. Dual-wavelength laser tuning range was 44.56 nm, and SMSR was larger than 30.5 dB. We experimentally realized triple-wavelength lasers, with SMSR larger than 30.06 dB. For single, dual, and triple-wavelength lasers, the power fluctuation were smaller than 0.51, 1.22, and 1.32 dB, respectively. The elaborated TDFL has wide tuning range and high stability; it operates in the eye safe band, i.e., it can be used as a light source in infrared detection, fiber sensing, and detection applications.

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