Wavelength switchable thulium-doped fiber laser operation incorporated with interferometer filter based on coreless fiber

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A wavelength switchable ring cavity thulium-doped fiber laser (TDFL) based on Mach-Zehnder interferometer (MZI) is designed. The MZI is fabricated by cascading single-mode and coreless fibers, and the proposed TDFL can generate single-, double-, and triple-wavelength laser emission. The single-wavelength laser tuning scope is 39.2 nm from 1896.1 to 1935.3 nm, and its power fluctuation is less than 0.665 dB. In the experiment, three different groups double-wavelength and two different groups triple-wavelength lasers can be generated through adjusting PC respectively. For the designed fiber laser, the signal to noise ratio is more than 30 dB.

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Keywords: Thulium-doped fiber laser, Wavelength switchable laser, MZI, Coreless fiber

1. Introduction

Fiber laser has compact structure, long working life, wide wavelength range, good beam quality characteristics [1-3] etc. Thus, it is widely used in optical fiber communication, optical sensing, material detection and so on [4]. In recent years, lasers wavelength has gradually shifted from 1.5 to 2 μm wavelength band, because corresponding lasers have important application in radar detection, biomedical treatment, wavelength division multiplexing [5-6]. Therefore, wavelength switchable thulium-doped fiber lasers (TDFL) have gradually become one of the research hotspots.

A wavelength switchable TDFL based on sampled fiber Bragg gratings was reported by Zhang, and 14.44 nm wavelength tuning range from 1942.09 to 1956.53 nm was realized, power fluctuation was less than 0.46 dB [7]. Tunable fiber Bragg gratings used as wavelength selector of TDFL for dual-wavelength tunable laser generation was reported by Ibarra-Escamilla, for its proposed fiber laser, 0.54 to 9 nm wavelength tuning range was realized [8]. An all-fiber tunable TDFL based on tapered fiber interferometer was presented by Hernández-Arriaga, and 19.4 nm single laser wavelength tuning range at 1761.8 and 1793.4 nm was achieved [9]. Wavelength switchable TDFL based on single-mode-multimode-single-mode fiber interferometer was demonstrated by Qin, and single-wavelength laser tuning range was 2.76 nm, and fluctuations of output power was less than 0.27 dB [10]. Wang reported a Fabry-Perot (F-P) filter-based wavelength-tunable TDFL, and lasers could be tuned from 1952.9 to 1934.9 nm by adjusting F-P fixed on a piezoelectric ceramic transducer [11]. Tunable dual-wavelength TDFL based on two tunable bandpass filters was realized by Ahmad, for the proposed fiber laser, 183.6 nm tuning range was obtained [12]. Tunable dual-wavelength thulium-doped fluoride fiber laser based on two tunable-bandpass filters and 11 km single-mode fiber was realized by Ahmad, and 1472.9 to 1506.5 nm wide tuning range could be obtained [13]. A single-and dual-wavelength tunable TDFL using an in-fiber acousto-optic tunable bandpass filter was demonstrated by Escobar, for the proposed fiber laser, 211.5 nm single-wavelength laser tuning output and 1802.67 to 1932.75 nm dual-wavelength laser generation could be realized [14]. Posada-Ramírez designed a wavelength tunable TDFL based on Hi-Bi fiber optical loop mirrors, 44.25 nm and 47 nm tuning range of single- and dual-wavelength lasers was realized respectively [15]. The polarization-maintaining photonic crystal fiber used in TDFL for wavelength switchable lasers output was reported by Li, and single-wavelength operation range was 43.64 nm [16].

It can be seen from the above reports that in order to achieve wavelength switchable thulium-doped fiber laser output, the Sagnac ring, Fabry-Perot cavity, high birefringence fiber, special grating and non-all-fiber components have been reported. Although the above methods can play a role in achieving wavelength-switchable thulium-doped laser output, the structures usually designed are complex and often require special non-fiber devices, reducing the integrity of the system. In addition, the wavelength tuning range and stability also needs to be considered comprehensively. To solve the above problems, this paper proposes and designs a TDFL based on the Mach-Zehnder interferometer (MZI) filter structure composed of coreless fiber, which realizes the switchable output of single wavelength, double wavelength and three wavelength lasers. Compared to previous research reports, the structure of thulium-doped fiber laser based on MZI filtering that we designed is more compact and can achieve single-wavelength, dual-wavelength, and triple-wavelength laser switchable output.

2. Experimental setup

The proposed wavelength-switchable TDFL scheme is shown in Fig. 1, the laser system is a ring cavity structure, composed of laser diode (LD) pump source, thulium-doped fiber as gain medium, WDM, optical coupler (OC), polarization controller (PC) and MZI filter. Thulium-doped fiber laser is a four-level system, thus a central wavelength of 793 nm LD is used in the experiment. The OC splitting ratio is 3:7, the pigtail fiber of 30% export is connected with optical spectrum analyzer (OSA, AD6375). For the designed MZI, as shown in Fig. 1, is fabricated by cascading single mode and coreless fiber. The input light transmitted in the core (SMF1) is injected into the first coreless fiber (CLF1), the fiber core of SMF is 6 μm, and cladding size of CLF is 125 μm, thus, the input light can be diffused at the splicing joints between SMF1 and CLF1. Then, the light is coupled into SMF2, and separated two paths, transmitting in core and cladding of SMF2. The transmitted light is then expanded by CLF2 and finally converged into SMF3. In the transmission process, MZ interference results will occur due to different optical ranges, an MZI structure is fabricated, and the free spectrum range (FSR) of MZI is expressed by Eq. (1):

$$\Delta\lambda = \frac{\lambda^2}{\Delta nL} \tag{1}$$

where, Δn is the refractive index difference, and L is the length of the two paths. In the experiment, the SMF2 length is 3cm, and CLF1 and CLF2 length is 1.5 cm. The designed MZI filter can generate comb spectrum, which is inserted into the laser cavity to adjust the TDFL gain and loss to achieve wavelength switchable lasers output.

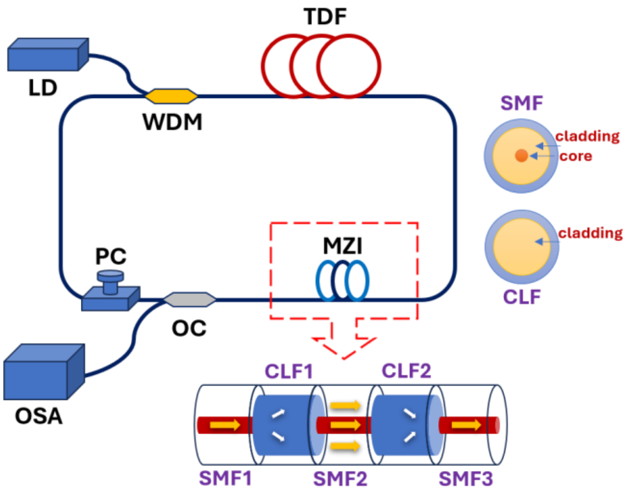

Fig. 1. Schematic of the TDFL based on MZI filter (color online)

Firstly, the designed MZI comb filter was fabricated in the experiment. The SMF and CLF were fused together by an optical fiber splicing machine, its relative intensity of the interferometer spectrum is shown in Fig. 2(a), modes interferometer result was realized, and FSR is 6.9 nm. Then, the TDFL with MZI filter was constructed, the gain medium length was 3.5 m (9/125 μm, Nufern), its core/cladding diameters are 9 and 125 μm, cutoff wavelength is 1750±100 nm, and mode field is 10.5 μm.

For the proposed fiber laser, multi-wavelength switchable fiber laser output can be achieved by adjusting the polarization controller. The mechanism is to control the polarization state of fiber laser cavity, thus the loss and gain characteristics of laser at different wavelengths can be adjusted. The output laser wavelength is determined by the resonance conditions of the resonant cavity, for different polarization states, these conditions are different. Adjusting the polarization controller can change the path and phase of the light within the cavity, the resonance conditions of different wavelengths are changed, and multi-wavelength switching can be realized.

3. Experimental results

The proposed TDFL with MZI filter was constructed in the experiment, the laser working threshold was 133 mW. With the pump power gradually increased to 200 mW, 1896.1 nm single-wavelength laser spectrum was collected, as shown in Fig. 1(b), the signal to noise ratio (SNR) is 35 dB, and 3dB linewidth is 0.8 nm. In the figure, it can be observed that there is no excess longitudinal mode near the laser, and the laser position is near the peak position of the filtered spectrum, so the effectiveness of the designed MZI filtering structure is proved. In the experiment, the resolution of the spectrometer was 0.02 nm.

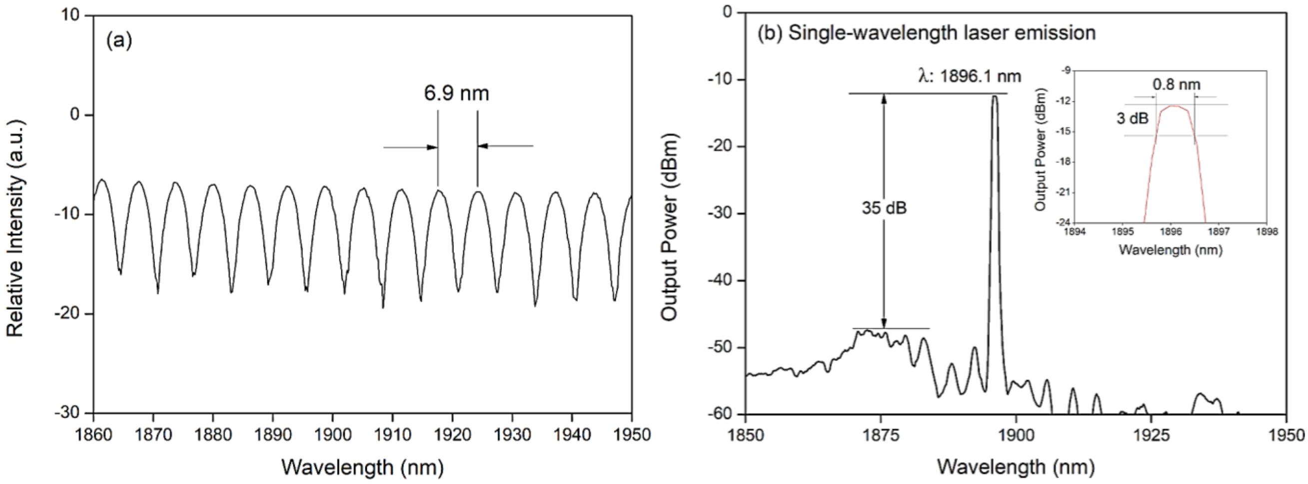

Fig. 2. MZI filtering effect. (a) Transmission spectrum of MZI; (b) Single-wavelength laser generation

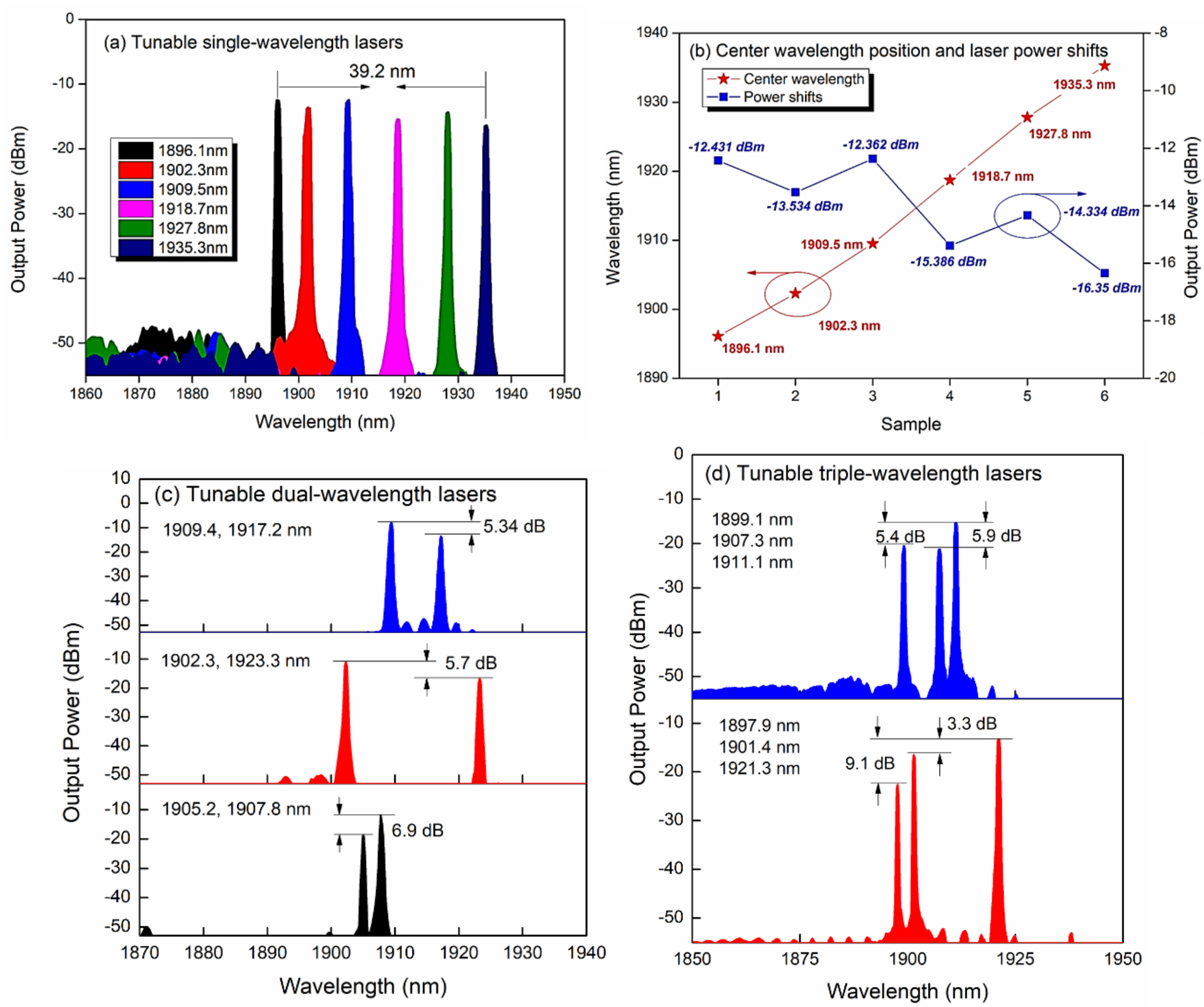

Fig. 3. Proposed TDFL wavelength tunability. (a) Single-wavelength laser spectrum; (b) Single-wavelength laser wavelength and power drift; (c) Dual-wavelength laser spectrum; (d) Triple-wavelength spectrum (color online)

The single-wavelength laser tunability was tested and analyzed in the experiment, when the pump power was 200 mW, single-wavelength laser could be realized from 1896.1 to 1935.3 nm scope through adjusting PC. The laser spectrum is shown in Fig. 3(a), the wavelength tuning scope is 39.2 nm with 9.2 nm maximum tuning wavelength interval, and SNR are larger than 32 dB. In the process of single-wavelength laser tuning, multi-wavelength laser was not appeared. The maximum power drift of the output single-wavelength laser is shown in Fig. 3(b), that is less than 3.988 dB. The gain loss in the laser cavity is changed by adjusting the polarization controller, and the wavelength switchable laser output is realized. In the experiment, multi-wavelength lasers generation was realized through adjusting PC. As shown in Fig. 3(c), dual-wavelength laser output with three different wavelength combinations is presented respectively from 1902.3 to 1923.3 nm, the minimum and maximum wavelength interval are 2.6 and 21 nm, and power difference is less than 6.9 dB, the SNR is more than 31 dB, the 3dB linewidth is less than 0.81 nm. As shown in Fig. 3(d), triple-wavelength switchable laser output spectrum could be realized from 1897.9 to 1921.3 nm, the minimum wavelength interval is 3.5 nm, power drift is less than 9.1 dB, and the SNR is more than 30 dB, and its 3dB linewidth is less than 0.81 nm. The multi-wavelength laser tuning output proves that the designed filter plays a key role in tuning TDFL laser wavelength.

After analyzing the laser wavelength tunability of the TDFL, the wavelength and power stability of the laser were tested in the experiment. The proposed laser could work stably in single-wavelength and dual-wavelength laser output state. For 1918 nm single-wavelength laser stability, during the 20-minute monitoring period, the collection was performed every 5 minutes. Single-wavelength laser spectrum is shown in Fig. 4(a), there is no significant wavelength drift and other clutter lasers generation, the center wavelength and power fluctuation are less than 0.4 nm and 0.665 dB respectively, shown in Fig. 4(b). Under the same test conditions, the wavelength stability of 1909 and 1917 nm dual-wavelength laser output is shown in Fig. 4(c), similarly, no serious wavelength shift occurs during the observed time; the laser two wavelengths drift are less than 0.3 nm, and power shifts are less than 2.556 and 0.329 dB. Through the above experiment and analysis, it can be seen that the designed TDFL based on MZI could operate stably in the state of single- and dual-wavelength laser emission. As the increase of laser wavelengths number, power fluctuations are serious gradually, because of multiple laser resonant modes competing, results an unstable light intensity distribution. With the increase of laser modes, the competition between different modes is more intense, thereby affecting the stability of the laser output.

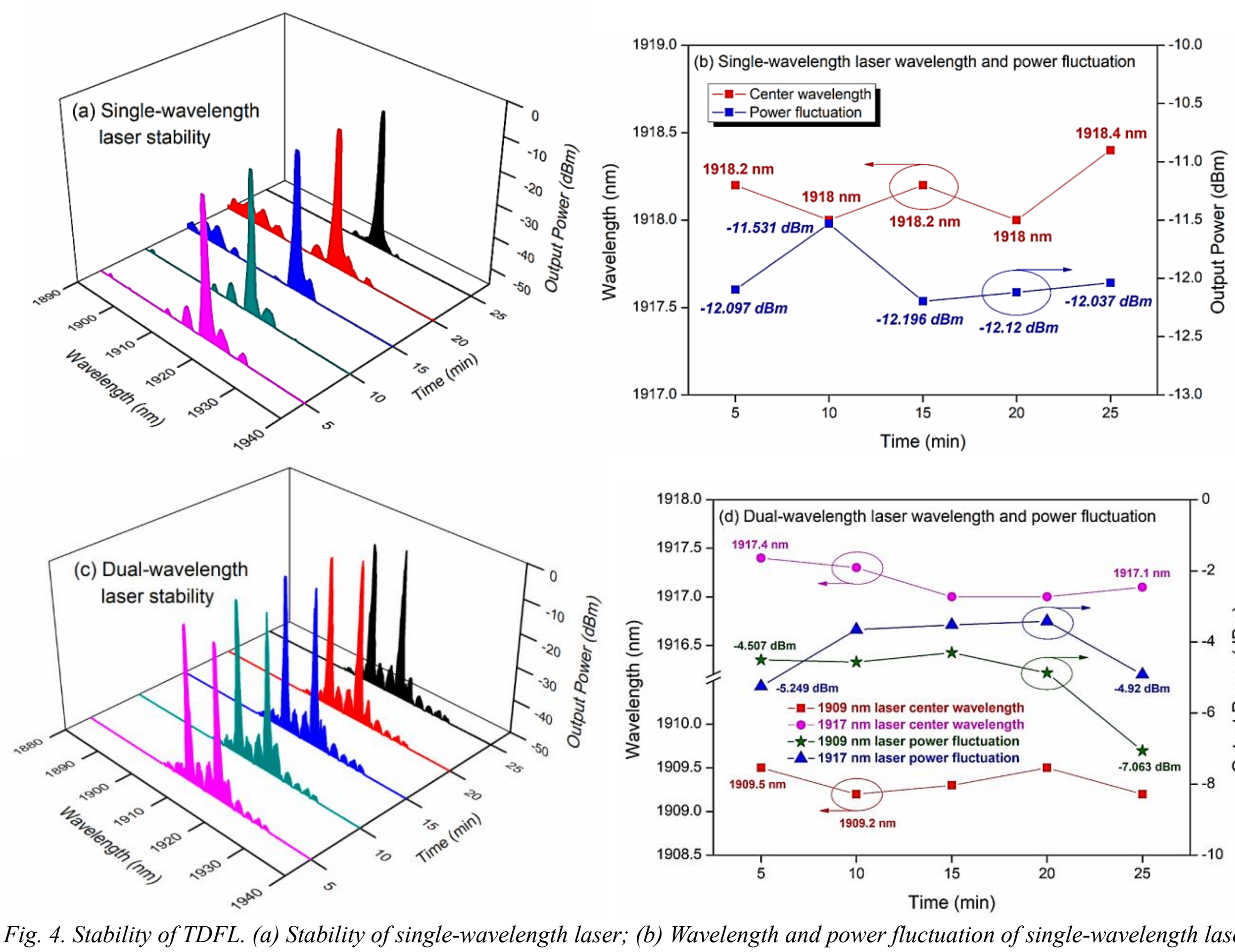

Fig. 4. Stability of TDFL. (a) Stability of single-wavelength laser; (b) Wavelength and power fluctuation of single-wavelength laser; (c) Stability of dual-wavelength laser; (d) Wavelength and power fluctuation of dual-wavelength laser (color online)

4. Conclusions

In the research, an all-fiber MZI filter based on SMF and CLF was designed, and wavelength switchable TDFL based on proposed MZI was realized. The single-, dual- and triple-wavelength switchable laser generation could be obtained. The 39.2 nm single-wavelength laser tuning scope was demonstrated, and its wavelength and power drifts were less than 0.4 and 0.665 dB. For dual-wavelength laser generation, the maximum wavelength tuning range was 21 nm, and the wavelength and power fluctuation were less than 0.3 nm and 2.556 dB. The designed TDFL has good wavelength tuning ability, and has great application value in fiber laser sensing and spectral analysis

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