IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 9, Number 3, June 2017

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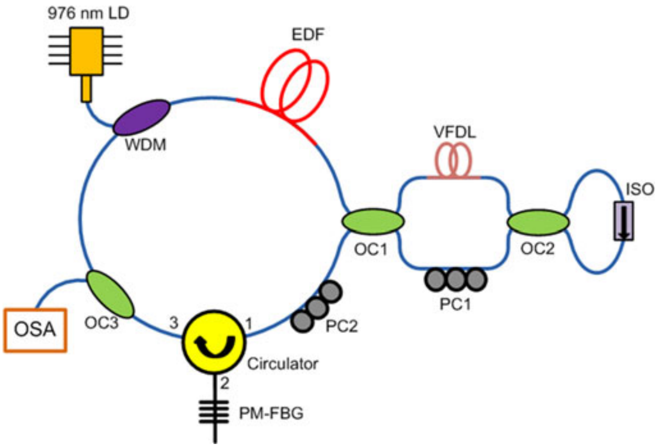

DOI: 10.1109/JPHOT.2017.2695671
1943-0655

Tunable Multiwavelength Erbium-Doped Fiber Laser Employing PM-FBG and Mach–Zehnder Interferometer with Optical Fiber Delay Line

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DOI:10.1109/JPHOT.2017.2695671

Manuscript received February 20, 2017; revised April 12, 2017; accepted April 16, 2017. Date of publication April 25, 2017; date of current version May 2, 2017. This work was supported in part by the Program for Changjiang scholars and innovative research team in university, in part by the PCSIRT under Grant IRT1212, in part by the Project Plan of Beijing Municipal Commission of Education for enhancing the innovation capability in 2015 under Grant TJSHG201510772016, and in part by the Beijing Municipal Education Commission Science and Technology Program under Grant KM201711232006. Corresponding author : Lianqing Zhu (e-mail: zhulianqing@sina.com).

Abstract: We propose the use of an erbium-doped fiber laser based on a polarization-maintaining fiber Bragg grating (PM-FBG) and all-fiber Mach–Zehnder interferometer (MZI) to realize a quadruple-wavelength 1.5-μm laser output. In the proposed system configuration, a 1535-nm center wavelength PM-FBG acts as the wavelength selector. The dual-pass MZI is fabricated using two couplers with a 50:50 splitting ratio, and the wavelength spacing of the comb is varied by using a spectrum power-driven optical fiber delay line inserted in MZI. The working threshold in the experiment is 82 mW. Tunable lasers of single-, dual-, triple-, and quadruple-wavelengths can be realized by adjusting the polarization controller. The generated wavelengths are in the range of 1534 to 1534.6 nm, the wavelength space is 0.2 nm, and the 3 dB linewidth is less than 0.05 nm. The power fluctuation is observed to be less than 0.912 dB, and the signal-to-noise ratio (SNR) is larger than 34.9 dB at 26 °C over a scan time of 10 min.

Index Terms: Mach–Zehnder, multi-wavelength erbium-doped fiber laser, optical fiber delay line, PM-FBG.

1. Introduction

Owing to advantages such as a high signal-to-noise ratio (SNR), flexible tuning ability, and long working life, wavelength switchable fiber lasers are widely used in applications such as fiber sensing, fiber communications, dense wavelength division multiplexing (DWDM), chemical analysis, and microwave generation [1]–[6]. In recent years, several design schemes have been proposed to realize multi-wavelength emission. A multi-wavelength tunable thulium-doped fiber laser based on nonlinear polarization rotation was proposed by Liu *et al.* [7]; stable multi-wavelength laser output was realized at room temperature using this method. A switchable and tunable erbium-doped fiber laser (EDFL) using a hollow-core Bragg fiber was reported by Zhao *et al.* [8]. In this work, the authors were able to tune single-wavelength lasing outputs in the range of 1562.4 nm to 1565.8 nm, with a minimum tunable wavelength range of 0.5 nm. A switchable quadruple-wavelength

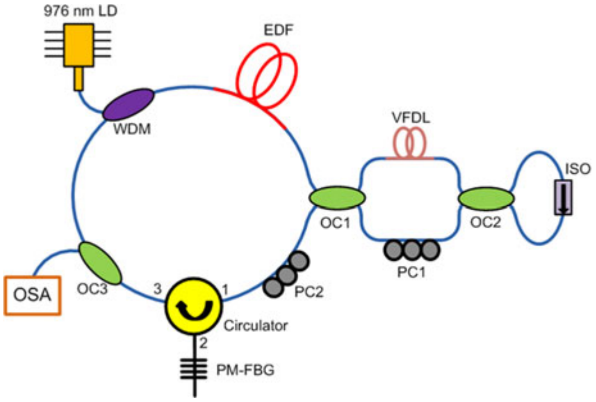

Fig. 1. Schematic of the multi-wavelength fiber laser.

EDFL based on a chirped fiber grating and polarization-maintaining fiber with a minimum peak-power shift of 4.5 dB was realized by Jianqun *et al.* [9]. Yeh *et al.* [10] reported a stable and tunable erbium-doped fiber laser using a fiber Bragg grating (FBG) with a lasing tuning range of 1531.7 nm to 1547.88 nm. A switchable EDFL based on modal interference was realized by Lin et al. [11]. The output laser could be switched among single-, dual-, and triple-wavelengths, and a side mode suppression ratio larger than 45 dB was obtained. A tunable and switchable dual-wavelength EDFL based on a polarization-maintaining chirped moiré fiber Bragg grating (PM-CMFBG) filter was reported by Yin *et al.* [12]. A 0.25 nm tuning range was achieved with a step of approximately 0.075 nm by stretching the uniform PM-CMFBG. A tunable EDFL based on a dual-pass Mach-Zehnder interferometer (MZI) filter using a section of a twin-core fiber (TCF) loop mirror was reported by Zou *et al.* [13].

From the abovementioned discussion, we can conclude that a multi-wavelength fiber laser is typically realized using components such as a photonic crystal fiber, Sagnac loop mirror, multi-mode fiber, and highly nonlinear fiber (HNLF). In order to achieve multi-wavelength lasing with a narrow interval space, some external non-fiber components and complex design structures are often used. Thus, it is necessary to study methods for producing lasers with high SNR, less space consumption, low wavelength shift, and low power fluctuation. In this work, we construct and study an erbium-doped ring fiber laser based on a dual-pass MZI comb filter with variable fiber delay line (VFDL) and realize a tunable and stable multi-wavelength laser at room temperature (26 °C).

2. Experimental Setup

The schematic of the proposed fiber laser is shown in Fig. 1. The experimental system is composed of a 976-nm pump laser, 980/1550-nm wavelength-division multiplexer (WDM), 10:90 coupler (OC3), two 2×2 3-dB OCs, two polarization controllers (PCs), an isolator (ISO), circulator, PM-FBG, and VFDL. All the components use 10/125-μm pigtail fibers. The pump light is coupled into the laser cavity by the WDM, and a 4-m-long erbium doped fiber (EDF) is used as the gain medium. The tunable dual-pass MZI filter is composed of two 3-dB couplers and VFDL. The PCs are used to adjust the polarization condition, the PC1 is used to control the flatness of the MZI comb spectrum, and the PC2 is used to tune the laser wavelength. The ISO inserted into the filter actually introduces additional loss in the MZI filter compared with a double-pass MZI without ISO. For the double pass MZI with ISO, due to ISO insertion, the suppositions of the beams at output includes unbalanced 1 pass and 2 pass with double phase shifts, which give rise to the switchable functionality of FSR. For proposed dual-pass MZI without VFDL, when an ISO was used in MZI, higher-contrast interference strips was experimentally demonstrated. The transmission spectrum of dual-pass MZI without ISO was collected in the experiment, and the resolution of optical spectrum analyzers (OSA) is 0.05 nm. As shown in Fig. 2, the intensity and wavelength interval of MZI without ISO are 7 dB and 1 nm,

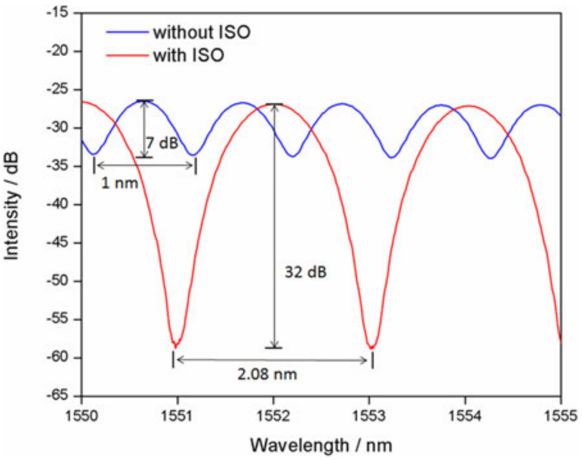

Fig. 2. Transmission spectrum of dual-pass MZI of with and without ISO.

respectively. For dual-pass MZI with ISO, the intensity and wavelength space are 32 dB and 2.08 nm, respectively.

In the designed EDFL, a 1535 nm PM-FBG with 99% reflectivity is adopted as the wavelength selector. An accurate and stable filtering effect is necessary to realize multi-wavelength laser emission around 1535 nm. The length of the interferometer beams cannot be controlled accurately through cleaving a fiber for two beams. Consequently, the wavelength interval of the MZI comb spectrum is uncontrollable and random. When the input light passes through a single-pass MZI, the wavelength spacing of the transmitted light can be expressed using (1) [14].

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

Here, λ is wavelength, n is the birefringence, and ΔL represents the difference between the length of the two beams. The fringe contrast of dual-pass MZI is twice as large as that of the single-pass MZI [14]. Taking into account the abovementioned factors, we use a wavelength interval tunable dual-pass MZI structure based on VFDL as the comb filter in the proposed multi-wavelength EDFL to achieve better filtering.

Light is introduced into the MZI through the input port of OC1. The transmitted light is ejected from two of the OC1 output ports, and it is coupled into OC2 after transmitting two beams. As shown in Fig. 1, the VFDL inserted into a beam is used to adjust the difference between the length of the two arms by changing the delay time. The other two ports of OC2 are spliced together to achieve an effect similar to that of the fiber loop mirror. Finally, the transmission light of a dual-pass MZI exits from an OC1 output port. This light is coupled into the ring cavity by circulator port 1, and passes through port 2 into the PM-FBG. Finally, the light is reflected by the PM-FBG, and is coupled into the ring cavity again by port 3. An optical spectrum analyzer (OSA, YOCOGAWA 6370C) is used to monitor the laser spectrum from the exit port of a 1 × 2 10:90 coupler. In the experiment, the laser diode is supported by Oclaro Co.; EDF is supported by Nufern Co., and the fiber type is EDFC-980-HP; OC, WDM, ISO, circulator, and PC are manufactured by Lightcomm Co. The PM-FBG is supported by Technica Co, the FBG is manufactured in PM1550 fiber and the beaten length is less than 2.0 mm. The power-driven VDFL is supported by COF Communications Co.

3. Experimental Results and Discussion

The proposed design was evaluated by constructing an experimental system, as shown in Fig. 1. The transmission spectrum of the PM-FBG was tested using a broadband source (BBS); the resulting spectrum is shown in Fig. 3.

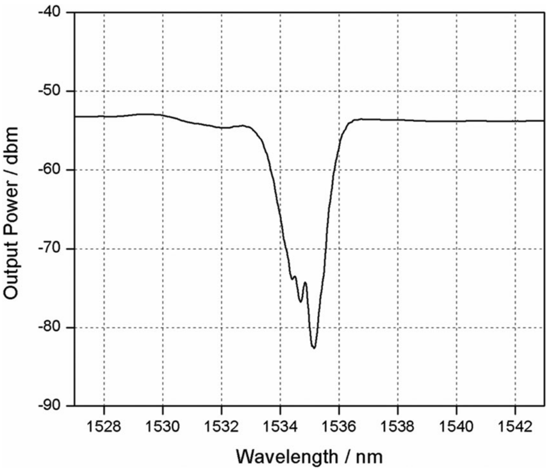

Fig. 3. Transmission spectrum of PM-FBG.

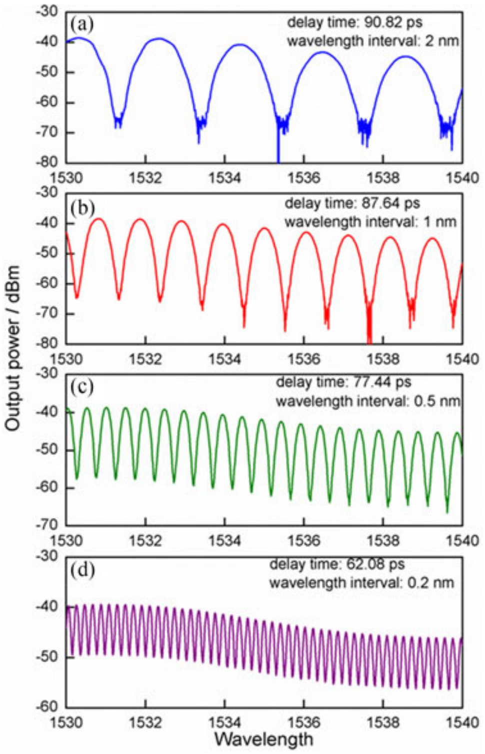

Fig. 4. Spectrum of the MZI filtering effect for different delay times.

The filtering effect of a dual-pass MZI was evaluated, and the variation in the filtering comb spectrum with delay time was captured by changing the VFDL. As shown in Fig. 4, the wavelength interval narrows and the fringe contrast decreases as the delay time decreases gradually. A delay time of 62.08 ps results in a wavelength interval comb spectrum of 0.2 nm between 1530 nm and 1540 nm, as shown in Fig. 4(d).

When the MZI comb filter was inserted into the ring cavity with a 37 mW pump power, single-wavelength lasing at 1534.4 nm was produced. As shown in Fig. 5(a), for a pump power of 100 mW, a 1534.4 nm single-wavelength laser with a SNR of 42 dB is emitted. The peak power and 3-dB linewidth is 0.382 dBm and 0.05 nm, respectively. By adjusting PC2, dual-wavelength

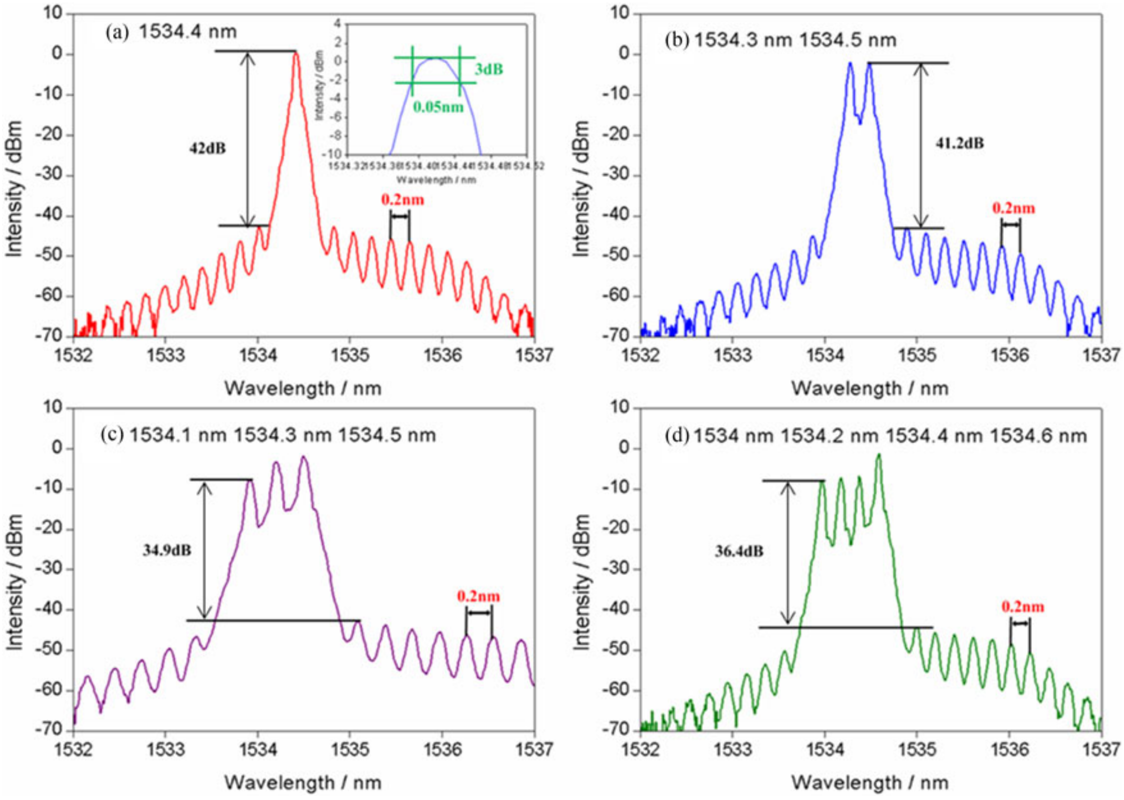

Fig. 5. Spectrum of switchable EDFL for a (a) single-wavelength emission, (b) dual-wavelength emission, (c) triple-wavelength emission, and (d) quadruple-wavelength emission.

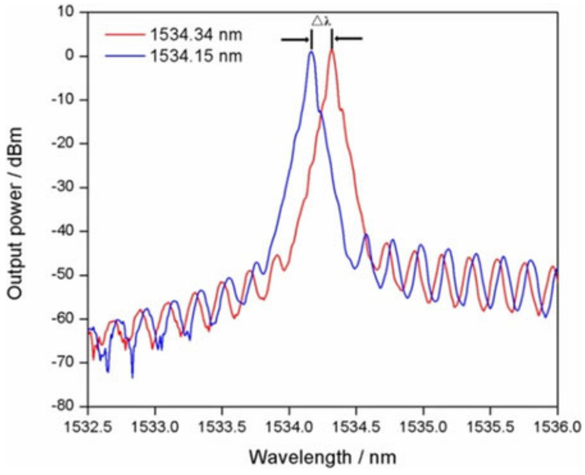

Fig. 6. Spectrum of the switchable single-wavelength fiber laser.

lasers at 1534.3 nm and 1534.5 nm can be realized simultaneously, as shown in Fig. 5(b); the wavelength interval between the two lasers is 0.2 nm. The peak power of the two lasers is −1.804 dBm and −1.835 dBm, and the SNR is larger than 41.2 dB. Similarly, triple-wavelength lasers can be achieved with a wavelength space of 0.2 nm, as shown in Fig. 5(c). The peak power is −7.779 dBm, −3.343 dBm, and −1.835 dBm for 1534.1 nm, 1534.3 nm, and 1534.5 nm, respectively, and the SNR is larger than 34.9 dB. Using the proposed design, a maximum of quadruple-wavelength lasers can be realized by adjusting PC2 for a filtering

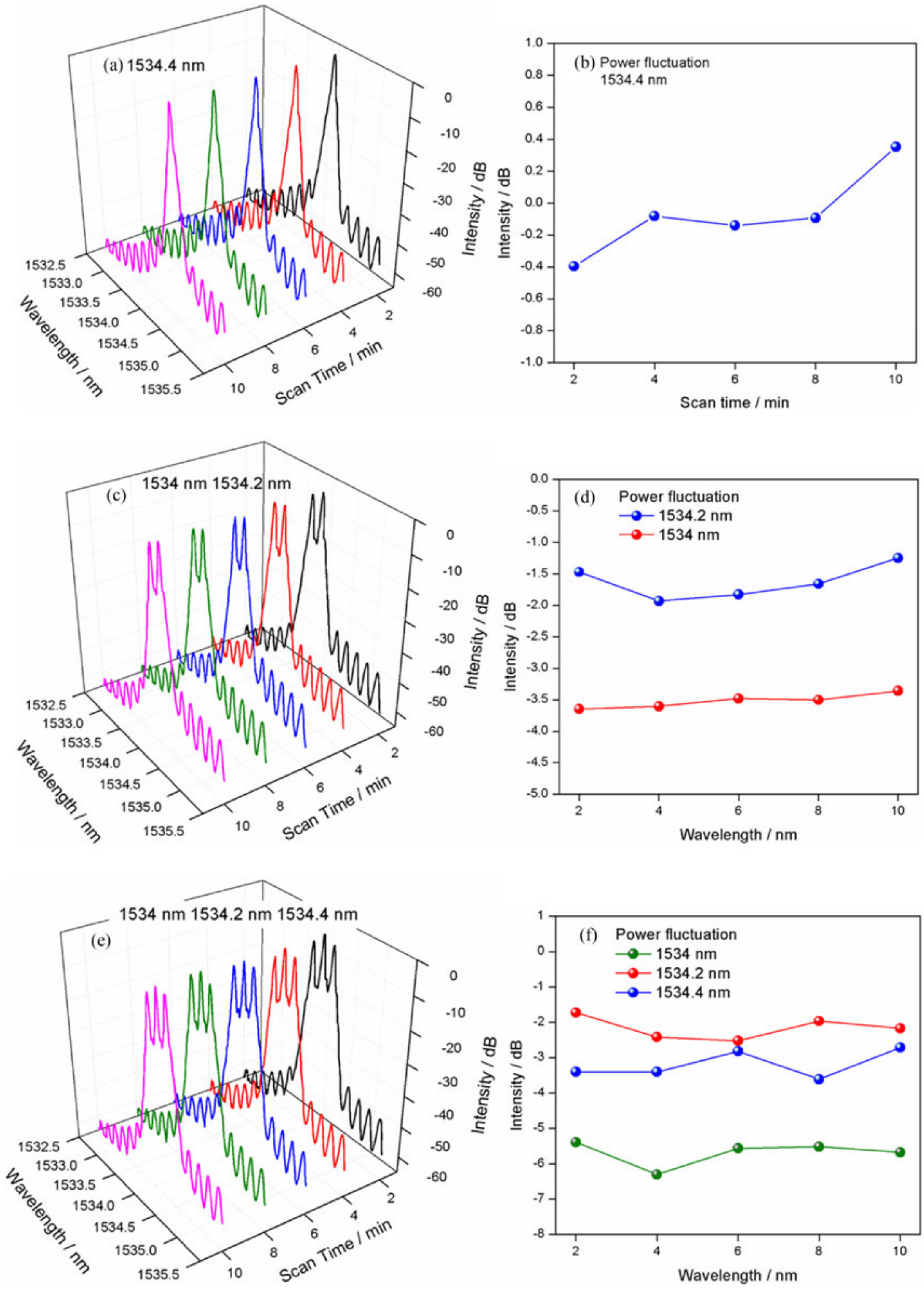

Fig. 7. Spectrum stability of single-, dual-, and triple-wavelength laser.

wavelength interval of 0.2 nm. This is shown in Fig. 5(d). The peak power of each laser is −7.912 dBm, −7.189 dBm, −6.842 dBm, and −1.222 dBm for 1534 nm, 1534.2 nm, 1534.4 nm, and 1534.6 nm, respectively, and the SNR is larger than 36.4 dB. When EDFL is used in the multi-wavelength emission mode, the 3-dB linewidth is less than 0.05 nm.

As shown in Fig. 6, switchable single-wavelength laser at 1534.34 nm and 1534.15 nm is realized by adjusting PC2. The wavelength interval is 0.19 nm, a value similar to the comb filtering spacing. The difference in the peak powers is 0.277 dBm, SNR is larger than 42 dB, and the 3-dB linewidth is less than 0.05 nm.

Moreover, the stability of the single-wavelength laser was monitored and studied. The spectrum stability for the emission of 1534.4 nm lasing over a scanning time of 10 min at 26°C room temperature is shown in Fig. 6(a). As shown in Fig. 6(b), the peak power fluctuation is less than 0.315 dB, and mode jumping and wavelength shifts do not appear during the scanning time. The lasers show a high stability when operated in a single-wavelength mode.

The power stability of the dual-wavelength lasing realized by adjusting PC2 was also studied, as shown in Fig. 7(c). The peak power fluctuation for 1534 nm and 1534.2 nm lasing is less than 0.683 dB and 0.288 dB, respectively, within 10 min scanning time, as shown in Fig. 7(d). The spectrum stability of triple-wavelength lasers realized by adjusting PC2 is shown in Fig. 7(e). When 1534 nm, 1534.2 nm, and 1534.4 nm lasing are produced simultaneously, the power fluctuation within 10 min testing time are 0.912 dB, 0.797 dB, and 0.897 dB, respectively, as shown in Fig. 7(f). Mode hopping or obvious wavelength shifts do not appear during the monitoring time when multi-wavelength lasers are produced. In this experiment, stable quadruple-wavelength lasers could not be obtained by adjusting two PCs. In our future work, we plan to use a pump source with higher output power and nonlinear fiber to achieve this.

In this evaluation, dual-pass MZI filtering effect corresponding to different delay times were studied, and the spectrum stability of switchable single-, dual-, and triple-wavelength EDFL was tested. From the results, we can conclude that stable and switchable multi-wavelength EDFL can be realized using the proposed system.

4. Conclusion

In this study, tunable multi-wavelength EDFL employing a dual-pass MZI comb filter and PM-FBG was demonstrated experimentally. A tunable wavelength interval comb filter based on a VFDL was proposed and realized. Switchable and stable single-, dual-, triple- and quadruple-wavelength lasers were experimentally achieved, with a 3-dB linewidth less than 0.05 nm, an SNR of more than 34.9 dB, and a peak power fluctuation less than 0.912 dB. The proposed EDFL showed excellent spectrum stability. The wavelength interval of the lasers was 0.2 nm, the same as the filtering wavelength space of the designed MZI. Thus, the approach proposed in this study can be used to realize stable and tunable multi-wavelength operation and can find potential applications. In the future, we plan to analyze different gain mediums and fine-tuning techniques to improve the tuning ability of the proposed system, and saturable absorber (SA) or external optical injection methods are planned to be used to improve spectrum stability.

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