

Single- and dual-wavelength tunable fiber laser based on a polarization-maintaining photonic crystal fiber Mach-Zehnder filter

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A single- and dual-wavelength-tunable ring cavity erbium-doped fiber laser based on an all-fiber Mach–Zehnder comb filter incorporating a multi-mode and polarization-maintaining photonic crystal fiber (PM-PCF) was proposed and experimentally demonstrated. For the proposed fiber laser, the M-Z interferometer comprised a cascaded multi-mode and 0.5 m length PM-PCF fiber, and the interferometer free spectral range was 3.1 nm. In the experiment, the gain medium L-band erbium-doped fiber length was 6 m, the laser threshold was 50 mW, and a 1568.91 nm single-wavelength laser output was generated. When the pump power was 200 mW, the 3 dB linewidth was 0.04 nm. The single wavelength-tunable laser output was realized from 1568.91 nm to 1583.68 nm through adjusting the polarization controller (PC). The wavelength spacing was more than 2.7 nm, the peak power difference was lower than 0.896 dB, and the signal to noise ratio (SNR) was more than 40.05 dB. For the proposed fiber laser, dual-, triple-, and quadruple-wavelength tunable lasers were generated by adjusting the PC, and the SNR was higher than 34.36 dB. The single- and dual-wavelength laser power fluctuations were less than 0.16 dB and 0.174 dB, respectively, with 20 min monitoring time.

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1. Introduction

Wavelength tunable erbium-doped fiber lasers can be widely used in fields of optical communications, fiber sensing, wavelength division multiplexing, spectrum analysis and laser detection [1-4] owing to its numerous advantages such as flexible wavelength tuning ability, compact structure, excellent stability, and long working life. [5-7] Thus, the wavelength tunable fiber laser realization techniques have been reported widely in recent years. Ahmad et al. reported a dual-wavelength tunable linear cavity L-band erbium-doped fiber laser (EDFL) based on a semiconductor optical amplifier, and the widest spacing was 18.7 nm. [8] Li et al. reported a tunable dual-wavelength EDFL based on a single multimode interference filter, and the dual-wavelength laser tuning range was more than 9 nm. [9] Bender-Perez reported an EDFL based on a spherical micro-ball lens Fabry-Perot filter, and the single-wavelength tuning scope was 1556.85–1569.72 nm. [10] Zhang et al. reported a C+L band wavelength-tunable EDFL incorporating a carbon nanotube filter, and the tuning range spanning was more than 70 nm. [11] Lv et al. reported a multi-wavelength ring cavity EDFL based on a triple-core photonic crystal fiber (PCF), and tunable single-, dual-, and triple-wavelength lasers can be obtained. [12] Gao et al. reported a tunable dual-wavelength ring cavity EDFL based on a fiber Bragg grating (FBG) and an external-injected distributed

feedback laser, and its dual-wavelength laser tuning range was 5.34 nm. [13] Wang et al. used a tunable single-wavelength fiber laser based on a chirped FBG for their proposed fiber laser, the wavelength tuning range was 30 nm. [14] Zhang et al. reported a wavelength-tunable thulium-doped fiber laser based on two sampled FBGs, and a 14.44 nm tuning range was realized for the designed fiber laser. [15] Peng et al. reported a continuously spacing-tunable dual-wavelength EDFL incorporating an in-line multimode-single-multimode fiber filter, and the wavelength spacing was lower than 3 nm. [16] Guzman-Chavez et al. reported a switchable, tunable and highly stable multi-wavelength fiber laser using polymer and silicon layers based fiber filter, laser emissions could be obtained within 1526-1565 nm range, and minimum wavelength spacing was ~3.6 nm. [17] Liu et al. reported a tunable dual-wavelength ytterbium-doped fiber laser incorporating a Sagnac loop interferometer, and a 17.9 nm tuning range was realized in the experiment. [18] Guzman-Chavez et al. reported an enhanced thermally tunable filter based on three layers and long sleeve structure for fiber laser temperature sensing application, and laser tuning scope was 19 nm [19].

As mentioned above, the fiber comb filter is an important component for realizing multi-wavelength EDF laser output, lasers can be generated and tuned at wavelength peak positions of the comb spectrum, and it

influences the flexibility and lasers stability. The comb filtering spectrum is usually generated by the special fiber gratings, Sagnac, Fabry-Perot, Mach-Zehnder (MZ) interference structures, nonlinear loop and other fragile fiber micro interference structure. Among them, the all-fiber MZI filter is most extensively adopted as a comb filter and can be fabricated by cascading different types of fibers: multicore fibers, dual-tapered fibers, and microfibers.

However, the all-fiber micro MZI structure fabrication procedure is complex, and its structure is fragile. Moreover, the scope of EDF lasing tuning usually covers the C band (1520–1560 nm). Thus, it is valuable to realize a EDF laser based on a simple and efficient MZI to generate lasers in L bands (1560–1600 nm). In our study, a single- and dual-wavelength-tunable narrow-linewidth ring cavity EDFL incorporating a polarization-maintaining photonic crystal fiber (PM-PCF)-based the Mach-Zehnder comb filter was designed and experimentally demonstrated. The designed fiber laser could potentially be applied in the fields of optical sensors and spectral analyses.

2. Operation principle

A schematic of the designed ring cavity EDFL based on a Mach-Zehnder (MZ) comb filter is shown in Fig. 1(a). The proposed fiber laser is composed of one laser diode (LD) with a 980 nm center wavelength, one wavelength division multiplexer (WDM), an L-band erbium-doped fiber (EDF), two optical couplers (OCs), one polarization controller (PC), multi-mode fiber, PM-PCF, and an optical spectrum analyzer (OSA). The pump light is coupled into the 6 m length EDF by the WDM. For the proposed EDFL, the MZ comprised OC1 with a 50:50 splitting ratio, 0.5 m long PM-PCF, and a 2 cm long multi-mode fiber to generate the comb spectrum filtering effect. For OC2 with a 90:10 splitting ratio, 90% of the export is connected with WDM to constitute the ring cavity to improve the laser working efficiency, and the remainder 10% export is connected with the OSA to collect the laser spectrum. A schematic of the MZ comb filter is presented in Fig. 1(b), which is fabricated by connecting the single-mode fiber (SMF), multi-mode fiber (MMF), and PM-PCF. When the input light is coupled into the MMF through the SMF, a high order mode is generated. Owing to the PM-PCF birefringence characteristic, the input light is divided into orthometric two-path fast axis mode and slow axis mode with different refractive indices, and the phase difference, $\Delta\delta_1$, can be expressed by Eq. 1.

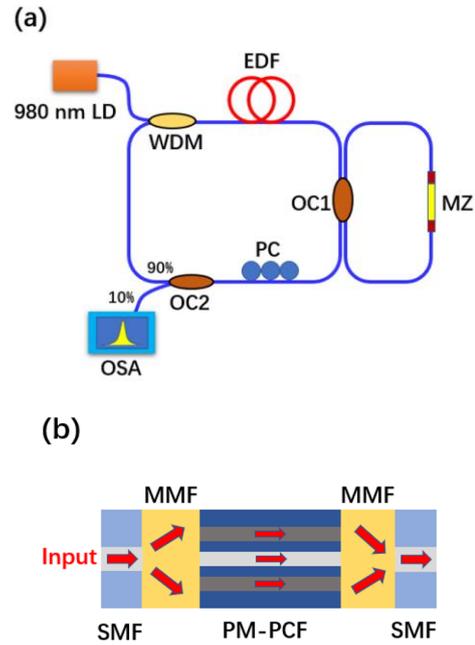


Fig. 1. Schematics of the erbium doped fiber laser. (a) Schematic of the proposed ring cavity EDFL and (b) the principle of MZ filter (color online)

$$\Delta\delta_1 = 2\pi B \frac{l}{\lambda} \quad (1)$$

where B is the refractive index difference between the fast and slow axes, l is the PM-PCF length, and λ is the input light wavelength. For the PM-PCF, the core part and micro-structured air hole part have different refractive indices; thus, the phase difference, $\Delta\delta_2$, of the core mode and high-order mode transmission in the PM-PCF can be expressed by Eq. 2, where Δn is the refractive index difference between the core and high order modes.

$$\Delta\delta_2 = 2\pi\Delta n \frac{l}{\lambda} \quad (2)$$

As shown in Fig. 1(b), the input light is transmitted through the SMF-MMF-PCF-MMF-SMF structure, and the two-phase differences $\Delta\delta_1$ and $\Delta\delta_2$ are generated, and the interference comb spectrum can be realized. After the MZ is used in the ring cavity, the comb filter effect can be realized, and wavelength-tunable lasers can be generated at the comb interferometer filtering effect. The PM-PCF has a stronger birefringent effect and lower thermal sensitivity; thus, the MZ based on PM-PCF has a better filtering effect to restrain laser mode jumping.

3. Experimental results and discussion

In the experiment, the pigtail fiber sizes of LD, WDM, PC, and OC were 9/125 μm ; the 6 m length L-band EDF

was supported by Nufern Co. (EDFL-980-HP), and the PM-PCF (NKT Co. PM-1550) core and outer cladding diameters were 6 μm and 125 μm , respectively. In the experiment, the 0.5 m length PM-PCF was connected to two 2 cm length MMFs. As shown in Fig. 2, the MZ interferometer spectrum is collected, and the comb filtering effect is obvious. The spectrum detail within the 1550–1590 nm range is shown in Fig. 2; the interferometer wavelength free spectral range is 3.1 nm and relative intensity is more than 6.1 dB. The comb interference spectrum was test by EDF amplified spontaneous radiation (ASE) light source, and that determines the light source flatness. At the long-wavelength direction, the EDF gain is decreased, thus, the MZI comb power curve is not at the same output power, and is drop gradually. The proposed MZ based on PM-PCF has an excellent interference effect, and it can be used as a comb fiber in EDFL.

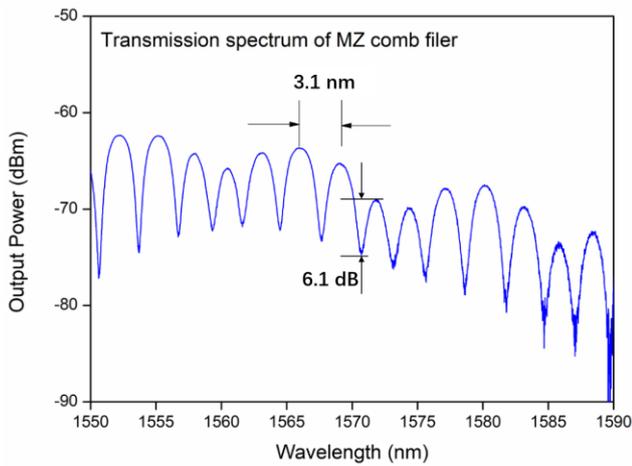


Fig. 2. MZ transmission comb spectrum

The designed comb filter was inserted in the ring cavity EDFL to generate a stable and tunable multi-wavelength laser output, as shown in Fig. 1(a). When the pump power was 50 mW, a 1568.91 nm single-wavelength laser was obtained in the experiment. As shown in Fig. 3(a), the pump power was increased to 200 mW, and as a result the signal-to-noise ratio (SNR) was more than 40.234 dB, and the laser with the 3 dB linewidth was 0.04 nm, as shown in Fig. 3(b). Thus, a single-wavelength narrow linewidth laser output was experimentally realized. In the experiment, a single-wavelength tunable laser output was generated by adjusting the PC to change the intracavity loss when the pump power was 200 mW. As shown in Fig. 3(c), 1568.91 nm, 1571.88 nm, 1575.17 nm, 1577.96 nm, 1580.66 nm, and 1583.68 nm single-wavelengths were obtained, and the SNR was more than 39.374 dB, as shown in Table 1; the wavelength spacing was more than 2.7 nm, and the peak power differences of every single-wavelength laser were less than 0.896 dB, as shown in Fig. 3(d). In the experiment, mode jumping was not observed during the single-wavelength tuning procedure; the 3 dB linewidth was less than 0.04 nm, and the SNR was higher than 40.05.

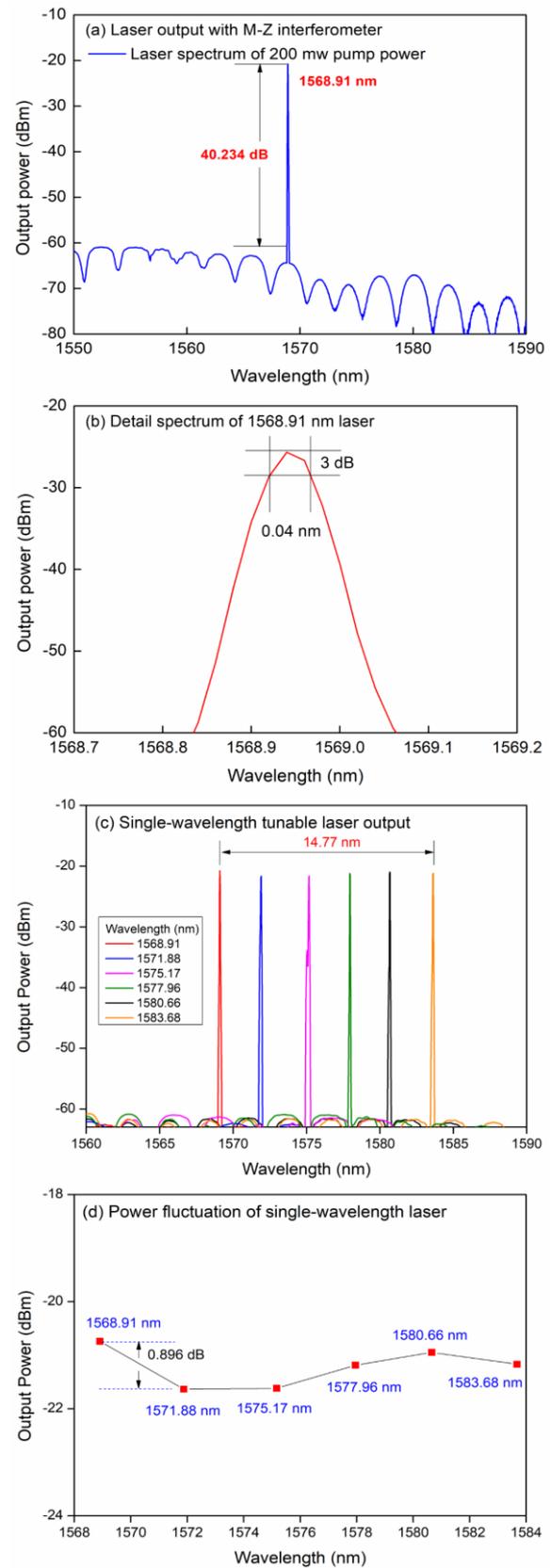


Fig. 3. Single-wavelength laser realization. (a) 1568.91 nm laser output, (b) 3 dB linewidth detail of the 1568.91 nm laser (c) single-wavelength laser tuning spectrum and (d) peak power fluctuation during tuning procedure (color online)

Table 1. Single-wavelength laser SNR

| Wavelength (nm) | 1568.91 | 1571.88 | 1575.17 | 1577.96 | 1580.66 | 1583.68 |
|-----------------|---------|---------|---------|---------|---------|---------|
| SNR (dB) | 40.234 | 40.461 | 39.374 | 39.567 | 40.638 | 40.58 |

In the experiment, dual-wavelength tunable lasers output was realized by adjusting the PC, as shown in Fig. 4(a). When the pump power was 200 mW, 1556.84 nm and 1560.07 nm dual-wavelength lasers were generated, and the peak power was -21.01 dBm and -20.89 dBm; the SNR was more than 40.01 dB. For the proposed EDFL, five dual-wavelength laser was realized, as shown in Table 2, and the max and min spacing are 3.31 and 2.17 nm respectively.

Table 2. Dual-wavelength laser output

| | |
|------------------------|------------------------|
| Dual-wavelength | 1556.84 nm, 1560.07 nm |
| | 1556.79 nm, 1560.11 nm |
| | 1562.84 nm, 1566.12 nm |
| | 1562.81 nm, 1566.12 nm |
| | 1571.24nm, 1573.41 nm |

As shown in Fig. 4(b), for dual-wavelength laser output, the SNR was higher than 36.71 dB, and the 3 dB linewidth was less than 0.04 nm. The dual-wavelength-tunable EDFL based on the proposed MZ filter showed excellent tuning ability.

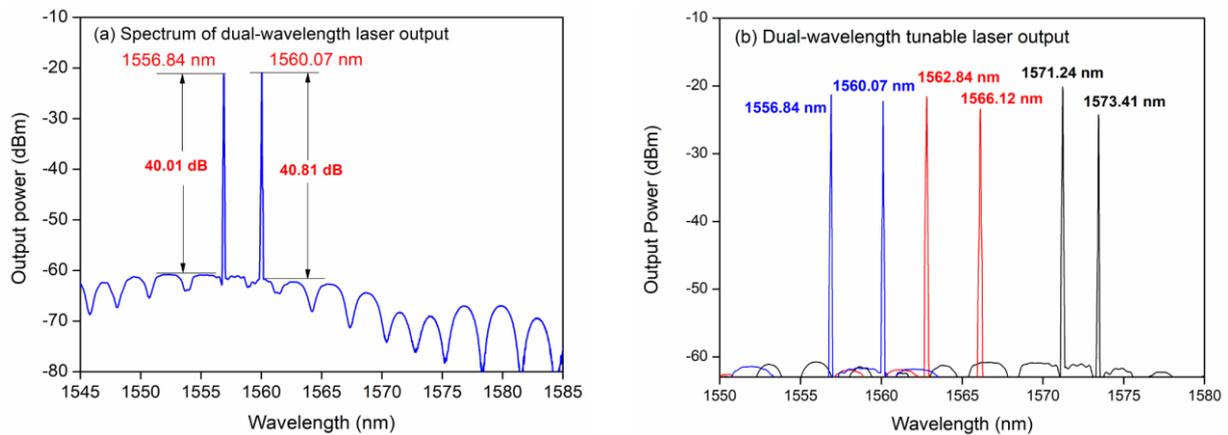


Fig. 4. Dual-wavelength lasers realization. (a) 1556.84 nm and 1560.07 nm dual-wavelength laser output, (b) dual-wavelength laser tuning spectrum (color online)

Then, the triple-wavelength laser output was realized by adjusting the PC. As shown in Fig. 5(a-c), three different groups of triple-wavelength lasers can be obtained simultaneously, the minimum and maximum spacing between them are 2.33 nm and 6.07 nm respectively. The SNR was higher than 37.5 dB, and the peak power difference was less than 2.134 dB. When the pump power was 200 mW, 1558.35, 1561.55, 1565.03 and 1569.11 nm quadruple wavelength lasers were generated simultaneously in the experiment, and the spectrum was shown in Fig. 5(d); the SNR was higher than 34.36 dB, and the peak power difference was less than 2.698 dB. For the triple- and quadruple-wavelength laser output, the 3 dB linewidth was less than 0.04 nm.

In the experiment, the peak power stability of the single- and dual-wavelength laser output was tested with 20 min monitoring. For the 1580.66 nm single-wavelength laser output, the spectrum stability is shown in Fig. 6(a), and the mode jumping is not shown. Furthermore, as shown in Fig. 6(b), 1556.84 nm and 1560.07 nm dual-wavelength laser spectrum stability is excellent. For single-wavelength laser power fluctuation, as shown in Fig. 6 (c), the power shift was less than 0.16 dB, and for the dual-wavelength laser power fluctuation, the power fluctuation was less than 0.14 dB, and 0.174 dB, respectively, as shown in Fig. 6 (d). The proposed EDFL based on the MZ comb filter exhibited excellent stability.

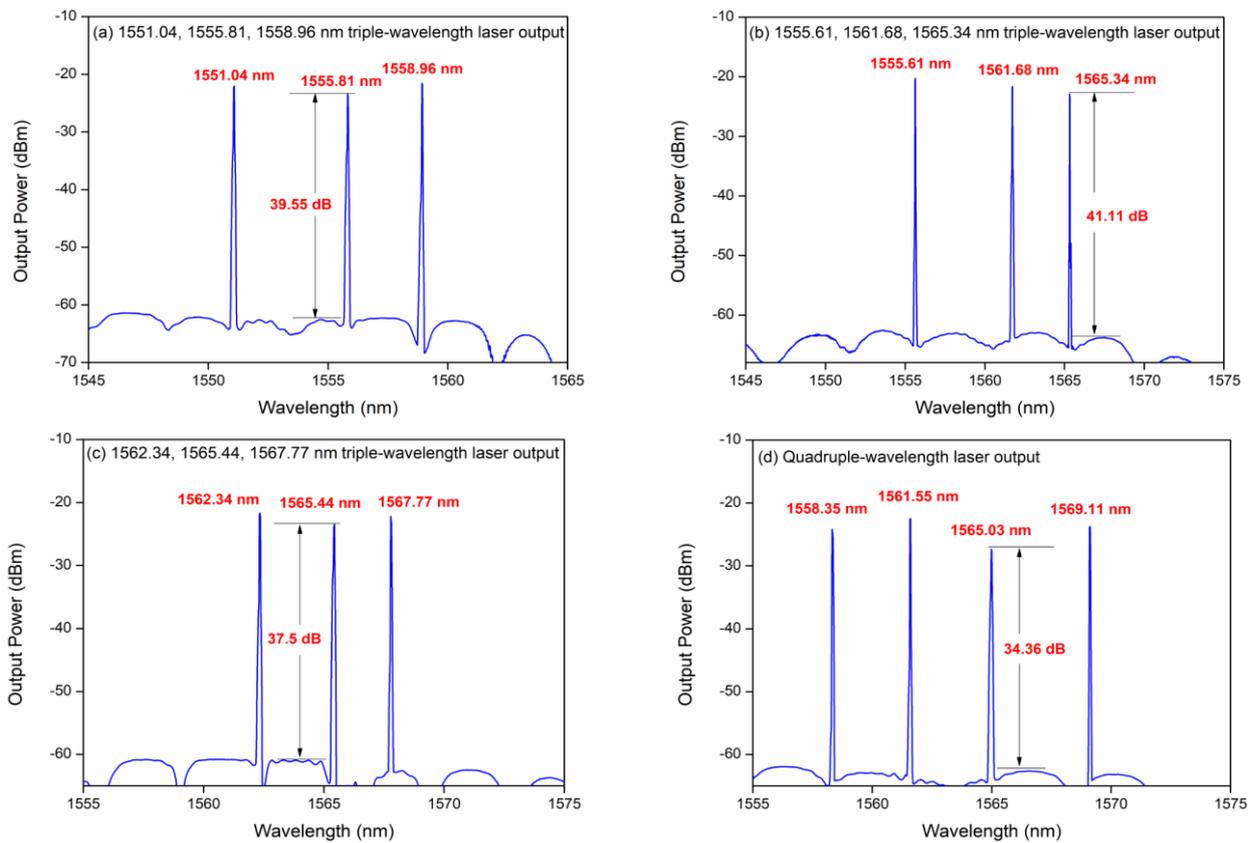


Fig. 5. Triple- and quadruple-wavelength lasers realization. (a) 1551.04 nm, 1555.81 nm, and 1558.96 nm triple-wavelength lasers, (b) 1555.61 nm, 1561.68 nm, and 1565.34 nm triple-wavelength lasers, (c) 1562.34 nm, 1565.44 nm, and 1567.77 nm triple-wavelength lasers, (d) quadruple-wavelength lasers realization (color online)

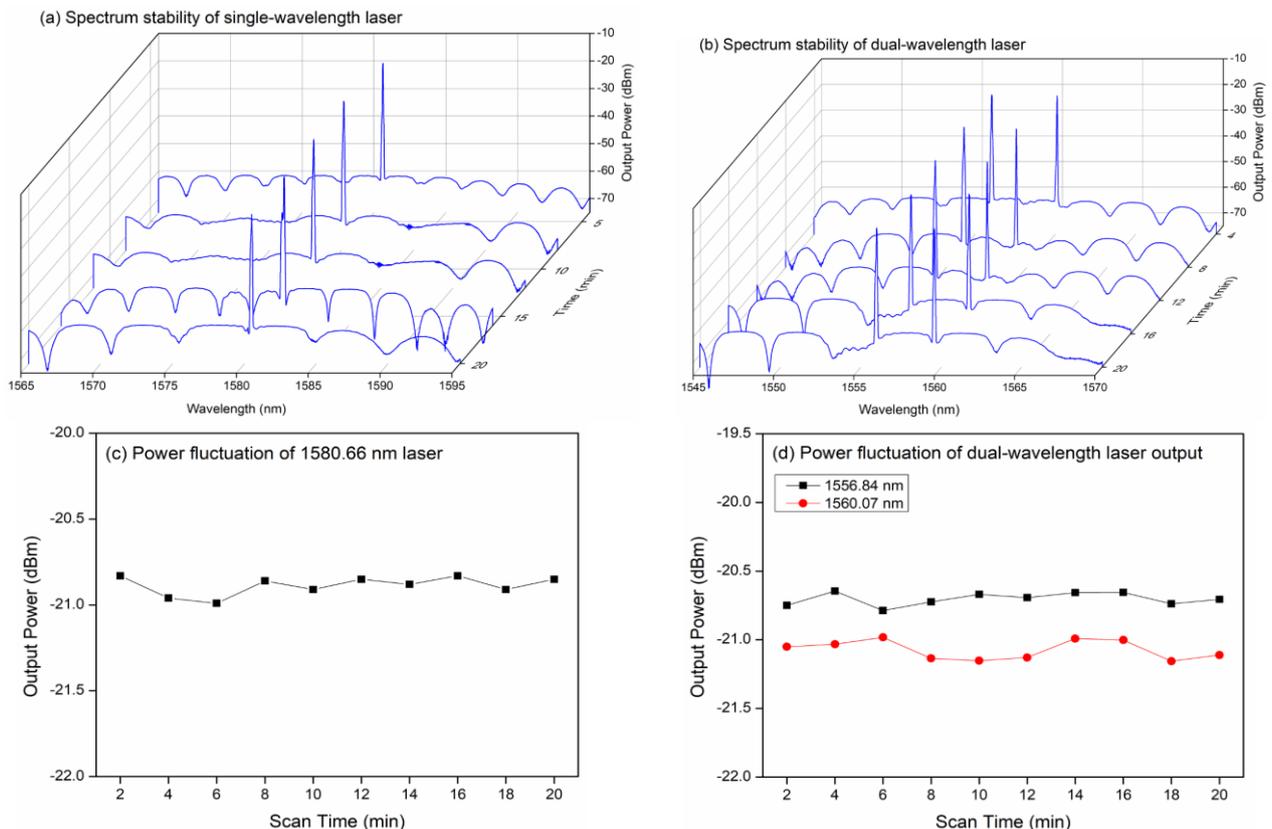


Fig. 6. Fiber laser stability characteristics. (a) Spectrum stability of the single-wavelength laser, (b) spectrum stability of the dual-wavelength laser, (c) single-wavelength laser power fluctuation, (d) dual-wavelength laser power fluctuation (color online)

In the above experimental demonstration, the proposed ring cavity EDFL could realize tunable single-, dual-, triple-, and quadruple-wavelength laser outputs, and exhibit

excellent stability. The EDFL characteristics is shown in Table 3.

Table 3. Single-wavelength laser characteristics

| | Tuning range | Tuning spacing | SNR | Power stability | Max laser number |
|--------------|-------------------------------------|----------------|----------|-----------------|------------------|
| In the paper | 1568.91 to 1583.68 nm (14.77 nm) | 2.7 nm | 34.36 dB | 0.174 dB | Four |
| Ref 3 | 1530 to 1535 nm | 0.8 nm | 14 dB | NA | Five |
| Ref 4 | 1536 to 1548 nm | NA | 28 dB | 1.06 dB | Six |
| Ref 7 | 1527.52 to 1534.40 nm | 0.6 nm | 34 dB | 1.5 dB | Six |
| Ref 8 | 18.7 nm | 0.8 nm | 42 dB | 0.1 dB | Two |
| Ref 9 | 1527.1 to 1585.4 nm | 8.8 nm | NA | 1.2 dB | Two |
| Ref 11 | 10.34 nm | 3.6 nm | 50 dB | 0.96 dB | Three |
| Ref 13 | 5.34 nm | 2.1 nm | 30 dB | NA | Two |
| Ref 17 | 1526 to 1565 nm | 3.6 nm | 36.48 dB | 3.14 dB | Four |
| Ref 18 | 17.9 nm | NA | 38 dB | 0.94 dB | Two |

4. Conclusions

In this study, a single- and dual-wavelength tunable narrow-linewidth EDFL incorporating an MZ comb filter based on PM-PCF was realized. The proposed comb filter interferometer free spectral range was 3.1 nm. The laser working threshold was 50 mW, and six different groups of single-wavelength laser outputs were generated within the 14.77 nm tuning range by adjusting the polarization condition, and the SNR was higher than 40.05 dB. In the experiment, three different groups of dual-wavelength laser outputs were realized, and the SNR was more than 36.71 dB. Finally, the triple- and quadruple-wavelength laser output was obtained by adjusting the PC with more than 34.36 dB SNR. For the laser output, the 3 dB linewidth was less than 0.04 nm. In addition, the single- and dual-wavelength laser output power stability was tested in the experiment with 20 min, and the power fluctuations were less than 0.16 dB and 0.174 dB, respectively. The proposed EDFL shows excellent tunable and stable capability; the proposed fiber laser shows better flexible tuning ability and stability. Furthermore it can be widely used in fiber communication, fiber sensing, and spectral analysis.

Acknowledgements

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