Wavelength switchable erbium-doped fiber laser incorporated with polarization maintaining photonics crystal fiber based Lyot filter

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In the paper, an erbium doped fiber laser (EDFL) based on Lyot comb filter for wavelength switchable laser generation was proposed and demonstrated. For the designed fiber laser, Lyot filter was fabricated by insert a 0.5 m length polarization maintaining photonic crystal fiber (PM-PCF) into ring cavity, and free spectral range was 3.3 nm. In the experiment, the 4 m length EDF was used as EDFL gain medium, and pump power was 38 mW. When pump power was 140 mW, for 1527.7 nm single wavelength laser, the signal-to-noise ratio (SNR) was 22 dB, and 3dB linewidth was 0.05 nm. Through adjusting polarization controller (PC), the single-wavelength switchable laser tuned from 1525.73 to 1534.07 nm was realized, the wavelength tuning spacing was more than 1.99 nm, and power shift was less than 2.92 dB. For the proposed EDFL, switchable dual-wavelength laser was realized, or triple- and quadruple-wavelength laser output could be obtained respectively by adjusting PC. The power stability for single and dual-wavelength lasers were less than 0.702 and 1.452 dB respectively during 25 min monitoring time.

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1. Introduction

Erbium-doped fiber laser (EDFL) is widely used in fiber communications, laser imaging, fiber sensing, biomedical, and material analysis [1-3], because of its numerous characteristics as narrow linewidth, high signal-to-noise ratio (SNR), compact laser system, long working span, and excellent heat dispersion [4-6]. Wavelength switchable EDFL, as one important kind of EDFLs, has been applied in wavelength division multiplexing, laser scanning, laser sensing, and optical detection, owing to its flexible tunable capability and high stability.

In recent years, some optical components were used to realize wavelength switchable laser generation. Zhao et al. designed a multi-wavelength switchable EDFL based on adjustable wavelength interval, for the proposed fiber laser, the tuning range was 13 nm, and dual-wavelength lasers could be obtained in the experiment [7]. Geng et al. reported an asymmetric biconical fiber taper based switchable EDFL, the single, dual, and triple-wavelength laser outputs was realized, and power fluctuation was less than 1.64 dB [8]. Chang et al. proposed a wavelength switchable EDFL using hybrid structure optical fiber filter, for the proposed fiber laser, the filter was manufactured by two ellipsoidal structures fabricated by connecting single-mode fiber and few-mode fiber. The lasers wavelength tuning spacing was 2 nm, and power shifts was less than 2.99 dB [9]. Liu et al. reported a multi-wavelength switchable EDFL incorporating with microbottle resonator, and quint-wavelength lasers could be obtained, for the designed fiber laser, the minimum tuning spacing was 0.3 nm, and power fluctuation was less than 6 dB [10]. Cheng et al. reported a wavelength switchable EDFL using chirped fiber grating and multimode fiber, for the proposed fiber laser, quadruple wavelength lasers was realized, the narrow linewidth was less than 0.28 nm, and SNR was more than 20 dB [11]. Zhou et al. reported an EDFL based on four-mode FBG for switchable multi-wavelength laser generation, and five laser wavelengths operation was realized respectively, the wavelength tuning range was 1547.5 to 1544.2 nm [12]. Guzman-Chavez et al. reported a switchable and stable multi-wavelength fiber laser based on spectral filter, single-, dual-, triple-, and quadruple-lasers was realized within the 1526 to 1565 nm span, and power fluctuation was less than 3.14 dB [13]. Tang et al. proposed an EDFL based on four-leaf clover suspended core fiber for dual-wavelength lasers switchable emissions, and power fluctuation was lower than 1.5 dB [14]. Guzman et al. reported a ring cavity EDFL based on thermal sensitive interferometric filter, sextuple-wavelength emissions could be generated, and its tuning scope was from 1527.52 to 1534.4 nm [15]. For the mentioned above EDFL, special optical fiber components, nonlinear effect and fiber interferometer were widely used to realize stable and switchable multi-wavelength laser emissions. However, the fabrication procedure of grating, fiber tapers, fiber micro-balls filter were complex and filter was fragile. Moreover, wavelength tuning scope is important of EDFL.

Thus, it is necessary to manufacture an all-fiber EDFL with excellent stability and flexibility.

In this study, an all-fiber Lyot comb filter based on polarization maintaining-photonic crystal fiber (PM-PCF) was manufactured, and filter was adopted in an EDFL ring-cavity. For the proposed fiber laser, wavelength-switchable single-, dual-, triple- and quadruple-wavelength laser emissions was realized.

2. Operation principle

For the proposed EDFL, its schematic is shown in Fig. 1. A laser diode (LD) with 976 nm center wavelength emission is used as pump source, connected with a wavelength division multiplexor (WDM). The 4 m length EDF is used as gain medium. Three optical couplers (OCs) are selected in the cavity, OC1, OC2 and OC3 are the same pigtail fiber parameters. For the OC1, export with 10% splitting ratio connect with an optical spectrum analyzer (OSA); for the OC2 and OC3, their splitting ratio are 50:50, and a total reflection mirror is fabricated by OC3 to improve EDFL working efficiency. The 0.5m length PM-PCF is inserted between OC2 and OC3 to be a Lyot comb filter. The two separated beams transfer at PMF slow and fast axes with the same amplitude and polarization state. When the signals recombine at the end of the PMF, the interference effect is realized, the unnecessary lasers modes can be filtered, and the wavelength spacing of interference Δλ is changeable according to the following equation:

$$\Delta\lambda = \frac{\lambda^2}{NL} \qquad (1)$$

where λ is the input light wavelength, N is the birefringence of the PMF valued, and L is the effective length of the PMF. A PC is used to control light suppression of intra-cavity. When PC is adjusted light transmittance in the cavity is suppressed, causing the lasers emissions tuning.

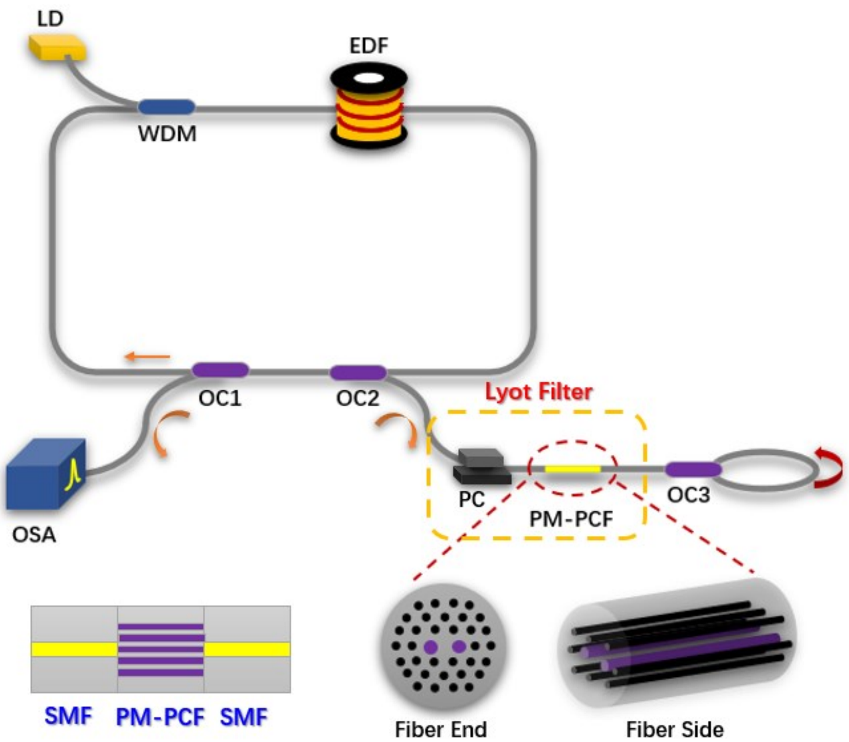

Fig. 1. Schematic of the proposed EDFL (color online)

3. Experimental results and discussion

In the experiment, 0.5 m length PM-PCF core and cladding diameters were 7.5 and 80 μm. The Lyot filter was manufactured through welding PM-PCF and single-mode fiber (SMF). For the proposed fiber laser, the laser working threshold was 38 mW, the 1527.7 nm laser was generated, and when pump power was improved to 140 mW, as shown in Fig. 2(a), the SNR is 22 dB and laser 3dB linewidth is 0.05 nm. As shown in Fig. 1(b), the interference comb spectrum is obvious, and FSR is 3.3 nm.

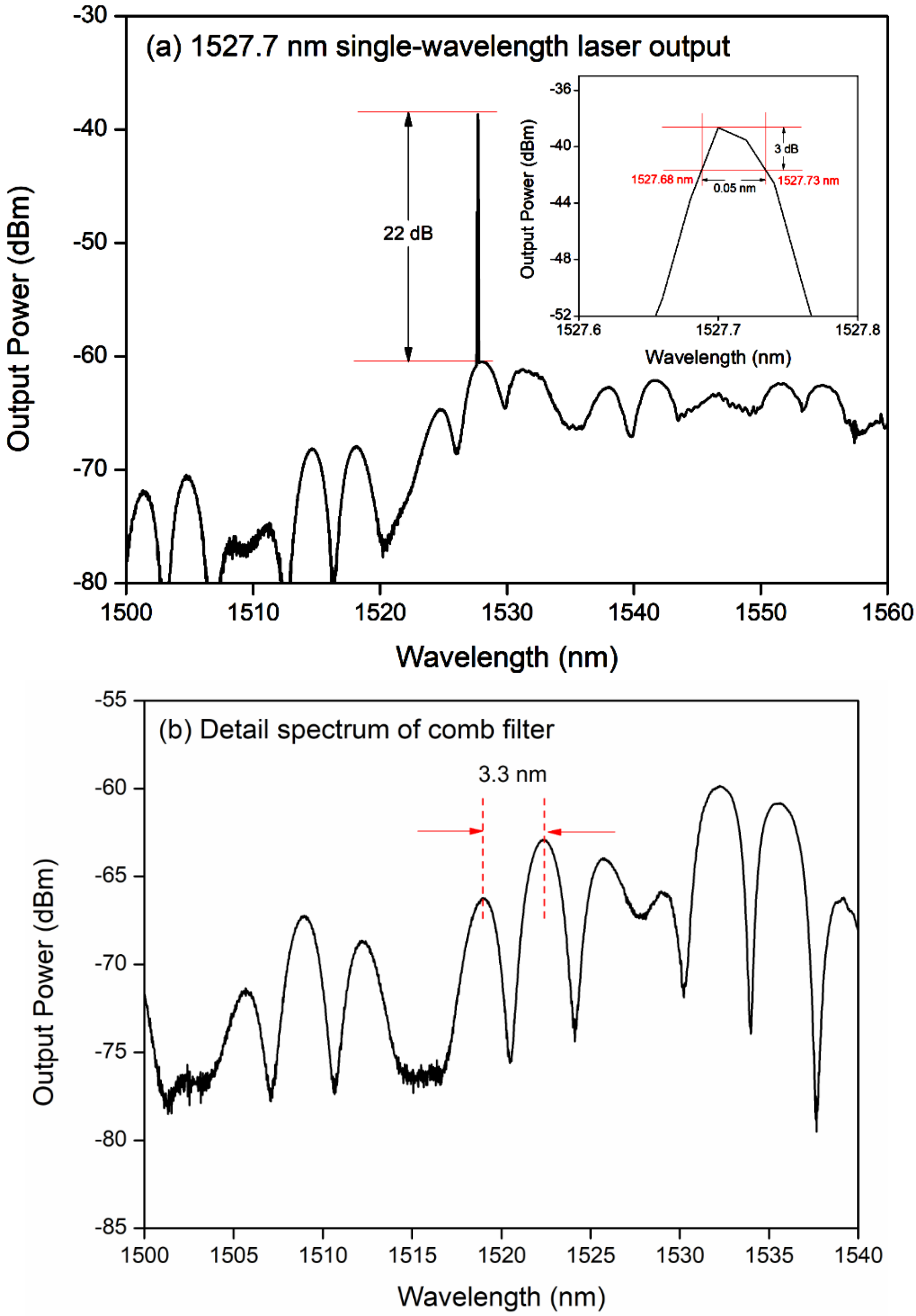

Fig. 2. 1527.7nm laser generation. (a) laser spectrum; (b) comb spectrum of Lyot filter (color online)

After single-wavelength laser was realized, the laser tunability was researched. In the experiment, the pump power was hold on 140 mW, and PC was adjusted, the intra-cavity loss was changed, and a single-wavelength tunable laser output could be realized. As shown in Fig. 3(a), 1525.73 to 1534.07 nm single-wavelength switchable laser emission was realized respectively, the switching scope is 8.34 nm, the minimum wavelength tuning spacing was more than 1.99 nm, and SNR is more than 22 dB. During tuning procedure, the single-wavelength laser peak power shifts is less than 2.92 dB, as shown in Fig. 3(b). The tuning range of the laser wavelength is related to the filtering effect, gain loss and the overall parameters of the laser system. The designed laser system adopts the Lyot filter structure, and the wavelength tuning range of nearly 10 nm was obtained by adjusting the polarization controller in the experiment. In order to further improve the wavelength tuning range, it is necessary to use the tunable filter in the system and optimize its position.

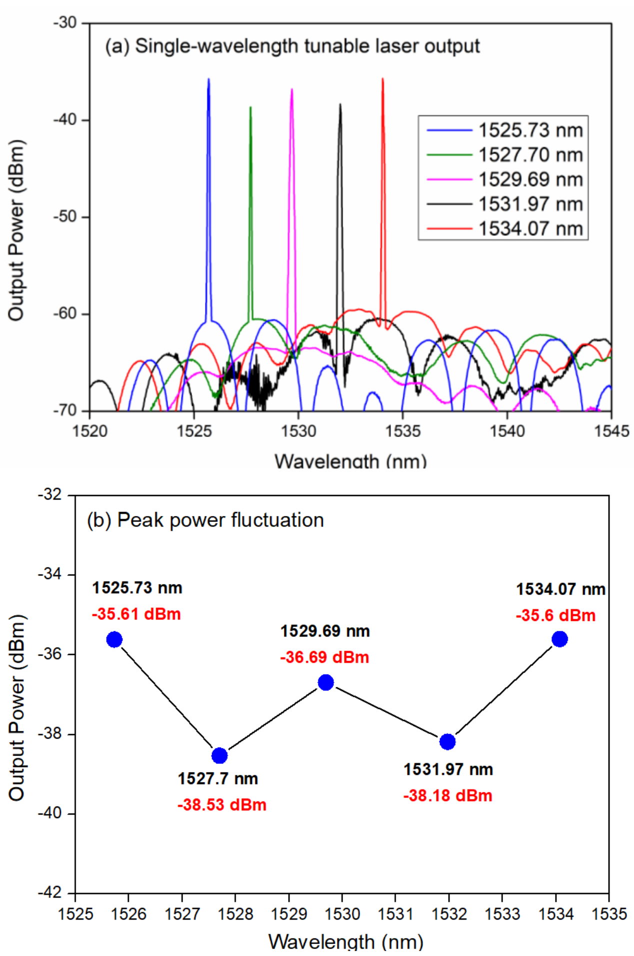

Fig. 3. Single-wavelength lasers realization: (a) single-wavelength switchable laser emissions; (b) peak power fluctuation (color online)

Then, multi-wavelength switchable laser emissions were realized by changing polarization condition. For the proposed EDFL, two different sets of dual-wavelength lasers were realized successively. As shown in Fig. 4(a), for 1525.86 and 1528.11 nm dual-wavelength lasers, the SNR is more than 22.51 dB, and intensity difference is 1.58 dB; for 1533.58 and 1536.5 nm lasers, SNR is more than 24.2 dB, and peak power difference is 0.19 dB. In the experiment, triple- and quadruple-wavelength lasers emission could be realized by adjusting PC, and its spectrum are shown in Fig. 4(b) and (c) respectively. For 1525.03, 1528.54 and 1531.52 nm triple-wavelength lasers, the light intensity difference is 2.8 dB; for 1523.63, 1525.83, 1528.46 and 1530.69 nm quadruple-wavelength lasers, the wavelength minimum spacing is 2.2 nm, and intensity difference is less than 2.58 dB during tuning process.

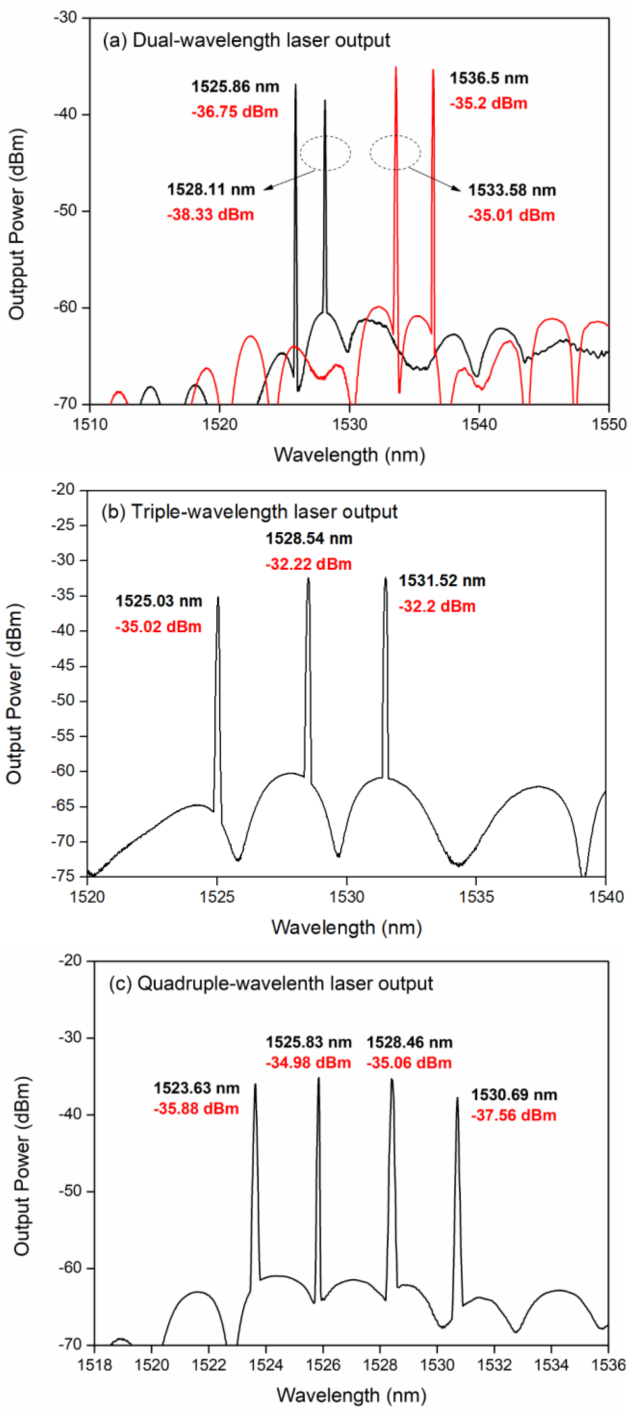

Fig 4. Switchable multi-wavelength lasers output: (a) dual-wavelength lasers; (b) triple-wavelength lasers; (c) quadruple-wavelength lasers (color online)

Finally, the single- and dual-wavelength laser stability was researched in the experiment. For 1527 nm single-wavelength laser emission, laser spectrum was collected every 5 min. As shown in Fig. 5(a), during 25 min, the laser wavelengths are stable, and its peak power fluctuation is less than 0.702 dB, its power shift is shown in Fig. 5(b). For dual-wavelength emissions of 1525.8 and 1528.1 nm, the macroscopic stability is shown in Fig. 5(c), and there was no obvious lasers mode jump during the 25 min time, the power fluctuation was less than 1.452 dB, as shown in Fig. 5(d). The experiment demonstrated the proposed EDFL based on Lyot filter shows excellent stability. In the above experiment, the proposed PM-PCF based Lyot filter was manufactured and selected to be the comb filter in the EDFL, which could generate stable single-, dual-, triple-, or quadruple-wavelength laser outputs. In the experiment, the single-wavelength laser output is realized by using the designed filter.

Compared with the self-excited oscillation, the single-wavelength laser has a narrower linewidth. Further, the tunable output of the single-wavelength laser is realized by adjusting the polarization controller. The designed laser can produce a narrow linewidth laser output, in order to further produce a single frequency laser output, in the next work, the laser structure and filter need to be optimized, such as the use of sub-cavity structure, external injection of laser, multiple filter combination method, and through heterodyne test method to test the width of the laser.

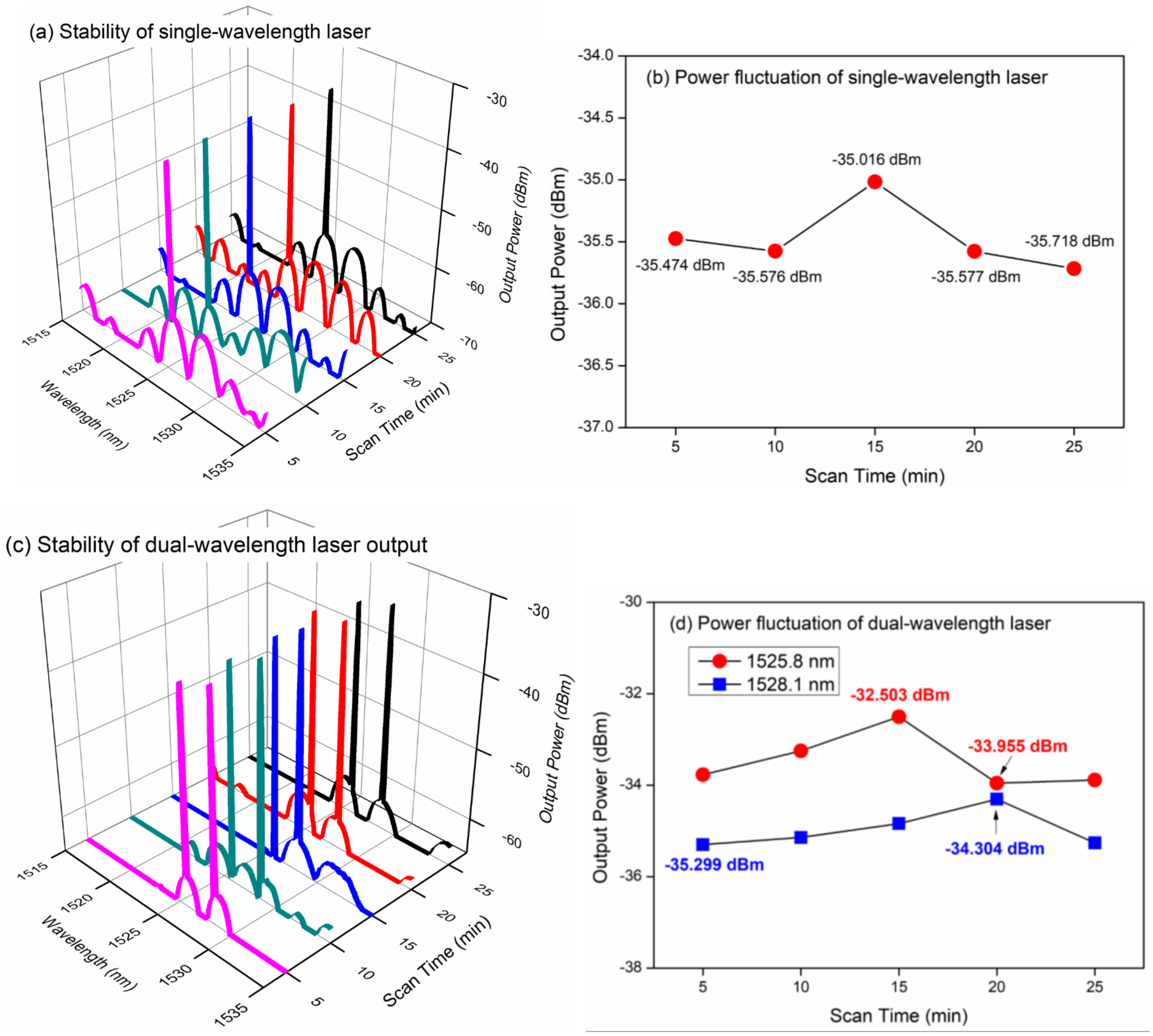

Fig. 5. Stability of laser emission: (a) single-wavelength spectrum; (b) single-wavelength power fluctuation; (c) dual-wavelength spectrum; (d) dual-wavelength power fluctuation (color online)

4. Conclusions

In this study, a switchable single-, dual-, triple-, and quadruple-wavelength EDFL based on an PM-PCF based Lyot comb filter is propose. The Lyot filter was manufactured by splicing PCF and SMF. For the proposed fiber laser, the single-wavelength switchable laser tuning range was 1525.73–1534.07 nm, and the minimum tuning space was 1.99 nm. For the switchable multi-wavelength laser emissions, the minimum wavelength spacing was 2.2 nm, and the SNR exceeds 22 dB. The power stabilities for the single-, and dual-wavelength lasers were less than

0.702, and 1.452 dB, respectively, and the 3 dB linewidth is less than 0.05 nm. This demonstrates that the proposed EDFL can generate single- and multi-wavelength lasers and exhibits flexible tuning capability and high stability.

Acknowledgements

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