A kind of multiwavelength erbium-doped fiber laser based on Lyot filter

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A multiwavelength tunable ring-cavity erbium-doped fiber laser (EDFL) based on a Lyot filter was presented. For the proposed Lyot filter, a comb filter consisting of an EDF-polarization-maintaining fiber (EDF-PMF), a polarization controller (PC), and a circulator with four ports was used to suppress the mode competition. The light transmission direction was guaranteed by the circulator. For the proposed fiber laser, tunable single, dual, triple, quadruple, quintuple, sextuple, and septuple wavelengths were realized. A single-wavelength laser output with an optical signal-to-noise ratio (SNR) of up to 30.56 dB was realized, and a tuning range of 1590.54 nm to 1599.54 nm was achieved by tuning the PC. The stability of the single, dual, triple, and quadruple-wavelength center power fluctuations was less than 0.05 dB, 0.98 dB, 5.07 dB, and 7.71 dB respectively. When the laser was operated in the multiwavelength condition, the SNR was more than 20.97 dB. The proposed erbium-doped fiber laser is suitable for fiber-sensing system applications.

Keywords: multiwavelength erbium-doped fiber laser, Lyot filter, polarization-maintaining fiber, circulator

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1. Introduction

In recent years, erbium-doped fiber lasers (EDFLs) have attracted significant attention in the field of optical fiber lasers[1] and have been widely used in infrared detection, optical radar, and dense wavelength division multiplexer (DWDM).[2,3] In the EDFL research field, mode-lock lasers,[4] tunable wavelength lasers,[5] Raman lasers,[6] and single-frequency[7] lasers are important research interests owing to their different applications. Multiwavelength tunable EDFLs have many advantages such as a large laser number, narrow linewidth, high stability, wide tunable laser wavelength, and high optical signal-to-noise ratio (SNR),[8,9] thus, they have been studied by many scientific research institutions.

In order to generate multiwavelength lasing emission during 1.5-μm wavelength band, the EDF is usually selected as the gain medium, but intensive modes competition weakened multiwavelength laser stability. To generate multiwavelength laser emissions, optical filters have been used in the laser cavity to maximize the number of laser emission lines. Ma *et al*. demonstrated a switchable multiwavelength fiber laser based on two cascaded uptapers.[10] Here, a switchable single, and dual and triple-wavelength laser emissions were achieved. The SNR was more than 45 dB, and the power fluctuation was less than 0.9 dB. However, the wavelength tuning scope was narrow, and the laser emission number was low because of the low extinction ratio of the designed comb filter. Hammadi *et al*. reported a microfiber Mach–Zehnder interferometer-based multiwavelength EDFL.[11] Here, a comb interferometer was fabricated using the flame-brushing technique, and a stable four-wavelength laser output was realized. The fluctuation was less than 2 dB, and the SNR was more than 31.8 dB. However, the configuration of the comb filter was fragile and cannot suppress the mode competition effectively. Lian *et al*. reported a multiwavelength fiber laser based on an erbium-doped twin-core fiber and nonlinear optical loop mirror. For the proposed fiber laser, eight wavelength laser oscillations were realized, the SNR was larger than 40 dB, and the fluctuation of peak power was less than 1 dB.[12] However, the configuration of this laser was complex, and the mismatch connection increased insertion loss in the cavity. Zhou *et al*. designed an EDFL based on the polarization hole burning effect and Lyot filter loop mirrors.[13] Here, the tunable bandwidth was 30 nm, the SNR was approximately 50 dB, the peak power fluctuation was less than 0.04 dB, and a multiwavelength with up to six laser emissions could be realized. Cheng *et al*. demonstrated an EDFL using a fiber Bragg grating and an interleaver.[14] For the designed fiber laser, tunable single-, dual-, and triple-wavelength lasers were obtained. The tuning range was 3 nm, and the SNR was more than 20 dB. However, the laser tuning scope was narrow and a special optical component was used. Martin–Vela *et al*. reported an EDFL based on a core-offset aluminum coated Mach–Zehnder interferometer, in which stable single, dual and triple-wavelength laser emissions could be generated. The tuning scope was 3 nm and the SNR was more than 55 dB.[15] Cai *et al*. reported a ring cavity EDFL based on a high EDF and nonlinear effects in a 3-km single mode

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fiber.[16] For the proposed fiber laser, multiwavelength with up to 5 laser emissions were realized. The SNR was more than 32 dB and the maximum variation in the output power was approximately 0.141 dB. However, the proposed nonlinear effect could not suppress the mode competition and the laser wavelength switchable ability was not shown. Salim *et al*. demonstrated an EDFL using a non-adiabatic microfiber to generate stable and tunable single, dual, and triple-wavelength laser emissions with a tuning range of 5 nm and an SNR of more than 42 dB.[17] However, the configuration of this comb fiber was fragile and the fabrication process was complex, which restricts its application. Zhao *et al*. designed a switchable multiwavelength EDFL based on a parallel dual Lyot filter.[18] Here, the single-wavelength laser tuning range was approximately 13 nm and the wavelength interval could be tuned from 3.03 nm to 17.15 nm. Stable single, dual, and triple-wavelength laser emissions were achieved and the maximum power change was 4.8 dB. Salceda-Delgado *et al*. also demonstrated a wavelength-switchable EDFL based on a modifiable intracavity fiber.[19] For the designed fiber laser, the maximum number of wavelength peaks was 13, the maximum wavelength tuning was about 2.3 nm and the SNR was approximately 50 dB. Zhou *et al*. reported a multiwavelength EDFL based on a tapered in-line Mach–Zehnder interferometer, in which switchable single, dual, triple, and quad-wavelength laser emissions were realized. The SNR exceeded 50 dB, and the power fluctuation was lower than 1.3 dB.[20]

As mentioned above, the multiwavelength tunable fiber lasers is usually realized by techniques such as the Lyot filter interferometer, Mach–Zehnder interferometer (MZI), nonlinear fiber loop, and mismatch fiber structure. The fiber laser spectrum characteristics are determined by the filter components, and it is difficult to realize a better filtering effect with a flexible interferometer comb spectrum, which results in the disadvantage of being less compact. Thus, it is important to propose an EDFL to realize tunable and stable multiwavelength laser output. As an important fiber interferometer filter, the Lyot filter is widely used in fiber laser and sensing applications because of its high contrast, low insert loss and all-fiber structure, so that, the proposed EDFL based on Lyot filter has compact structure and excellent filtering effect.

In this study, a simple multiwavelength tunable EDFL based on a Lyot comb filter was proposed and demonstrated experimentally. A Lyot filter composed of a polarization-maintaining fiber (PMF), a PC, and a four-port circulator was designed. Its lasing tunability and stability characteristics were demonstrated experimentally. By adjusting the PC, stable and tunable single, dual, triple and quadruple-wavelength laser emissions were attained, and up to seven laser emissions could be realized.

2. Experimental setup

A schematic diagram of the proposed EDFL is shown in Fig. 1. The 976-nm pump light generated by a laser diode (LD) is coupled to the EDF by the WDM. The Lyot filter is composed of a panda EDF-PMF, a PC and a four-port circulator. For the circulator, ports 2 and 3 are connected to construct a loop structure, and the light transmission direction is guaranteed to improve laser working performance. The light is coupled into the Lyot filter by circulator port 1, exported from port 2, then inserted into the circulator by port 3, and ultimately exported from port 4. After light passes traveling through the PMF, the PMF and PC provide a phase difference because the effective refractive index of the PMF's fast axis is different from that of the slow axis, and interference is realized, the filter transmission can be described as

$$T(\lambda) = \cos^2\left(\frac{\pi}{\lambda}\Delta nL\right). \tag{1}$$

For the Lyot filter, the wavelength spacing λ can be expressed using

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

where λ is the transmission light, Δn is the refraction-index birefringence between the fast and slow axes of EDF-PMF, and L is the EDF-PMF length.

The Lyot filter is connected to an OC with a 10:90 splitting ratio. The OC's 10% port is connected to the WDM to construct the ring cavity. A PC is used to tune the laser wavelength, and an optical spectrum analyzer (OSA) is used to collect the output laser.

After the Lyot filter is used in the ring cavity, the comb filter effect can be realized, and wavelength-tunable lasers can be generated by the comb interferometer filtering effect. The EDF-PMF has a stronger birefringent effect; otherwise, it can be used as a saturable absorber to improve laser performance. Thus, the Lyot filter based on an EDF-PMF has a better filtering effect to suppress mode competition caused by the homogeneous broadened line in the erbium-doped fiber amplifier.

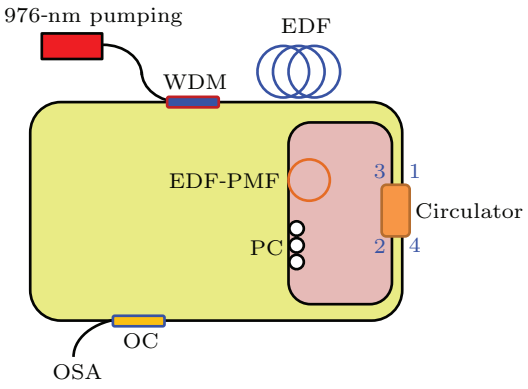


Fig. 1. Schematic diagram of the proposed EDFL based on a Lyot filter.

3. Experimental results and discussion

In the experiment, the EDFL experimental system was constructed, and the pigtail fiber size of the EDF-PMF fiber components was 5.5 μm/125 μm. A 2.5-m length L-band EDF was used as the gain medium. First, the laser output without the comb filter and Lyot filter spectrum was measured and analyzed. As shown in Fig. 2(a), when the Lyot filter was not used in the ring cavity, the lasing spectrum details were collected, numerous lasing modes were generated, and single-wavelength lasing could not be realized. The Lyot filter interferometer spectrum is shown in Fig. 2(b), where an abundant filtering effect was achieved and the comb spectrum interferometer interval was 3.05 nm. The proposed Lyot filter loop has an excellent interference effect, and it can be used as a comb fiber in an EDFL.

The proposed Lyot filter was then inserted into the ring cavity of the EDFL. When the pump power was 53 mW, a 1596.08-nm single-wavelength laser was obtained in the experiment. When the pump power was increased to 100 mW, as shown in Fig. 3(a), 1590.54-nm, 1593.01-nm, 1596.08-nm, and 1599.54-nm single-wavelength lasers were obtained respectively. The wavelength spacing exceeded 2.47 nm by adjusting the polarization controller, and the SNR exceeded 30.56 dB.

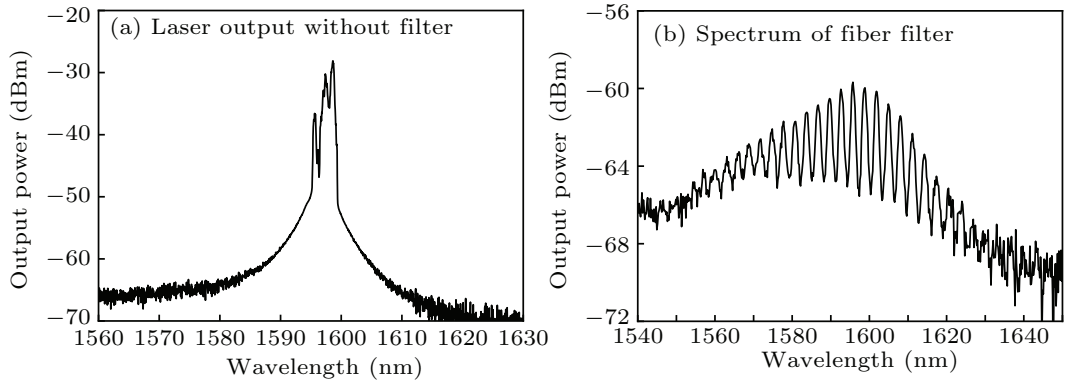


Fig. 2. Measured laser output without the comb filter and Lyot filter spectrum: (a) laser output without filter, (b) spectrum of the proposed Lyot filter.

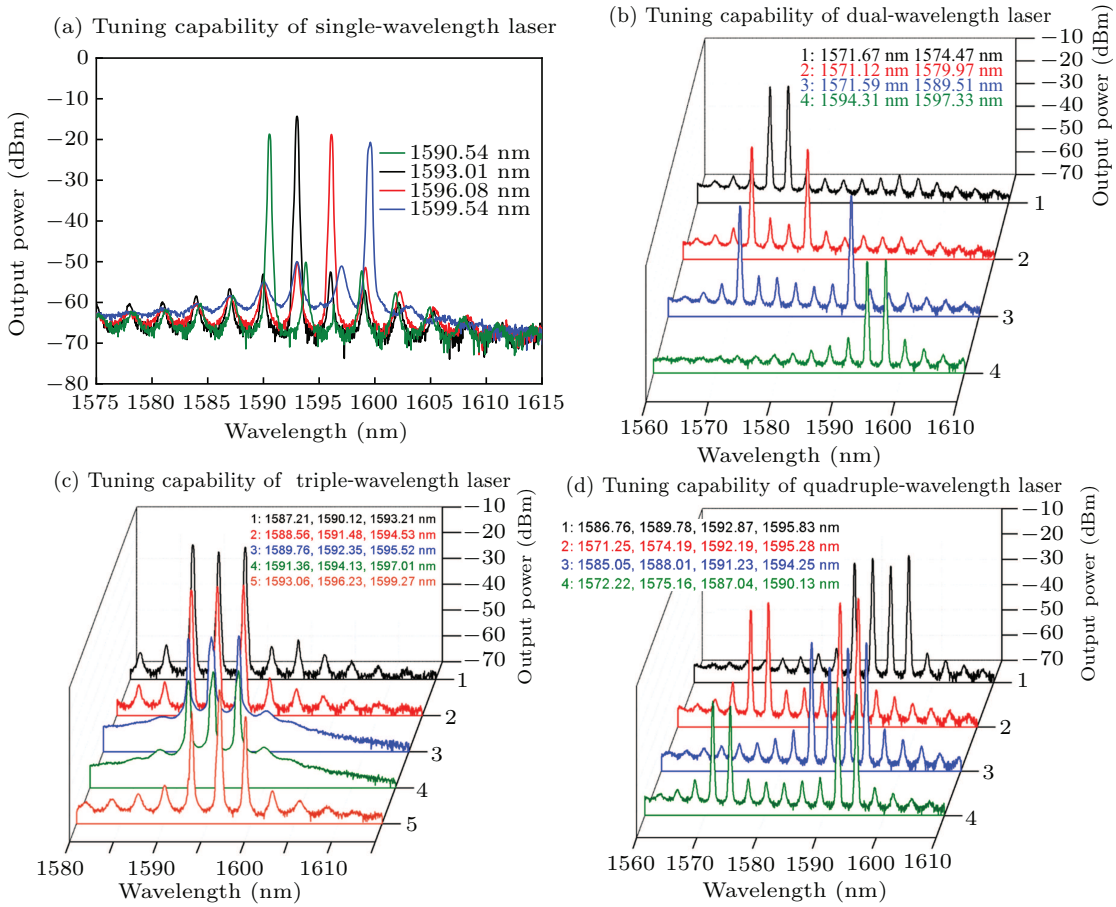


Fig. 3. Wavelength tunable laser emission: (a) single-wavelength tunable laser emission, (b) dual-wavelength laser output, (c) triple-wavelength laser output, (d) quadruple-wavelength laser output.

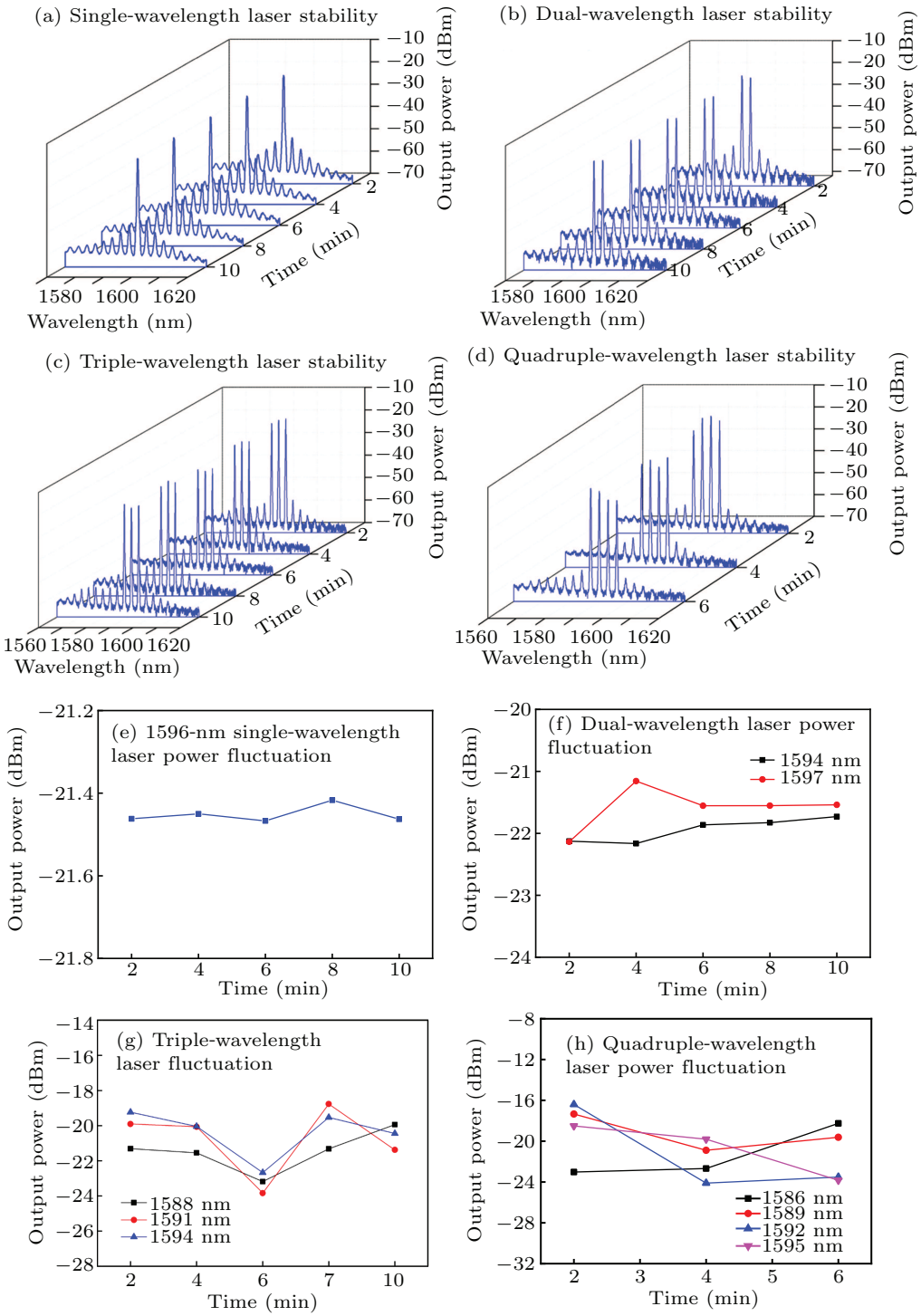


Fig. 4. Laser stability: (a) single-wavelength laser stability, (b) dual-wavelength laser stability, (c) triple-wavelength laser stability, (d) quadruple-wavelength stability, (e) single-wavelength laser power fluctuation, (f) dual-wavelength laser power fluctuation, (g) triple-wavelength laser fluctuation, (h) quadruple-wavelength laser power fluctuation.

In the experiment, a dual-wavelength tunable laser output was realized, as shown in Fig. 3(b). The dual-wavelength laser interval can be tuned from 2.8 nm to 17.92 nm, and the SNR was more than 31.51 dB. As shown in Fig. 3(c), four different groups of triple-wavelength lasers were realized by adjusting the PC, and the SNR was more than 30.97 dB. As shown in Fig. 3(d), tunable quadruple-wavelength lasers could be generated in the range of 1571.25 nm–1595.83 nm, with a change in the loss of intracavity, and the SNR was more than 30.33 dB. For the single, dual, triple, and quadruple-wavelength laser emissions, a stable laser output was realized in the experiment, and the spectra are shown in Fig. 4.

The spectral stability of the single-, dual-, triple-, and quadruple-wavelength lasers is shown in Fig. 4. Mode hopping was not observed during the scanning time at room temperature for the 1596-nm single-wavelength laser. Its spectrum stability is shown in Fig. 4(a), and the power fluctuation was lower than 0.05 dB, as shown in Fig. 4(e). The spec-

trum stability and power fluctuation of the 1594-nm and 1597-nm dual-wavelength laser emissions are shown in Figs. 4(b) and 4(f), and the power fluctuation was less than 0.44 dB and 0.98 dB, respectively. For the 1588-nm, 1591-nm, and 1594-nm triple-wavelength laser outputs, the stability is shown in Fig. 4(c), its power fluctuation was lower than 3.25, 5.07, and 3.44 dB respectively. For the 1586-nm, 1589-nm, 1592-nm, and 1595-nm quadruple-wavelength laser emissions, the spectrum stability during 6 min is shown in Fig. 4(d); the power fluctuation was less than 4.77, 3.55, 7.71, and 5.33 dB respectively, as shown in Fig. 4(h). As mentioned above, the laser stability gradually decreased as the number of laser emissions increased.

Tunable quintuple, sextuple and septuple-wavelength laser emissions could be realized by adjusting the PC. As shown in Figs. 5(a)–5(d), four different groups of quintuple-wavelength lasers were obtained and the SNR was higher than 27.66 dB. As shown in Fig. 5(e), a sextuple-wavelength laser output was generated in the experiment and the SNR was higher than 20.97 dB. For the septuple-wavelength laser output, the SNR was more than 21.98 dB as shown in Fig. 5(f). As shown in Fig. 5, the proposed EDFL exhibited excellent multiwavelength tenability. In the experiment, for the proposed fiber laser, more emission lines are obtained. However, these lines become highly unstable due to modal competition. This can be seen in the uniformity of the lines and fluctuation in power. The multiwavelength laser emission could be realized by adjusting the PC. The polarization hole burning effect is changed through adjusting PC, and the loss and gain of certain lasers wavelengths is adjusted accordingly. When the loss is lower than the gain, the lasers can be generated, which will result in laser wavelength number change. In our next step, the temperature control system of pump LD will be used to guaranteed pump power stability, and additional all-fiber comb filter will be inserted into the cavity to improve multiwavelength laser stability and tunability.

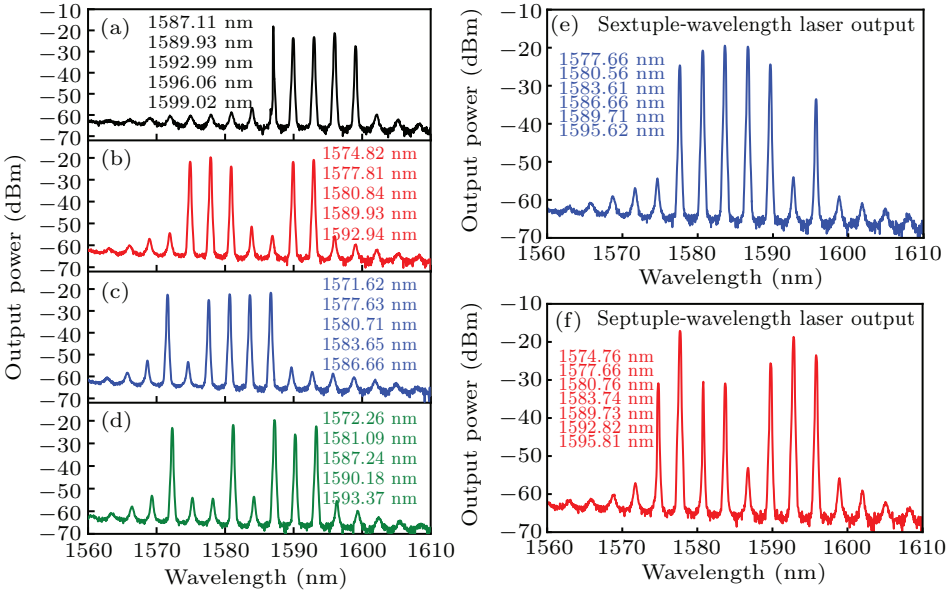


Fig. 5. Quintuple, sextuple, and septuple-wavelength laser generations: (a)–(d) quintuple-wavelength laser output, (e) sextuple-wavelength laser output, (f) septuple-wavelength laser output.

4. Conclusion

In this study, a multiwavelength tunable EDFL based on a Lyot filter loop was realized. The proposed Lyot filter comb filter based on an EDF–PMF and a four-port circulator was fabricated, and its interference period was 3.05 nm. For the proposed EDFL, tunable single, dual, triple, quadruple, quintuple, sextuple, and septuple-wavelengths were realized in the experiment. The SNR was more than 20.97 dB. Stable and tunable single, dual, triple, and quadruple-wavelength laser emissions were achieved and the power fluctuations were less than 0.05 dB, 0.98 dB, 5.07 dB, and 7.71 dB respectively, at room temperature. By adjusting the PC, quintuple, sextuple, and septuple-wavelength laser outputs were generated. Compared with traditional multiwavelength EDFL, the proposed EDFL shows excellent tunable and stable capabilities, and it can be widely used in fiber communication, fiber sensing, and spectral analysis.

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