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Flexible wavelength-, pulse-controlled mode-locked all-fiber laser based on a fiber Lyot filter

DONGDONG HAN,[1,2,4] LINGZHI MEI,[1,2] ZHANQIANG HUI,[1,2,5] ABDEL-HAMID SOLIMAN,[3] KAILI REN,[1,2] YIPENG ZHENG,[1,2] TIANTIAN LI,[1,2] AND JIAMIN GONG[1,2]

[1] *School of Electronic Engineering, Xi'an University of Posts and Telecommunications, Xi'an 710121, China*
[2] *Xi'an Key Laboratory of Microwave Photonics and Optical Communication, Xi'an, China*
[3] *School of Creative Arts & Engineering, Staffordshire University, Staffordshire, ST4 2DE, UK*
[4] *handongdong@xupt.edu.cn*
[5] *zhanqianghui@xupt.edu.cn*

Abstract: In this paper, we report a flexible wavelength-, pulse-controlled mode-locked all-fiber laser based on a novel fiber optic Lyot filter. The wavelength, pulse duration and spectral bandwidth of passive mode-locked lasers can be tuned by controlling the polarization controller. The proposed Lyot filter was constructed by a single-mode fiber insertion between two polarization-maintaining fibers. The filter bandwidth and laser output tunability were based on the birefringence characteristics of the polarization-maintaining fibers. This all-fiber laser is simple and stable and can be used for various applications where width-tunable or wavelength-tunable pulses are necessary.

1. Introduction

In recent years, mode-locked fiber lasers have been extensively used in industrial applications and scientific research owing to their various advantages (e. g., simple and compact structure, high stability, low cost) [1–9]. In addition, wavelength-convertible, tunable, and multi-wavelength mode-locked fiber lasers have important application value in wavelength division multiplexing optical fiber communication, optical fiber sensing, biological imaging, and terahertz generation, which has received considerable research interest. Effectively regulating the wavelength of passive mode-locked fiber lasers has important research value [10–15]. The pulse duration

It is well known that spectral filtering can greatly affect the pulse pattern in a laser cavity. Therefore, adding a tunable filter device to a laser cavity is a simple and stable way of effectively regulating the wavelength. For example, Wang *et al*. achieved a tunable locked pulse with wavelengths ranging from 1518 to 1558 nm using a carbon nanotube mode-locked fiber laser with a tunable band-pass filter [16]. However, such tunable filtering devices are composed of spatial optical devices such as prisms and gratings, which destroy the all-fiber structure and are expensive. Therefore, all-fiber spectral filters have gradually become a research hotspot, which is conducive to the construction of an all-fiber laser cavity. X. Liu *et al*. report the pulse-controlled mode locked fiber laser by put pressure on the CFBG [17]. C. Wang *et al*. realize the tunable in both wavelength and bandwidth by changing the temperature of a cascaded long-period fiber grating filter [18]. However, FBG is very sensitive to the environmental perturbations and temperature, which cause the output of the mode locked fiber laser is very sensitive outside of the laboratory.

In recent years, Lyot filter mainly composed by polarization maintaining fiber (PMF), which is low-cost, low-loss, compactness, and high stability, have been widely used in multi-wavelength erbium-doped fiber (EDF) lasers [19–21]. The basic structure of a Lyot birefringence filter is a linear combination of a birefringent crystal delay sheet added to the middle of two parallel

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polarization plates. At present, many researchers have proposed a series of optimization schemes based on improvements to the Lyot filter [22,23]. Li *et al.* obtained tunable soliton pulses in the wavelength range of 1952.63-1971.62 nm by changing the temperature of PMF in a thulium-doped hybrid mode-locked fiber laser [24]. Zhu *et al*. proposed and demonstrated a novel dynamic tunable fiber optic Lyot filter that can achieve a wavelength tuning range of 30 nm (1532-1562 nm) in a single wavelength mode-locked state by adjusting the polarization controller (PC) [23]. Despite the performances of all these lasers being satisfactory with regard to their ability of tuning wavelengths, these filters do not have the ability to tune both the wavelength and bandwidth at the same time. The bandwidth of the filter is determined by the length of the PMF [25]. If the bandwidth of the filter is to be adjusted, the length of the PMF must be changed. A Lyot filter consisting of PMFs and a single-mode fiber can work with a PC to generate phase delays, the wavelength and spectral bandwidth of the filter could be changed simultaneously. A. Khanolkar *et al*. have realized the transition between all-normal dispersion laser spectrum and self-similar operation in an Yb-doped laser cavity with a bandwidth tunable fiber-based spectral filter [26].

Here, we report an all-fiber mode-locked erbium-doped laser whose pulse duration and pulse wavelength can be precisely controlled by adjusting the PC in the novel Lyot filter. We insert a single-mode fiber spliced between two PMFs to demonstrate a novel all-fiber spectral filter. The improved Lyot filter has a simple structure that does not require a change in the length of the fiber, replacing the conventional filters. Furthermore, with the improved Lyot filter, our laser can deliver pulses with the spectral bandwidth and pulse duration from 0.9~6.3 nm and 2.9 to ~0.623 ps, respectively. The wavelengths of pulse can be tuned in a range of approximately ∼32 nm. Our work presents an effective way to control the wavelength and pulse duration in the mode locked fiber laser.

2. Experimental details and principles

The all-fiber laser based on the novel fiber Lyot filter is shown in Fig. 1(a). The proposed laser cavity consists of a wavelength division multiplexer (WDM), a carbon nanotubes saturable absorber (SA), a 5-m-long erbium-doped fiber (EDF), two polarization sensitive isolators (PS-ISO), a polarization controller (PC), a 30% output coupler (OC), two segments of polarization maintaining fiber (PMF), and a piece of single-mode fiber (SMF). A 980 nm single-mode semiconductor laser diode (LD) with a maximum output drive current of 1200 mA was used as the pumping source. The 980/1550 nm WDM (1×2) was used to couple the 980 nm pump light into the fiber laser ring cavity. The EDF was used as a gain medium with 3 dB/m absorption at 980 nm. The nonlinear absorption curve of the CNT used in the laser was measured with a homemade ultrafast laser, as shown in Fig. 1(b). The modulation depth and saturation light intensity of the CNT are 175 MW/cm^2 and 2.96%, respectively. The PS-ISO converts the input light into linearly polarized light and forms a filter device with the PC to achieve a tunable wavelength, while ensuring that light always travels in one direction. The total length of the SMF and PMF in the cavity is approximately 13.2 m, with the dispersion parameter of 17 ps/nm/km, respectively. As the dispersion parameter of EDF is -9 ps/nm/km, the cavity net dispersion could be calculated as approximately -0.228 ps^2. The acquisition of the mode-locked pulse state was all performed by the 30% port of the OC. In the experiment, the output data were monitored in real time by means of a spectrum analyzer (Yokogawa AQ6370D), a digital oscilloscope (Tektronix MDO3014), an autocorrelator (Pulsecheck USB), and a radio frequency (RF) spectrum analyzer (Keysight N9020B).

The key component of this laser, shown in the dotted box of Fig. 1, is the novel Lyot filter. It consists of a SMF insertion between two PMFs (e.g. PMF1 and PMF2). The PMF1 (PMF2) contains of two section PM fiber with spliced angle between their principal axes of 45°, the splicing points are shown in the red marker point in Fig. 1. The input light passes through the first

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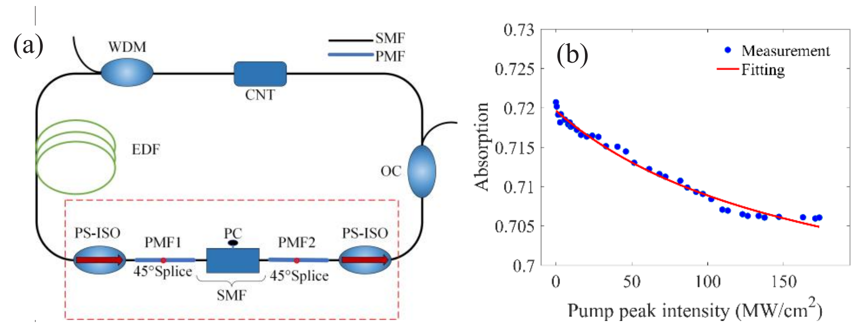

Fig. 1. (a) Experimental configuration of the laser. WDM: wavelength-division multiplexer; CNT: carbon nanotubes; EDF: erbium-doped fiber; PS-ISO: polarization sensitive isolator; PC: polarization controller; OC: optical coupler; PMF: polarization-maintaining fiber; SMF: single-mode fiber. Red dots indicate fiber splices. The fiber marked in blue is referred to as PMF in the text. (b) Nonlinear absorption curve of the CNT in the laser.

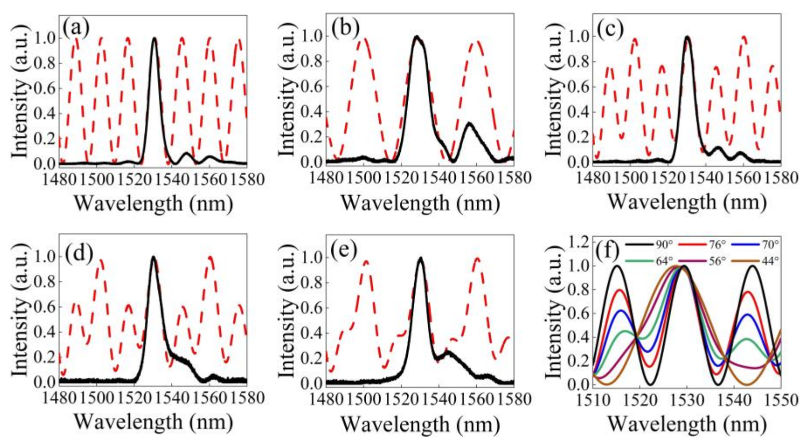

Fig. 2. Theoretical and experimental transmission spectra of the filter. (a)-(e) Theoretical (dashed line) transmittance of the filter when Θ=90°, 45°, 75°, 70° and 62°, and the experimental (solid line) transmittance of the filter measured with the ASE of EDF by adjusted the PC state. (f) The theoretical transmission spectra when Θ=90°, 76°, 70°, 64°, 56° and 44°, respectively.

isolator and then propagates along PMF1, SMF, and PMF2, eventually accumulating a relative phase shift in each segment of the fiber due to the birefringent nature of the PMF. By adjusting the PC, the transmitted spectral signal is modulated and the birefringence effect is changed so that the laser pulse duration and pulse wavelength are tuned.

We firstly performed a numerical analysis on the novel all-fiber PM Lyot filter by using Jones matrices. The transmission Jones matrix (T) can be expressed by successively multiplying the Jones matrices of each optical element:

$$T=\begin{pmatrix}\cos^2\theta_2 & \frac{1}{2}\sin 2\theta_2\\ \frac{1}{2}\sin 2\theta_2 & \sin^2\theta_2\end{pmatrix}\begin{pmatrix}e^{-i\frac{\Delta\phi_3}{2}} & 0\\ 0 & e^{i\frac{\Delta\phi_3}{2}}\end{pmatrix}R(-\Theta)\begin{pmatrix}e^{-i\frac{\Delta\phi_2}{2}} & 0\\ 0 & e^{i\frac{\Delta\phi_2}{2}}\end{pmatrix}R(\Theta)\begin{pmatrix}e^{-i\frac{\Delta\phi_1}{2}} & 0\\ 0 & e^{i\frac{\Delta\phi_1}{2}}\end{pmatrix}\begin{pmatrix}\cos^2\theta_1 & \frac{1}{2}\sin 2\theta_1\\ \frac{1}{2}\sin 2\theta_1 & \sin^2\theta_1\end{pmatrix} \tag{11}$$

In this equation, θ_1 and θ_2 are the fixed splicing angles between the PMF, which are 45°. Θ is the angle of rotation between the SMF and PMF, which could be changed by adjusted the PC state in the experiment. $\Delta\phi_1$, $\Delta\phi_2$, and $\Delta\phi_3$ are the phase differences caused by the propagation of light in PMF1, SMF, and PMF2, respectively. The phase difference can be expressed as $\Delta\phi=2\pi\Delta nL/\lambda$, where Δn and L represent the birefringence and length of the fiber, respectively, λ is wavelength.

The lengths of PMF1(L1), SMF(L2), and PMF2(L3) are approximately 12.2 cm, 1 m, and 33.8 cm, respectively. The length of PMF1 is approximately half that of PMF2. The birefringence values of the three fibers are approximately $\Delta n_1 = 3.06\times10^{-4}$, $\Delta n_2 = 3.8\times10^{-6}$, and $\Delta n_3 = 3.06\times10^{-4}$.

Theoretical transmittance of the proposed filter are shown by the red dotted line in Figs. 2(a) and (b), when the rotation angle Θ between the SMF and PMF is approximately 90° and 45°. The spectral bandwidths (BWs) are ~5.9 nm and ~14.5 nm (the obtained minimum and maximum spectral width), respectively. The spectral BW could be tuned between ~5.9 and ~14.5 nm by changing the value of Θ, as shown in Figs. 2(c)-(d). The corresponding filter BWs are about 7.5, 8.7 and 9.3 nm, when Θ=75°, 70° and 62°, respectively. In the experimental cavity, the CNT and OC was connected by two FC/APC fiber patch cables. The experimental transmission spectra could be measured from the output of OC with the amplified spontaneous emission spectrum

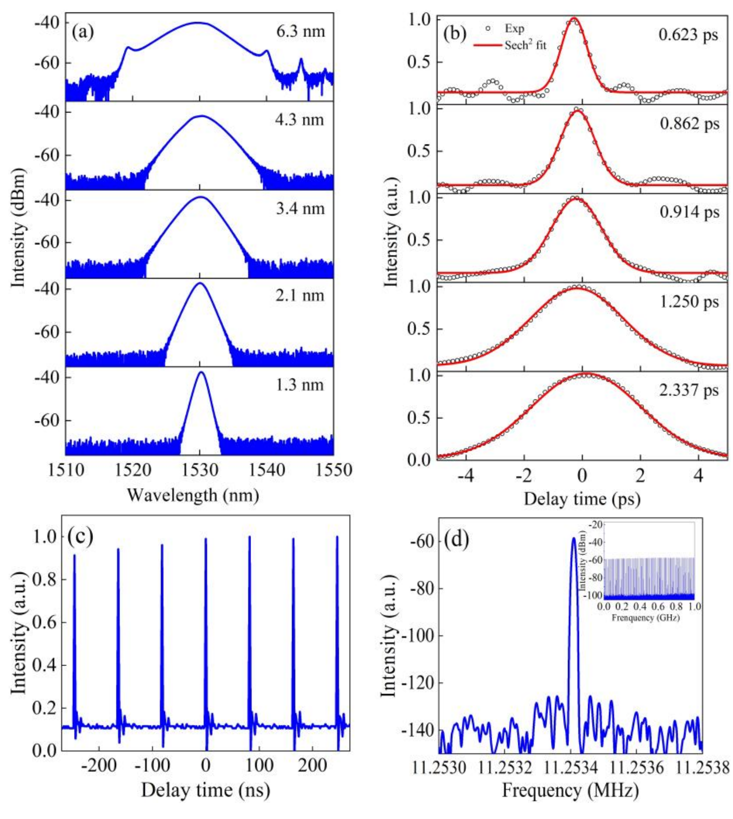

Fig. 3. Tunable performance of spectral width and pulse duration. (a) Different spectral and (b) corresponding autocorrelation traces by adjusting the PC. The spectral BWs and the corresponding pulse durations are approximately 6.3 nm and 0.623 ps, 4.3 nm and 0.862 ps, 3.4 nm and 0.914 ps, 2.1 nm and 1.25 ps, and 1.3 nm and 2.337 ps, respectively. (c) Oscilloscope traces with a separation of ~82 ns, corresponding to ~3.4 nm of the spectral BW. (d) Fundamental RF spectrum with a spectral BW of ~3.4 nm. The inset shows the RF spectrum with a span of 1 GHz.

(ASE) of EDF, when the connector between OC and CNT was broken. The typical experimental spectral BWs of the proposed filter are shown by the solid black lines in Figs. 2(a)-(e), which are also corresponding to the filter states in the subsequent mode locking states in Fig. 3 (a). Because of the profile of EDF ASE, the peak on ~1530 nm is higher than other peaks. However, the positions of the peaks are in good agreement with the theoretical data. Moreover, the position of transmission peak could also be tuned with the different Θ, as shown in Fig. 2(f).

3. Experimental results and discussion

In the experiment, stable single-pulse mode-locked generation was achieved for a drive current of 90 mA. With an appropriate tuning of the PC, the proposed laser delivers pulses with different durations. The typical output spectra are shown in Fig. 3(a) with a central wavelength of ~1530 nm. The 3 dB spectral BWs are approximately 6.3, 4.3, 3.4, 2.1, and 1.3 nm. The Kelly sidebands could be observed when the 3 dB BW of the spectrum is 6.3 nm. The sidebands are suppressed in the narrower soliton spectrum because of filter effect with the narrower filter BW [27]. The corresponding autocorrelation traces of the experimental data and the sech^2 shaped fit are shown in Fig. 3(b). The corresponding pulse durations are approximately 0.623, 0.862, 0.914, 1.250, and 2.337 ps. The calculated time-bandwidth products (TBPs) are approximately 0.50, 0.48, 0.40, 0.34, and 0.39, respectively, which are slightly larger than the transform limit (0.315) of sech^2-shaped pulses, indicating that the output pulses are little chirp. Several ripples appear at the both sides of the autocorrelation trace when pulse duration is 0.623 ps. The ripples weaken and disappear when the pulse is broadening, which could be attributed to the suppression of the sidebands [27,28]. Figure 3(c) demonstrates the oscilloscope curve at a spectral BW of ~3.4 nm. It can be seen that the intensity of each pulse is basically equal, and the interval between the two pulses is ~82 ns, corresponding to the time when the pulse runs in the cavity for one period. The unequal height of the oscilloscope pulse train strength is due to the limitations of the electronic detection system. Figure 3(d) shows the corresponding fundamental frequency curve of the mode-locked pulse at 11.25 MHz, and the inset in Fig. 3(d) shows the 1 GHz-range spectrum curve. In the experiment, the tuning range of the pulse duration was limited by the BW of the filter. As can be seen from the above data, different BW laser outputs can be obtained near a center wavelength by properly adjusting the PC in the filter, which demonstrates the tunable performance of the laser spectral BWs and pulse durations.

In the experiment, a tunable output can be achieved for the mode-locked wavelength by adjusting the PC and maintaining the drive current. As shown in Figs. 4(a)-(d), mode locking can also be achieved at multiple wavelengths such as ~1540, ~1545, ~1555, and ~1560 nm. Figures 4(e)-(h) are the corresponding autocorrelation traces of the experimental data and the sech^2 shaped fit. As shown in Fig. 4(a), the spectral BWs obtained at a central wavelength of ~1540 nm are approximately 4.9, 2.3, 1.5, and 0.9nm. The corresponding pulse durations are approximately 0.890, 1.675, 2.256, and 2.9 ps, as shown in Fig. 4(e), and the calculated TBPs are approximately 0.55, 0.48, 0.43, and 0.33, respectively. Figure 4(b) reveals that the spectral BWs of a central wavelength at ~1545 nm are approximately 4.5, 3.0, 1.7, and 1.2 nm, and the corresponding pulse durations are approximately 0.973, 0.998, 1.495, and 2.414 ps, as shown in Fig. 4(f), respectively. The TBPs are approximately 0.55, 0.38, 0.32, and 0.36. As shown in Fig. 4(c), at a central wavelength of ~1550 nm, the spectral BWs with 0.906, 0.995, 1.613, and 2.550 ps pulse durations are approximately 4.0, 3.2, 1.7, and 1.0 nm, respectively. The calculated TBPs are approximately 0.45, 0.40, 0.34, and 0.32. As shown in Fig. 4(d), the spectral BWs obtained at a center wavelength of ~1560 nm are approximately 4.4, 3.1, 1.8, and 1.3 nm. The corresponding pulse durations are approximately 0.909, 0.945, 1.513, and 2.103 ps, as shown in Fig. 4(h), and the calculated TBPs are approximately 0.49, 0.37, 0.34, and 0.34, respectively. These data amply illustrate the tunable performance of the laser pulse duration and spectral width.

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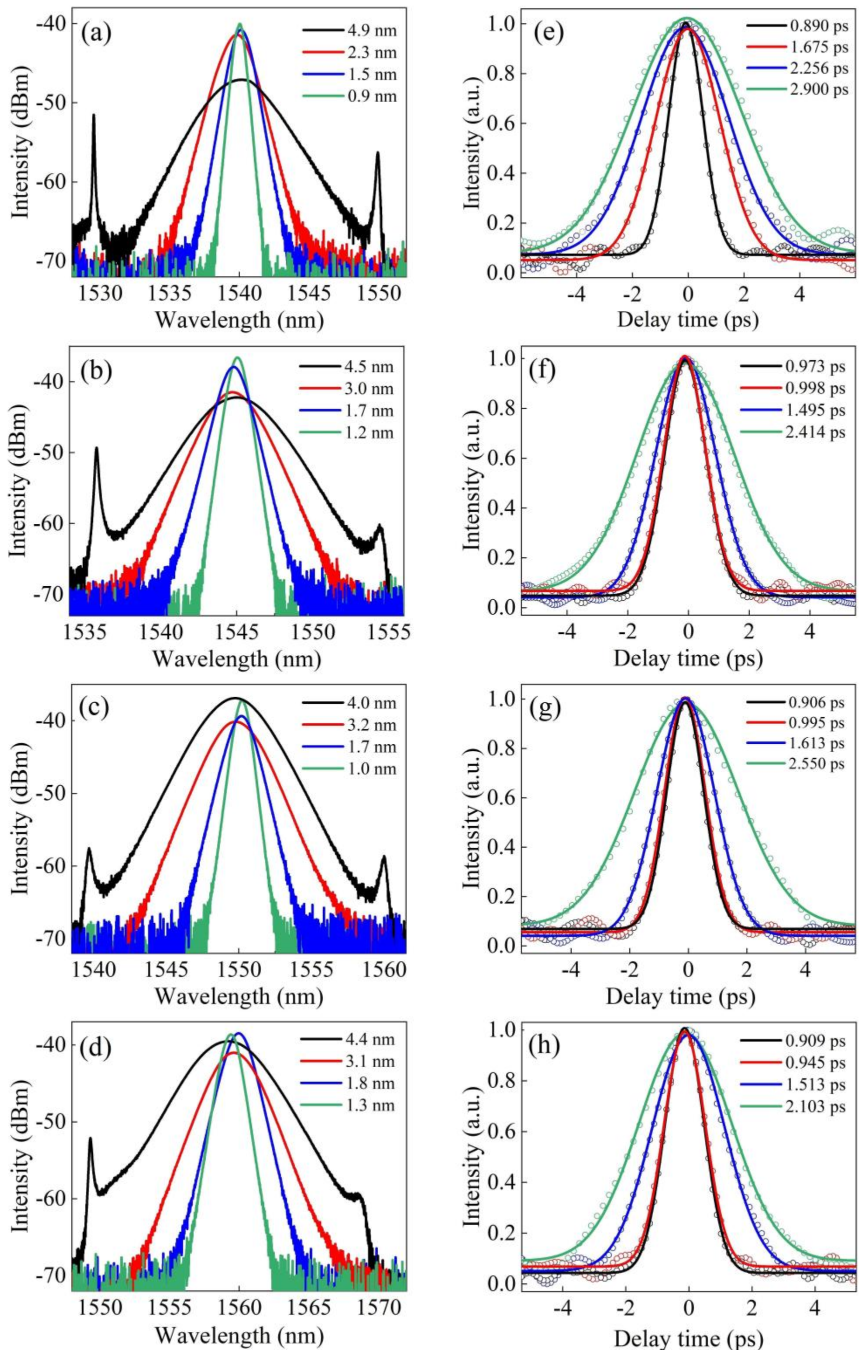

Fig. 4. (a)-(d) Mode-locked pulse wavelength and spectral bandwidth can be changed by properly adjusting the PC (e. g., the central wavelength was fixed at approximately ~1540, ~1545, ~1550, and ~1560 nm). (e)-(h) Autocorrelation traces of the experimental data (circle symbols) and sech^2-shaped fits (solid curves).

Figure 5 demonstrates a typical output achieved by appropriately adjusting the PC while maintaining the drive current at 300 mA. The experimental results show that the spectral BW and pulse duration change slightly, although the central wavelength of the pulses can be evidently

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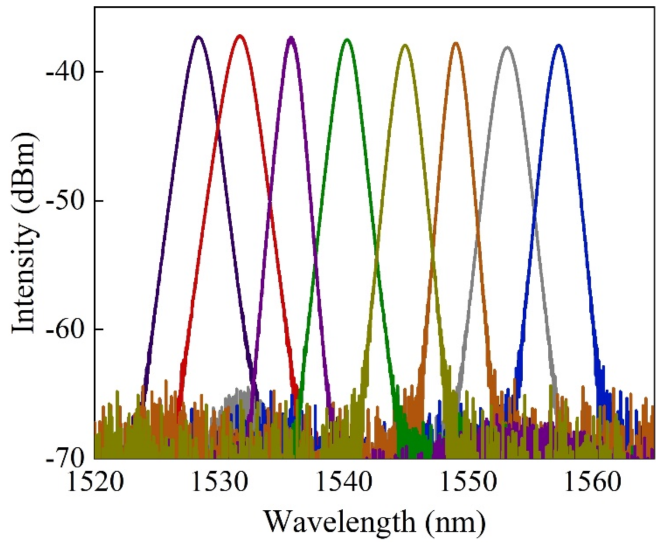

Fig. 5. Wavelength tuning ability of the laser when appropriately tuning the PC in the Lyot filter. The central wavelength of the spectrum can be tuned in the range of ~30 nm, although the spectral profile changes slightly.

tuned, indicating the stability of our output pulses. As shown in Fig. 5, the wavelength tuning range is approximately ~32 nm for a 3-dB spectral BW of ~2 nm. The central wavelength could be adjustable between ~1528 and ~1560 nm, which is determined by the transmission spectra of the filter and the ASE profile of the EDF. Experimental observations have shown that our lasers can operate stably for a long time with an adjustable width and wavelength.

4. Conclusion

A flexible wavelength-, pulse-controlled mode-locked all-fiber laser based on a novel fiber Lyot filter was studied experimentally. Polarization-maintaining fibers and a polarization controller were used to act as the Lyot birefringence filter, where the PMF was used as the birefringent medium. The output parameters of the laser, including its spectral bandwidth and pulse duration, could be altered by slightly changing the PC to affect the birefringence effect in the cavity. Narrowband and broadband pulses with a 0.9~6.3 nm bandwidth were realized for this laser. Additionally, by fine-tuning the PC, the different pulse durations and spectral bandwidths could be achieved at multiple wavelengths, such as ~1530, ~1540, ~1550, and ~1560 nm. Moreover, the spectral width is tunable in the ~32 nm range. The results have important reference value for the study of different mode-locked pulse durations and multi-wavelength fiber lasers.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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