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Switchable multiple lasing oscillations in an erbium-doped fiber ring laser using a single stage of a Sagnac loop mirror

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Abstract A simple scheme for a switchable multi-wavelength erbium-doped fiber (EDF) ring laser is investigated by using a single stage of a Sagnac loop mirror. The multiple lasing outputs are obtained and switched readily by controlling the state of polarization (SOP). Since the transmission characteristics of the Sagnac loop mirror in terms of peak wavelengths and peak powers strongly depend on the SOP, the switching performance of the proposed multi-wavelength EDF laser can be effectively obtained. The proposed multi-wavelength EDF laser has versatile lasing outputs in states of a single-, dual-, triple-, and quadruple-wavelength oscillations. The multiple outputs are effectively switchable by adjusting the SOP.

1 Introduction

Switchable multi-wavelength erbium-doped fiber (EDF) lasers have been attracting more interest in wavelength-division-multiplexed (WDM) communication system, optical remote sensing, spectroscopy, and RF-photonics. Especially they can be exploited to be excellent light sources in fiber sensors and wavelength routers of the WDM network. They have a lot of advantages, such as narrow line width, high output power, high stability, and excellent fiber compatibility. However, an EDF is primarily a homogeneous gain medium at room temperature, which leads to strong mode competitions and unstable lasing oscillation. Therefore, EDF-based multi-wavelength fiber lasers have drawbacks in terms of the number of lasing wavelengths and switching performance. On the other hands, to achieve switchable multi-wavelength oscillations at room temperature, various cavity-design techniques have been proposed. For the multi-wavelength fiber laser by using cascaded cavities based on fiber Bragg gratings (FBGs), switching performance was realized by controlling peak wavelength of FBGs independently [1, 2]. The polarization-maintaining long-period fiber grating within a ring cavity was applied to switch lasing wavelength [3]. A switchable external cavity laser based on a Fabry–Pérot laser diode incorporating a sampled FBG was demonstrated [4]. The switchable triple-wavelength laser by using a polarization-maintaining (PM) FBG within a Sagnac loop mirror was realized by controlling input polarization states [5, 6]. A pair of long-period fiber gratings was applied to generation of triple-wavelength fiber laser [7]. The interleaved multi-wavelength erbium-doped fiber (EDF) laser was investigated by using a double passed Mach–Zehnder interferometer [8]. However, they realized only dual- or triple-wavelength oscillations operation, and also few lasing states for switching operation.

The Sagnac loop mirror with nonlinear polarization characteristic was employed in fiber lasers for producing multi-wavelength oscillating, wavelength switching, and mode locking [9–14]. The Sagnac loop mirror has several advantages, such as fiber flexibility, high extinction ratio, temperature insensitivity, and polarization independence [10–12]. A triple-wavelength EDF laser based on a Sagnac loop mirror was demonstrated [13, 14]. In the previous techniques, however, two different segments of Sagnac loop mirrors were exploited to control lasing wavelengths in the multi-

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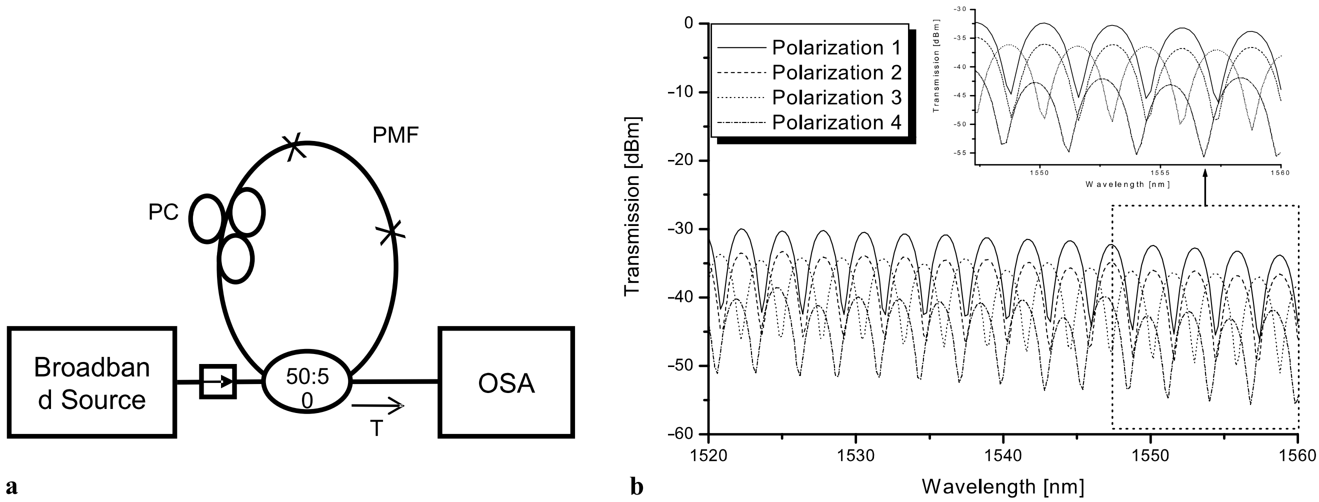

Fig. 1 (**a**) Experimental scheme for a single stage Sagnac loop mirror and (**b**) transmission spectra of the Sagnac loop mirror with variation in the SOPs

wavelength fiber laser, which had drawbacks of complicated structure of the laser cavity and additional insertion loss. It is not easy to stabilize the polarization state because of the multiple stages of Sagnac loop mirrors. Therefore, it is necessary to simply the cavity structure of the switchable multi-wavelength fiber laser.

In this paper, we present a simple configuration for a switchable multiple lasing oscillations in an EDF laser using a single stage of a Sagnac loop mirror which is operated as a transmission-type comb filter in a laser cavity. Since the wavelength-dependent transmission spectra of a Sagnac loop mirror controls the multi-wavelength output of the proposed EDF laser, multiple lasing outputs can be switchable effectively by adjusting the polarization states of a Sagnac loop mirror. Various lasing outputs in states of single-, dual-, triple- and quadruple-wavelength oscillations were obtained by controlling transmission characteristics of a Sagnac loop mirror. By suppressing homogeneous line broadening of erbium ions, seven lasing wavelengths were achieved.

2 Transmission characteristics of a Sagnac loop mirror

Figure 1(a) shows the experimental scheme for the Sagnac loop mirror which is configured by a 3-dB directional coupler, a polarization-maintaining fiber (PMF), and a PC. The PC consists of two quarter-wave plates and one half-wave plate. The PMF with a birefringence of 2.4×10^{-4} and a length of 3.445 m induces the phase shift within the Sagnac loop mirror. In a Sagnac loop mirror, the interference pattern resulting from phase difference between two counter-propagating lightwaves in opposite direction can provide a multi-wavelength filter function. Figure 1(b) shows transmission spectra corresponding to different SOPs of the

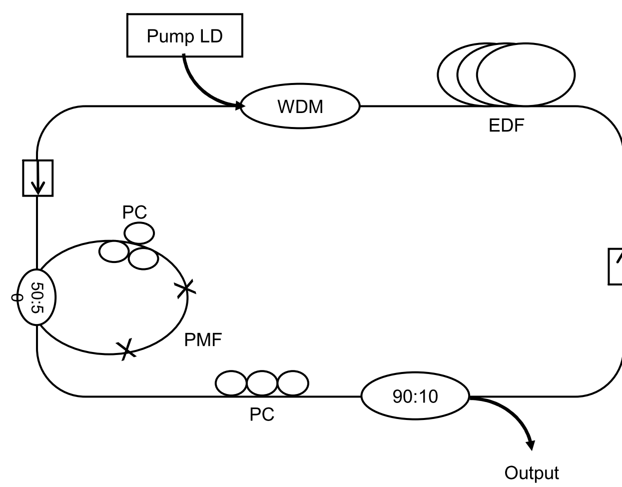

Fig. 2 Experimental setup for the proposed switchable multi-wavelength EDF ring laser based on a single stage Sagnac loop mirror

Sagnac loop mirror controlled by the PC. The transmission characteristics of a single stage Sagnac loop mirror can be expressed by using Jones matrix [15]. The transmittivity (T(λ)) of the single stage Sagnac loop mirror with a 3-dB directional coupler is given by [15]

$$T(\lambda) = \left(\sin(\theta)\cos\left(\frac{\beta}{2}\right)\right)^2, \qquad \beta = \frac{2\pi \Delta n L}{\lambda}, \tag{1}$$

where θ is the rotation angle of the polarization state controlled by the PC, L is the length of the PMF, and Δn is the refractive index difference of the fast and the slow axes. Since a single stage Sagnac loop mirror includes the PMF for phase retardation and the PC for polarization rotation,

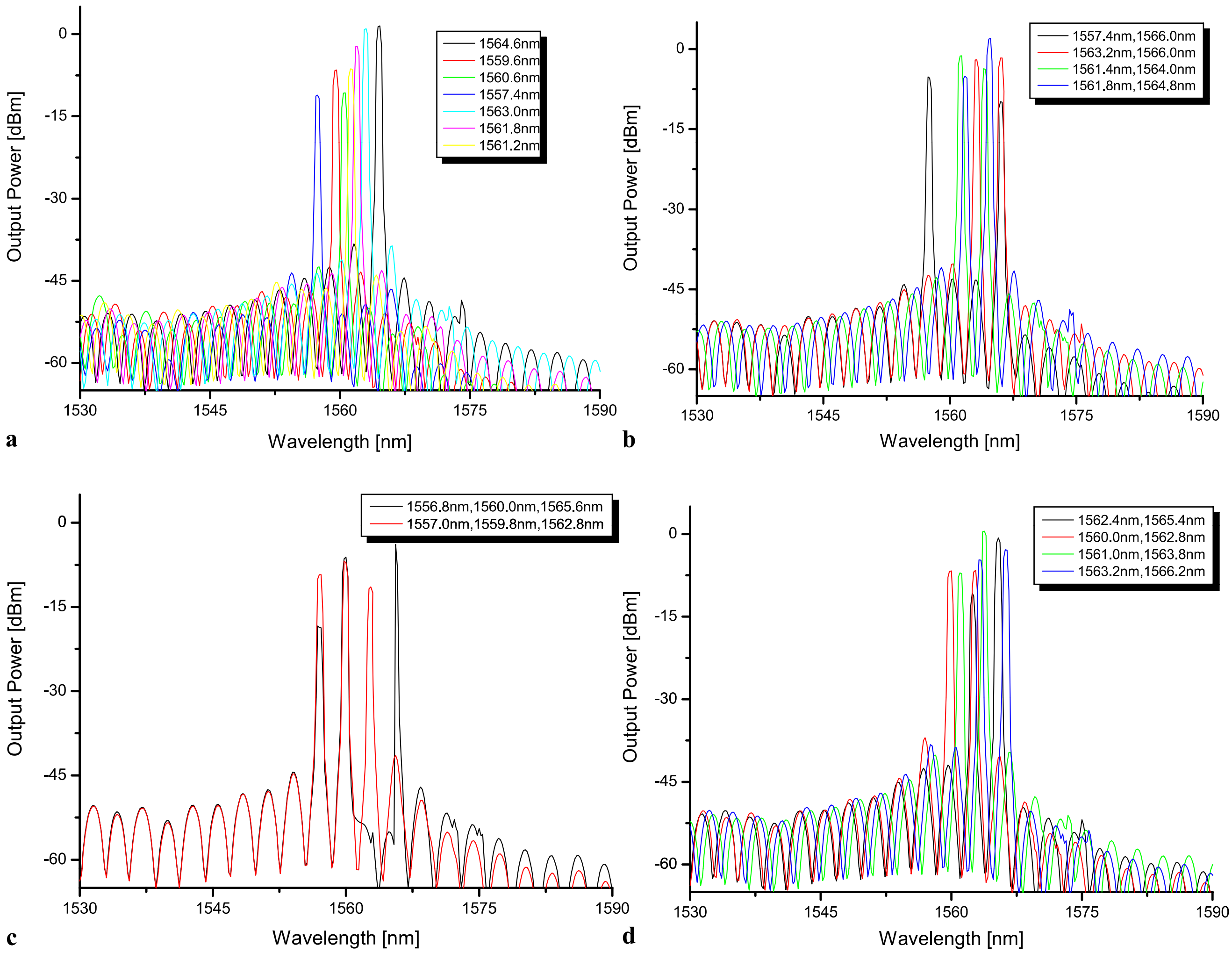

Fig. 3 Output spectra of switchable multiple lasing oscillations in the proposed multi-wavelength EDF laser at room temperature: (**a**) single-wavelength oscillating lasers, (**b**) dual-wavelength oscillating lasers, (**c**) triple-wavelength oscillating lasers, and (**d**) dual-wavelength oscillating lasers

the different phase shift in according to different SOPs can be induced by adjusting azimuthal angles of the PC. When the quarter-wave plate in the PC is adjusted from 0 to π in a condition of the half-wave plate set to $\pi/4$ and the other quarter-wave plate set to $\pi/6$, the one periodic transmission spectrum can be created. When the half-wave plate is adjusted from 0 to π in a condition of two quarter-wave plates set to $\pi/2$ and $\pi/9$, respectively, the two types of periodic transmission spectra with different transmission peak powers can be obtained [14, 16]. It means that versatile lasing states in a single-, dual-, and triple-oscillations of the multi-wavelength EDF laser can be generated by controlling SOPs within a single stage Sagnac loop mirror. In all transmission spectra of the Sagnac loop mirror, the peak wavelengths can be switched as the each wave plate is adjusted. These results show that the multi-wavelength outputs can be switched effectively by changing the SOPs.

3 Switchable multi-wavelength EDF laser with multiple lasing oscillations

Figure 2 shows the scheme for the proposed switchable multi-wavelength EDF laser with multiple lasing oscillations based on the single stage of a Sagnac loop mirror. The proposed switchable multi-wavelength fiber laser consists of an EDF with a length of 28 m, a 980-nm pump laser diode (LD), a 980/1550 nm WDM coupler, a PC, a 90:10 output coupler, an optical isolator, and a single stage of a Sagnac loop mirror. The 980-nm pump signal was injected in the opposite direction from the lasing signal using two optical isolators. The 28-m EDF with a peak absorption coefficient of 6.5 dB/m at 1530 nm was pumped by using a 980-nm LD with a power of 300 mW through a WDM coupler. The PC in the ring cavity was exploited to control polarization states. The laser output of 10% was monitored by an optical

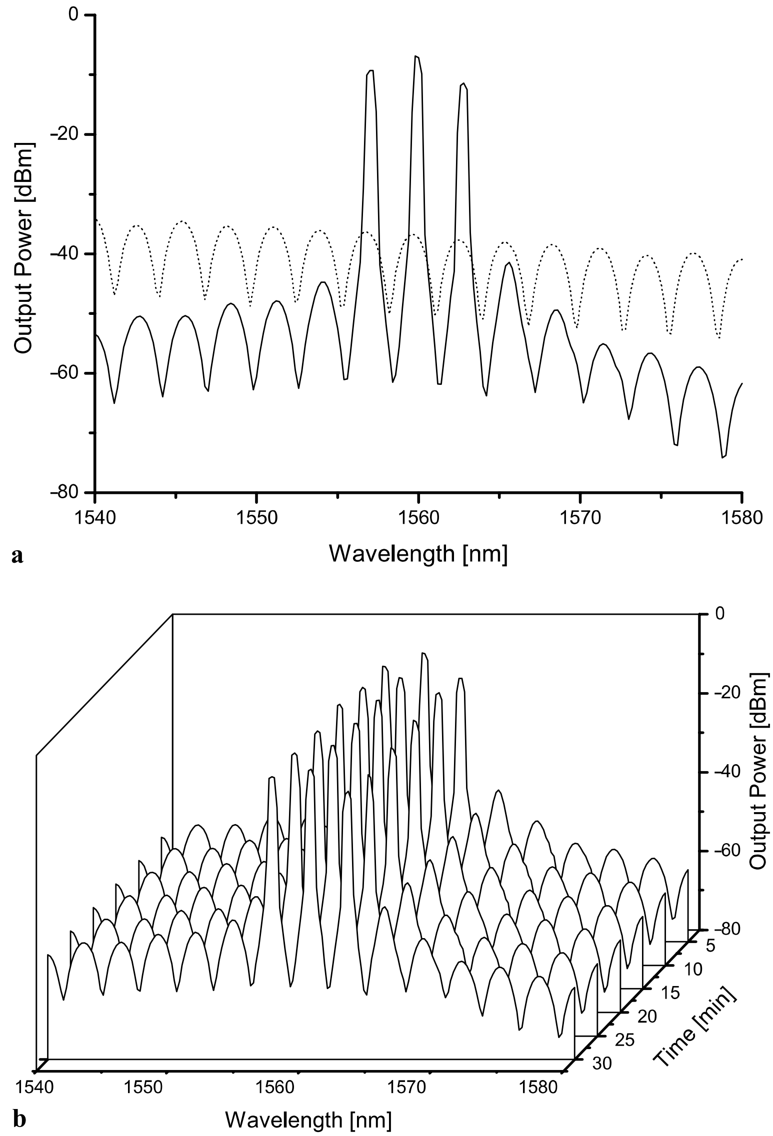

Fig. 4 (**a**) Output spectra of triple-wavelength EDF laser. (**b**) Repeated scans of optical spectra of triple-wavelength EDF laser

spectrum analyzer (OSA), and the 90% of laser output was repeatedly circulated within the ring cavity.

A single stage of a Sagnac loop mirror can select lasing wavelengths of the multi-wavelength output in the EDF laser cavity. The filter spectrum strongly depends on the SOPs in a Sagnac loop. Since two wave plates control the phase within a Sagnac loop mirror depending on wavelength, the periodic transmission spectrum of a Sagnac loop mirror can be tuned finally. It means that the versatile filter functions with different peak powers and different peak wavelengths depending on wavelength can be generated. Controlling peak powers of a Sagnac loop mirror induces wavelength-dependent cavity loss within the laser ring cavity. Lasing output can be created at a certain wavelength where the cavity loss is minimized because of mode competition of the EDF. Therefore, switching performance of the multi-wavelength fiber laser can be achieved. We simply obtained the switchable multi-wavelength fiber laser by using a single stage of a Sagnac loop mirror. Figure 3 shows various lasing outputs, such as a single-, dual-, and triple-lasing oscillations. The multi-wavelength outputs were switched independently by arbitrary controlling the PC inside the Sagnac loop mirror. As seen in Fig. 3(a), a single lasing output was switched and seven different lasing spectra were generated by controlling the PC within the Sagnac loop mirror. By changing the wavelength-dependent cavity loss regarding the phase of the Sagnac loop mirror, dual- or triple-lasing oscillations were generated. As seen in Fig. 3(b), 3(c), and 3(d), multi-wavelength outputs were switched by adjusting the PC as similar as the case of the single lasing operation. The PC placed outside the Sagnac loop mirror did not change the laser outputs. It means that a Sagnac loop mirror is independent on the incident polarization state [14].

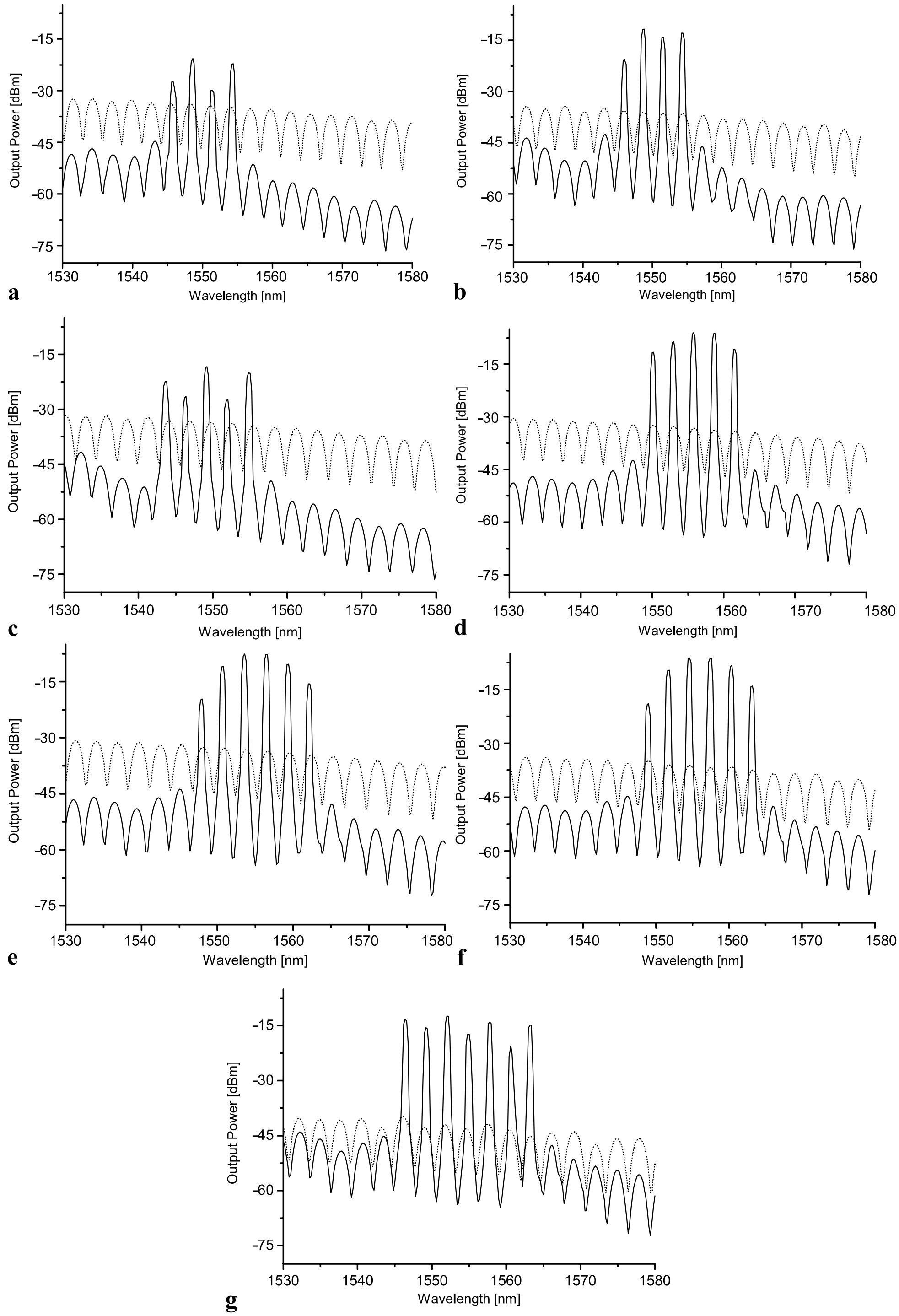

Fig. 5 Output spectra of switchable multi-wavelength EDF laser at cryogenic temperature

Figure 4(a) shows output spectra of the triple-wavelength EDF laser. The solid and dot lines show the output spectrum of the multi-wavelength EDF laser and the corresponding transmission spectrum of the Sagnac loop mirror, respectively. The triple-wavelength outputs at lasing wavelengths of 1557 nm, 1559.8 nm, 1562.8 nm were achieved, which were consistent with peak wavelengths of the Sagnac loop mirror. The peak powers of triple-wavelength lasing outputs were −9.3 dBm, −6.9 dBm, and −11.4 dBm, respectively. To validate the operation stability of the triple-lasing EDF laser at room temperature, lasing spectra were repeatedly scanned during 30 min with 5-min intervals, as shown in Fig. 4(b). Power fluctuations for three lasing outputs were measured to be 2.4 dB, 0.6 dB, and 2.9 dB. A wavelength shift for three lasing outputs was measured to be 0.2 nm. It is evident that the output of the proposed triple-wavelength

EDF is unstable at room temperature because of mode competition of erbium ions. Mode competition of erbium ions should be suppressed by the use of cooling the EDF at cryogenic temperature to obtain stable switchable multi-wavelength oscillations.

Figure 5 shows output spectra of the proposed switchable multi-wavelength EDF laser and corresponding transmission spectra of the Sagnac loop mirror when the EDF was cooled down by using liquid nitrogen. Multi-wavelength oscillations were achieved by mitigating mode competition of erbium ions at cryogenic temperature (77 K). The multi-wavelength switching performance of the proposed multi-wavelength EDF laser was obtained by adjusting PC inside the Sagnac loop mirror. The four-, five-, six-, and seven-wavelength oscillation spectra (the solid lines) of the multi-wavelength EDF laser were observed, which corresponded to the transmission spectra (the dot lines) of the Sagnac loop mirror. In Figs. 5(a) and 5(b), the four-wavelengths fiber lasers were switched. Once the transmission characteristic of the Sagnac loop mirror was precisely controlled by using the PC, the seven-lasing-wavelength fiber laser could be realized as seen in Fig. 5(g). However, it is not evident if the proposed multi-wavelength has a single longitudinal mode because of the long cavity length. The output power has somewhat low stability because optical components, such as a 3-dB coupler and two isolators have different bandwidth and different operating wavelengths. When the multi-wavelength lasing outputs are switched, the output flatness is degraded because of the inequality of cavity loss. These limitations of the proposed switchable multi-wavelength fiber laser should be improved.

4 Conclusions

In conclusion, we demonstrated a simple configuration for a switchable multiple lasing oscillations in an EDF ring laser using a single stage of a Sagnac loop mirror. The Sagnac loop mirror was implemented to be a transmission-type comb filter in a ring cavity. By adjusting the PC inside a Sagnac loop mirror, versatile wavelength-dependent transmission spectra of a Sagnac loop mirror was obtained by controlling the SOPs, which clearly showed the possibility of different laser oscillations at different wavelengths. Various lasing outputs with random combinations in states of single-, dual-, triple- and quadruple-wavelength oscillations were achieved. The multiple lasing outputs of the proposed multi-wavelength EDF laser were effectively switched by controlling the PC.

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