Stable and tunable multi-wavelength erbium-doped fibre laser with cascaded Sagnac loops incorporating polarization-maintaining fibres

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A tunable multi-wavelength erbium-doped ring cavity fibre laser based on a cascaded Sagnac loop comb filter was developed. The hybrid filter is composed of two Sagnac loops with different lengths of polarization-maintaining fibres. Tunable and stable single-, double-, and triple-wavelength lasers were realised experimentally with wavelength shifts and power fluctuations of <0.04 nm and <1.93 dBm, respectively. The side mode suppression ratio was >40.11 dB, and the 3-dB laser linewidth was <0.05 nm. Quadruple- and quintuple-wavelength lasers were achieved by adjusting the polarization controller, and the side mode suppression ratio was >38.56 dB.

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Keywords: Multi-wavelength, Erbium-doped fibre laser, Sagnac loop, Polarization controller

1. Introduction

Multi-wavelength fibre lasers have attracted significant attention in areas such as fibre sensing, optical communications, dense wavelength division multiplexing, and microwave generation [1–5] because of their numerous advantages, such as their dense lasing wavelengths, high signal-to-noise ratios, flexible and tunable lasing scopes, and long working lives [6–8]. Several techniques have been proposed for realising multi-wavelength fibre lasers. Shamsudin et al. [10] reported on a multi-wavelength thulium-doped fibre laser based on a broadband mirror and flat-cleaved fibre end with a tuning spacing of 1.2 nm and noise ratio of more than 27 dB. Gong et al. [11] proposed a multi-wavelength tunable thulium-doped fibre laser using a Sagnac loop as a filter with a 2.5 nm wavelength interval in the range from 1898 nm to 1915 nm and a side-mode suppression ratio (SMSR) of 45 dB. Zhou et al. [12] realised a multi-wavelength Brillouin erbium-doped fibre laser with 0.16 nm spacing. Zou et al. [13] constructed a double-wavelength laser based on a double-pass Mach–Zehnder interferometer filter with a twin-core fibre with a double-wavelength laser shift and power fluctuation of about 0.02 nm and 0.35 dB, respectively. Al-Mashhadani et al. [14] constructed a tunable multi-wavelength Brillouin erbium fibre laser with a 24.4 nm tuning scope. Kim and Han [15] reported on a switchable multi-wavelength fibre laser based on a single Sagnac loop with a polarization-maintaining fibre; they realised a stable quadruple-wavelength laser with a wavelength interval of 3 nm. Sun et al. [16] achieved a switchable multi-wavelength fibre ring laser by using a Sagnac loop with a few-mode, high-birefringence fibre; they obtained a triple-wavelength laser with a 2-nm wavelength interval.

As described above, multi-wavelength fibre lasers can be realised with different methods, including photonic crystal fibres [17], Brillouin fibres [18], single Sagnac loops [19], multi-mode fibres, and highly nonlinear fibres [20]. To achieve multi-wavelength fibre lasers, external non-fibre components and complex structures are often used. Thus, researching efficient methods of realising tunable and stable multi-wavelength fibre lasers is a worthwhile endeavour. In our study, we constructed an erbium-doped fibre laser based on a double Sagnac loop comb filter. The use of double Sagnac loops in the ring cavity fibre laser is novel and enables the realisation of tunable and stable multi-wavelength lasers at room temperature.

2. Experimental setup

The proposed fibre laser scheme is depicted in Fig. 1. The experimental system was composed of one 976 nm pump laser; one 980/1550 nm wavelength-division multiplexer (WDM); one 10:90 optical coupler (OC); two 2 × 2, 3 dB OCs; two polarization-maintaining fibres (PMFs) with different lengths; one circulator; one broadband metal reflector; and two polarization controllers (PCs). For each of the components, the pigtail fibre size was 10/125 μm. The pump light was coupled to the laser cavity with the WDM, and a 4-m-long erbium-doped fibre (EDF) was used as the gain medium. The comb filter was composed of double Sagnac loops, and each loop was fabricated with a 3 dB OC, PMF, and PC. The reflector was utilised as the wavelength selector.

In some experiments, an isolator is typically used in the ring cavity fibre laser. The isolator is inserted between the two loops to reduce the influence of two Sagnac loops; moreover, the isolator is used to confirm the direction of light transmission. In the proposed fibre laser, one circulator is used in the ring cavity. The circulator has three ports, the light can be coupled into port one and reflected by broadband reflector through port 2, and then the light exports from port 3. In the experiment, because of the circulator used in the ring cavity, the light transmission direction can be guaranteed. An optical spectrum analyser (OSA, YOCOGAWA 6370C) was employed to monitor the laser spectrum from the exit port of a 1 × 2, 10:90 coupler.

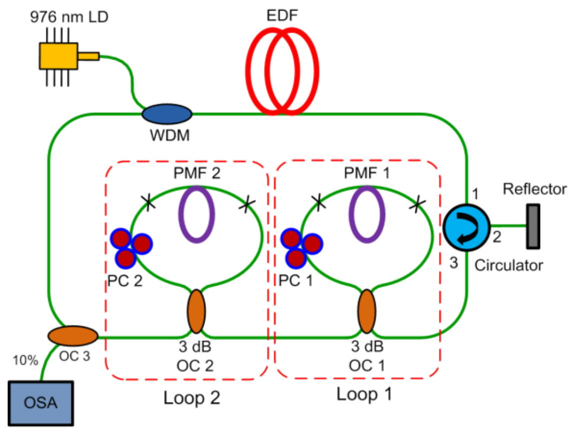

Fig. 1. Setup of the multi-wavelength laser based on double Sagnac loops

When the single Sagnac loop was used, the comb spectrum wavelength spacing can be calculated using Eq. (1), where λ is the transmission wavelength, Δn is the birefringence, and L represents the PMF length. The wavelength interval $\Delta\lambda$ is inversely proportional to L. By using cascaded loops, when optimum fibre length ratio of PMF1 and PMF2 is 2:1, the maximal side mode suppression ratio (SMSR) of Sagnac loop transmissivity is realised. When the dual loops were inserted into the Sagnac loop, a prominent adjusting effect could be achieved. For the proposed cascaded Sagnac filter, the filter design methods can be expanded, a greater filtering effect can be achieved, and more accurate tuning ability can be realised.

$$\Delta\lambda = \frac{\lambda^2}{\Delta n L} \tag{1}$$

For the proposed multi-wavelength fibre laser, the comb filter was composed of double Sagnac loops. Loops 1 and 2 were fabricated by using two PMFs with lengths of 2 m and 1 m, respectively, and two 2 × 2, 3 dB couplers. The input light was injected into Loop 1 at the input port of OC1, and the reflected light of Loop 1 was ejected from the output ports of OC1. Then, the light was coupled into Loop 2 by the input port of OC2. Finally, the light transmitted by the double Sagnac loops was exported from the output ports of OC2. When the input light passes through a single Sagnac loop, the transmitted light can be described by Eq. (2):

$$\begin{cases} T = [\frac{1}{2}(1+\mathrm{e}^{\frac{i2\pi L\Delta n}{\lambda}})\sin(\theta_1+\theta_2)]^2 = (\cos\frac{\beta\lambda}{2}\sin\varphi)^2 \\ \varphi = \theta_1+\theta_2 \\ \beta = \frac{2\pi L\Delta n}{\lambda} \end{cases}, \tag{2}$$

where θ_1 is the rotary angle of the polarised light after transmission through the PMF, θ_2 is the rotary angle of the polarised light after transmission through the single-mode fibre and PC, λ is the wavelength of the light, β is the propagation constant of the loop, L is the length of the PMF, and Δn is the refringence difference. For the double Sagnac loops, the output light intensity I_{out} is given by

$$\begin{cases} I_{out} = t_1 t_2 I_{in} = (\cos\frac{\beta_1\lambda}{2}\sin\varphi_1)^2 I_{in} = C(\cos\frac{\beta_1\lambda}{2}\cos\frac{\beta_2\lambda}{2})^2 I_{in} \\ C = (\sin\varphi_1\sin\varphi_2)^2 \end{cases}, \tag{3}$$

where I_{in} is the input light intensity; t_1 and t_2 are the transmission rates of Loops 1 and 2, respectively; φ_1 and φ_2 are the rotary angles of the polarised light after transmission through Loops 1 and 2, respectively; β_1 and β_2 are the propagation constants of Loops 1 and 2, respectively; and C is a constant that represents the magnitude of the output light.

The cascaded Sagnac loop simulation transmission curve is shown in Fig. 2, the SMSR is more than 20 dB, however, the effect cannot be realised by one Sagnac loop. Through the cascaded Sagnac loops, the filter design methods can be expanded, the more abundant filtering effect can be achieved, and more accurate tuning ability can be realised. In the experiment, the laser stability is improved by using two Sagnac loops, and the spectrum can be adjusted by changing PC. By using double Sagnac loops, the optimum ratio between the length of PMF1 and PMF2 is 2:1, and a filter effect better than that attainable using a single Sagnac loop can be achieved.

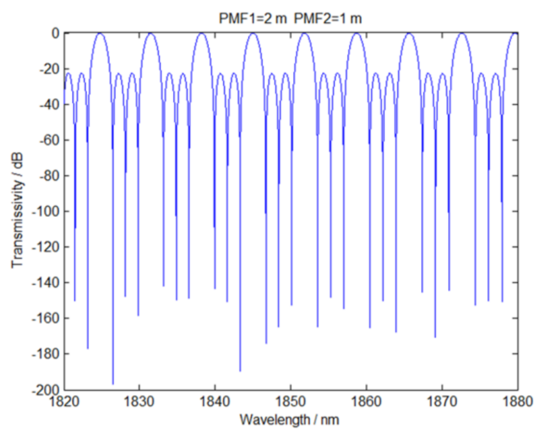

Fig. 2. Cascaded Sagnac loop simulation transmission curve

3. Experimental results and discussion

In the experiment, a laser diode (LD) produced by Oclaro Co. and an OC, a circulator, and a WDM manufactured by Lightcomm Co. were used. The effect of our proposed double Sagnac loop filter was experimentally tested. A broadband laser was injected into the filter, and the OSA was used to obtain the transmission spectrum. As shown in Fig. 3(a) for the single Sagnac loop, when the PMF was 2 m long, the comb filter spectrum was collected in the range from 1500 nm to 1580 nm, and the filter interval $\Delta\lambda$ was about 4 nm. By adjusting the PC, the comb filter spectrum was obtained under different polarization conditions in the range from 1540 nm to 1560 nm, and the resulting spectrum is presented in Fig. 3(b). $\Delta\lambda$ was not changed.

Fig. 3(c) depicts the comb filter transmission spectrum in the range from 1500 nm to 1580 nm when the input light was injected into the double Sagnac loops and the lengths of PMF1 and PMF2 were 2 m and 1 m, respectively. As shown in Fig. 3(d), $\Delta\lambda$ was about 1.5 nm for the double Sagnac loops. Compared with the single Sagnac loop, the proposed double Sagnac loops yielded a higher contrast ratio and narrower wavelength interval.

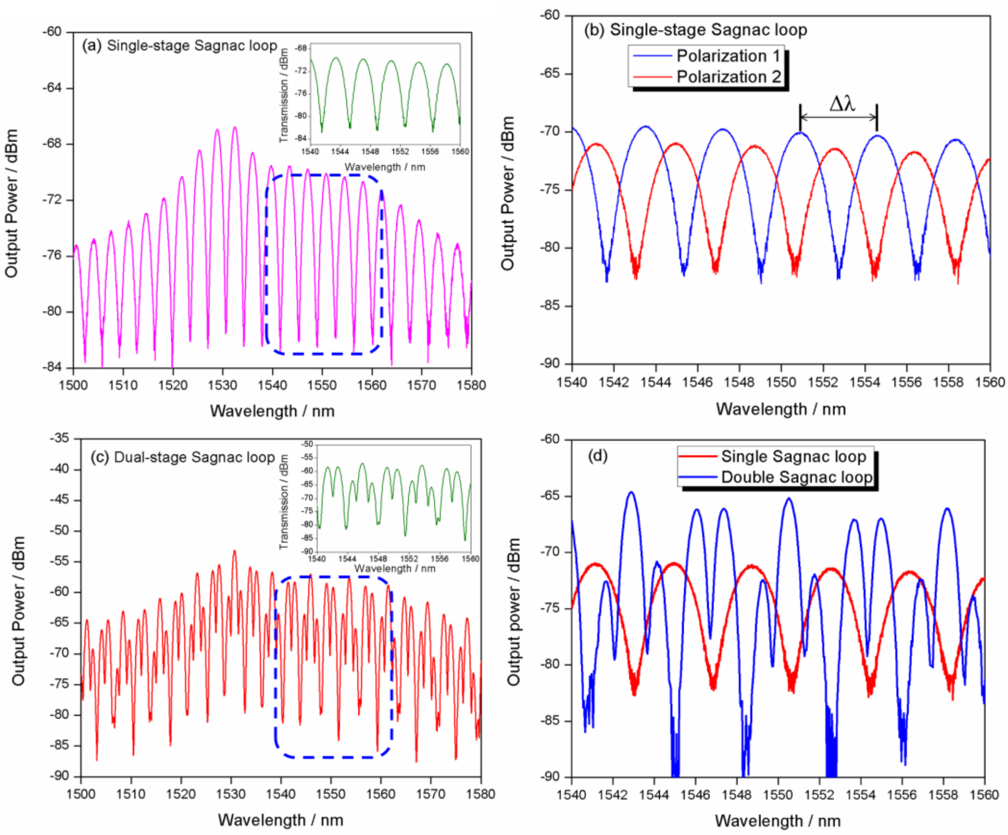

Fig. 3. (a) Transmission spectrum of the single Sagnac loops within 1500–1580 nm; (b) single Sagnac loops within 1540–1560 nm; (c) transmission spectrum of the double Sagnac loops within 1500–1580 nm; (d) double Sagnac loops within 1540–1560 nm

Then, the double Sagnac loop comb filter was inserted into the ring cavity. When the pump power was 30 mW, single-wavelength lasing at 1558.8 nm was produced. As can be seen from Fig. 4, using the proposed filter enhanced the laser spectrum. In the experiment, when filter was not used, the laser was realised at around 1566 nm with a considerably large number of longitudinal modes. On the contrary, when filter was used, the laser was realised at around 1558.8 nm, because two PCs in the loops were adjusted and the wavelength tuning effect was subsequently achieved. In addition, the fibre laser length and intracavity loss were changed after the filter was used; therefore, lasers were not of the same wavelength.

Fig. 5(a) shows that when the pump power was 80 mW, switchable single-wavelength lasers at 1557.3 nm, 1558.8 nm, and 1560.2 nm were realised by adjusting the two PCs. As shown in Fig. 5(b), when the 1558.8 nm laser was produced, the peak power and SMSR were -15.63 dBm and 52.6 dB, respectively. Similarly, the peak power and SMSR of the 1560.2 nm laser were -13.99 dBm and 51.44 dB, respectively, while those of the 1557.3 nm laser were -14.89 dBm and more than 51.91 dB, respectively. The 3-dB linewidth of the single-wavelength laser was less than 0.05 nm.

The stability of the single-wavelength laser was monitored. When 1558 nm lasing was realised over a scanning time of 10 min at room temperature, as shown in Fig. 6(a), no mode jumping was observed. Fig. 6(b) demonstrates that the wavelength shift and peak power fluctuation were less than 0.04 nm and 0.65 dB, respectively. The proposed fibre laser exhibited high stability when the laser was operated under the single-wavelength conditions.

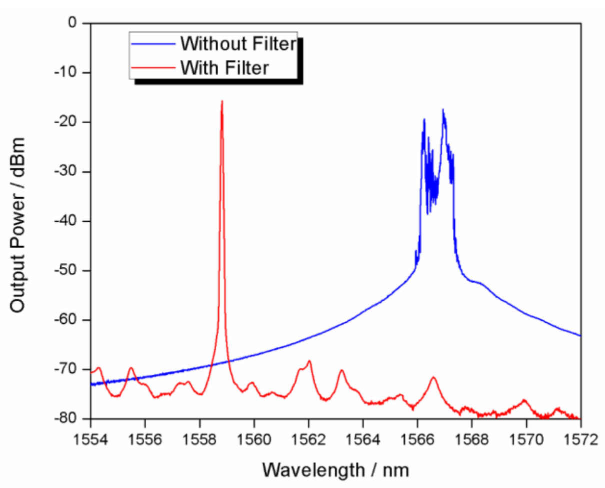

Fig. 4. Laser spectrum before and after using the filter

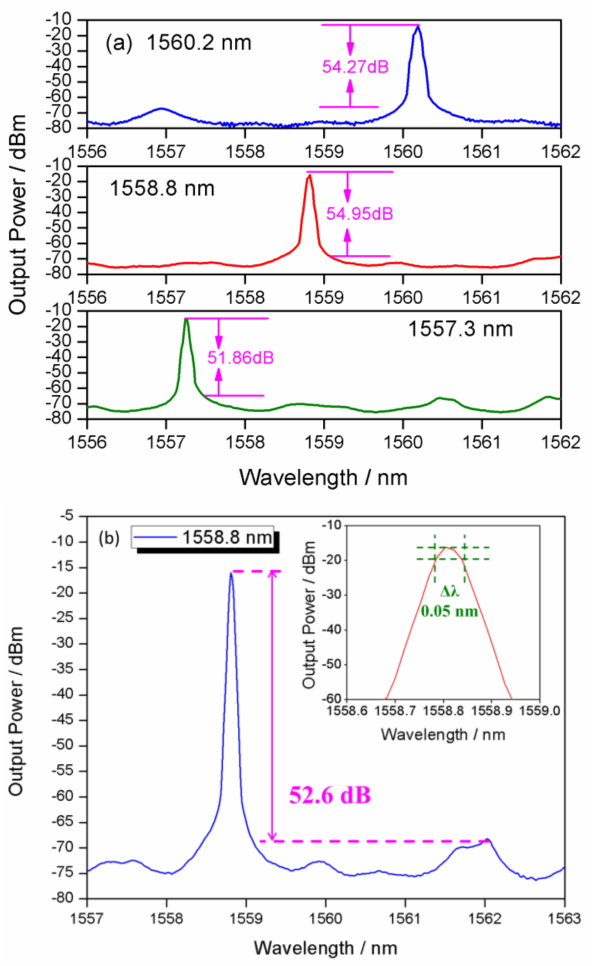

Fig. 5. (a) Single-wavelength tuning ability; (b) spectrum of the 1558.8-nm laser

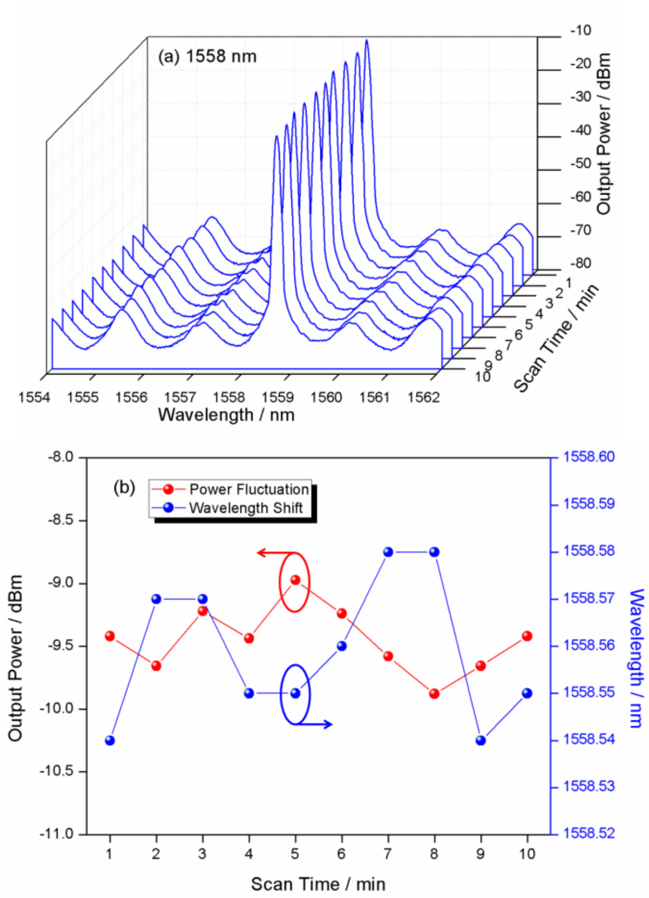

Fig. 6. (a) Scanning spectrum and (b) stability of the 1558 nm laser

When the pump power was 80 mW, a tunable double-wavelength laser was obtained by adjusting the PC. As shown in Fig. 7(a), 1555.5 nm and 1558.4 nm lasers were produced simultaneously with a peak power difference of 2.01 dBm. When 1557.2 nm and 1558.8 nm lasers were realised, the peak power difference was 3.49 dBm, and similarly, when 1557.2 nm and 1560.4 nm lasers were achieved, the peak power difference was 0.89 dBm. The SMSR was more than 44.25 dB, and the 3-dB laser linewidth was less than 0.05 nm when the double-wavelength laser was realised in the experiment. When the 1557.2 nm and 1560.4 nm double-wavelength laser was produced within a 10-min scanning time at room temperature, as shown in Fig. 7(b), the double-wavelength fibre laser exhibited good stability and no mode jumping. The wavelength variation and peak power fluctuation for the 1557.2 nm laser were less than 0.04 nm and 0.53 dB, respectively, and they were 0.02 nm and 0.78 dB, respectively, for the 1560 nm laser, as shown in Figs. 7(c) and 7(d).

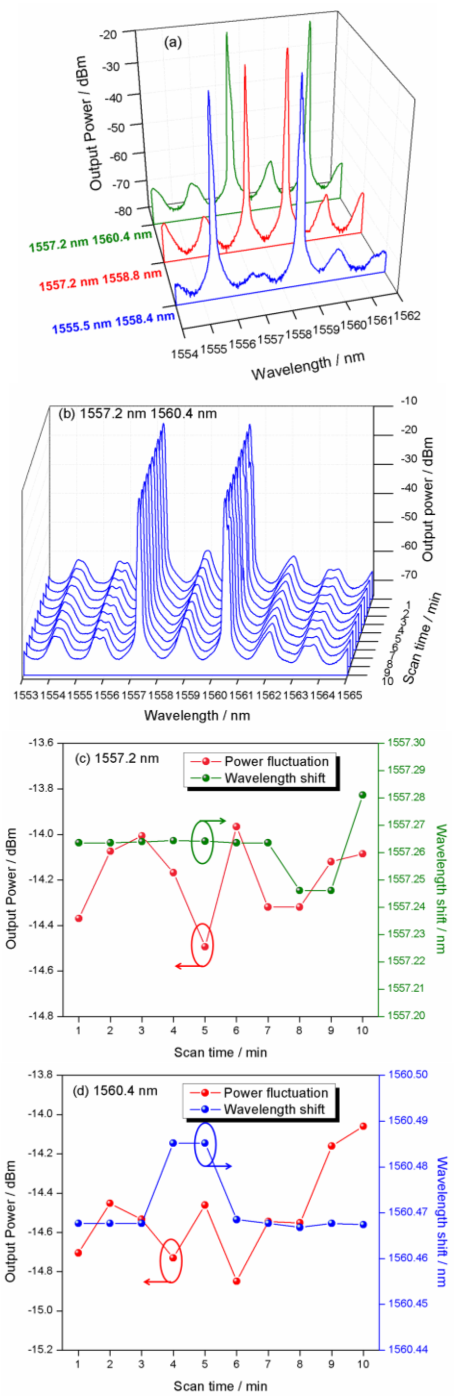

Fig. 7. (a) Tunable double-wavelength laser; (b) spectrum of the double-wavelength laser obtained by scanning for 10 min; (c) stability of the 1557.2 nm laser; (d) stability of the 1560.4 nm laser

A tunable triple-wavelength laser was realised by changing the polarization condition under the same pump power. As shown in Fig. 8(a), when 1555.4, 1558.5, and 1561.6 nm lasers were produced, the peak powers were −24.26, −14.74, and −15.96 dBm, respectively, and the maximum peak difference was 9.52 dBm. When the 1557, 1558.5, and 1561.6 nm triple-wavelength fibre laser was obtained, the maximum peak difference was 5.83 dBm. When the 1557.3, 1558.9, and 1560.5 nm lasers were realised simultaneously, the maximum peak difference was less than 2.35 dBm. The SMSR was more than 40.11 dB, and the laser 3-dB linewidth was less than 0.05 nm for the obtained triple-wavelength lasers. As shown in Fig. 8(b), obvious mode hopping was not observed within a 10-min scanning time when the 1557, 1558.5, and 1561.6 nm lasers were produced simultaneously. The wavelength shift and power fluctuation were less than 0.02 nm and 1.93 dB, respectively, for the 1557 nm laser; 0.02 nm and 1.26 dB, respectively, for the 1558.5 nm laser; and 0.02 nm and 1.65 dB, respectively, for the 1561.6 nm laser. These are shown in Figs. 8(c) and (d).

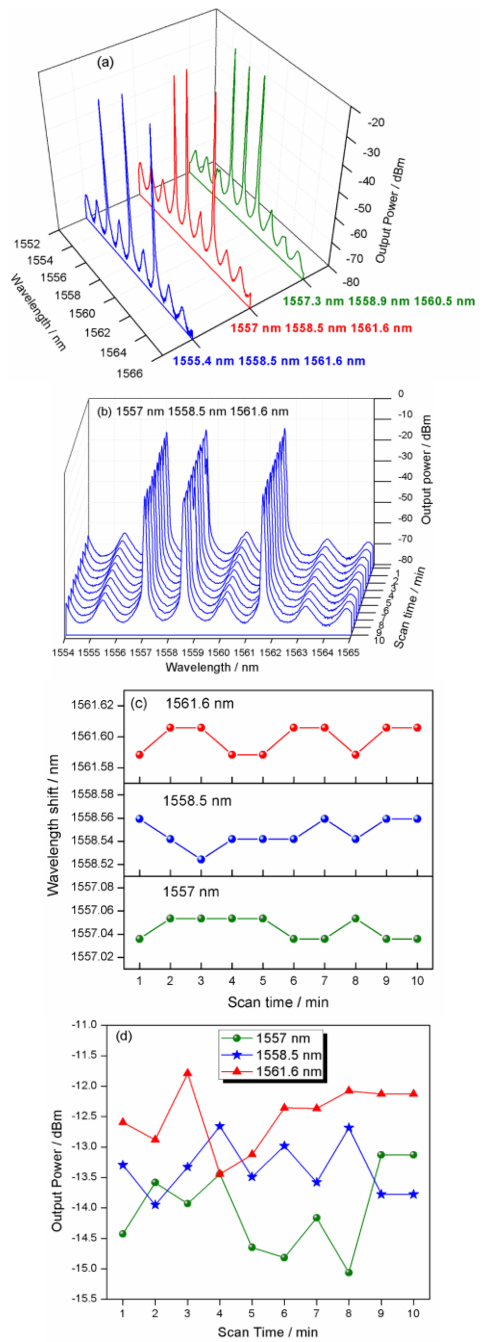

Fig. 8. (a) Tunable triple-wavelength laser; (b) spectrum of the triple-wavelength laser obtained by scanning for 10 min; (c) wavelength stability of the triple-wavelength laser; (d) power stability of the triple-wavelength laser

A quadruple-wavelength laser was realised by adjusting the PC when the pump power was 80 mW. As shown in Fig. 9(a), lasers were produced at 1555.4, 1557.1, 1558.5, and 1561.6 nm, and the maximum peak power difference was 13.20 dBm. When the fibre laser was working under polarization condition 2, as shown in Fig. 9(b), lasers were realised at 1555.4, 1558.5, 1560.2, and 1561.6 nm, and the maximum peak power difference was 4.17 dBm. Similarly, the peak power difference was 6.25 dBm when a quadruple-wavelength laser was obtained at 1557.1, 1558.6, 1560.2, and 1561.6 nm, as shown in Fig. 9(c). The SMSR was more than 38.56 dB, and the laser 3-dB linewidth was less than 0.05 nm for the quadruple-wavelength laser.

Finally, as shown in Fig. 10, a quintuple-wavelength laser was realised at 1555.4, 1556.9, 1558.5, 1560.2, and 1561.6 nm by adjusting the PC in the experiment. The peak power difference was 4.12 dBm. The laser 3-dB linewidth was less than 0.05 nm, and the SMSR was more than 44.76 dB. The double Sagnac loop filter showed a narrower filter interval space than the single Sagnac loop.

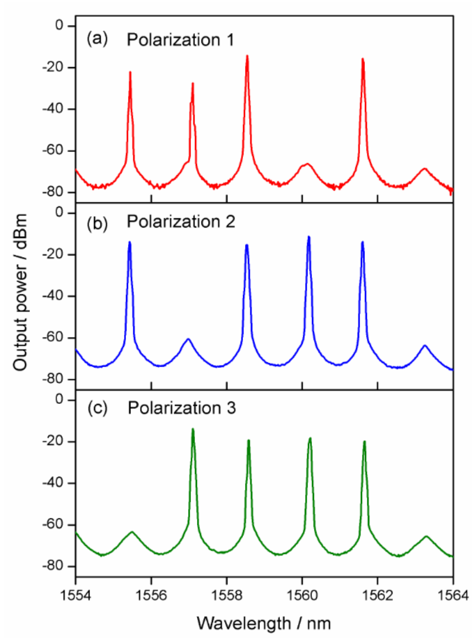

Fig. 9. Tunable quadruple-wavelength laser

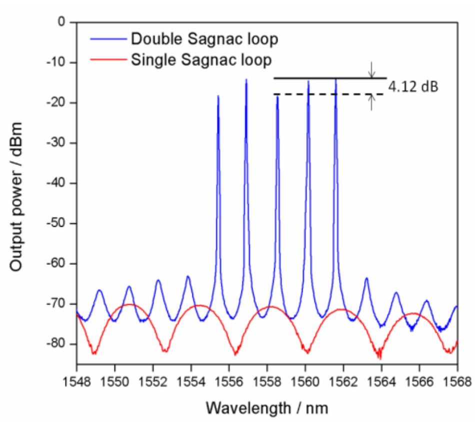

Fig. 10. Quintuple-wavelength laser

4. Conclusion

In this study, a multi-wavelength erbium-doped fibre laser based on a double Sagnac loop comb filter was realised. In the experiments, switchable and stable single-, double-, and triple-wavelength lasers were achieved. The laser 3-dB linewidth was less than 0.05 nm, the SMSR was more than 40.11 dB, and the wavelength shift and peak power fluctuation were less than 0.04 nm and 1.93 dB, respectively. Tunable quadruple- and quintuple-wavelength lasers were realised in the experiment; the SMSR was larger than 38.56 dB, and their 3-dB linewidths were less than 0.05 nm. The approach in this study can be used to realise stable and tunable multi-wavelength operation. The proposed fibre laser has clear applications in optical sensors, fibre communications, and spectral analysis.

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References

[1] J. Q. Cheng, L. L. Zhang, K. Sharafudeen, Z. J. Ma, J. R. Qiu, Laser Phys. **24**, 015102 (2014).
[2] M. T. Ahmad, A. A. Latiff, H. Shamsudin, Z. Zakaria, H. Ahmad, S. W. Harun, Optoelectron. Adv. Mat. **9**(5-6), 623 (2015).
[3] W. He, C. M. Shangguan, L.Q. Zhu, M. L. Dong, F. Luo, Optik. **137**, 254 (2017).
[4] T. S. Wang, X. F. Miao, X. F. Zhou, S. Qian, Appl Optics. **51**(10), C111 (2012).
[5] T. G. Sun, Y. B. Guo, T. S. Wang, J. Y. Huo, L. Zhang, Opt. Laser Technol. **67**, 143 (2015).
[6] J. J. Sun, Z. F. Wang, M. Wang, Z. Y. Zhou, N. Tang, J. B. Chen, X. J. Gu, Appl. Optics **56**(32), 9114 (2017).
[7] M. Duran-Sanchez, R. I. Alvarez-Tamayo, B. Posada-Ramirez, B. Ibarra-Escamilla, E. A. Kuzin, J. L. Cruz, M. V. Andres, IEEE Photonic Tech. L. **29**(21), 1820 (2017).
[8] M. V. Hernandez-Arriaga, M. Duran-Sanchez, B. Ibarra-Escamilla, R. T. Alvarez-Tamayo, H. Santiago-Hernandez, M. Bello-Jimenez and E. A. Kuzin. J. Optics, **19**(11), 115704 (2017).
[9] R. Anirban, A. L. Chakraborty, C. K. Jha, Appl. Optics **56**(12), 3562 (2017).
[10] H. Shamsudin, A. A. Latiff, N. N. Razak, H. Ahmad, S. W. Harun, Optoelectron. Adv. Mat. **10**(3-4), 129 (2016).
[11] A. H. Gong, W. Z. Ma, T. S. Wang, Q. S. Jia, P.

Zhang, C. M. Wan, Microw. Opt. Technol. Lett. **57**(2), 401 (2015).
[12] X. F. Zhou, Y. Q. Liu, S. Yuan, Optik **125**, 5218 (2014).
[13] H. Zou, S. Q. Lou, W. Su, X. Wang, Appl. Phys. B **112**, 441 (2013).
[14] T. F. Al-Mashhadani, M. H. Al-Mansoori, M. Z. Jamaludin, F. Abdullah, A. K. Abass, N. I. M. Rawi, Opt. Fiber Technol. **19**, 593 (2013).
[15] R. K. Kim, Y. G. Han, Appl. Phys. B **103**, 813 (2011).
[16] G. Y. Sun, Y. W. Zhou, Y. H. Hu, Y. J. Chung, Opt. Commun. **284**, 1608 (2011).
[17] J. Q. Cheng, S. C. Ruan, Opt. Commun. **284**, 5185 (2011).
[18] N. M. Ali, S. W. Harun, K. Dimyati, H. Ahmad, J. Optoelectron. Adv. M. **14**(1-2), 13 (2012).
[19] W. He, L. Q. Zhu, M. L. Dong, F. Luo, Opt. Fiber Technol. **29**, 65 (2016).
[20] C. L. Yang, L. Xia, Y. W. Wang, D. M. Liu, Opt. Commun. **318**, 171 (2014).

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