Multi-wavelength Brillouin erbium-doped fiber laser with 40 GHz frequency shift interval assisted by Sagnac loop filter*

QI Hexin, ZHOU Xuefang, ZHANG Yinghui, YANG Guowei, BI Meihua, and HU Miao**
School of Communication Engineering, Hangzhou Dianzi University, Hangzhou 310018, China

(Received 17 July 2023; Revised 26 October 2023)

A switchable and tunable multi-wavelength Brillouin erbium-doped fiber laser (MWBEFL) is designed and experimentally demonstrated. A Sagnac loop filter is employed as the switcher to obtain the double Brillouin frequency shift (BFS) of 0.172 nm (~20 GHz) and the quadruple BFS of 0.35 nm (~40 GHz). The working principles of the proposed laser are theoretically analyzed. The experimental results show that up to 8 Stokes lines with a wavelength interval of 0.172 nm can be obtained. When the Sagnac loop filter is used, two different output spectra with wavelength interval of 0.35 nm are obtained by adjusting the polarization controller (PC) and the optical signal-to-noise ratio (*OSNR*) is greater than 33 dB. By adjusting the Brillouin pump (BP) wavelength to investigate the tunability of the fiber laser, the output of 2—5 laser channels can be realized corresponding to 20 nm wavelength range. This approach is simple and can be employed for the microwave generation of other frequency ranges subject to the filtering shift of the Sagnac loop.

Document code: A **Article ID:** 1673-1905(2024)05-0265-7
DOI https://doi.org/10.1007/s11801-024-3136-z

With the rapid development of wireless communication technology, the demand for bandwidth is increasing, and the frequency band resources in the low-frequency band are almost completely occupied, while the high-frequency microwave signals can well meet the transmission bandwidth requirements of modern communication technology[1-4]. Therefore, obtaining stable high-frequency microwave signals has become a key issue in wireless communication. The main generation methods are electron-generated microwave and photon-generated microwave. Electron-generated microwave usually has complex system structure and high cost, and is also affected by the electronic bottleneck effect, which is not suitable for the development of communication system. But photon-generated microwave not only overcomes the electronic bottleneck effect but also has a strong anti-interference ability and large bandwidth[5,6], so it attracts more attention. There are many ways to generate microwave signals using photons, such as optical heterodyne[7], optical injection locking[8-10], and optoelectronic oscillator (OEO)[11,12]. Optical heterodyne is a relatively simple technique for generating microwave signals, but there is no phase relationship between the two optical signals and the stability of the generated microwave signals is poor. Although optical injection locking can make the optical signal phase-correlated, it requires a high-quality microwave reference signal. OEO is mainly composed of a laser, electro-optic modulator, photo detector, and other devices to form a feedback loop. The advantage is that the phase noise is very low and the frequency can be tuned. For example, CHEN et al[13] proposed an OEO based on a directly modulated laser. The semiconductor laser serves as both a light source and an electro-optic modulator and obtains a microwave signal of 8.6—15.2 GHz by using single-period oscillation as a frequency selection mechanism. TANG et al[14] proposed an OEO based on a microwave photonic filter and obtained a microwave signal with a frequency tuning range of 0—40 GHz through stimulated Brillouin scattering (SBS) in highly nonlinear fiber. In addition, dual-wavelength single longitudinal mode fiber laser can also produce microwave signals[15]. FENG et al[16] demonstrated a scheme to achieve single longitudinal mode selection by using a figure-8 compound ring cavity and a polarization-managed four-channel filter, and obtained four stable single-wavelength and tunable microwave signals. However, the structure of these systems is complex, and the OEO is also affected by electronic devices, which cannot avoid the electronic bottleneck effect. Therefore, in recent years, many researchers have used Brillouin fiber lasers to generate high-frequency microwave signals.

* This work has been supported by the National Natural Science Foundation of China (No.601705055), and the Zhejiang Province Key Research and Development Program (No.2019C01G1121168).
** E-mail: zhouxf@hdu.edu.cn

SBS is an important nonlinear effect in optical fiber, and its low threshold and frequency shift characteristics contribute to the generation of microwave signals[17,18]. The frequency of the microwave signal is determined by the Brillouin frequency shift (BFS) of the Brillouin gain fiber. For the conventional quartz single mode fiber (SMF), the BFS is about 11.1 GHz. If want to output a higher-frequency microwave signal, we need to cascade the SBS effect to generate higher-order Stokes light. For example, PEDRUZZI et al[19] used nonzero dispersion shifted fiber as Brillouin gain medium and obtained microwave signals of 9.78 GHz, 19.56 GHz, and 29.12 GHz through different experimental devices. JIA et al[20] used a Brillouin fiber laser with a double-loop structure and unpumped erbium-doped fiber (EDF) to generate dual-wavelength lasers. After filtering the third order Brillouin Stokes light (BS3) by fiber Bragg grating (FBG), BS1 and BS5 can be output, so the microwave signal of 42.85 GHz is obtained. WANG et al[21] obtained a microwave signal of about 40 GHz by cascading multiple Brillouin gain fibers, but the fiber length is as long as 112 km and the pump power is as high as 1.1 W. The above system structure of generating high-frequency microwave signals based on the SBS effect is more complex, because it requires multiple Brillouin gain fibers and excessive pump power, resulting in separation from practical applications.

In this paper, we propose a multi-wavelength Brillouin erbium-doped fiber laser (MWBEFL) which combines the nonlinear effect of SBS with the Sagnac loop filter, and the BFS in SMF and the output high-order Stokes light is theoretically analyzed. When the 980 nm pump power and Brillouin pump (BP) power are 140 mW and 4 mW, respectively, adjusting the polarization controller (PC) can output two different comb spectra with a wavelength interval of quadruple BFS (0.35 nm) and optical signal-to-noise ratio (*OSNR*) is greater than 33 dB. Subsequently, the variation of output spectrum when changing 980 nm pump power and BP power is studied, and the tuning range of 20 nm is achieved by adjusting BP wavelength without the appearance of self-excited oscillation mode. The peak power fluctuation of Stokes light measured within 20 min is less than 0.5 dB, indicating that the proposed MWBEFL has stable multi-wavelength output.

BFS can be understood as that the frequency of the Stokes light will shift down relative to the frequency of the BP light, that is, there is a certain difference, and BFS can be expressed as[20]

$$V_{\mathrm{B}} = \frac{2n_{\mathrm{eff}}V_{\mathrm{a}}}{\lambda_{\mathrm{p}}}\sin(\frac{\theta}{2}), \tag{1}$$

where n_{eff} represents the refractive index of the fiber medium, V_{a} represents the moving speed of the sound wave in the fiber, λ_{p} is the wavelength of incident light, and θ is the angle between the pump light and the Stokes light. Since the core diameter of the SMF is negligible, the optical signal can only propagate forward or backward along the axis, and other propagation modes will be suppressed. It can be seen from the above Eq.(1) that the frequency shift of Stokes light is related to θ. When the incident light propagates forward (θ=0), there is a minimum value, that is, BFS is 0; when the incident light propagates backward ($\theta=\pi$), the Brillouin frequency shift reaches the maximum value, which can be expressed as

$$V_{\mathrm{B}} = \frac{2n_{\mathrm{eff}}V_{\mathrm{a}}}{\lambda_{\mathrm{p}}}. \tag{2}$$

Based on the previous research[22], $n_{\mathrm{eff}}\approx1.45$ is obtained when the pump wavelength changes in the range of 1 550 nm, and V_{a}=5 945 m/s and λ_{p}=1 550 nm are brought into Eq.(2) to obtain V_{B}=11.1 GHz.

After the theoretical derivation of BFS, the Stokes light in the output spectrum is analyzed. When the BP light reaches the threshold at the SMF, the first order Brillouin Stokes light (BS1) with reverse transmission is generated, and its frequency V_1 is expressed as follows

$$V_1 = V_{\mathrm{BP}} - V_{\mathrm{B1}} = V_{\mathrm{BP}} - \frac{2n_{\mathrm{eff}}V_{\mathrm{a}}}{\lambda_{\mathrm{p}} + \lambda_{\mathrm{B}}}, \tag{3}$$

where V_{BP} represents the frequency of BP light, $\lambda_{\mathrm{B}}=2n_{\mathrm{eff}}V_{\mathrm{a}}\lambda_{\mathrm{p}}/c$ is the fixed wavelength interval between adjacent Stokes light signals, c is the speed of light, and λ_{B}= 0.088 nm is calculated.

Similarly, when BS1 is amplified by erbium-doped fiber amplifiers (EDFAs) and reaches the threshold again, BS2 with reverse transmission is generated, and its frequency is represented by V_2, as shown below:

$$V_2 = V_{\mathrm{BP}} - V_{\mathrm{B1}} - V_{\mathrm{B2}} = V_{\mathrm{BP}} - \frac{2n_{\mathrm{eff}}V_{\mathrm{a}}}{\lambda_{\mathrm{p}} + \lambda_{\mathrm{B}}} - \frac{2n_{\mathrm{eff}}V_{\mathrm{a}}}{\lambda_{\mathrm{p}} + 2\lambda_{\mathrm{B}}}. \tag{4}$$

Therefore, as long as the total gain in the cavity is greater than the total loss, higher-order Stokes light can be output, and its frequency can be obtained by the following formula:

$$V_i = V_{\mathrm{BP}} - \sum_1^i V_{\mathrm{B}i} = V_{\mathrm{BP}} - \sum_1^i \frac{2n_{\mathrm{eff}}V_{\mathrm{a}}}{\lambda_{\mathrm{p}} + \mathrm{i}\lambda_{\mathrm{B}}}, \tag{5}$$

where i represents the order of Brillouin Stokes light.

Finally, the obtained high-frequency microwave signal with a frequency interval of about 20 GHz and 40 GHz can be described as

$$f_{20\ \mathrm{GHz}} = V_{\mathrm{BP}} - V_2 = \frac{2n_{\mathrm{eff}}V_{\mathrm{a}}}{\lambda_{\mathrm{p}} + \lambda_{\mathrm{B}}} + \frac{2n_{\mathrm{eff}}V_{\mathrm{a}}}{\lambda_{\mathrm{p}} + 2\lambda_{\mathrm{B}}}, \tag{6}$$

$$f_{40\ \mathrm{GHz}} = V_{\mathrm{BP}} - V_4 = \frac{2n_{\mathrm{eff}}V_{\mathrm{a}}}{\lambda_{\mathrm{p}} + \lambda_{\mathrm{B}}} + \frac{2n_{\mathrm{eff}}V_{\mathrm{a}}}{\lambda_{\mathrm{p}} + 2\lambda_{\mathrm{B}}} + \frac{2n_{\mathrm{eff}}V_{\mathrm{a}}}{\lambda_{\mathrm{p}} + 3\lambda_{\mathrm{B}}} + \frac{2n_{\mathrm{eff}}V_{\mathrm{a}}}{\lambda_{\mathrm{p}} + 4\lambda_{\mathrm{B}}}. \tag{7}$$

The experimental structure of MWBEFL with 40 GHz frequency shift interval is shown in Fig.1. The laser cavity structure consists of a four-port circulator (CIR) and two 3 dB 2×2 couplers (OC1 and OC2). The BP provided by the tunable laser (TLS) enters the cavity through OC1. The gain in the cavity is mainly provided by EDFA1 and EDFA2, both of which are composed of a

980 nm pump light source, wavelength division multiplexer (WDM), and EDF with a length of 5 m. They are used to provide linear gain to amplify BP and low-order Stokes light. The SMF with a length of 10 km contained on the left side of the CIR is used as the Brillouin gain medium. The Sagnac loop filter connected at OC1 consists of OC2, PC, and polarization-maintaining fiber (PMF) with a length of 13.5 m. PC is used to adjust the polarization state of the input light. Isolator (ISO) is used to prevent the light of the filter from damaging the TLS. The output spectrum is measured by an optical spectrum analyzer (OSA, YOGAWA AQ6370B) at the OC2 port with a resolution of 0.02 nm.

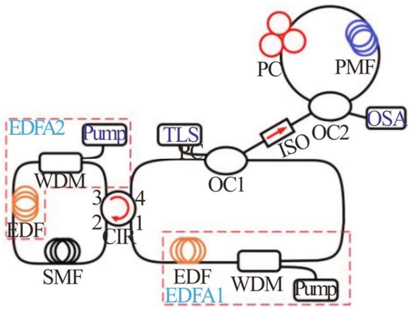

Fig.1 MWBEFL experimental structure with 40 GHz frequency shift interval

The optical transmission process of the Sagnac loop filter in the experimental structure is analyzed. When the incident light enters OC2 through ISO, the light will be divided into two beams that propagate clockwisely and counterclockwisely. The beams pass through PMF respectively. The birefringence of PMF results in a phase difference between two beams. The interference coupling output occurs when returning to OC2 again. Through the analysis of Jones matrix theory, the transfer function T of the Sagnac loop filter is as follows[23]

$$T=(1-2k)^2+4k(1-k)\sin^2\theta_1\cos^2\varphi, \quad (8)$$

where k is the coupling ratio of OC2, θ_1 is the rotation angle of PC, $\varphi=\pi\Delta nL_{\mathrm{PMF}}/\lambda$ represents the phase difference generated when light is transmitted on the fast and slow axes of PMF, Δn denotes the effective birefringence difference between the fast and slow axes, L_{PMF} is the length of PMF, and λ is the wavelength of incident light.

The wavelength interval is calculated by $\Delta\lambda=\lambda^2/\Delta nL_{\mathrm{PMF}}$. Since the length of the PMF used in the experimental device is 13.5 m, and the difference between the birefringence of the fast axis and the slow axis is 5.1×10^{-4}, the wavelength interval is calculated to be 0.35 nm. The simulated transmission spectrum of the Sagnac loop filter is shown in Fig.2(a). In order to verify the above theoretical analysis of the filter, the experimental test is carried out shown in Fig.2(b), and the experimental transmission spectrum with a wavelength interval of 0.35 nm is obtained, indicating that the measured results are consistent with the simulation analysis.

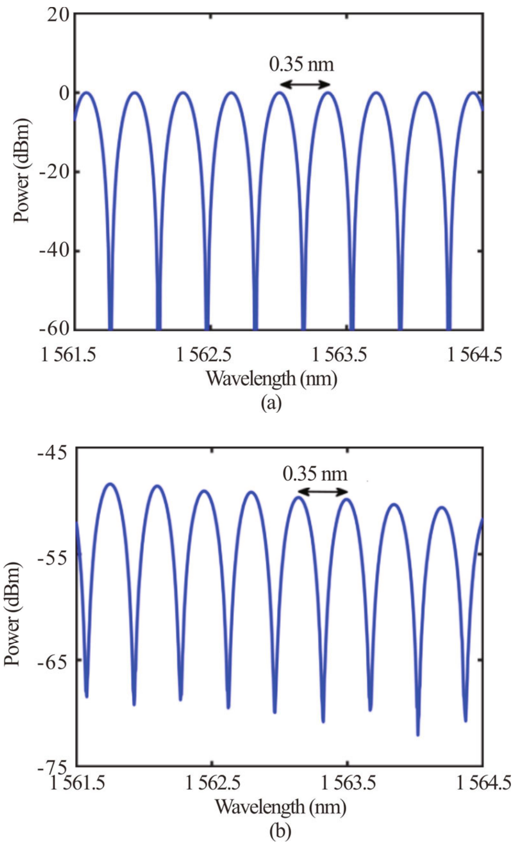

Fig.2 (a) Simulated and (b) experimental transmission spectra of the Sagnac loop filter

The process of generating high-order Stokes light by the proposed laser is as follows. When the TLS output BP light is injected into the cavity through OC1, it is pre-amplified by EDFA1, and transmitted clockwisely to SMF through port 1 of CIR. Once the BP light reaches the threshold of SBS, BS1 can be generated. Due to the backward propagation property of Brillouin scattering, BS1 propagates counterclockwisely from port 2 of CIR and enters SMF again after amplification by EDFA2. When the power of BS1 is greater than the threshold power, the generated BS2 propagates in the opposite direction and enters OC1 through port 4 of CIR. One part of the BS2 enters the Sagnac loop filter, and the other part enters the CIR as new BP light, continuously circulating the above process until the total gain in the cavity does not exceed the SBS threshold. After the part of high order Stokes light enters the Sagnac loop filter, the transmission spectrum of the filter can be continuously moved to select corresponding comb lines by adjusting PC. Finally, two different output spectra with a wavelength interval of 0.35 nm are obtained, that is, microwave signal with a frequency shift of about 40 GHz.

Firstly, the self-excited oscillation spectra of the designed multi-wavelength laser are researched. With TLS off, the output characteristics of the designed multi-wavelength laser are tested experimentally. When the 980 nm pump power is set to 350 mW, the self-excited oscillation mode is found near 1 562.5 nm in the 40 nm span, as shown in Fig.3. It shows that the maximum net gain of the multi-wavelength laser is around 1 562.5 nm. Since the self-excited oscillation mode consumes the EDF gain, the BP wavelength should be set near the gain peak to suppress the influence on the output spectrum.

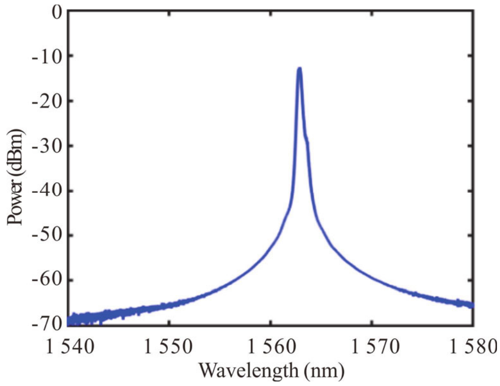

Fig.3 Self-excited oscillation spectrum of the designed multi-wavelength laser

Secondly, the output spectra of the proposed multi-wavelength laser are researched without the Sagnac loop filter in the cavity. The wavelength and power of TLS are set at 1 562.23 nm and 4 mW, and the 980 nm pump power is 130 mW. Eight Stokes lines with a wavelength interval of 0.172 nm can be obtained and the peak powers are −0.93 dBm, −1.1 dBm, −1.3 dBm, −1.9 dBm, −2.4 dBm, −3.6 dBm, −5.66 dBm, 38.78 dBm, respectively, as shown in Fig.4. It can be seen from Fig.4 that even order Stokes light is mainly generated, while the peak power of odd order Stokes light is much lower than that of even Stokes light, but it still exists. The reason for this phenomenon is the randomly distributed feedback mechanism takes place in SMF and the Stokes light is randomly backward scattered following the Rayleigh law of scattering. In addition, there are weak anti-Stokes light and higher-order Stokes light on both sides of the output spectrum. This phenomenon is due to the four-wave mixing effect of Stokes light in 10 km SMF and the use of two EDFAs in the experimental structure, so that the anti-Stokes light and higher-order Stokes light are increased.

Thirdly, when the Sagnac loop filter is connected in the proposed multi-wavelength laser by OC1, the 980 nm pump power is set to 140 mW, the BP power is 4 mW, and the BP wavelength is 1 562.23 nm. Two different comb spectra with a wavelength interval of 0.35 nm are obtained, as shown in Fig.5. By adjusting PC, part of the even order Stokes light is located at the peak of the Sagnac loop filter to obtain the maximum transmittance, namely BP, BS4, BS8, BS12, and BS16. The peak power of each lasing channel is −7.46 dBm, −8.16 dBm, −9.6 dBm, −11.68 dBm, −18.21 dBm, and the *OSNR* is greater than 33 dB. While the rest of the even Stokes light and anti-Stokes light is at the valley value of the filter, almost suppressed, and the minimum transmittance is obtained, namely BS2, BS6, BS10, and BS14, as shown in Fig.5(a). After carefully adjusting the angle of the PC again, the comb spectrum of the output four wavelengths can be obtained, indicating that these wavelengths are at the peak of the filter, which are BS2, BS6, BS10, and BS14, respectively. Their peak power is −7.17 dBm, −7.74 dBm, −9.19 dBm, −13.37 dBm, and the *OSNR* is greater than 33 dB, as shown in Fig.5(b). The wavelength interval of the two output spectra is almost the same as the 0.35 nm wavelength interval of the Sagnac loop filter analyzed above, that is, quadruple BFS between each Stokes light, so a microwave signal of about 40 GHz is obtained.

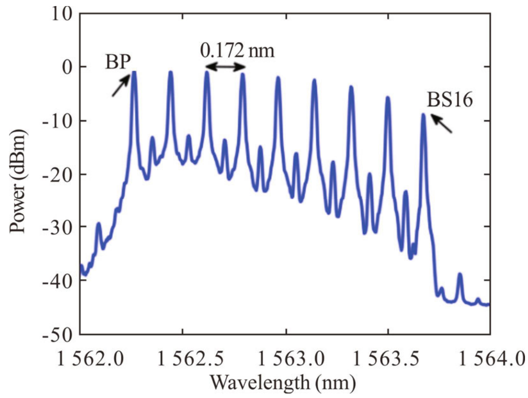

Fig.4 Output spectrum with a wavelength interval of double BFS

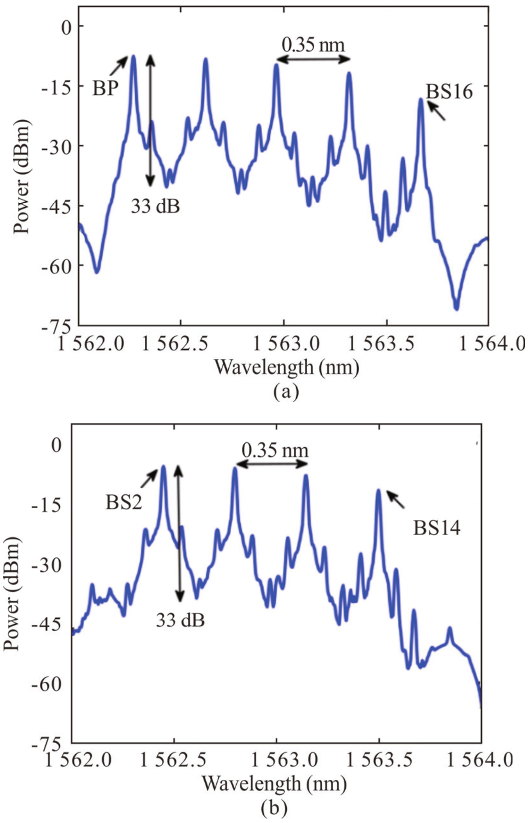

Fig.5 Different output spectra with a wavelength interval of quadruple BFS at different PC angles

Next, further discussion of the influence of 980 nm pump power and BP power on multi-wavelength output properties is executed. The BP wavelength is set to be 1 562.23 nm and the power is 4 mW. The output spectra at different 980 nm pump powers are measured, shown in Fig.6. When the pump power is 50 mW, there are 3 laser channels. The pump power is increased to 90 mW to generate the fourth wavelength. Further adjusting the pump power to 140 mW, the fifth laser channel appears in the output spectrum. As the pump power increases to 200 mW, the wavelength number of the output spectrum is reduced to 3. Therefore, it can be concluded from Fig.6 that the number of output wavelengths increases first and then decreases with the increase of pump power. This is because when the pump power is at a low value, the gradually increasing pump power makes the low-order Stokes light obtain more linear gain, and it is easier to reach the SBS threshold, thereby generating higher-order Stokes light. When the pump power is 140 mW, there is a maximum number of output wavelengths. However, if the pump power is further increased, the number of wavelengths will decrease. The reason may be that the self-excited oscillation mode in the cavity gradually enhanced, which will absorb part of the pump gain, resulting in the low-order Stokes light cannot overcome the loss in the cavity to generate higher-order Stokes light.

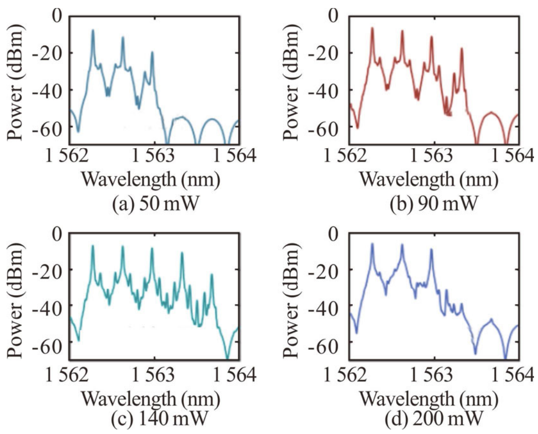

Fig.6 Output spectra at different 980 nm pump powers

The BP power is also an important factor affecting the Stokes light output and appropriate BP power is helpful to improve the number of Stokes light. The 980 nm pump power is fixed at 140 mW and the BP wavelength is 1 562.23 nm, when the BP power is set to 4 mW, 8 mW, 16 mW, and 25 mW, the number of output Stokes light is 5, 4, 4, 3 respectively, as shown in Fig.7. It can be seen from Fig.7 that with the increase of BP power, the Stokes light gradually decreases. The reason for this phenomenon is that high BP power makes EDF reach gain saturation, and low-order Stokes light obtains less linear gain, which leads to the gradual weakening of the SBS effect and the inability to produce higher-order Stokes light. At the same time, high BP power is easy to produce anti-Stokes light, which will also consume part of the gain. Therefore, BP power and 980 nm power need to be optimized to prevent EDF from reaching gain saturation.

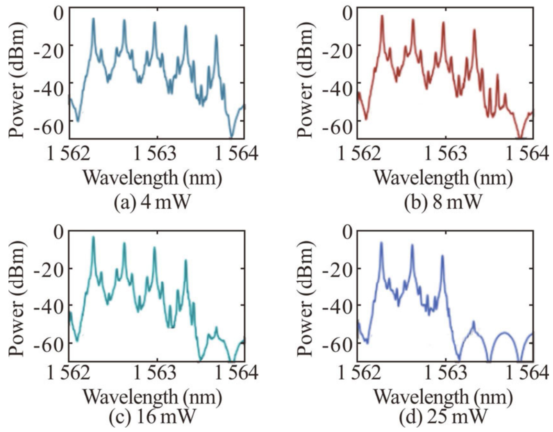

Fig.7 Output spectra at different BP pump powers

The tunability of multi-wavelength laser is researched by adjusting the BP wavelength. When the 980 nm pump power is fixed at 140 mW and the BP power is set as 4 mW, the BP wavelength is gradually increased from 1 552 nm to 1 572 nm with a step length of 1 nm. The number of output wavelengths in the range of 20 nm is 2 to 5, and there is no self-excited oscillation mode in the whole test range. Stable multi-wavelength output is always maintained, and some BP wavelength output results are shown in Fig.8. Obviously, the number produced near 1 562 nm is the largest, because it is near the optimal gain wavelength, that is, the self-excited oscillation mode. When the BP wavelength is gradually adjusted away from the gain peak, it is found that the number of laser channels decreases. The reason is that when the BP wavelength exceeds the gain range of the EDFA, the low-order Stokes light cannot be fully amplified and cannot reach the threshold of higher-order Stokes light. At the same time, it is also seen from Fig.8 that *OSNR* gradually decreases with the increase of BP wavelength. The reason may be that when the BP wavelength is small, the BP power can suppress the spontaneous emission of background noise. When the BP wavelength gradually increases, the increased EDF gain brings higher spontaneous emission background noise, but the BP power remains unchanged, so the *OSNR* gradually decreases to 31 dB.

In order to better evaluate the performance, Tab.1 compares the proposed scheme with the reported multi-wavelength Brillouin erbium-doped fiber random lasers, where / indicates that the item is not mentioned. Compared with the literature in Tab.1, the main difference of this paper is that the simple Sagnac loop filter is used to realize the switching of the frequency interval of the laser, which improves the flexibility and the pump power is lower. Although Refs.[19,20] can also switch the frequency interval, the experimental structure is relatively complex due to the use of multiple SMFs. At the same time, the number of output wavelengths of the laser proposed in this paper is significantly increased when the pump power is comparable to that of Ref.[20]. Compared with Refs.[24,25], the required pump power is significantly reduced, but the number of wavelengths is not significantly reduced. In addition, the tunable range of the output spectrum is also improved compared to Ref.[25].

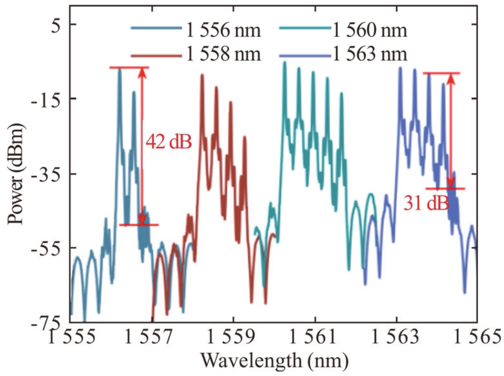

Fig.8 Output spectra of different BP wavelengths

Tab.1 Comparison of lasers between this work and other works

Reference	Frequency interval	Wavelength number	Pump power	Tuning range
[19]	9.78/19.56/ 29.12 GHz	11	336 mW	/
[20]	10.66/21.39/ 32.12/42.85 GHz	2	130 mW	/
[24]	22 GHz	12	450 mW	20 nm
[25]	43.5 GHz	7	520 mW	14.9 nm
This work	**20/40 GHz**	**8**	**140 mW**	**20 nm**

In order to explore the stability of the proposed MWBEFL at room temperature, the PC angle is kept in the case where the output spectrum has 5 laser channels. The multi-wavelength output spectrum is recorded every 6 min within 60 min. The stability of the obtained multi-wavelength output spectrum and output power are shown in Fig.9(a) and (b), respectively. It can be seen that the output spectrum maintains a relatively constant multi-wavelength shape during the test period, and no laser channel disappears in the spectrum or has a large offset. However, the measured BS16 has a large peak power fluctuation, with a maximum fluctuation of 2.4 dB. The reason is that the high-order Stokes light is excited by the low-order Stokes light, and the instability of the low-order Stokes light will gradually accumulate to the high-order Stokes light with the cascade process of SBS, resulting in the last-order Stokes light usually a large power fluctuation. But other Stokes light is in a stable oscillation state, and the measured peak power fluctuation is less than 0.5 dB. The results show that the proposed laser can achieve stable multi-wavelength output at room temperature.

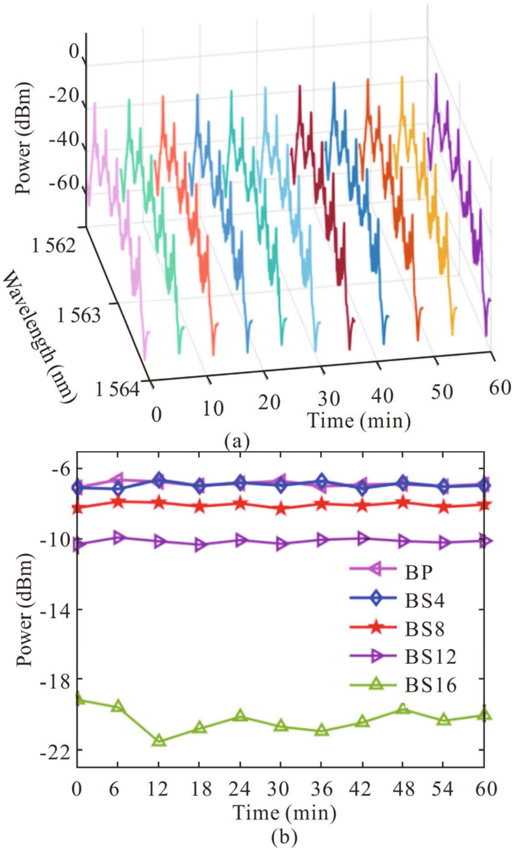

Fig.9 (a) Stability of multi-wavelength output spectra and (b) peak power fluctuation of lasing lines

We have successfully demonstrated an MWBEFL with a 40 GHz frequency shift interval and researched by theoretical analysis and experimental verification. The microwave signal of about 40 GHz can be obtained by nonlinear effect SBS and comb filter. When the Sagnac loop filter is not used, up to 8 Stokes lines with wavelength intervals of 0.172 nm are generated. When contacting the Sagnac loop filter into the proposed laser cavity, two different output spectra with wavelength interval of 0.35 nm are obtained by adjusting the PC, and the *OSNR* is greater than 33 dB. The effects of different 980 nm pump power, BP power, and BP wavelength on the output spectrum are analyzed in detail. The experimental results show that the BP power and 980 nm power need to be optimized to prevent the EDF from reaching gain saturation. When the BP wavelength is set near the self-excited oscillation mode, the number of output wavelengths reaches the maximum and the multi-wavelength output can be tuned in the wavelength range of 20 nm. In addition, the laser also has good stability, and the peak power fluctuation is less than 0.5 dB. In summary, the designed MWBEFL not only has a simple structure but also has the characteristics of switchability and tunability. The 40 GHz channel interval reduces the difficulty of multiplexing, and better meets the needs of the dense wavelength division multiplexing system. The generated high-frequency microwave signals can have good application prospects in radar detection, optical fiber sensing, and other fields.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

References

[1] VARUN M K, RAVI P. Efficient microwave photonic bandpass filter with large out-of-band rejection, high-resolution and low loss up to 40GHz[J]. Journal of lightwave technology, 2021, 39(21): 6724-6732.

[2] ZHANG Z, LIU Y, EGGLETON B J. Photonic generation of 30GHz bandwidth stepped frequency signals for radar applications[J]. Journal of lightwave technology, 2022, 40(14): 4521-4527.

[3] YUAN J, ZHANG M S, MEI Y, et al. Photonic generation of millimeter-wave and multi-waveform signals based on external modulation and polarization control[J]. Applied optics, 2022, 61(30): 8967-8973.

[4] WANG L Y, LIU Y, YOU Y J, et al. Microwave photonic filter with a sub-kHz bandwidth based on a double ring Brillouin fiber laser[J]. Optics letters, 2022, 47(16): 4143-4146.

[5] LIU C Y, XIE Q Y, WANG R X, et al. Microwave photonic radar system with improved SNR performance utilizing optical resonant amplification and random Fourier coefficient waveforms[J]. Optics express, 2023, 31(10): 15537-15552.

[6] DU S, LIU X, DU P, et al. Broadband microwave photonic frequency measurement based on optical spectrum manipulation and stimulated Brillouin scattering[J]. IEEE photonics journal, 2023, 15(2): 1-8.

[7] LI Q, HU L, ZHANG J, et al. Photonic millimeter-wave transfer with balanced dual-heterodyne phase noise detection and cancellation[J]. Optics express, 2023, 31(17): 28078-28088.

[8] LI S, LIU Z, ZHANG A, et al. High-speed and high-resolution optical fiber sensor interrogation based on optical injection in semiconductor laser and microwave filtering[J]. Journal of lightwave technology, 2022, 40(20): 6805-6812.

[9] CHEN H, LEE M, WON Y H, et al. High-speed switchable dual-passband microwave photonic filter with dual-beam injection in an SMFP-LD[J]. Journal of lightwave technology, 2021, 39(24): 7966-7972.

[10] ZHANG R H, ZHOU P, LI K X, et al. Photonic generation of high-performance microwave frequency combs using an optically injected semiconductor laser with dual-loop optoelectronic feedback[J]. Optics letters, 2021, 46(18): 4622-4625.

[11] HAO T, LI W, ZHU N, et al. Perspectives on optoelectronic oscillators[J]. APL photonics, 2023, 8(2).

[12] LIU S, DU C, YANG L, et al. Coherent dual-frequency signal generation in an optoelectronic oscillator[J]. Optics letters, 2023, 48(11): 2921-2924.

[13] CHEN G, LU D, GUO L, et al. Frequency-tunable OEO using a DFB laser at period-one oscillations with optoelectronic feedback[J]. IEEE photonics technology letters, 2018, 30(18): 1593-1596.

[14] TANG H, YU Y, WANG Z, et al. Wideband tunable optoelectronic oscillator based on a microwave photonic filter with an ultra-narrow passband[J]. Optics letters, 2018, 43(10): 2328-2331.

[15] SUN T, GUO Y, WANG T, et al. Dual-wavelength single longitudinal mode fiber laser for microwave generation[J]. Optics and laser technology, 2015, 67: 143-145.

[16] FENG T, WEI D, BI W, et al. Wavelength-switchable ultranarrow linewidth fiber laser enabled by a figure 8 compound ring cavity filter and a polarization-managed four-channel filter[J]. Optics express, 2021, 29(20): 31179.

[17] Al-MASHHADANI M K S, Al-MASHHADANI T F, GOKTAS H H. Tunable 50GHz laser comb generation of multiwavelength Brillouin erbium fiber laser[J]. Optics communications, 2020, 464: 125542.

[18] Al-MASHHADANI M K S, Al-MASHHADANI T F, GOKTAS H H. Broadly tunable 40GHz Brillouin frequency spacing multiwavelength Brillouin-erbium fiber laser for DWDM[J]. Optics communications, 2019, 451: 116-123.

[19] PEDRUZZI E, SILVA L C B, LEAL-JUNIOR A G, et al. Generation of a multi-wavelength Brillouin erbium fiber laser with low threshold in multiple frequency spacing configurations[J]. Optical fiber technology, 2022, 69: 102832.

[20] JIA Q, ZHANG P, WANG T, et al. 40GHz narrow linewidth frequency-switched microwave signal generation based on a single-longitudinal-mode double-Brillouin frequency spaced Brillouin fiber laser[J]. Applied optics, 2017, 56(19): 5323-5328.

[21] WANG X, YANG Y, LIU M, et al. Frequency spacing switchable multiwavelength Brillouin erbium fiber laser utilizing cascaded Brillouin gain fibers[J]. Applied optics, 2016, 55(23): 6475-6479.

[22] SONG Y, WANG L. Effect of fiber dispersion on pulse width[J]. Laser technology, 2008, 32(6): 568-571.

[23] LI T, YAN F, CHENG D, et al. Switchable multi-wavelength thulium-doped fiber laser using a cascaded or two-segment Sagnac loop filter[J]. IEEE access, 2022, 10: 13026-13037.

[24] ZHANG H, SHU X W, XU Z W, et al. Tunable multiwavelength random fiber laser with odd and even order stokes separated[J]. IEEE photonics technology letters, 2018, 30(5): 455-458.

[25] XU R H, ZHANG X Q, XUE M M, et al. A novel quadruple-spaced multiwavelength Brillouin-erbium fiber laser[J]. Laser physics letters, 2021, 11: 18.