

Wavelength-interval switchable Brillouin-Raman random fiber laser through Brillouin pump manipulation

Yang Li(李阳), En-Ming Xu(徐恩明), Rui-Jia Chen(陈睿佳), Yu-Gang Shee, and Zu-Xing Zhang(张祖兴)

Citation: Chin. Phys. B, 2024, 33 (**7**): 074209. DOI: 10.1088/1674-1056/ad3efb
Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Frequency-tunable single-photon router based on a microresonator containing a driven three-level emitter

Jin-Song Huang(黄劲松), Jing-Lan Hu(胡菁兰), Yan-Ling Li(李艳玲), and Zhong-Hui Xu(徐中辉)
Chin. Phys. B, 2024, 33 (**6**): 064202. DOI: 10.1088/1674-1056/ad362a

High-frequency microwave cavity design for high-mass dark matter axion searches

Chi Zhang(张驰), Jia Wang(王佳), Chunguang Li(李春光), Shiguang Chen(陈石广), Hang Cheng(程航), Liang Sun(孙亮), and Yun Wu(吴云)
Chin. Phys. B, 2024, 33 (**5**): 054211. DOI: 10.1088/1674-1056/ad34ca

Broadband bidirectional Brillouin-Raman random fiber laser with ultra-narrow linewidth

Qian Yang(杨茜), Yang Li(李阳), Hui Zou(邹辉), Jie Mei(梅杰), En-Ming Xu(徐恩明), and Zu-Xing Zhang(张祖兴)
Chin. Phys. B, 2024, 33 (**2**): 024206. DOI: 10.1088/1674-1056/ad09cb

Finesse measurement for high-power optical enhancement cavity

Xin-Yi Lu(陆心怡), Xing Liu(柳兴), Qi-Li Tian(田其立), Huan Wang(王焕), Jia-Jun Wang(汪嘉俊), and Li-Xin Yan(颜立新)
Chin. Phys. B, 2024, 33 (**1**): 014205. DOI: 10.1088/1674-1056/acd8ad

A low-threshold multiwavelength Brillouin fiber laser with double-frequency spacing based on a small-core fiber

Lu-Lu Xu(徐路路), Ying-Ying Wang(王莹莹), Li Jiang(江丽), Pei-Long Yang(杨佩龙), Lei Zhang(张磊), and Shi-Xun Dai(戴世勋)
Chin. Phys. B, 2021, 30 (**8**): 084210. DOI: 10.1088/1674-1056/abff47

Wavelength-interval switchable Brillouin–Raman random fiber laser through Brillouin pump manipulation

Yang Li(李阳)[1], En-Ming Xu(徐恩明)[1], Rui-Jia Chen(陈睿佳)[1], Yu-Gang Shee[2,‡], and Zu-Xing Zhang(张祖兴)[1,†]

[1] *Advanced Photonic Technology Laboratory, College of Electronic and Optical Engineering & College of Microelectronics, Nanjing University of Posts and Telecommunications, Nanjing* 210023, *China*

[2] *Department of Electrical and Electronic Engineering, Lee Kong Chian Faculty of Engineering & Science (LKC FES), Universiti Tunku Abdul Rahman (UTAR) Sungai Long Campus, Malaysia*

(Received 19 March 2024; revised manuscript received 12 April 2024; accepted manuscript online 16 April 2024)

A wavelength-interval switchable Brillouin–Raman random fiber laser (BRRFL) based on Brillouin pump (BP) manipulation is proposed in this paper. The proposed wavelength-interval switchable BRRFL has a full-open cavity configuration, featuring multiwavelength output with wavelength interval of double Brillouin frequency shifts. Through simultaneously injecting the BP light and its first-order stimulated Brillouin-scattered light into the cavity, the laser output exhibits a wavelength interval of single Brillouin frequency shift. The wavelength-interval switching effect can be manipulated by controlling the power of the first-order stimulated Brillouin scattering light. The experimental results show the multiwavelength output can be switched between double Brillouin frequency shift multiwavelength emission with a broad bandwidth of approximately 60 nm and single Brillouin frequency shift multiwavelength emission of 44 nm. The flexible optically controlled random fiber laser with switchable wavelength interval makes it useful for a wide range of applications and holds significant potential in the field of wavelength-division multiplexing optical communication.

Keywords: wavelength-interval switchable fiber laser, Brillouin fiber laser, stimulated Brillouin-scattered, random fiber laser

PACS: 42.60.Da, 42.60.Fc, 42.60.Jf, 42.65.Ky **DOI:** 10.1088/1674-1056/ad3efb

1. Introduction

Random fiber laser (RFL) has exhibited significant advancements and promising applications across various domains including optical communication, fiber sensing, optical measurement, and random bit generation, since its first demonstration in 2010.[1] The RFL operation leans upon randomly distributed feedback through Rayleigh scattering induced by the inherent inhomogeneous refractive index within the fiber, offering advantages such as a simple yet efficient structure, stable power output, and flexible design possibilities. Notably, Brillouin RFLs can achieve the cascaded random multiwavelength emission due to the low threshold of stimulated Brillouin scattering (SBS).[2,3] Over the past few decades, various types of Brillouin RFLs, including broadband,[4,5] wavelength-tunable,[6,7] and narrow linewidth,[8,9] have been developed to cater to specific application requirements.

Raman amplification in optical fibers can provide broadband and flat gain for SBS, thus attracting extensive research. In a Brillouin–Raman random fiber laser (BRRFL), various nonlinear effects such as Rayleigh scattering, stimulated Raman scattering, and SBS are cooperating with each other to generate a broadband multiwavelength Brillouin frequency comb.[10] However, most BRRFLs have fixed wavelength spacing of single or double Brillouin frequency shifts (BFS), which limits their applications in optical communications. Several schemes to achieve wavelength-interval switching have been reported, such as cavity rearrangement, adoption of variable optical couplers and introduction of variable attenuators.[11–15] Hu *et al.*[11] implemented a 2-μm switchable frequency-spacing multiwavelength laser by rearranging the connection ports, and seven lasing channels with single BFS spacing and eleven lasing channels with double BFS spacing were obtained at a flatness of 20 dB. Mamdoohi *et al.*[12] proposed a multiwavelength Brillouin–Raman fiber laser with an optical coupler of tunable coupling ratio. Multiwavelength lasing at 10-GHz spacing was achieved by a 50:50 coupler, and multiwavelength lasing at 20-GHz spacing after changing to a 99:1 coupler. In 2021, Al-Alimi *et al.*[13] presented a switchable multiwavelength Brillouin–Raman fiber laser, where the switching operation for single and double BFS spacing was implemented by controlling Brillouin pump (BP) power distribution and its direction using a 30/70 optical coupler. In the next year, the same group[14] reported a switchable single-double frequency spacing multiwavelength Brillouin Raman fiber laser, assisted by a micro air cavity introduced adjustable attenuation to the cascaded forward SBS light. However, the above schemes need to modify the physical structure of the cavities to achieve wavelength spacing switching, and are mechanically adjustable. Bai *et al.*[15] proposed and constructed a comb filter based on a few-mode fiber

†Corresponding author. E-mail: zxzhang@njupt.edu.cn
‡Corresponding author. E-mail: sheeyg@utar.edu.my

© 2024 Chinese Physical Society and IOP Publishing Ltd

(FMF), achieved by misaligned splicing of a few-mode long-period fiber grating (FM-LPFG) with SMF. The all-fiber laser, incorporating an FMF-based comb filter, enables switchable single-, dual-, triple-, and quad-wavelength continuous light generations. Huang *et al.*[16] proposed an RFL with flexible wavelength spacing switching, achieved through controlling the gain provided by two erbium-doped fibers (EDFs) pumped by three 976-nm semiconductor pump lasers. It can be seen as optically controlled, but its performance is very limited by the EDF gain bandwidth.

In this paper, we present a wavelength-interval switchable BRRFL. By adjusting the power ratio of the two branches from a tunable laser source (TLS) through the erbium-doped fiber amplifier (EDFA), referred to as BP1 branch (orange line in Fig. 1) and BP2 branch (green line in Fig. 1), the output multiwavelength can be switched between single and double BFS intervals. In our experiment, when the EDFA is turned off, i.e., only the BP1 light enters the random cavity, a Brillouin comb with double BFS wavelength interval has been attained. While the EDFA is turned on, i.e., the BP1 and BP2 are turned on simultaneously, a Brillouin comb with single BFS interval has been realized. Wavelength interval switching can be achieved by simply controlling the gain of the EDFA.

2. Experimental setup and principle

Figure 1 depicts the experimental setup of a full-open cavity wavelength-interval switchable BRRFL. The laser comprises of a TLS (AQ2200-136), which offers a wavelength tuning range of 1440 nm to 1640 nm, and a hybrid fiber combination as the Brillouin and Raman gain medium. The hybrid fiber consists of 7.2 km of dispersion-compensated fiber (DCF) and 10 km of single-mode fiber (SMF). Our previous work had demonstrated that this is the optimal fiber combination for broadband multiwavelength Brillouin comb generation as reported in Ref. [4]. The hybrid fiber provides Raman gain through bidirectional pumping of two Raman-pump lasers (OS8147-850-1455) with their center wavelengths of 1455 nm. The TLS output is divided into two paths after a 50:50 optical coupler (OC). The lower branch of the BP (BP1) is injected to the hybrid fiber through a circulator (Cir1) and a 2×2 50:50 OC. The upper branch of BP is amplified by an EDFA and then fed into a 20-km SMF through another circulator (Cir2) and the 2×2 50:50 OC. The amplified BP generates the counter-propagating first order SBS signal in the 20-km SMF and it is then directed into the hybrid fiber as a new BP (BP2). Thus, it can be seen that there are two pump lights at work, namely, BP1 and BP2. They will each induce cascaded SBS in the fiber combination, which are referred to as BP1 branch and BP2 branch. Isolators are placed at the left and right ends of the laser to mitigate interference from Fresnel-reflected light.

The double BFS multiwavelength comb is realized as follows: By turning off the EDFA, the upper branch of the BP is not amplified and hence the first order Brillouin–Stokes signal cannot be generated in the 20-km SMF, i.e., BP2 branch does not work. The lower branch of the BP is fed into the full-open cavity structure. BP1 in the hybrid fiber is amplified by the Raman amplification contributed by both the Raman pump. First order Brillouin–Stokes signal is generated when the amplified BP1 exceeds the Brillouin threshold. This first order Brillouin–Stokes signal counter-propagates with the BP1 direction is also being amplified by the Raman gain in the hybrid fibers and hence generates the second order Brillouin–Stokes signal. This cascading generation of Brillouin–Stokes signals is supported by the Raman amplification and the distributed Rayleigh scattering in the hybrid gain fiber as long as the Brillouin threshold is met, until the saturation of the gain. Upper right inset in Fig. 1 illustrates the propagation directions of odd and even order Brillouin–Stokes signals, which are output at the port 3 of Cir1 and isolator 2 (ISO2), respectively.

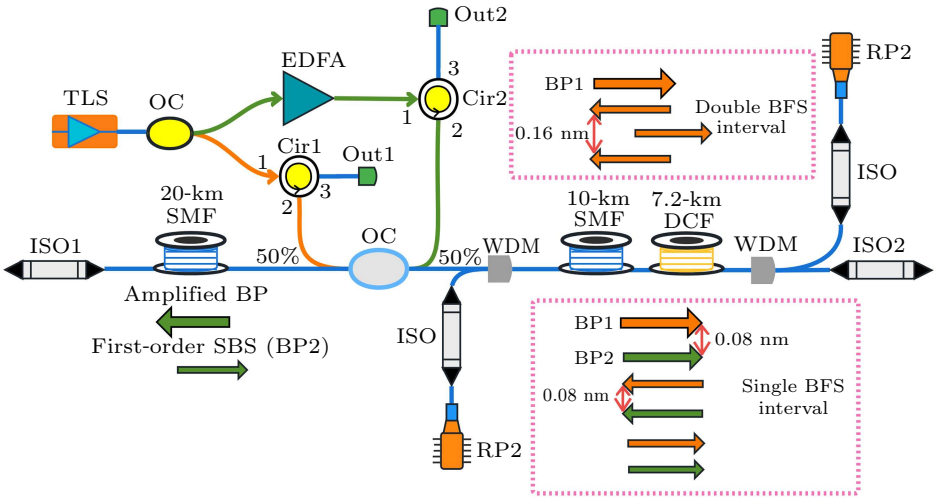


Fig. 1. Experimental diagram schematic diagram of wavelength-interval switchable BRRFL with BP manipulation. Upper/lower right inset shows generation schematic diagram of double/single BFS interval comb with BP1 working alone or BP1 and BP2 working simultaneously.

Comparatively, the Brillouin multiwavelength comb with single BFS interval is produced by combining two BP branches. The BP that is amplified by the EDFA generates its first order Brillouin–Stokes signal (BS1) in the 20-km SMF. BS1, as a new BP2, is injected to the hybrid fibers together with the BP1 through the 2×2 50:50 OC. Under strong Raman pumping condition, Brillouin multiwavelength comb with even-order Stokes lines relative to the BP1 (odd-order relative to the BP2) output from output1 (Out1) and odd-order Stokes lines relative to the BP1 (even-order relative to the BP2) output from ISO2 on the right are finally excited. As mentioned above, from the individual BP1 branch, the odd-order SBS light is output at port 3 of Cir1 and the even-order SBS light is output at ISO2. By complementary superimposition of odd and even orders, a Brillouin multiwavelength comb with single BFS interval can be obtained from both Out1 and ISO2, as shown in lower right inset of Fig. 1. The switching between single and double BFS wavelength interval can be achieved by simply adjusting the power of the EDFA.

3. Results and discussion

In order to characterize the Brillouin multiwavelength comb with double BFS spacing, BP power was set to 10 mW and the EDFA was turned off. Raman pump1 (RP1) and Raman pump 2 (RP2) were set to their maximum power of 831 mW and 871 mW, respectively. The BP1 was fed into the Raman-pumped hybrid gain fiber to stimulate a double BFS interval multi-wavelength comb in the full-open cavity. Figure 2 depicts the spectra obtained at Out1 by varying the BP wavelength. As the BP wavelength is gradually adjusted from 1550 nm to shorter wavelengths, the achieved double BFS interval spectra hold broader bandwidth. When the BP wavelength is tuned to 1516 nm, double BFS interval multiwavelength comb with a width of approximately 60 nm (1516 nm–1576 nm) can be achieved as shown in Fig. 3(a). An enlarged view of the spectrum is shown in Fig. 3(b), where the odd-order Stokes lines with a wavelength interval of 0.168 nm can be clearly seen. Further increasing the RP power may produce a broader multiwavelength comb.

To attain Brillouin multiwavelength comb with single BFS interval, EDFA is turned on to amplify the BP, and thus generate BS1 to be injected into the cavity along with the unamplified BP1. For instance, the black line in Fig. 4(a) indicates the spectrum of the TLS with center wavelength of 1550.6 nm and power of 10 mW, while the red line denotes the spectrum of BS1 produced in the 20-km SMF, both of which were measured at output 2 (Out2) under the absence of Raman pumps. The rightward-propagating first-order SBS light enters the hybrid gain fiber, which serves as BP2 to generate another set of double BFS wavelength-interval Brillouin comb. To clearly understand formation process of single BFS Brillouin comb, the BP1 and BP2 branches are firstly turned on individually. When the BP1 branch works alone, the odd-order SBS spectrum observed at Out1 is shown as the black line in Fig. 4(b). The red line in Fig. 4(b) is the even-order SBS spectrum (relative to the BP1), as only the BP2 branch functions with the output power of the EDFA set to 76.8 mW. Therefore, the BP1 branch produces odd-order Stokes light, while the BP2 branch produces even-order Stokes light at Out1, when the two branches are turned on simultaneously.

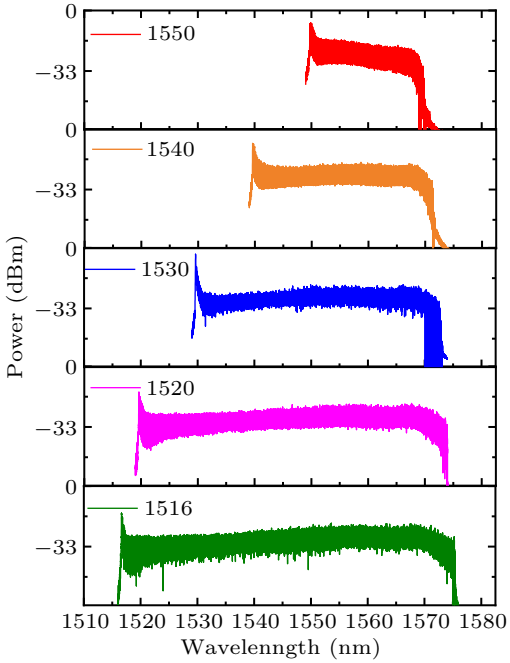


Fig. 2. The evolution of double BFS interval spectra measured at Out1 with BP wavelength tuned from 1550 nm to 1516 nm, under maximum Raman pump power.

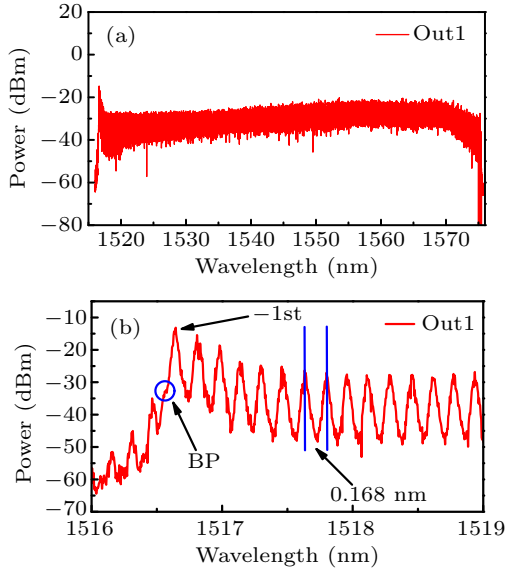


Fig. 3. (a) Spectrum of double BFS interval ranging from 1516 nm to 1576 nm observed at Out1 with the BP wavelength set to 1516 nm, (b) partial enlarged spectrum of Fig. 3(a).

Then, the output spectrum at Out1 of two BP branches working simultaneously is shown in Fig. 4(c). The wavelength

interval is 0.08 nm, which is the superposition of odd-order SBS light and even-order SBS light in Fig. 4(b). Figure 4(d) shows the spectra of BP1 branch excitation alone when EDFA is turned off, where the red line is the even-order Stokes light observed at ISO2, the black line is the odd-order Stokes light observed at Out1. Therefore, this random fiber laser can also achieve the separated output of odd-order Stokes light and even-order Stokes light.

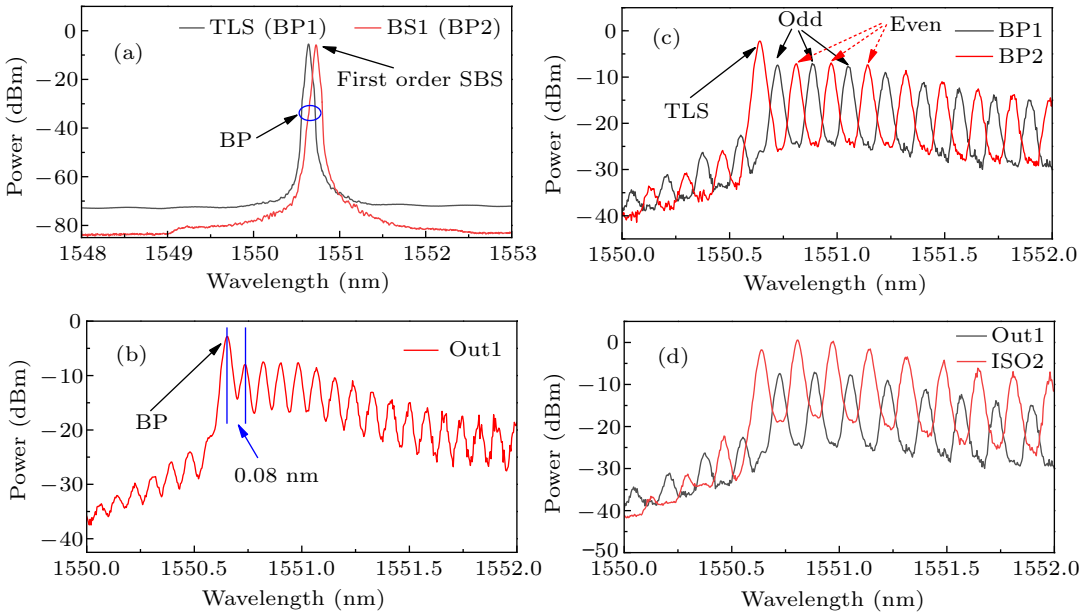


Fig. 4. (a) Spectra of BS1 (red line) and the TLS (black line) with center wavelength set at 1550.6 nm, spectra measured at Out2, (b) when the BP1 and BP2 are turned on individually (black line is odd-order SBS, red line is even-order SBS), (c) when the two BP branches are turned on simultaneously, (d) spectra measured at Out1 (black line) and ISO2 (red line) when only BP branch is turned on.

For the generation of single BFS wavelength-interval Brillouin comb with larger bandwidth, the BP wavelength was tuned to shorter wavelength of 1530.7 nm. Figure 5(a) is the single BFS wavelength-interval spectrum measured at Out1 with a bandwidth of 44 nm (1530 nm–1574 nm), when the BP power is 10 mW, and the EDFA output power is 119 mW. Figure 5(b) is the enlarged spectrum within wavelength range of 1530 nm–1532 nm, which clearly shows that the wavelength spacing is single BFS of 0.08 nm. However, since it originates from spectral superposition, the signal-to-noise ratio is deteriorated by half with respect to that of the double BFS wavelength-interval Brillouin comb. Due to the broad bandwidth, the average intensity of single-spaced and double-spaced multi-wavelength lasers is approximately −25 dBm. To utilize this laser for subsequent applications, additional optical amplifiers with C-band flatness gain are required.

If the BP wavelength is adjusted to longer wavelength, the bandwidth of single BFS wavelength-interval Brillouin comb will decrease. On the other hand, when the BP wavelength is further tuned to shorter wavelength of 1525 nm, the output power of the EDFA needs to be increased to 366.5 mW to support stable random lasing against self-excitation.[17] The evolution of single BFS interval spectra measured at Out1 with BP wavelength is shown in Fig. 6. The flatness of the spectrum with BP wavelength of 1525 nm is not very good. There are two peaks near 1535 nm, and the peaks will truncate the spectrum if the BP wavelength is further tuned to shorter wavelength. This is attributed to that the introduction of EDFA inevitably brings amplified spontaneous emission (ASE). And higher output power of the EDFA is required to excite the first-order SBS in the 20-km long SMF. Due to the limitation of used EDFA, the single BFS wavelength-interval Brillouin laser can only be tuned to 1530 nm. Utilizing an EDFA with a flat gain spectrum and low noise, it would be beneficial to obtain a single BFS wavelength-interval Brillouin comb with a larger bandwidth.

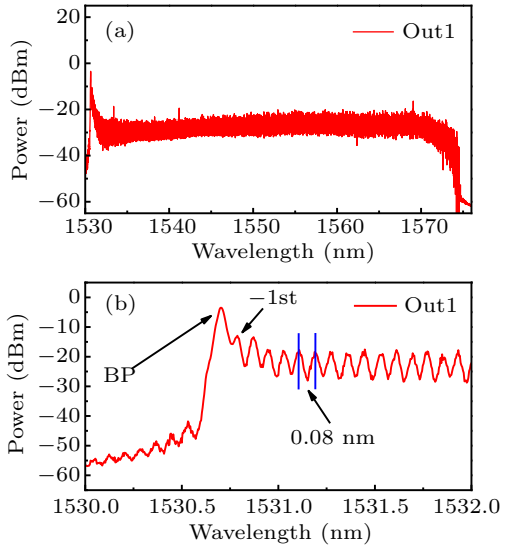


Fig. 5. (a) Spectrum of 1530 nm–1574 nm single BFS interval measured by Out1. (b) Spectrum of 1530 nm–1532 nm measured by Out1 when the wavelength of BP light is 1530 nm.

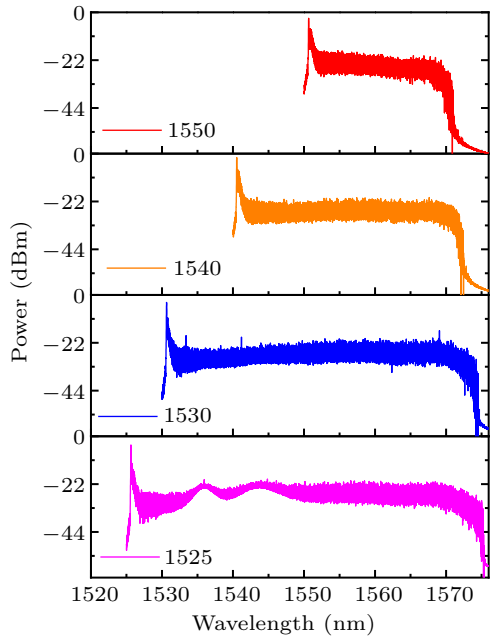


Fig. 6. The evolution of single BFS interval spectra measured at Out1 with BP wavelength tuned from 1550 nm to 1525 nm.

Figure 7 shows the effect of EDFA output power on the gain spectrum when RP1 and RP2 are set to their maximum pump power levels. With TLS turned off, the gain spectrum is represented by the green line in Fig. 7, as the gain peak located near 1555 nm. When the EDFA power is increased to 76.8 mW, two peaks in the gain spectrum, indicated by the blue line, become visible. Further increasing the power to 366.5 mW results in two gain peaks appearing at 1535.48 nm and 1543.40 nm. This observation is consistent with the spectrum with the BP wavelength of 1525 nm shown in Fig. 6.

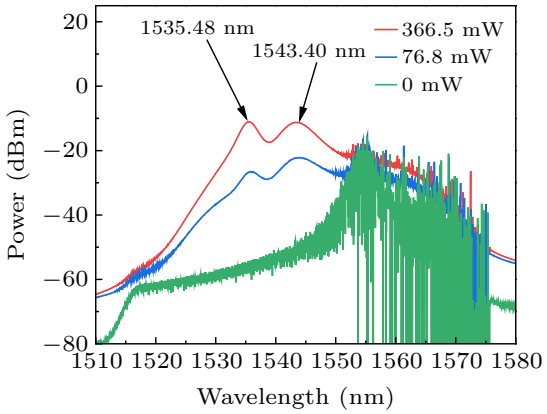


Fig. 7. Effect of EDFA spontaneous emission light on the gain spectrum when TLS is turned off.

The distinguishing feature of the proposed BP manipulation to switch the wavelength interval of Brillouin comb is optical control, i.e., the control of EDFA output power. Compared with previously similar lasers, this approach enables wavelength interval switching without altering the physical structure of the fiber laser. Figure 8(a) shows the dynamics of the wavelength interval switching with the EDFA power under BP wavelength of 1550.6 nm. It can be seen that when the EDFA is turned off, the output spectrum is an odd-order SBS comb with double BFS interval of 0.168 nm (shown in purple line). As the output power of the EDFA is increased to 76.8 mW, it can be seen that the wavelength interval changes to single BFS interval of 0.08 nm (shown in red line). With the EDFA output power further increased, the spectrum changes to even-order SBS comb with double BFS interval of 0.168 nm (shown in green and black lines) again, as the BP2 branch predominates over the BP1 branch under high EDFA power. It is worth noting that EDFA power required for switching the Brillouin comb from double BFS to single BFS interval is related to the BP wavelength, as shown in Fig. 8(b). The power required increases from 76.8 mW to 119 mW, when the BP wavelength is tuned from 1550 nm to 1530 nm. There are two reasons, one is the uneven gain of EDFA, and the other is that the required BP power at short wavelength will be higher. Additionally, in this experiment, 20-kM SMF was used for first-order SBS generation and the required EDFA power is also related to the used SMF length. The threshold power can be reduced by using longer SMF.

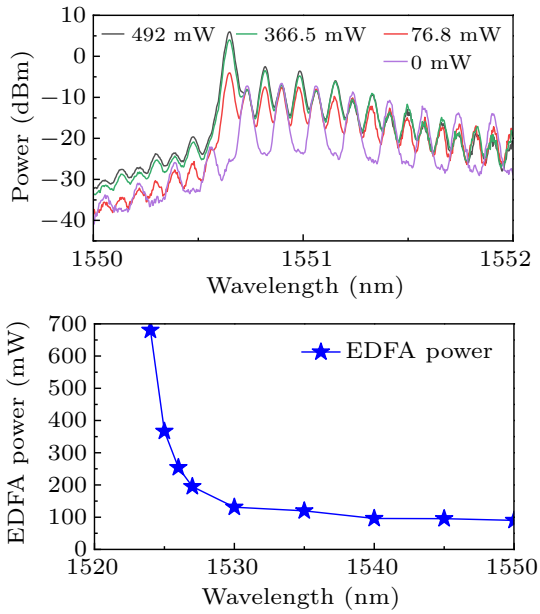


Fig. 8. (a) Dynamical wavelength-interval switching with the EDFA power, (b) EDFA power required for single BFS wavelength-interval switching.

4. Conclusions

In summary, we proposed and demonstrated a full-open cavity BRRFL with switchable wavelength interval, which is realized through BP manipulation, i.e., the deliberately generated first-order SBS light as new BP light. Wavelength spacing switching can be achieved by controlling the power ratio between the BP2 branch and the BP1 branch with an EDFA. Switchable Brillouin combs of 60-nm bandwidth and double BFS interval, and 44-nm bandwidth and single BFS interval have been achieved. This optically controlled BRRFL with

wavelength-interval switching, has broad application prospect in the fields of optical communication, and fiber sensing.

Acknowledgements

Poject supported by the National Natural Science Foundation of China (Grant Nos. 62175116 and 62311530343) and the Postgraduate Research Innovation Program of Jiangsu Province, China (Grant No. KYCX22_0913).

References

[1] Turitsyn S K, Babin S A, El-Taher A E, Harper P and Podivilov E V 2010 *Nat. Photon.* **4** 231
[2] Pang M, Bao X Y and Chen L 2013 *Opt. Lett.* **38** 1866
[3] El-Taher A, Harper P, Babin S A, Churkin D, Podivilov E V, Ania-Castañón A and Turitsyn S 2011 *Opt. Lett.* **36** 130
[4] Yang Q, Zou H, Shee Y G and Zhang Z 2023 *IEEE J. Selec. Top. Quantum Electron.* **29** 0900106
[5] Wang Z, Wu H, Fan H, Li Y, Yuan Y and Rao Y 2013 *Opt. Expess* **21** 29358
[6] Li Y, Lu P, Bao X and Ou Z 2014 *Opt. Lett.* **39** 2294
[7] Wang L, Dong X, Shum P P and Su H 2014 *IEEE Photon. J.* **6** 1501705
[8] Pang M, Xie S, Bao X, Zhou D, Lu Y and Chen L 2012 *Opt. Lett.* **37** 3129
[9] Pang Y, Xu Y, Zhao X, Qin Z and Liu Z 2022 *J. Lightwave Technol.* **40** 2988
[10] Zamzuri A K, Mahdi M A, Ahmad A, Ali M I Md and AlMansoori M H 2007 *Opt. Express* **15** 3000
[11] Hu K, Kabakova I V, Lefrancois S, Hudson D, He S and Eggleton B J 2014 *Opt. Express* **22** 31884
[12] Mamdoohi G, Sarmani A R, Bakar M H A and Mahdi M A 2018 *IEEE Photon. J.* **10** 1
[13] Al-Alimi A W, Cholan N A, Salam S, Kamil Y M, Ahmed M H M and Mahdi M A 2021 *Results in Physics* **25** 104149
[14] Al-Alimi A W, Khaleel W A, Sadeq S A, Cholan N A, Al-Mansoori M H, Ahmed M H M and Mahdi M A 2022 *Opt. Laser Technol.* **146** 107464
[15] Bai S, Xiang Y and Zhang Z 2023 *Chin. Phys. B* **32** 024209
[16] Huang P, Shu X and Zhang Z 2020 *Opt. Express* **28** 28686
[17] Al-Alimi A W, Cholan N A, Shee Y G, Alresheedi M T, Goh C S and Mahdi M A 2022 *Results in Physics* **37** 105469