Tunable and narrow linewidth multi-wavelength Brillouin-erbium fiber laser using dual-wavelength pumping*

ZHU Kaiyan, HE Jiangyong, CHANG Kun, XING Dengke, LIU Yange, and WANG Zhi**

Tianjin Key Laboratory of Optoelectronic Sensor and Sensing Network Technology, Institute of Modern Optics, Nankai University, Tianjin 300350, China

(Received 12 November 2021; Revised 24 December 2021)

We demonstrate a multi-wavelength Brillouin-erbium fiber laser (BEFL) with narrow linewidth and tunable wavelength interval using dual-wavelength Brillouin pumping. The generation of multi-wavelength output in BEFL is based on the combination of stimulated Brillouin scattering (SBS) and four-wave mixing (FWM) effect in a fiber cavity. The tunable wavelength interval is determined by the artificially controlled wavelength interval of the pumping lasers. The BEFL could compress a 1 MHz pump laser to a 340 Hz Brillouin Stokes laser, which proves the BEFL has excellent capability of linewidth compression. An erbium-doped fiber pumped by 980 nm laser is inserted into the cavity to further amplify the Brillouin laser. The wideband multi-wavelength BEFL covering over 50 nm is successfully generated when the 980 nm pump power is 400 mW. These features of multi-wavelength BEFL provide an effective method for optical communication systems and optical fiber sensing.

Document code: A **Article ID:** 1673-1905(2022)06-0349-5

DOI https://doi.org/10.1007/s11801-022-1173-z

Multi-wavelength fiber lasers with equal wavelength interval have important applications in dense wavelength division multiplexing (DWDM) systems[1], microwave photonics[2], and optical sensor[3]. In general, the stable multi-wavelength lasers can be achieved based on the four-wave mixing (FWM) effect[4], stimulated Brillouin scattering (SBS) effect[5], frequency shift and phase shift technology[6], and nonlinear optical loop mirror[7]. Among these techniques, SBS effect can significantly suppress the linewidth of the multi-wavelength lasers, which is usually critical for applications in coherent optical communications[8], microwave photonics[9] and high resolution spectral analysis[10]. Assisted by FWM effect, the multi-wavelength Brillouin fiber laser has achieved a wider wavelength range with more convenience[11]. However, the frequency interval of a multi-wavelength laser based on the SBS effect is relatively fixed by a multiple of the Brillouin frequency shift. The outputs of multi-wavelength Brillouin laser with single (~10 GHz)[12], double (~20 GHz)[13], triple (~30 GHz)[14] and quadruple (~40 GHz)[15] Brillouin frequency intervals have been achieved at 1 550 nm. Moreover, Brillouin fiber laser could generate a multi-wavelength source spanning from 1 545 nm to 1 575 nm[16]. The previous work mainly used single Brillouin pumping[17], which made the wavelength interval limited by the Brillouin frequency shift in FWM effect[18]. With the increase of the frequency interval, the cavity architectures become very complicated while continuous adjustment of the frequency interval is still impossible. In order to conveniently adjust the wavelength interval flexibly and increase the spectral range, we need an effective approach. We use dual-Brillouin laser injects to generate a broadband multi-wavelength BEFL with an operating wavelength range.

In this paper, we report a multi-wavelength BEFL with tunable wavelength interval and narrow linewidth based on the combination of SBS and FWM effects in a fiber cavity. By using dual-wavelength Brillouin pumping, the output wavelength interval of the laser is continuously adjustable. An erbium-doped fiber pumped by 980 nm laser is inserted into the cavity to further amplify the Brillouin laser. The wideband multi-wavelength BEFL covering over 50 nm and 39 lasing lines with an optical signal-to-noise ratio (*OSNR*) more than 10 dB is successfully generated under a 980 nm pump power of 400 mW. At the same time, the BEFL compressed a 1 MHz Brillouin pump laser to the 340 Hz Stokes laser, which proves that the laser linewidth is reduced by more than 2 900 times through the BEFL. We hope the multi-wavelength BEFL with tunable and narrow linewidth can open up the possibilities in diverse applications.

Our experimental setup is shown in Fig.1. Two continuous wave (CW) single frequency lasers, two polarization controllers (PCs), a 3 dB optical coupler (OC) and a high-power erbium-doped fiber amplifier (EDFA)

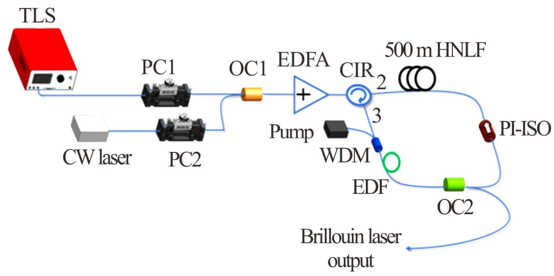
* This work has been supported by the National Key Research and Development Program of China (No.2018YFB0504400), the National Natural Science Foundation of China (Nos.61775107, 11674177 and 61640408), and the Tianjin Natural Science Foundation (No.19JCZDJC31200).

** E-mail: zhiwang@nankai.edu.cn

are used to form the pump source outside the cavity for achieving dual-wavelength Brillouin lasers. Two CW single frequency lasers, one is a narrow linewidth laser with fixed frequency, and the center wavelength is 1 550.12 nm. The other is a tunable narrow linewidth laser in C-band. We use the PC to adjust the polarization of the two lasers separately, which can make the FWM effect in the cavity achieve the best efficiency. The two lasers are coupled together by a 3 dB OC, and then amplified by an EDFA. Then, the two lasers inject into the fiber ring cavity through port 1 of the circulator. The lasers enter the ring cavity and propagate clock-wise through the 500-m-long highly nonlinear fiber and then are blocked by a polarization independent isolator, so it can not be cyclically transmitted. The nonlinear coefficient, the dispersion at 1 550 nm and the dispersion slope of the highly nonlinear fiber are 10 $W^{-1}\cdot km^{-1}$, 0.263 $ps\cdot nm^{-1}\cdot km^{-1}$ and 0.018 $ps\cdot nm^{-2}\cdot km^{-1}$, respectively. At the same time, because highly nonlinear fiber has higher nonlinear coefficients compared to single-mode fiber, the SBS effect is more likely to occur. After reaching the threshold of the SBS effect, the Brillouin lasers propagate backward and oscillate in the cavity to form a counterclock-wise loop. The function of the wavelength division multiplexer (WDM) is to connect the 980 nm pump source and an erbium-doped fiber with a length of 0.7 m. Erbium-doped fiber can compensate for the cavity loss and amplify the reverse Brillouin Stokes signals. The output Brillouin lasers are analyzed by using an optical spectrum analyzer, a radio frequency (RF) spectrum analyzer equipped with a photodetector and a power meter.

Firstly, we perform the experiment with the capability of linewidth compression about the BEFL. Generally, the linewidth of Brillouin laser is several orders of magnitude narrower than the pump laser. To confirm it, the linewidth of the Brillouin laser and the pump laser are measured by using the delayed self-heterodyne method[19,20]. As shown in Fig.2, after the pump or Brillouin laser passes through the 3 dB OC, one way is delayed through a single-mode fiber with a length of 50 km, while the frequency of the other beam is shifted by 70 MHz with an acoustic-optical modulator. The two signals are combined through another 3 dB OC and detected by a photodiode. The photodetector converts the optical signal into an electrical signal. Finally, the linewidth can be obtained through an electrical spectrum analyzer (ESA).

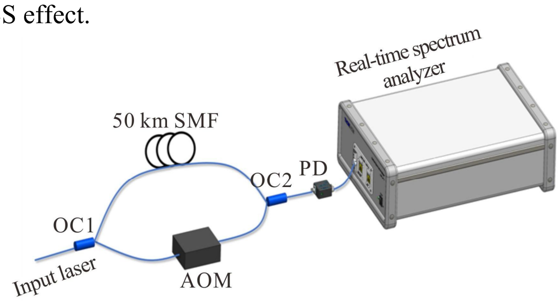
Fig.3 shows the delayed self-heterodyne beating RF spectra of the pump and Brillouin laser, respectively. In order to reduce the influence of $1/f$ frequency noise on the delayed self-heterodyne method[21], we use the 20 dB spectral width of the delayed self-heterodyne spectrum to estimate the ultra-narrow linewidth of the output Brillouin laser. We use the Lorentzian line shape to fit the linewidth of the Brillouin laser, which could calculate the value of the linewidth. We can obtain that a 20 dB linewidth of Brillouin laser is 6.81 kHz for the tunable laser. It shows the linewidth of Brillouin laser is 340 Hz. In addition, we measured that the 3 dB linewidth of the pump laser is about 1 MHz for the tunable laser. The linewidth of Brillouin laser was about 2 900 times narrower than the pump laser. It has been confirmed that the BELF has a strong capability of linewidth compression in both theory[22] and experiment[23]. This is due to the combined influence of the continuous oscillation of the acoustic wave and the feedback in the cavity, which leads to the compression of linewidth. When the pump laser is converted into Brillouin Stokes laser, the linewidth will be greatly reduced. In the same way, we can obtain the 20 dB linewidth of the Brillouin laser is about 7.12 kHz for the CW laser, indicating that its Lorentzian linewidth is 356 Hz. The 3 dB linewidth of the pump laser is about 20 kHz for the CW laser. The linewidth of Brillouin laser compared to the linewidth of pump laser reduced by 56 times. Although the linewidths of the two input pump lasers have a large gap, the final linewidths of output Brillouin lasers have a small difference, which is caused by reaching the linewidth compression limit of the laser. It is determined by the limit linewidth of the BEFL itself. More essentially, it is determined by the influence of spontaneous scattering noise, spontaneous radiation noise and other factors. These factors make the compressed linewidth limited to the order of 100 Hz. In other words, the dual-Brillouin lasers with the linewidths of 340 Hz and 356 Hz are generated by the linewidth compression of BEFL. Furthermore, the output multi-wavelength laser originated from the interaction between the dual-wavelength Brillouin lasers can inherit the narrow linewidths by the FWM effect.



TLS: tunable laser source; EDFA: erbium-doped fiber amplifier; CIR: circulator; HNLF: highly nonlinear fiber; OC: optical coupler; PC: polarization controller; PI-ISO: polarization independent isolator; WDM: wavelength division multiplexer

Fig.1 Experimental setup of the proposed multi-wavelength BEFL

Erbium-doped fiber is used as the gain medium in the BEFL. The gain of 980 nm pump, amplified spontaneous emission noise and other factors may affect the compression of the output Brillouin laser. We detect the influence of output linewidth of Brillouin laser under different 980 nm pump power in the cavity. We adjusted the 980 nm pump power from 100 mW to 500 mW at intervals of 100 mW, and compared the linewidths of each pump power. It is found that there is almost no difference in linewidths as shown in Fig.4, which shows the relationship between the linewidth of two Brillouin lasers and the 980 nm pump power. Fig.4(a) shows the tunable laser and Fig.4(b) shows the CW laser. The small figures show the linewidth compression multiples under each pump power. It is found that although the magnification of each laser has a small change, it is independent of the pump power. This is because although the Brillouin power in the cavity will continue to increase with the increase of the pump power, once the pump power exceeds the threshold of the SBS effect, the Brillouin laser will circulate stably in the cavity. Pump power does not affect the multiple of linewidth compression in the state of reaching the threshold of the SBS effect.



SMF: single-mode fiber; AOM: acousto-optic modulator; PD: photodetector

Fig.2 Experimental setup for measuring linewidth by delayed self-heterodyne method

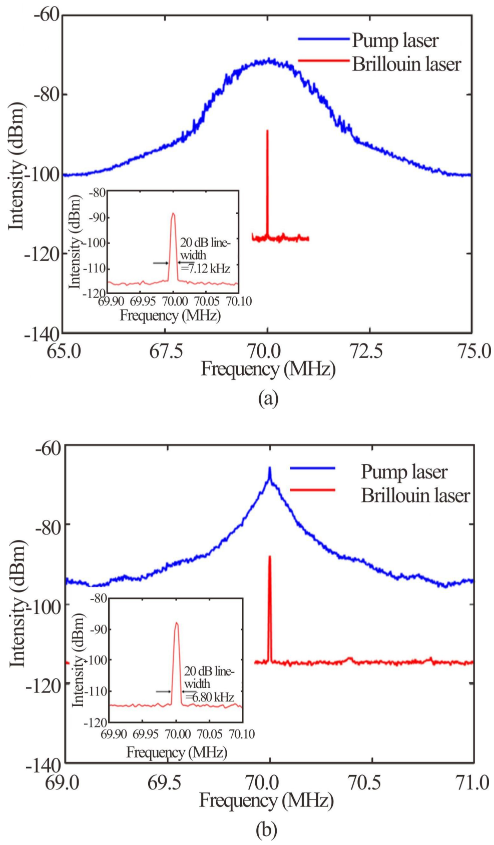


Fig.3 Delayed self-heterodyne spectra of the pump laser and the Brillouin laser for the (a) tunable laser and (b) CW laser

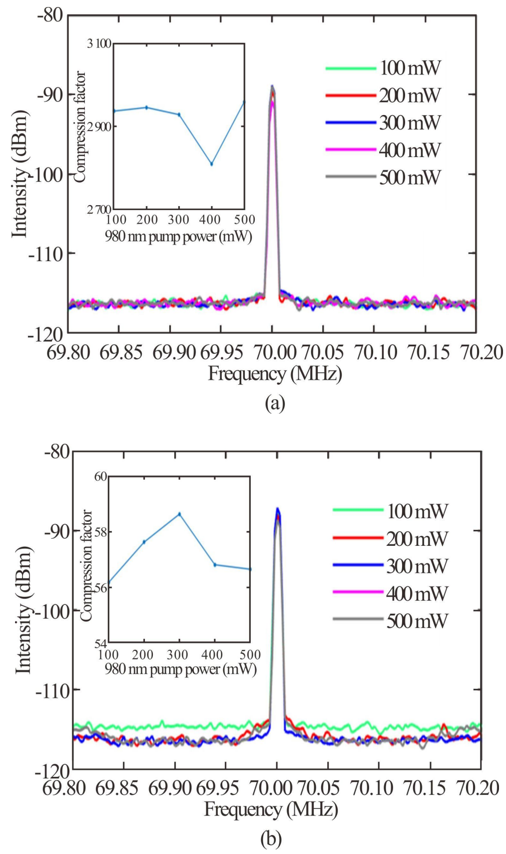


Fig.4 Delayed self-heterodyne spectra of Brillouin laser at different 980 nm pump power of (a) TLS and (b) CW laser

In the following experiment, we set the wavelengths of two continuous-wave lasers to 1 550.12 nm and 1 551.72 nm. The wavelength interval of dual-laser is 1.6 nm. With the increase of pump power outside the cavity, the FWM effect continues to increase, more and more energy is stored in the loop and the number of lasing lines is also increasing, as shown in Fig.5. It is shown from the initial two Brillouin lasers evolved into dozens of output wavelengths with the increase of 980 nm pump power. The wavelength range of the multi-wavelength BEFL is improved from 10 nm to 60 nm when the 980 nm pump power increases from 0 mW to 400 mW. When the pump power of the EDFA outside the cavity is 300 mW and the 980 nm pump power is 400 mW, the output wavelength range is over 50 nm, and there are 39 wavelengths with an *OSNR* exceeding 10 dB.

At the same time, we study the effect of the 980 nm pump power on the performance of the multi-wavelength BEFL. The evolution of the number of lasing lines with the *OSNR* more than 10 dB is plotted in Fig.6 as a function of the 980 nm pump power. The result shows that the number of lasing lines reaches a maximum of 39 at the 980 nm pump power of 400 mW. This can be attributed to that the wavelength range of about 100 nm is limited by the gain spectrum of the 500-m-long highly nonlinear fiber, so the number of output wavelengths will not increase indefinitely as the pump power increases.

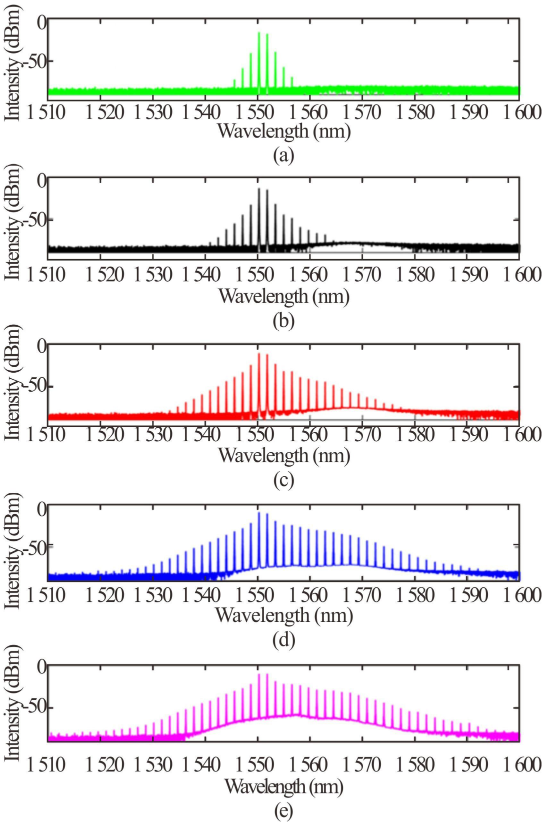


Fig.5 Output spectra under different 980 nm pump power in cavity: (a) 0 mW; (b) 100 mW; (c) 200 mW; (d) 300 mW; (e) 400 mW

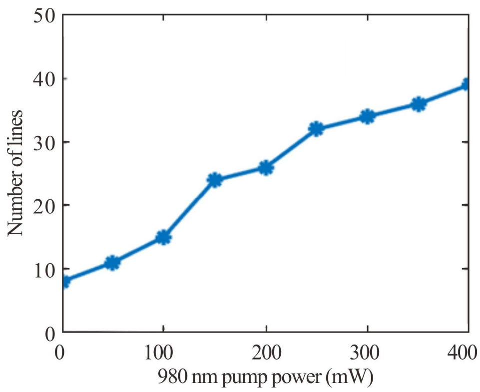


Fig.6 Number of lasing lines of the wideband BEFL as a function of the 980 nm pump power

When the dual-wavelength pump laser power reaches the threshold of the SBS effect, the center wavelengths of first-order Brillouin lasers are 1 550.206 nm and 1 551.800 nm, and their *OSNRs* are as high as 70 dB. Hence, the Brillouin laser is equivalent to a narrow-band low-pass filter, which can reduce and remove the relative intensity of the pump lasers. With the increase of pump power inside and outside the cavity, the dual-wavelength Brillouin laser in the cavity generates numerous lasing lines through cascaded FWM effect. At the same time, we found that high-order (≥2) Brillouin lasers are still greatly suppressed even under high power pumping. Interestingly, we observed that the number of lasing lines at the red end is more than that at the blue end. This is because the wavelength of the best gain of the erbium-doped fiber is around 1 560 nm, which has a stronger amplification effect at the red end in the multi-wavelength BEFL. In addition, the output Brillouin laser has a dispersion wave around 1 500 nm as shown by the black line in Fig.7, which is caused by the high-order dispersion in the highly nonlinear fiber[24].

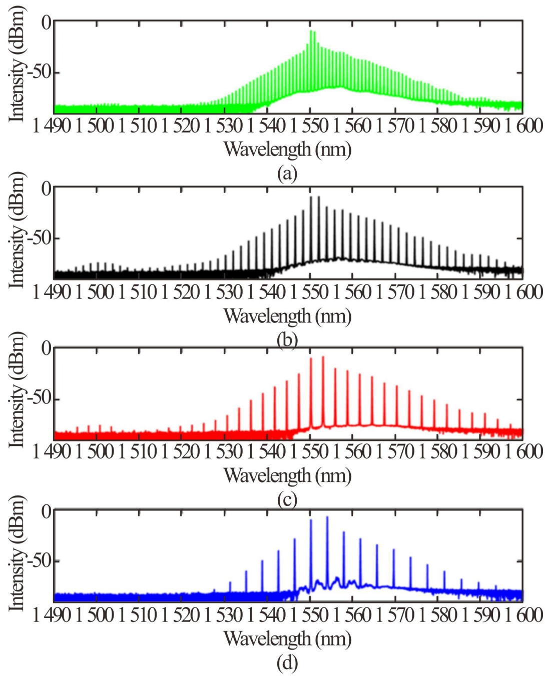


Fig.7 Output spectra at different wavelength intervals under 980 nm pump power of 300 mW: (a) 0.8 nm; (b) 1.6 nm; (c) 2.4 nm; (d) 3.2 nm

In order to verify the tunability of the wavelength interval, while fixing the pump power to 300 mW, we adjust the different wavelength intervals and observe the output spectrum, as shown in Fig.7. The experimental results show that the number of output wavelengths in the multi-wavelength BEFL decreases significantly as the wavelength interval of the injected dual-pump lasers increases. The main reason for this situation is that more wavelengths are located near the peak gain of the erbium-doped fiber, which makes it easier to overcome the loss in the cavity and obtain the output multi-wavelength. Another reason is that the narrower wavelength interval is easier to meet the phase-matching condition to perform the FWM effect. Both of these make the output wavelengths more and more and the output wavelength range is further broadened. When the wavelength interval is 3.2 nm as shown in Fig.7, small fluctuations are generated in the vicinity of the double-pumped Brillouin laser. This is because the fewer the number of output wavelengths, the higher energy contained in a single wavelength when the pump power is constant. This proves that the multi-wavelength BEFL with continuously tunable wavelength intervals from 0.8 nm to 3.2 nm can be achieved by varying the wavelength interval of dual lasers.

In conclusion, we demonstrated the generation of tunable and narrow linewidth multi-wavelength BEFL via FWM effect. The wideband multi-wavelength BEFL covering over 50 nm and 39 lasing lines with the *OSNR* more than 10 dB is successfully generated at 980 nm pump power of 400 mW. The use of dual-laser injection can flexibly adjust the output wavelength interval. Furthermore, the dual-wavelength Brillouin lasers with linewidths of 340 Hz and 356 Hz are measured by using the delayed self-heterodyne method. The multi-wavelength BEFL can increase the communication capacity and will be widely used in optical communication systems in the future.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

References

[1] AMA B, AM A, HHG A, et al. Broadly tunable 40 GHz Brillouin frequency spacing multiwavelength Brillouin-erbium fiber laser for DWDM[J]. Optics communications, 2019, 451：116-123.
[2] 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.
[3] DIAZ S, LEANDRO D, LOPEZ-AMO M, et al. Stable multiwavelength erbium fiber ring laser with optical feedback for remote sensing[J]. Journal of lightwave technology, 2015, 33：2439-2444.
[4] WANG P, CHEN L, ZHANG X, et al. Multi-wavelength fiber laser generated by Brillouin-comb assisted four-wave mixing[J]. Optics communications, 2019, 444：63-67.
[5] SONG Y J, ZHAN L, JI J H, et al. Self-seeded multi-wavelength Brillouin-erbium fiber laser[J]. Optics letters, 2005, 30(5)：486.
[6] ZHOU K J, ZHOU D Y, DONG F Z, et al. Room temperature multi-wavelength erbium-doped fiber ring-laser employing sinusoidal phase-modulation feedback[J]. Optics letters, 2003, 28(11)：893-895.
[7] SULAIMAN A H, YUSOFF N M, ABDULLAH F, et al. Tunable multiwavelength fiber laser based on bidirectional SOA in conjunction with Sagnac loop mirror interferometer[J]. Results in physics, 2020, 18：103301.
[8] ISMAIL A, ALMANSOORI M H, ABDULLAH F, et al. Tunable C + L bands triple frequency spacing multi-wavelength Brillouin-erbium fiber laser[J]. Optical fiber technology, 2021, 64：102535.
[9] DO I H, KIM D Y, JEONG D, et al. Self-stabilized soliton generation in a microresonator through mode-pulled Brillouin lasing[J]. Optics letters, 2021, 46：1772-1775.
[10] FRANÇOIS M, DENIS B, JAOUAD Z, et al. Ultrahigh resolution spectral analysis based on a Brillouin fiber laser[J]. Optics letters, 2010, 35(3)：432-434.
[11] AL-TAIY H, WENZEL N, PREUBLER S, et al. Ultra-narrow linewidth, stable and tunable laser source for optical communication systems and spectroscopy[J]. Optics letters, 2014, 39(20)：5826-5829.
[12] TIU Z C, AIDIT S N, HASSAN N A, et al. Single and double Brillouin frequency spacing multi-wavelength Brillouin erbium fiber laser with micro-air gap cavity[J]. IEEE journal of quantum electronics, 2016：1-5.
[13] SHEE Y G, AL-MANSOORI M H, ISMAIL A, et al. Multiwavelength Brillouin-erbium fiber laser with double-Brillouin-frequency spacing[J]. Optics express, 2011, 19(3)：1699-1706.
[14] ZHOU X F, LIU Y Q, MIAO H, et al. Multi-wavelength Brillouin fiber laser with triple Brillouin frequency spacing[J]. IEEE photonics technology letters, 2016, 28(21)：2379-2382.
[15] AMA B, AM A, HHG A, et al. Broadly tunable 40 GHz Brillouin frequency spacing multiwavelength Brillouin-erbium fiber laser for DWDM[J]. Optics communications, 2019, 451：116-123.
[16] AL-ALIMI A W, CHOLAN N A, YAACOB M H, et al. Enhanced multiwavelength generation in Brillouin fiber laser with pump noise suppression technique[J]. Laser physics, 2016, 26(6)：065102.
[17] AHMAD H, SAMION M Z, KAMELY A A, et al. Multi-wavelength Brillouin generation in bismuth-doped fiber laser with single and double frequency spacing[J]. Journal of lightwave technology, 2020, 38(24)：6886-6896.
[18] AL-MASHHADANI M, AL-MASHHADANI T F, GOKTAS H H. Tunable 50 GHz laser comb generation of multiwavelength Brillouin erbium fiber laser[J]. Optics communications, 2020, 464：125542.
[19] CHEN M, MENG Z, WANG J F, et al. Strong linewidth reduction by compact Brillouin/erbium fiber laser[J]. IEEE photonics journal, 2014, 6(5)：1502107.
[20] ZHANG A, JIN Y, FENG X, et al. Multiwavelength narrow linewidth erbium-doped fiber laser based on FP-LDs[J]. Optics express, 2013, 21(14)：16928-16933.
[21] MERCER L B. 1/f frequency noise effect on self-heterodyne linewidth measurements[J]. Journal of lightwave technology, 1991, 9(4)：485-493.
[22] DEBUT A, RANDOUX S, ZEMMOURI J. Linewidth narrowing in Brillouin lasers：theoretical analysis[J]. Physical review A, 2000, 62(2)：578-592.
[23] LOH W, YEGNANARAYANAN S, ODONNELL F, et al. Ultra-narrow linewidth Brillouin laser with nanokelvin temperature self-referencing[J]. Optica, 2019, 6：152-159.
[24] ERKINTALO M, XU Y Q, MURDOCH S G, et al. Cascaded phase matching and nonlinear symmetry breaking in fiber frequency combs[J]. Physical review letters, 2012, 109(22)：223904.