Switchable Wide-Band Multi-Wavelength Brillouin-Erbium Fiber Laser Based on Random Distributed Feedback

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ABSTRACT A wavelength-interval switchable wide-band multi-wavelength Brillouin-erbium fiber laser with a half-open cavity is proposed and experimentally demonstrated, which is constructed by random distributed feedback (RDFB) mirrors provided by Rayleigh backscattering in a 1-km-long highly nonlinear fiber (HNLF) and a fiber loop mirror (FLM) incorporated a high-power erbium-doped fiber amplifier (HP-EDFA). A strong RDFB and high stimulated Brillouin scattering (SBS) gain are provided by the HNLF. The HP-EDFA is incorporated into the FLM to boost power of the Brillouin pump and feedback Stokes, enhanced SBS and multiple four-wave mixing are stimulated in the HNLF. Using the presented scheme, up to 118 stable Stokes laser lines with a power deviation of less than 15 dB, 70 stable Stokes laser lines with a power deviation of less than 5 dB and a fix wavelength spacing of 0.075 nm are obtained. Peak power fluctuations of arbitrarily chosen 27 Brillouin comb lines are less than 1.95 dB during a 60-minute measurement period, indicates that the proposed laser has a good stability. The effect of pump power of the HP-EDFA on Stokes generating in the laser is also investigated. Furthermore, when a polarization-maintaining fiber loop mirror is cascaded with the free end of the HNLF via an optical isolator, wavelength-interval switchable laser can be conveniently achieved.

INDEX TERMS Fiber lasers, distributed feedback devices, fiber nonlinear optics, four-wave mixing.

I. INTRODUCTION

Random fiber lasers (RFLs) are characterized by a nonresonant positive feedback, which are proved be an important new light source for applications in nonlinear optics, sensing and telecommunications [1]. The simplest method of achieving nonresonant feedback consists of substituting a scattering medium for one of the mirrors, the feedback in this case is due to the backward scattering of the emission. The mean emission frequency of a nonresonant feedback laser is determined by the resonance frequency of the active medium, or the maximum-gain frequency, and does not depend on the distance between the scatterer and the mirror [2].

Multi-wavelength fiber lasers have attracted a lot of interests due to their potentials for wide applications in optical communication, optical sensing, and optical component characterization [3]. One of the viable approaches to achieve low-cost multi-wavelength lasing is utilizing stimulated Brillouin scattering (SBS) in the fiber. Multi-wavelength Brillouin fiber lasers (MBFLs) take the advantage of Rayleigh backscattering from Brillouin gain medium itself, a Doppler frequency shift that is introduced when the Brillouin pump (BP) light is backscattered by a moving acoustic wave, which cause the frequency downshift of the Stokes light [4], as a result of this feedback-seeding, multiple Brillouin Stokes (BS) lines can be generated successfully. Because the amount of the Stokes frequency shift is determined by the speed of the acoustic wave in the fiber core, and it is typically around 10 GHz for silica-based fibers. To get the more multi-wavelength lasing lines, hybrid gain mechanisms are often used, such as the multi-wavelength Brillouin-Raman fiber lasers (MBRFLs) [5], [6], multi-wavelength Brillouin-erbium fiber lasers (MBEFLs) [7]–[9], multi-wavelength Brillouin–thulium fiber lasers (MBTFLs) [10]–[12], and so on.
In addition, frequency intervals of Stokes lasing are required to be switchable in practical application, so, some methods for adjusting frequency spacing of multiple Stokes lights have also been reported [5], [13], [14].

Since Rayleigh scattering (RS) can be used as non-resonant feedback of random fiber laser, and the inherent frequency interval of SBS can be used to achieve multi-wavelength lasing without filter, these characteristics can be naturally unified in multi-wavelength random fiber laser. For example, a Brillouin-Raman multichannel fiber laser with supportive RS in a linear cavity without employing any feedback mirrors at the ends of cavity was proposed, in which Brillouin and the consequences of RS in a section of large effective area fiber in addition to a section of dispersion compensating fiber (DCF) work as virtual mirrors [15]. An S-band multimode Brillouin-Raman random fiber laser based on distributed feedback of Rayleigh scattered light is demonstrated, which relies on a 7.7-km long angle-cleaved DCF in a mirror-less open cavity [16]. A mirror-less cavity for MBFL by combining the “active” DCF and the “passive” single mode fiber (SMF) to enhance the RS effect on the Stokes combs was proposed [6]. A multi-wavelength Brillouin-Raman random fiber laser (MBRRFL) utilizing a half-open cavity formed by a fiber loop mirror (FLM) and a 10-km DCF for generating random distributed Rayleigh backscattering was experimentally demonstrated [17]. In the previous work [18], we also presented a tunable and switchable multi-wavelength Brillouin–Erbium random fiber laser (MW-BERFL) with a half-open cavity, however, the generated very limited oscillating comb lines may be inadequate in practical application.

In this paper, a wavelength-interval switchable wideband multi-wavelength Brillouin-erbium fiber laser based on virtual mirrors provided by random distributed Rayleigh backscattering in a 1-km-long highly nonlinear fiber (HNLF) and a FLM incorporating a high-power erbium-doped fiber amplifier (HP-EDFA) is proposed and experimentally demonstrated. The HNLF provides a strong random distributed feedback (RDFB) and high SBS gain. The HP-EDFA is incorporated into a FLM to boost optical power of the BP and feedback Stokes. When the amplified BP light and feedback Stokes light travel in the same direction in the HNLF, enhanced SBS and four-wave mixing (FWM) are stimulated, which results in up to 118 stable Stokes with a power deviation of less than 5 dBm and the main fiber cavity, via the PC1 and the 20% port of the optical coupler (OC) OC1. The polarization direction of the BP light is adjusted by the PC1. A HP-EDFA is incorporated into the FLM to boost optical power of the BP light and feedback Stokes. The HP-EDFA is with a saturation output optical power of 33 dBm, polarization dependent gain of 0.3 dB and the maximum incident optical power of 5 dBm. Because the HP-EDFA is incorporated into the FLM to use, therefore necessary energy restriction measures should be considered to protect the HP-EDFA. The main fiber cavity includes a 1-km long of HNLF (NL-1550-Zero) with a nonlinear coefficient of $10 \text{ W}^{-1}\text{km}^{-1}$, zero-dispersion wavelength (ZDW) of 1550 nm and dispersion slope of 0.03 ps/nm$^2$/km at 1550 nm. The main fiber cavity is connected to the FLM through a circulator (CIR). 50% of the light energy is extracted from the FLM via a 3-dB coupler (OC2). On the one hand, the energy of the feedback light can be reduced; on the other hand, the evolution of the backscattering light field in the HNLF can be monitored to help to explore the source of multi-wavelength lasing generation. The remaining 50% of the energy of the feedback light continues to circulate in the cavity. The feedback Stokes and the injected BP light are combined at the OC1 and then together launched into the HP-EDFA. The polarization direction of the feedback Stokes is adjusted by the PC2. At the free port of the HNLF, angled cleaves is used at the fiber end facets to eliminate reflections and ensure that the feedback was due only to the randomly distributed scattering. A PMFLM is cascaded with the free port of the HNLF to achieve wavelength-interval switching laser via an optical isolator, which can prohibit power reflected of the PMFLM effect on the multi-wavelength construction in the HNLF. The laser output is monitored by an optical spectrum analyzer (OSA, Anritsu MS9740A, the minimum resolution is 0.03 nm).

The proposed MW-BERFL is illustrated in Fig. 1. A CW provided by a tunable laser source (TLS, OSICS TLS-50) with an instantaneous linewidth (FWHM) of less than 100 kHz and power stability of $\pm 0.03$ dB, served as BP is injected into the half-open cavity constructed by the FLM and the main fiber cavity, via the PC1 and the 20% port of the optical coupler (OC) OC1. The polarization direction of the BP light is adjusted by the PC1. A HP-EDFA is incorporated into the FLM to boost optical power of the BP light and feedback Stokes. The HP-EDFA is with a saturation output optical power of 33 dBm, polarization dependent gain of 0.3 dB and the maximum incident optical power of 5 dBm. Because the HP-EDFA is incorporated into the FLM to use, therefore necessary energy restriction measures should be considered to protect the HP-EDFA. The main fiber cavity includes a 1-km long of HNLF (NL-1550-Zero) with a nonlinear coefficient of $10 \text{ W}^{-1}\text{km}^{-1}$, zero-dispersion wavelength (ZDW) of 1550 nm and dispersion slope of 0.03 ps/nm$^2$/km at 1550 nm. The main fiber cavity is connected to the FLM through a circulator (CIR). 50% of the light energy is extracted from the FLM via a 3-dB coupler (OC2). On the one hand, the energy of the feedback light can be reduced; on the other hand, the evolution of the backscattering light field in the HNLF can be monitored to help to explore the source of multi-wavelength lasing generation. The remaining 50% of the energy of the feedback light continues to circulate in the cavity. The feedback Stokes and the injected BP light are combined at the OC1 and then together launched into the HP-EDFA. The polarization direction of the feedback Stokes is adjusted by the PC2. At the free port of the HNLF, angled cleaves is used at the fiber end facets to eliminate reflections and ensure that the feedback was due only to the randomly distributed scattering. A PMFLM is cascaded with the free port of the HNLF to achieve wavelength-interval switching laser via an optical isolator, which can prohibit power reflected of the PMFLM effect on the multi-wavelength construction in the HNLF. The laser output is monitored by an optical spectrum analyzer (OSA, Anritsu MS9740A, the minimum resolution is 0.03 nm).

When CW emitted by the TLS as BP is launched into the FLM, its power is first amplified in the HP-EDFA, and then injected into the HNLF, RS, SBS and multiple FWM will be
stimulated in turn. When the BP light transmit forward in the HNLF, Rayleigh backscattering served as RDFB is induced and strengthened through SBS. With increasing of BP power, SBS exceed its threshold, the 1st order Stokes (S1) with a frequency $\omega_{S1}$ is generated, which is downshifted by $\Delta \omega_B$ from the BP frequency, namely, $\omega_{S1} = \omega_{P} - \Delta \omega_B$. S1 propagates along the HNLF opposite to transmission direction of the BP. In order to distinguish transmission direction of Stokes, the direction same as transmission direction of the BP light is defined as forward, and the direction in the contrary with transmission direction of the BP light is defined as backward. Then S1 is fed back and amplified in the HP-EDFA, the amplified S1 propagates forward in the HNLF; it also acts as another BP and generates the second-order BS (S2) with a frequency $\omega_{S2}(\omega_{S2} = 2\omega_{S1} - \omega_{P} = \omega_{P} - 2\Delta \omega_B)$ opposite to the transmission direction of the amplified S1. Meantime, the amplified S1 and BP light travel forward in the HNLF, the first-order anti-Stokes signal (AS1) with a frequency $\omega_{AS1}(\omega_{AS1} = 2\omega_{P} - \omega_{S1} = \omega_{P} + \Delta \omega_B)$ is generated by the mixing of between $\omega_{S1}$ and $\omega_{P}$. With increase of power of the amplified BP, S1 and S2, the third-order BS ($\omega_{S3} = \omega_{P} - 3\Delta \omega_B$) will be generated backward. Then power of S3 is also amplified in the EDFA, and the amplified S3 travel forward in the HNLF. It is important to note that, there is a big difference in energy distribution between the light fields in the two contrary transmission directions due to existing of the HP-EDFA, which also determines the difference of the output spectrum in the two contrary transmission directions. When the generated Stokes lines loop in the cavity, the effective length of interaction between the Stokes and BP is extended, which results in SBS threshold being lowered [19] and SBS efficiency being improved. The Stokes and anti-Stokes interact and create higher order Stokes and anti-Stokes through multiple FWM processes. So, more and more Stokes are initiated. In this way, multiple Stokes lights oscillate in the laser cavity formed by the FLM, and RDFB mirrors provided by Rayleigh backscattering in the HNLF. As a consequence, multi-wavelength Brillouin–erbium random fiber lasing with equalized power level can be achieved. In addition, in order to realize wavelength-interval switching lasing, a PMFLM is cascaded with the free port of HNLF via an optical isolator. The operation principle of the PMFLM has been described in the previous work [18]. By adjusting polarization direction of the PC3 in the PMFLM, comb transmission spectrum of the PMFLM can be continuously moved to aim and select corresponding comb lines, wavelength-interval switching of the laser is achieved.

III. EXPERIMENTAL RESULTS

The first, free running spectrum of the half-open cavity as BP being shut down is measured and reported in Fig. 2. When pump power of the HP-EDFA is 2.51 W, free running spectrum consisting of two spectral peaks respectively located at 1535.717 and 1542.476 nm is obtained. In comparison, bandwidth of the spectral peak at 1542.476 nm is wider than that of the spectral peak at 1535.717 nm, and it is closer to the center of the gain spectrum, which mean to be able to generate more Brillouin comb lines. Moreover, because the cavity modes’ oscillation and SBS based Stokes lasing induce gain competing in laser cavity, wavelength of BP is required to locating near the cavity modes’ oscillation range to suppress the cavity modes’ competing [20]. So, BP is set at ~ 1542.476 nm, the maximum number of stable multi-wavelength lasing can be achieved, and because gain of cavity is consumed by BP, threshold of the cavity self-excited lasing is improved.

Wavelength and power of the BP is kept on 1542.476 nm and 6.03 dBm, respectively. When pump power of the HP-EDFA is increased to 7.63 W, output spectrum of the laser has the maximum number of output wavelengths, as shown in Fig. 3. It should be noted that the polarization direction of the laser is still not optimized in this process. Fig. 3(a) shows spectrum of the generated Brillouin combs in a wavelength range of 12 nm, and Fig. 3(b) shows the details of the spectrum in a wavelength range of 5 nm. 87 stable Stokes laser lines with a power deviation of less than 15 dB, 35 stable Stokes laser lines with a power deviation of less than 15 dB.
5 dB and a minimum optical signal-to-noise ratio (OSNR) of 19.21 dB, are obtained, which have a fix wavelength spacing of 0.075 nm. Since gain of the HP-EDFA, SBS and FWM are polarization-dependent, in order to generate more Brillouin comb lines, polarization direction of the laser need to be carefully optimized. Polarization direction of the PC1 and PC2 is constantly adjusted, and output spectrum of the MW-BERFL after optimizing polarization direction is shown in Fig. 4. Fig. 4(a) shows spectrum of the generated Brillouin combs in a wavelength range of 12 nm, and Fig. 4(b) shows the details of spectrum in a wavelength range of 6 nm. Up to 118 stable Stokes laser lines with a power deviation of less than 15 dB, 70 stable Stokes with a power deviation of less than 5 dB and a minimum OSNR of 13.64 dB, are obtained, and all comb lines is with a fix wavelength spacing of 0.075 nm.

FIGURE 4. (a) Output spectrum of the MW-BERFL in a wavelength range of 12 nm after optimizing polarization direction (b) the details of the spectrum in a wavelength range of 6 nm.

Then, stability of the MW-BERFL is also investigated. Wavelength and power of the BP is kept on 1542.476 nm and 6.03 dBm, respectively. Pump power of the HP-EDFA is kept on 7.63 W. The repeated scanning spectra of the MW-BERFL output every ten minutes for total 60 minutes are recorded and shown in Fig. 5. As a demonstration, arbitrarily chosen 27 Brillouin comb lines are stable during a 60-minute measurement period. In addition, the achieved spectrum has a relatively lower signal-to-noise ratio, this is because 0.075-nm wavelength spacing of Brillouin Comb lines is relatively smaller and the resolution of the used OSA is also relatively limited. Fluctuation of peak power for each channel is plotted in Fig. 6. The recorded fluctuation of peak power is respectively 1.12, 1.34, 1.34, 1.42, 1.80, 1.54, 1.69, 1.01, 0.97, 1.00, 1.54, 1.61, 1.80, 1.84, 1.95, 1.80, 1.56, 1.29, 1.26, 1.14, 1.05, 0.70, 1.01, 0.68, 0.81, 0.70 and 0.56 dB. These fluctuations are less than 1.95 dB during 60 minutes. The forward output spectra from HNLF are accumulated every 30 seconds for 30 minutes, and then the means and standard deviations of the Stokes peaks are calculated. The results are reported in Fig. 7. Compared to the previous work [18], an improved output stability are achieved from the MW-BERFL, which can be explained as that, in the forward transmission direction of the HNLF, the power of BP, generated Stokes and anti-Stokes light are first amplified in the HP-EDFA, the enhanced SBS and multiple FWM effects occur in the HNLF, which result in an improved stability of the MW-BERFL.

The generated Brillouin comb lines are sent to a photodetector (PD, u2t, XPDV2120R) to beat, and the generated RF signal through beating is monitored by a spectrum analyzer (Anritsu, MS2830A) to perform noise analysis. Responsive bandwidth of the PD is 50 GHz. The results are reported in Fig. 8. An obvious frequency tone at 9.48 GHz is observed, which is consistent with the fix wavelength spacing of Brillouin comb stemmed from the Stokes frequency shift of SBS. In addition to the beat signal and its harmonic components, no other frequency noises are captured by the spectrum analyzer, the electrical spectrum has a clean base noise, which owe to the enhanced SBS and FWM effects caused by the amplified light fields in the forward transmission direction of the HNLF.
the HNLF. The inset is the zoom-in view of the beating signal spanning 1-GHz in Fig. 8, resolution bandwidth (RBW) of spectrum analyzer is set to 3 MHz.

The influence of pump power of the HP-EDFA on Stokes generating in the laser is also investigated. Wavelength and power of the BP is kept on 1542.476 nm and 6.03 dBm, respectively. In order to comprehend generation mechanism of broadband Stokes comb, the backward feedback light field of HNLF is also monitored via the OUT2 port, the results are reported in Fig. 9(a), and the different forward output spectra of the MW-BERFL are obtained from the OUT1 port only by adjusting pump power of the HP-EDFA and shown in Fig. 9(b). When pump power of the HP-EDFA is equal to 0.32 W, only Rayleigh backscattering light BP-induced is observed in the backward propagation direction of HNLF; in the forward propagation direction, only the amplified pump light is observed. When pump power of the HP-EDFA is increased to 0.48 W, two peaks are observed in the backward propagation direction, which is respectively corresponding to BP-induced Rayleigh backscattering light and the 1st order Stokes; in the forward propagation direction, still only the amplified pump light is observed, but its power is further raised. When pump power of the HP-EDFA is further increased to 0.85 W, well above the threshold of SBS, only the 1st order Stokes is observed from output spectrum in the backward propagation direction, and stability measurement of the 1st order Stokes output spectra being taken over more than 20 minutes reveals that there are almost no observable fluctuations in the peak power and central wavelength over the measured period, which indicates that the 1st order Stokes lasing is stable; however, in the forward propagation direction, a main peak accompanied by six small side peaks are observed, referring to the amplified BP, amplified 1st, 2nd and 3rd order BS and amplified 1st, 2nd and 3rd order anti-BS, respectively. When pump power of the HP-EDFA is 1.4 W, apart from the stable 1st and 2nd order Stokes, the 3rd order stimulated BS is newly initiated and unstable, until to new higher order BS generation, that are observed in the backward propagation direction; in the forward propagation direction, a main peak accompanied by 20 side peaks are observed,
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referring to the amplified BP, amplified 1-10th order BS and amplified 1-10th order Brillouin anti-Stokes, respectively. With increasing of pump power of the HP-EDFA, lasing wavelength number in the backward propagation direction linearly increases, 1-7th order Stokes lines have been generated when pump power of the HP-EDFA is 6.3 W; in the forward propagation direction, more and more Stokes laser lines are generated and their amplitudes become more and more even. From Fig. 9 (a), we can see that, in the backward propagation direction, the backward Stokes is not amplified by the HP-EDFA and is directly output from the OUT2 port, power of these Stokes lines is relatively weak, and 1 ∼ 7 order Stokes with an increasing wavelength number are generated in turn with increasing of the HP-EDFA pump power. It shows that SBS plays a leading role in this process, while efficiency of FWM is relatively limited. So, the number of generated Stokes lines is also very limited. In addition, the transmission direction of the BP light is opposite to that of the generated Stokes, and power of BP-induced Rayleigh backscattering light is also very weak, which results in that anti-Stokes cannot be effectively triggered and is suppressed in the backward propagation direction, which leads to an asymmetric output spectrum. By comparing Fig. 9 (a) and (b), we can see that, in the forward and backward propagation direction of HNLF, the steps for each order Stokes exceeding their respective thresholds and beginning to lasing are different, and the generation of the forward Stokes precedes the backward Stokes. This is because power of the forward transmitting light field in the HNLF are firstly amplified in the HP-EDFA before entering the HNLF, efficiency of SBS and FWM of the forward transmitting light field in the HNLF is much higher than that of the backward transmitting light field, and they complement each other in the forward transmission direction, so both the number of excited Stokes lines and amplitude equilibrium degree of the forward transmitted light field are much higher than that of the backward transmitting light field. In addition, because the transmission direction of the amplified BP light is same with that of the amplified Stokes in the forward direction of the HNLF, the output spectrum has a good symmetric distribution. It needs to be emphasized that, RS works as a virtual mirror for Brillouin-Stokes lines in the Brillouin-erbium fiber laser cavity. As a result of these self-feedback-seeding effects, Brillouin-Stokes lines are generated. Not only does the pump light can excite RS, but the generated Brillouin stokes also can excite RS. This is also the reason why the laser still keeps a certain randomness after forming stable oscillation.

A PMFLM is cascaded with the free end of the HNLF to achieve wavelength-interval switchable laser via an optical isolator and the output spectra are reported in Fig. 10. Since the PMFLM serves as a comb filter, free spectral range (FSR) of the PMFLM transmission spectrum can be expressed as, \( \Delta \lambda = \lambda / (\Delta n L_{eff}) \), here, \( \lambda \) is wavelength of the incident light, \( \Delta n \) is the effective birefringence between two orthogonal polarization modes of the PMF in the PMFLM and \( L_{eff} \) is the effective length of the PMF. Therefore, when length of the employed PMF in the PMFLM is about 38 m, transmission spectrum of the PMFLM measured shows a 0.154-nm FSR (approximately twice 0.075-nm wavelength spacing of the laser) and an about 12-dB extinction ratio. If valley values of the comb transmission spectrum of the PMFLM aim at valley values of the generated Brillouin comb, the transmittance of all Stokes is roughly equal, so, Stokes lasing with a single-BFS are obtained. The output spectrum of the laser with a single BFS is demonstrated in Fig. 10(a). Then, when the odd-order Stokes are aligned with peak values of the comb transmission spectrum of the PMFLM to obtain the maximum transmittance, meanwhile the even-order Stokes are just aligned with valley values of the transmission spectrum to get the minimum transmittance and are almost completely suppressed. So, the odd-order Stokes with a double BFS are obtained, as shown in Fig. 10(b). When the even-order Stokes
are aligned with the peaks of the comb transmission spectrum of the PMFLM, the even-order Stokes with a double BFS are obtained, as shown in Fig. 10(c). However, it should also be noted that when Stokes with a double BFS are generated, odd or even order stokes lines are not completely suppressed, some residual Stokes lines still can be seen. This is mainly due to that the FSR of the PMFLM and BFS of the Stokes lines are not exactly matched. This problem can be solved by optimizing the PMF length in the PMFLM.

IV. CONCLUSION

A wavelength-interval switchable wide-band MW-BERFL has been proposed and experimentally demonstrated. A HP-EDFA is incorporated into a FLM to boost power of the Brillouin pump light and feedback Stokes, enhanced SBS and multiple four-wave mixing are stimulated in the HNLF, which result in up to 118 stable Stokes laser lines with a power deviation of less than 15 dB, 70 stable Stokes laser lines with a power deviation of less than 5 dB and a fix wavelength spacing of 0.075 nm, are obtained. Furthermore, wavelength-interval switchable laser is conveniently achieved only by using a PMFLM. The proposed method can be applied to dense wavelength division multiplexing (DWDM) systems and other fields.

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