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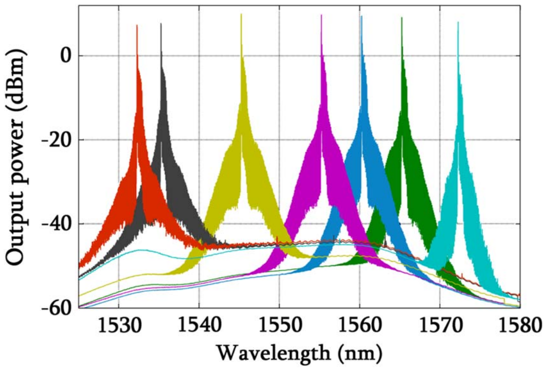

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150-Channel Four Wave Mixing Based Multiwavelength Brillouin-Erbium Doped Fiber Laser

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Abstract: A wide band tunable multiwavelength Brillouin-erbium fiber laser (BEFL) is developed. In this structure, the laser is formed between a double pass amplification box and a highly nonlinear fiber (HNLF), which acts as a virtual mirror, results in removing the reflective physical mirror from one side of the laser structure. A large number of Stokes and anti-Stokes lines are generated through cascading stimulated Brillouin scattering and inducing four wave mixing process inside the HNLF. Due to optimizing Brillouin and erbium doped fiber (EDF) pump powers, the Rayleigh back scattering is efficiently suppressed, and the generated BEFL wavelengths are free from self lasing cavity modes over a wide tuning range. At EDF pump power and Brillouin pump power of 100 mW and 3 dBm, respectively, up to 150 Stokes lines with wavelength spacing of 0.076 nm, and a tuning range of 40 nm were achieved.

Index Terms: 140.3460 Lasers, 140.3500 Lasers, erbium, 140.3510 Lasers, fiber, 140.3600 Lasers, tunable.

1. Introduction

The high capacity transmission in optical communication system requires multiwavelength laser source. For this reason, different multiwavelength laser structures have been adopted such as multiwavelength Brillouin/Raman fiber lasers (MW-BRFLs) [1], multiwavelength Brillouin fiber lasers (MW-BFLs) [2], multiwavelength erbium doped fiber lasers (MW-EDFLs) [3]–[5] and multiwavelength Brillouin/erbium fiber lasers (MW-BEFLs) [6], [7]. MW-BRFs and MW-BEFLs are the most interesting laser sources among multiwavelength laser approaches. Both lasers can generate wavelengths with wavelength spacing of around 10 GHz (or 0.08 nm). However, MWBEFL is better than MWBRFL in terms of the optical signal to noise ratio (OSNR). Cowle and Stepanov demonstrated the first hybrid structure of the Brillouin erbium fiber laser (BEFL), which consisted of two gain mediums: Brillouin gain and erbium doped fiber amplifier (EDFA) gain [8], [9]. In this type of laser structure, to get a large number of Brillouin Stokes (BS) lines, the Brillouin pump (BP) wavelength must tune closer to or within the EDF peak, where the self lasing cavity modes is appeared [10]. Moreover, due to the gain competition between BS lines and self-lasing cavity modes as the BP wavelength tunes away from

EDF peak gain, it is difficult to get stable wavelengths over a wide tuning range. In other words, the major disadvantage of the conventional BEFL is its low Stokes lines number and tuning range limitation. Efficient suppression of the self lasing cavity modes throughout a wide range was obtained by varying the gain profile of the erbium doped fiber amplifier (EDFA), which changes by utilizing a Sagnac loop filter in a ring cavity [11]. In that setup, up to 12 Stokes lines with tunability of 14.5 mm were achieved. In another approach, up to 11 channels tuned over 6 nm were achieved by utilizing a variable optical attenuator, which acts as self lasing cavity modes shifter [12]. Similar idea was realized by carefully optimizing two polarization controllers [13]. However, similar to cavity loss optimization [12], the BP wavelength must be tuned to the EDF peak gain for each loss optimization process. Also, enough BP power with low EDF pump power was used to get tuning range of 60 nm [14]. By adjusting a tunable bandpass filter and the BP wavelength simultaneously in a linear cavity, up to 14 Stokes lines can be tuned over 29 nm [15]. 53-Stokes lines were generated by enhancing the feedback mechanism of BS lines utilizing reverse S-shape [16]. However, because of the self lasing cavity modes, it was observed that the Stokes lines above channel 30 have higher peak power compared with the previous channels. Therefore, only 30 channels can be counted. Although the tuning range of the BEFL has been improved in the previous approaches, two tuning range controllers were required, and also the self lasing cavity modes was not suppressed completely [12], [13], [15].

Up to 120 [17], 160 [18], and a total of 200 lines of Stokes lines [19] were reported in self-seed BEFL cavities. Without tunability, 34 output channels based on exciting the FWM process in a Sagnac loop mirror was also demonstrated [20]. Beside the large number of wavelengths that can be achieved in this type of fiber laser, a wide tuning range can be obtained. By adjusting the polarization controllers (PCs) in a high-birefringent Sagnac loop mirror, up to 70 Stokes lines tuned throughout a range of 11 nm [21], and 45 nm of tuning range were obtained [19]. Recently, a tunable self-seeded multiwavelength Brillouin-erbium fiber laser (BEFL) using an in-line two-taper Mach–Zehnder interferometer (MZI) was demonstrated [22]. In that setup, a total of 35 lines can be tune over a tuning range of 11 nm. Although large number of wavelengths and wide tuning range can be achieved in the self-seed BEFL cavities [18], [19], [21], [22], its main disadvantage is the low OSNR, low channels peak power, and the complexity of adjusting the polarization controller.

It is noted that all the previous ring and linear configurations [12]–[16], [18], [19], [21], [22] allow the amplified spontaneous emission (ASE) to circulate inside the cavity, which results in growing self lasing cavity modes. This self lasing cavity modes limits the tunability of BEFL. Therefore, a wide tuning rang can be achieved by completely suppression this unwanted self lasing cavity modes. Recently, the tunability of the BEFL was improved by utilizing the concept of the virtual mirror which is an optical fiber [23]–[25]. The generated Rayleigh back scattering from the virtual mirror show up as a noise in the BEFL output spectrum, which affects the BEFL performance. A wide tuning range was obtained by completely suppression this noise [23]–[25]. Since the optical fiber acts as a weak reflective mirror, a few number of Stokes lines can only be generated, for instance, 4 Stokes lines in [23] and 11 Stokes lines in [24], [25]. In this paper, by inducing the FWM process inside HNLF utilizing a VOC which makes the Brillouin pump power and the Brillouin Stokes and anti-Stokes lines to propagate inside HNLF in opposite directions, up to 150 wavelengths BEFL were obtained. By efficiently suppress the Rayleigh back scattering; these wavelengths can be tuned over a range of 40 nm. Therefore, we do not only demonstrate a new approach to generate larger number of wavelengths but also the larger number of wavelengths can easily be tuned over wide range.

2. Experimental Setup

The experimental setup of the proposed tunable multiwavelength BEFL is shown in Fig. 1(a). The laser structure consists of a double pass amplification box and two optical components; circulator (C1) used to insert the Brillouin pump power as well as an output port, and a variable optical coupler (VOC) was deployed to guide the generated Stokes lines to the gain cavity and to output port as well. The double pass amplification box, as shown in Fig. 1 (dash line), was designed by using one

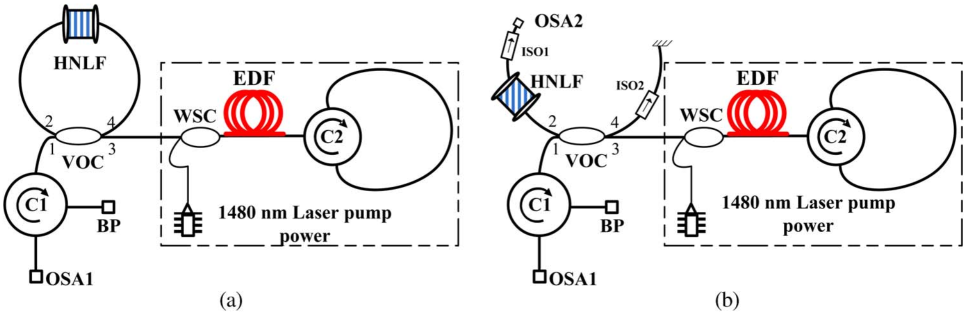

Fig. 1. Experimental setup of the multiwavelength BEFL based on four-wave mixing generated in HNLF. C: Circulator. WSC: Wavelength selective couple. VOC: Variable optical coupler. EDF: erbium doped fiber. HNLF: Highly nonlinear fiber. BP: Brillouin.

circulator (C2) which acts as a high reflective physical mirror and ensure that the signal pass the EDF twice, 10 m long of EDF with absorption coefficient of 5.6 dB/m at 1531 nm, a 1480 nm semiconductor laser with a maximum output power of 150 mW as primary light source for the EDF, and a 1480 nm wavelength selective coupler (WSC). To activate EDF, the signal of 1480 nm pump was launched into the EDF through the WSC. A highly nonlinear fiber (HNLF) was used as Brillouin gain medium and spliced between ports 2 and 4 of the VOC. The length, the dispersion slope, the attenuation, the total loss, the cut off coefficient, and the Nonlinear coefficient of the HNLF are 2015 m, 0.007 $\text{ps}/(\text{nm}^2 \cdot \text{km})$ at 1550 nm, 0.75 dB/km, 1.78 dB at 1550 nm, 1250 nm, and 10.8 $(\text{W} \cdot \text{km})^{-1}$, respectively. The Brillouin pump (BP) was formed by an external-cavity tunable laser source (TLS) with maximum power of 5 dBm and 200 kHz linewidth. The TLS can be tuned over a range of 100 nm (1520–1620 nm). To monitor the output spectra of the BEFL, an optical spectrum analyzer (OSA) with 0.01 nm resolution bandwidth was connected to port 3 of C1.

To observe the generated Brillouin Stokes (BS) lines by utilizing the HNLF, which acts as a virtual mirror, the HNLF was disconnected from port 4 of the VOC. Referring to Fig. 1(b), the generated BS lines were prevented from the back scattering reflection of the air-glass interface by utilizing two isolators; one isolator was connected to port 4 of the VOC, and the other one was connected to the HNLF. The output spectrum of the BEFL was observed by connecting port 4 of the VOC to OSA2 with resolution bandwidth of 0.01 nm. The BEFL working principle is described as follow: when the intensity of the BP signal is above the stimulated Brillouin scattering (SBS) threshold power, the first-order BS signal is generated by SBS effect inside HNLF, which is down-shifted by 0.076 nm from the BP signal and propagates in the opposite direction to the BP signal. The first-order BS signal in the cavity is amplified twice by the double pass amplification box. Then, the first-order BS signals will serve as BP signal and creates the second-order BS signal. These processes will continue and only be terminated when the power of the next higher-order BS signal is not high enough to satisfy the SBS threshold condition [26].

In the previous linear BEFL cavities, the Stokes lines are reflected back into the laser cavity by utilizing two reflective physical mirrors [10]–[12]. In this work, the physical mirror at one side of the linear structure was removed and replaced by a virtual mirror, i.e., the HNLF. The reflectivity of the virtual mirror is determined by the Brillouin gain in the HNLF. Since one physical mirror from one side of the linear cavity was removed, the source of reflection could be due to the Rayleigh back scattering [23]. The Rayleigh back scattering from the optical fiber is weaker compared with SBS effect. Therefore, it is easy to suppress it sufficiently throughout a wide range by injecting adequate BP power [23]. By inserting EDF pump power of 100 mw with 5 dBm, it is found up to 9 Stokes lines can be tuned throughout range of 40 nm. Fig. 2 depicts an example of the output spectra of the multiwavelength BEFL at BP wavelength of 1550 nm, which based only on the reflectivity of the virtual mirror before connecting the HNLF to port 4 of the VOC.

To explain the MW-BEFL behavior, the experiment was also conducted to measure the output power of the double pass amplification box. In this measurement, the HNLF was removed from the

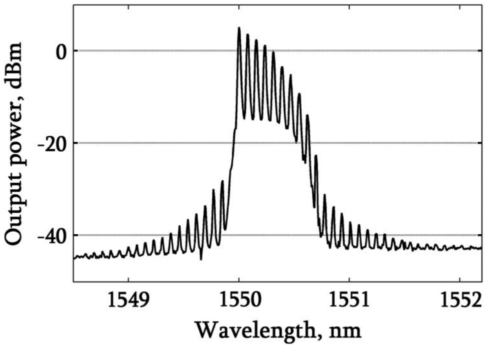

Fig. 2. The output channels of the MW-BEFL configuration that are generated from the virtual mirror before inducing four wave mixing inside the HNLF.

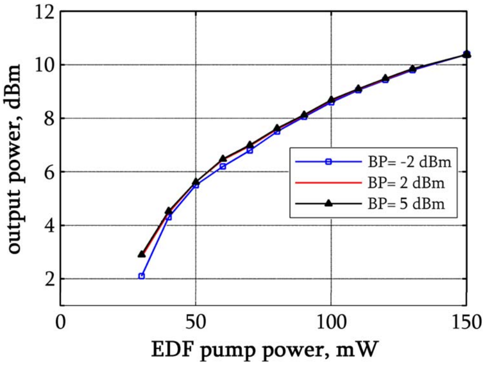

Fig. 3. The dependence of the output power of the double pass amplification box on the EDF pump power with different input Brillouin pump power.

setup and the BP wavelength was fixed at 1550 nm while BP power varied from −2 dBm to 5 dBm. The EDF pump power was varied from 30 mW to 150 mW for each value of BP power. The output power of the EDFA was taken from port 2 of the VOC and measured by using an optical meter. Fig. 3 shows the dependence of the signal output power on the EDF pump power.

It is noted that the output power gradually increases as the EDF pump power increases, as shown in Fig. 3. Additionally, no significant sign of output power saturation was observed. It is found that when the EDF pump power below than 100 mW, the output power of the injected BP power slightly improved for BP power changed from −2 to 3 dBm, as shown in Fig. 4. On the other hand, the output power saturation level occurred when the BP power was above 3 dBm. This is due to the fact that the high BP power makes the EDFA to operate in deep saturation. Fig. 4 shows an example of the BP output power with EDF pump power of 30, 60, 90, 120 mW. Referring to Fig. 4(a)–(d), the output power was approximately unchanged as the EDF pump power higher than 100 mW. Therefore, 100 mW and 3 dBm of EDF pump power and BP power, respectively, were chosen as the optimum values for the double pass amplification box operation.

The experimental structure of the BEFL based on the cascaded FWM process is shown in Fig. 1(a). The purpose of this connection is to reinsert the generated Stokes lines to the HNLF. This connection allows the generated Stokes lines to propagate inside HNLF in opposite direction which results in generating multiple sideband wavelengths. These sideband wavelengths are generated due to the cascaded FWM process. The FWM wavelengths occur when the phase matching condition is satisfied. The optimum phase matching is obtained at zero dispersion wavelength [20]. In this wavelength range, high power conversion efficiency of the FWM can be achieved. Therefore,

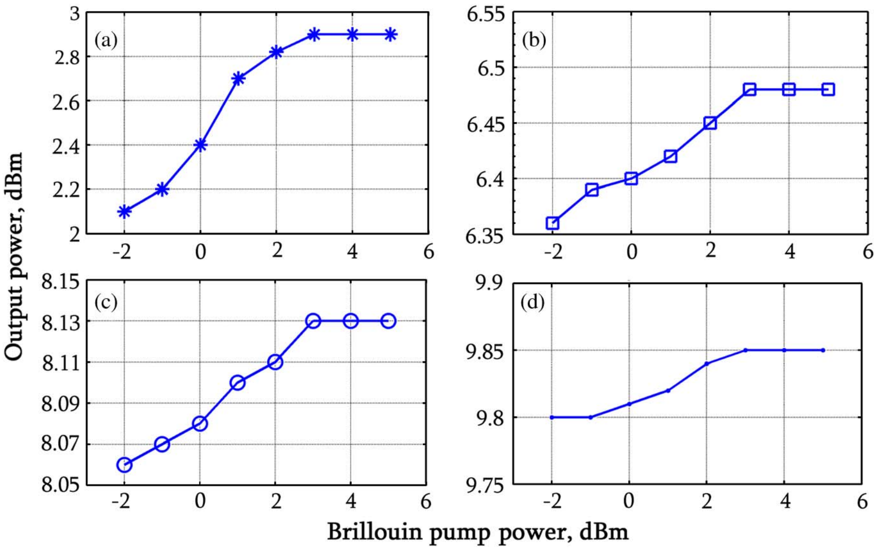

Fig. 4. Output power of the amplified wavelength at 1550 nm with different Brillouin pump power and fixed EDF pump power: a) 30 mW, b) 60 mW, c) 90 mW, and d) 120 mW.

due to use a fiber with low dispersion at 1550 nm (such as HNLF), a large number of wavelengths can be obtained through cascaded FWM process. As these wavelengths counter-propagate inside a fiber, they mix and generate sideband wavelengths. For example, the first Stokes line at frequency of w_s, that generated from the Brillouin pump wavelength and shifted by $\Delta w_B = w_p - w_s$, and BP wavelength at frequency of w_p interact with each other and create new sideband wavelengths at frequency of $w_{as} = 2w_p - w_s$ and $w_{s=2}w_{s-}w_p$. The newly generated sideband wavelengths can mathematically be calculated by summing the positive or negative multiples N_i of the all the original wavelengths [27], see Eq. (1)

$$f_{IM} = N_1 f_1 + N_2 f_2 + N_3 f_3 + \cdots \tag{1}$$

$$\mathrm{IM} = \sum_{1}^{M} N_i \tag{2}$$

where f_{IM} is the generated sideband wavelength center, f_i is the original wavelength center where $\mathrm{i} = 1$ to M, N_i is any integer with + or − coefficients including zero, M is the total number of original wavelengths, and IM is the wavelength order.

In general, for M wavelengths propagated in a fiber, the maximum possible number of FWM wavelength components is

$$N_{\mathrm{IM}} = \frac{(M-1)M^2}{2}. \tag{3}$$

3. Result and Discussion

The aim of this work is to investigate the possibility of generating a large number of Stokes lines with a wide tuning range and appropriate OSNR. Although no physical mirror was installed in one side of the laser cavity, unstable self lasing cavity modes appeared with spectral width of about 40 nm, and centered at around 1558 nm, as shown in Fig. 5. Since one physical mirror from one side of the linear cavity was removed, the source of reflection could be due to the Rayleigh back scattering [23]. As a result, the Rayleigh back scattering considers as the main noise source, which can affect the performance of BEFL. Therefore, a wide tuning range can be achieved by eliminate this noise. Fig. 5 shows the dependence of the self lasing cavity modes on the EDF pump power. In BEFL operation, due to the SBS effect inside Brillouin gain medium, HNLF in this experiment, the generated Brillouin

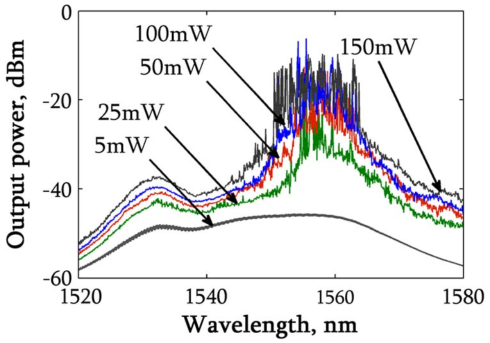

Fig. 5. The dependence of the Rayleigh scattering spectrum on the erbium doped fiber pump power.

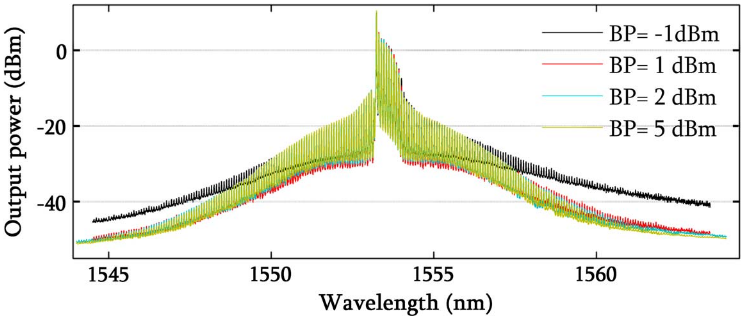

Fig. 6. The output spectrum of the BEFL at different Brillouin pump power with erbium pump power of 70 mW.

Stokes lines are reflected back to the laser cavity. Therefore, the Brillouin gain medium can be used to act as a virtual mirror.

The effect of BP power on the OSNR and multiwavelength generation at a given pump power was investigated. An OSA with bandwidth resolution of 0.01 nm was used to measure the OSNR. The OSNR was calculated by measuring the peak power to the highest noise floor level of the signal. Fig. 5 shows the location of the self lasing cavity modes which indicates to the EDF peak gain. Therefore, to obtain the best BEFL performance, the BP wavelength must be closer to or within the EDF peak gain. The BP wavelength was fixed at 1553 nm where the EDF peak gain can be obtained while the BP power was changed from -2 dBm to 5 dBm. Fig. 6 shows that at EDF pump power of 70 mW, the number of Brillouin Stokes lines reached its maximum number for BP power change from -2 dBm to 5 dBm. This is due to the high gain provided by the EDF at high 1480 nm pump power. At high EDF pump and low BP power, the EDF provides gain to the self lasing cavity modes rather than the BS wavelengths which results in reducing the OSNR of the signals. Therefore, high BP power was required to suppress this noise, as depicted in Fig. 6. Although the BP has no significant effect on the increment of Brillouin Stokes lines at high EDF pump power, sufficient BP power is necessary to reduce the noise level of the BEFL spectrum which led to improve the OSNR and Stokes and anti-Stokes lines number, as shown in Fig. 6.

Fig. 7 shows the output spectrum of BEFL as a function of EDF pump power. In this investigation, the EDF pump power was varied from 20 mW to 150 mW whereas the BP power and wavelength were fixed at 2 dBm and 1553 nm, respectively. For each value of EDF pump power, the OSNR and the number of lines were calculated.

Referring to Fig. 7, the number of lines increases as the pump power gradually increases. This is due to the fact that EDF provides more gain to Brillouin Stokes lines as the power of 1480 nm

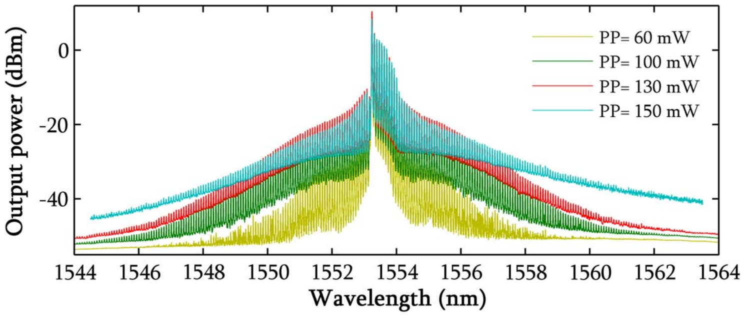

Fig. 7. The output spectrum of the BEFL at BP power of 2 dBm and different EDF pump power.

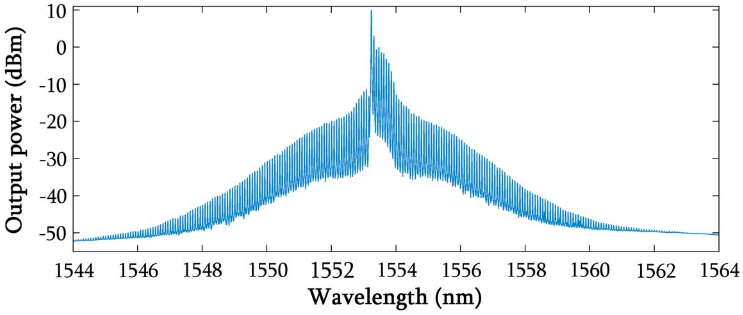

Fig. 8. The output spectra of the BEFL at pump power of 100 mW and Brillouin pump power of 3 dBm.

increases [26]. Since the number of the FWM wavelengths depends on the Brillouin Stokes lines, the FWM wavelengths increases as the BS lines increases [27]. The EDF reached its saturation level as further pump power injected to the laser cavity, which led to limit Stokes lines generation. In this case, the EDF provides gain to the self lasing cavity modes rather than BS lines results in raising the noise floor. As a result, the OSNRs of the signals are reduced. In general, due to the effect of both pump powers on the EDF saturation level, OSNR, and the number of Stokes lines, as shown in Figs. 6 and 7, it is important to prevent the EDF from reaching its saturation level by optimizing the BP power and EDF pump power. Thus, the gain provided by the EDF can be used efficiently to improve the OSNR and Stokes lines count. In this regards, a good output spectrum of BEFL in terms of OSNRs and Stokes lines count was obtained at EDF pump power of 100 mW and BP power of 3 dBm.

Fig. 8 depicts the output spectra of multiwavelength BEFL at BP wavelength, EDF pump power, and BP pump power of 1553 nm, 100 mW, and 3 dBm, respectively. Due to the effect of cascaded SBS inside HNLF, nine Brillouin Stokes lines with wavelength spacing of 0.076 nm and individual peak powers of greater than −8 dBm were generated compared with 4 Stokes lines in [23] and 7 Stokes in [28]. The other channels (Stokes and anti-Stokes lines) were generated due to the interaction between BP wavelength and Brillouin Stokes lines through FWM process. A total of 35 Stokes lines with peak power of higher than −20 dBm were obtained compared with 11 Stokes lines in [24], [25]. Referring to Fig. 8, although more than 190 Stokes lines in a broad optical spectrum ranging from 1546 nm to 1561 nm were observed, only the Stokes line with OSNR of higher than 5 dB was taken into account. More than 150 Stokes lines with OSNR exceed 5 dB in range from 1547.5 nm to 1559 nm were counted, as depicted in Fig. 9(a) and (b). It is expected that a large number of Stokes lines could be obtained if long length of HNLF is used.

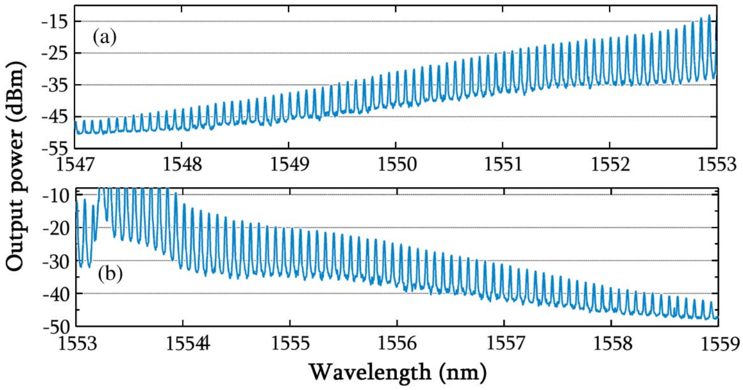

Fig. 9. The magnified view of the output Spectra of the generated multiwavelength BEFL at Brillouin pump power of 3 and erbium doped fiber pump power of 100 mW (a) from 1547.5 to 1553 nm and (b) from 1553 to 1559 nm.

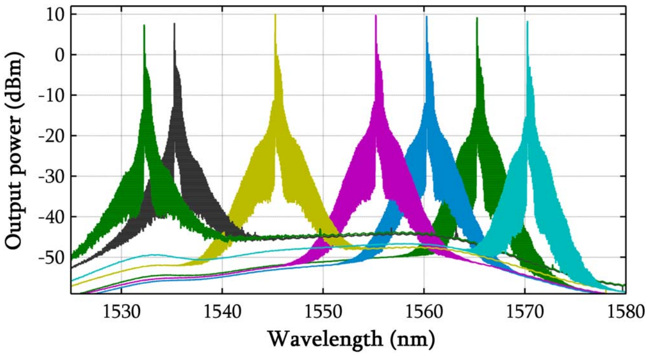

Fig. 10. The output spectra of the tunable BEFL at BP power of 3 dBm, EDF pump power of 100 mW, and different BP wavelengths.

Due to increase of the pump power to the EDF, the competition between self lasing cavity modes and Brillouin Stokes lines is increased; thus, the Stokes lines become unstable [14]. Moreover, the free running cavity modes appears when the BP wavelength tuned away from the EDF peak gain. This phenomenon prevents Stokes lines of the BEFL from using the EDF gain efficiently over wide range. As a result, the tuning range of the BEFL is limited. However, by injecting high Brillouin pump and low EDF pump power, the tuning range of the BEFL was improved at the expense of Stokes lines count [14]. In this new configuration, due to low reflectivity of the virtual mirror, the self-lasing cavity modes can be efficiently suppressed at high EDF pump power throughout wide range. Thus, the tunability of the BEFL depends only on the availability of the linear gain medium. Fig. 10 depicts the output spectra of some selected wavelengths at pump power of 100 mW and BP power of 3 dBm. We found that a fixed number of 9 Brillouin Stokes lines can be tuned over a range of 40 nm with peak power of higher than −8 dBm. Up to 160 channels with OSNR of above 5 dB can be tuned over a tuning rang of 26 nm from 1539 nm to 1565 nm. These channels are free from unwanted lasing cavity modes as compared to 80 channels tuned over 6 nm in [6]. The tuning range of BEFL can also be extended to more than 35 nm. However, due to the low EDF gain at longer and shorter wavelength, the number of Stokes lines was dropped to 120 channels at wavelengths 1535.2 nm and 1570.2 nm and to 100 lines when the BP wavelength was tuned to 1532.2 nm and to 1572.2 nm. In general, when a suitable linear gain medium is available, the tuning range can be extended to longer or shorter wavelength with large number of Stokes lines. The performance of the new multiwavelength BEFL is better compared with the results obtained in [6] in terms of pump power consumption which is reduced from 165 mW to 70 mW, BEFL tunability which is improved from 6 nm to 40 nm, and even BP power which reduced from 12 to 3 dBm.

Referring to Fig. 10, the proposed laser structure has the advantage of wide tuning range of 40 nm without the requirement to change the EDF gain profile [19], [21], filtering [15], or utilizing a variable optical attenuator [12]. In addition, it is clearly seen that the first 9 channels have individual peak power levels above −8 dBm and 100 channels are kept constant through the 40 nm tuning rang compared with the conventional laser structure [12]–[16], [18], [19], [21], [22], which achieved a wide tuning range at the expense of the output wavelengths count. Also, good OSNR is maintained above 10 dB by 85 channels throughout the tuning range.

4. Conclusion

We have successively demonstrated a new BEFL linear cavity structure that improves the number of output Stokes lines of BEFL. Based on inducing FWM and cascading SBS in HNLF, more than 150 Stokes lines with wavelength spacing of the 0.078 nm was achieved at Brillouin pump power of 3 dBm and EDF pump power of 100 mW. Therefore, the FWM process can effectively be used to increase the number of BEFL output wavelengths. Moreover, due to efficiently suppression the Rayleigh back scattering, which acts as self lasing cavity modes, a large number of Stokes lines can be tuned to cover a wide wavelength region (from 1532.2 nm to 1572 nm). Therefore, this configuration has the advantage of the large number of wavelengths and the wide tuning range which could be used for potential applications in DWDM and optical sensor systems. For future work, more efforts will be given to improve the OSNR to approach the requirements of the optical communication system.

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