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Multiwavelength L-band fiber laser with bismuth-oxide EDF and photonic crystal fiber

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Abstract A multiwavelength laser comb using a bismuth-based erbium-doped fiber and 50 m photonic crystal fiber is demonstrated in a ring cavity configuration. The fiber laser is solely pumped by a single 1455 nm Raman pump laser to exploit its higher power delivery compared to that of a single-mode laser diode pump. At 264 mW Raman pump power and 1 mW Brillouin pump power, 38 output channels in the L-band have been realized with an optical signal-to-noise ratio above 15 dB and a Stokes line spacing of 0.08 nm. The laser exhibits a tuning range of 12 nm and produces stable Stokes lines across the tuning range between Brillouin pump wavelengths of 1603 nm and 1615 nm.

1 Introduction

Multiwavelength fiber lasers (MFLs) have been of great interest in the field of optical communication networks due to their wide applications, namely in wavelength division multiplexing (WDM) systems. The wide amplification bandwidth of erbium-doped fibers (EDF) in the 1550 nm region is beneficial to support their utilization as sources of multiwavelength output. However, other active gain media such as semiconductor optical amplifiers (SOAs) and Raman amplifiers have also been attempted. These include an SOA-based MFL incorporating a novel double-pass waveguide-based Mach–Zehnder interferometer (MZI) [1] and 82-channel multiwavelength comb with a double SOA ring cavity in a dual-pass MZI filter [2]. Another example is a multiwavelength Raman fiber laser using a sampled chirped fiber Bragg grating [3].

The first hybrid Brillouin-erbium fiber laser (BEFL) combining the gain of EDF and Brillouin gain in a single-mode fiber has been achieved. It produces a laser output at a Brillouin frequency that is shifted from the injected Brillouin pump with a 10 GHz line spacing [4]. However in EDF systems, the homogeneous gain broadening hinders the multiwavelength oscillations at room temperature. One of the techniques to reduce this broadening is the exploitation of nonlinear effects. The high nonlinear gain in fibers suppresses the mode competition in EDF systems [5]. In the search for new fiber structures with a high nonlinearity, photonic crystal fibers (PCFs) present an attractive solution with optical properties superior to those of the step-index fibers. PCFs enhance the nonlinear effects through extreme confinement of light in hollow cores, and hence offer an effective nonlinearity per unit length of 10–100 times higher than the conventional fibers [6]. In addition, PCFs also offer characteristics that ordinary optical fibers do not exhibit, such as lower numerical aperture (NA) values, better dispersion properties, and extreme confinement of air core. Therefore, for the application of nonlinear devices in fiber optics communication systems, PCFs can offer a much shorter length than conventional fibers.

Stable multiwavelength lasing based on the PCF loop mirror and Rayleigh scattering has been achieved [7]. In

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addition to this, multiple lasing wavelengths with 0.8 nm line spacing have been reported by utilizing a sample-fiber Bragg grating [8]. In the proposed structure, the four-wave mixing effect in a 101 m long PCF is exploited due to its high nonlinear coefficient. A recent work on BEFL systems using a PCF and 49 cm bismuth-oxide based erbium-doped fiber (Bi-EDF) generated 3 Stokes lines together with 3 anti-Stokes lines [9]. Thirteen lines including those of anti-Stokes at 8 dBm Brillouin pump (BP) power and 280 mW Raman pump power have also been reported using a holey fiber and 215 cm Bi-EDF [10]. Additionally, a BEFL with 14 Stokes lines at 7 dBm power has also been achieved by employing a 100 m PCF and tunable bandpass filter [11].

The use of Bi-EDF in the L-band window presents a broader amplification spectrum. However, the broader the desired bandwidth is, the more difficult it becomes to obtain a sufficient gain over the whole bandwidth region [12]. Therefore, the Bi-EDF has to be pumped with high pumping powers to achieve an optimized gain spectrum. Almost all Bi-EDF pumping schemes deployed so far have been through the use of high-power 980 nm and 1480 nm laser diodes [10–12]. An article on a multiwavelength BEFL deploying bidirectional and unidirectional propagation of Brillouin pump and Brillouin signal reported a higher tuning range but with lower number of Stokes lines in a unidirectional configuration [13].

In comparison to the prior work, an enhanced multiwavelength fiber laser with a PCF and Bi-EDF pumped by a 1455 nm Raman pump power in a ring cavity is demonstrated in this paper. Up to 26 Stokes lines and 11 anti-Stokes lines are realized at 264 mW Raman pump power and 1 mW BP power that all the channels have an optical signal-to-noise ratio (OSNR) above 15 dB. To the best of the authors' knowledge, this is the highest number of output channels in a multiwavelength fiber laser that is composed of a combination of PCF and Bi-EDF. The Stokes lines exhibit a channel spacing of 0.08 nm with a tuning range of 12 nm. Although the unidirectional configuration is deployed in this work, we are able to report a high channel count while maintaining a large tuning range.

2 Experimental setup

The experimental setup for the operation of multiwavelength BEFL using a Bi-EDF and PCF in a unidirectional configuration is shown in Fig. 1. The setup consists of a wavelength division multiplexing (WDM) coupler, a 249 cm long Bi-EDF, an optical circulator, a 3-dB optical coupler, a 50 m long PCF and a high reflectivity mirror. A 1455 nm Raman pump laser with a maximum power of 2 W is used as the primary light source for the Bi-EDF. The PCF used as the nonlinear gain medium has a nonlinear coefficient of about 11 $(\mathrm{W\,km})^{-1}$ and a mode field diameter of 2.8 µm. The Bi-EDF that serves as the linear gain medium has an erbium ions concentration of 3200 ppm, a cut-off wavelength of less than 1450 nm, a numerical aperture of 0.2 and a mode field diameter of 6.2 µm at 1550 nm. The WDM coupler's function is to multiplex the Raman laser pump and the oscillating signal. An external tunable laser source (TLS) provides the BP signal with a maximum output power of 5 mW. The output of the cavity is extracted from the 3 dB coupler and directly connected to an optical spectrum analyzer (OSA) with the resolution bandwidth set at 0.015 nm. Both the BP and Brillouin Stokes (BS) lines pass through the optical circulator in a unidirectional path. The BP signal produced by the TLS is injected into the laser structure and it is initially amplified by the bismuth-based erbium-doped fiber. The amplified signal then passes to the PCF, through the optical circulator. When the threshold power of the Brillouin gain medium is exceeded, stimulated Brillouin scattering (SBS) will be initiated. This creates the first Stokes line that propagates in the opposite direction to the propagation of BP signal. The first Stokes line passes through the optical circulator into the WDM coupler where it is amplified by the Bi-EDF, before reaching the Brillouin gain medium. As soon as the threshold power of the SBS is exceeded, the first Stokes line acts as the BP signal and thus induces the generation of the second Stokes line. Other subsequent Stokes lines are also generated in the same way until the power of the next higher order Stokes is less than the Brillouin threshold in the PCF.

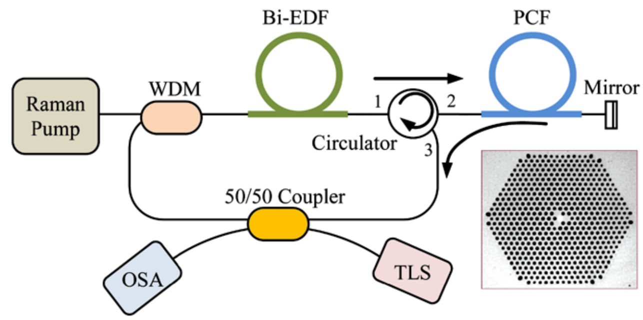


Fig. 1 Experimental setup of the proposed MWBEFL

3 Results and discussions

Generation of the highest number of output channels in the operating wavelength range of the laser is determined by observing free-running cavity modes region when no BP power is injected. Figure 2 shows the free-running (self-lasing) cavity modes at 198 mW Raman pump power with a peak power of approximately −10 dBm and a bandwidth around 3.2 nm. By choosing the operating wavelength to be close to the peak of the free-running cavity modes at around

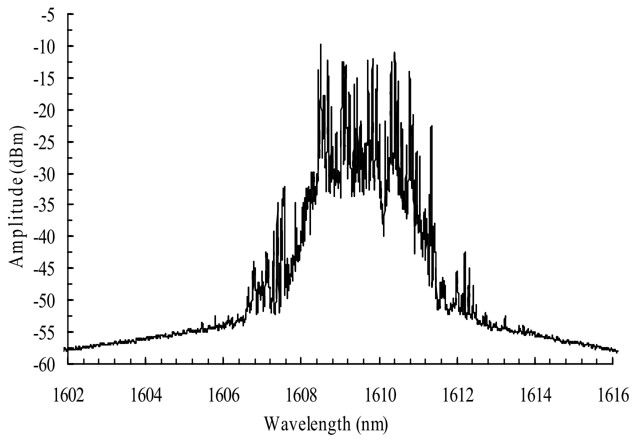


Fig. 2 Self-lasing cavity modes at Raman pump power of 198 mW

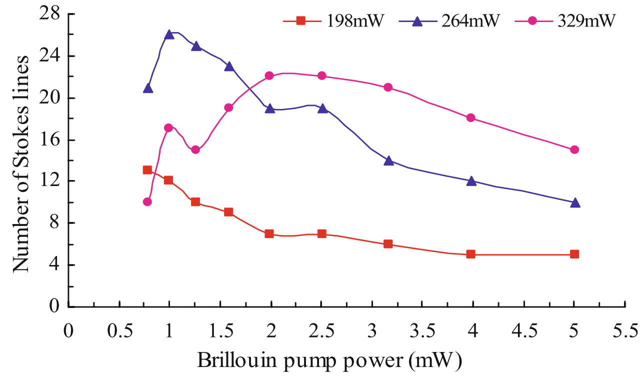


Fig. 3 Number of Stokes lines generated against BP power at different Raman pump powers and BP wavelength of 1608 nm

1608 nm, maximum number of Stokes lines is generated while these modes are suppressed.

To study the effect of Raman pump and BP powers on the number of generated Stokes lines, the BP wavelength is set to the Bi-EDF peak gain wavelength at 1608 nm. The threshold power to create the first Stokes line is found to be 124 mW. Theoretically, the SBS threshold can be approximated by the following equation [14]:

$$P_{th} \cong \frac{21A_{eff}}{g_B L_{eff}}, \tag{1}$$

where g_B is the peak value of the Brillouin gain, A_{eff} is the effective core area of the fiber, and L_{eff} is the effective interaction length of the optical fiber, which is given by

$$L_{eff} = \frac{1}{\alpha}\left[1 - \exp^{(-\alpha l)}\right], \tag{2}$$

where α is the optical fiber loss coefficient and l is the optical length. The output spectrum is measured at different Raman pump powers and the BP power is varied from 0.8 to 5.0 mW. Figure 3 shows the relationship between the BP power, Raman pump power and the number of Stokes lines generated at 1608 nm BP wavelength. The count of Stokes lines and anti-Stokes lines that are considered as suitable are those with a peak power higher than −30 dBm and an OSNR that is greater than 15 dB. It can be seen that the number of Stokes lines is proportional to the Raman pump power. As the Raman pump power increases, more Stokes lines are generated due to the increment of erbium gain in the laser cavity, as long as the free-running cavity modes are totally suppressed. This can be further examined for the case of BP that is less than 2 mW and at a high Raman pump power of 329 mW. In that specific case, it is observed that the number of Stokes lines below 2 mW BP is lower at 329 mW than that at 264 mW Raman pump power. This is because at higher Raman pump powers, analogously to higher EDF gains, higher mode competition between the free-running cavity modes and the group of Brillouin Stokes lines is generated. In this case, the Brillouin pump is not high enough to increase the Brillouin gain and, hence, it is unable to suppress the growth of the free-running cavity modes [15, 16]. Therefore, for the same Raman pump power and BP power that are lower than 0.8 mW, cavity modes are present together with Brillouin Stokes lines, which results in unstable operation. This explains the reduction in number of Stokes lines since most of the Raman pump power is absorbed for the amplification of the free-running cavity modes, thus leaving inadequate Raman pump powers for the Brillouin Stokes lines.

On the other hand, Fig. 3 also shows the relationship between the BP power and the number of Stokes lines generated. As shown in the figure, the general trend is that the higher the BP power is, the lesser number of Stokes lines are generated. Since the BP power initially sets the starting value for the Brillouin gain, it also sets the threshold value for the Stokes signal to become a BP. Hence for a BEFL, the threshold is higher at higher BP powers as reported in [17]. In addition to this, the increment of BP power also leads to the gain saturation in the Bi-EDF which requires more pumping photons [18]. However in our case, this is only true for the BP power that is greater than 1 mW in the 264 mW Raman pump power. The same phenomenon is also observed for 2 mW BP power for 329 mW Raman pump power. In both cases, the presence of free-running cavity modes limits the number of Stokes lines. This is because these cavity modes have much higher gain and utilize most of the energies from the laser cavity for their own oscillation modes. Therefore, for higher Raman pump powers, a higher BP power is required to reduce the mode competitions between the free-running cavity modes and the Stokes lines.

To study the effect of wavelength on the number of Stokes lines generated, the BP wavelength is tuned within the EDF gain spectrum. Figure 4 shows the effect of BP wavelength on the Stokes lines generated at three different wavelengths of 1600, 1608, and 1610 nm. As can be seen from the figure, the highest number of Stokes lines recorded is 26 which is found at a BP wavelength of 1608 nm. It corresponds to the peak Bi-EDF gain at 264 mW Raman pump power and 1 mW BP. In contrast to the previously reported research [10], 7 Stokes lines with 280 mW and 8 dBm of Raman pump and BP powers were produced respectively. The figure also shows that the number of Stokes lines reduces with an increase in BP power from 1 to 5 mW for both 1608 and 1610 nm wavelengths. Below 1 mW BP power, the number of lines decreases owing to the fact that the free-running cavity modes starts to build up at that low BP power. These free-running cavity modes are also dominant when the BP power is reduced further to 0.8 mW. At 1600 nm, the number of Stokes lines is almost proportional to the BP power up to 2.5 mW. Since the Stokes lines amplification is shared with the cavity modes around 1608 nm, the Brillouin gain is not sufficient to suppress the modes around the region where the BP power is lesser than 2.5 mW. These results agree well with those obtained from [16]. For higher BP powers up to 5 mW, 10 Stokes lines are maintained. It is expected that the Stokes lines will be reduced if a higher BP power is applied.

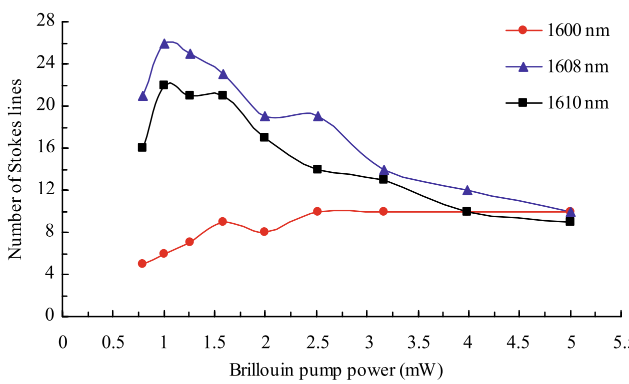
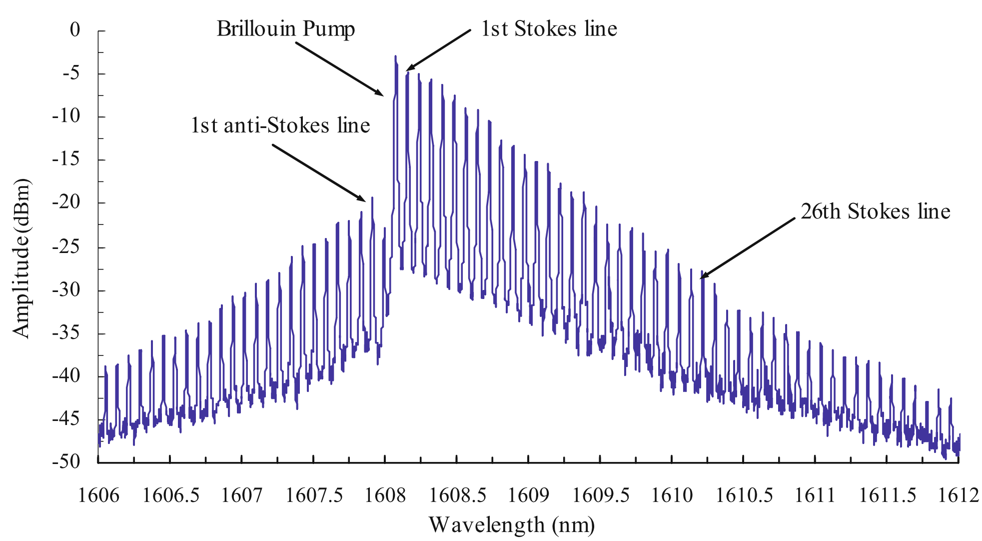


Fig. 4 Number of Stokes lines versus BP power at different BP wavelengths and Raman pump power of 264 mW

Figure 5 shows the output spectrum of the laser at a Raman pump power of 264 mW, BP power of 1 mW, and BP wavelength at 1608 nm. Up to 38 output channels are achieved at 264 mW Raman pump power and 1 mW BP power. The number of output channels includes 26 Stokes lines, 11 anti-Stokes lines and BP. It is clearly observed that the peak power of the Stokes line in general is always lower than that of the preceding one. The Stokes lines exhibit a regular spacing of 0.08 nm and an OSNR above 15 dB. Previous reports demonstrate only 6 Stokes lines and 13 anti-Stokes with less than 15 dB OSNR [9, 10]. The peak power difference between the first and second Stokes lines is 0.16 dB in our case, compared to more than 10 dB in [9] and 15 dB in [10]. Also in [10], out of 13 Stokes and anti-Stokes lines reported, four channels have a peak power below −30 dBm, whereas the Stokes lines peak power is above −30 dB for all 38 output channels in our setup. Moreover, the difference in peak power between the first Stokes line and the 26th Stokes line is around 23 dB in our setup, whereas it is more than 35 dB in both [9, 10].

It is also crucial to have both high number of Stokes lines and wide tuning range. Figure 6 shows the tuning range with variations in BP powers for different Raman pump powers. In this experiment, a wide span is used to observe the generation of Brillouin Stokes signals in the absence of the free-running cavity modes. This is done for each BP wavelength while maintaining the Raman pump and BP powers at 264 and 5 mW respectively. Referring to Fig. 6, the tuning range is proportional to the intensity of BP and inversely proportional to the Raman pump power. This observation is in compliance with the results obtained in [16]. For lower Raman pump powers, a higher tuning range is obtained. That is because at a lower Raman pump power a lower Bi-EDF gain is

Fig. 5 Output spectrum at 264 mW Raman pump power, 1 mW BP power and 1608 nm BP wavelength



present, thus leading to a lower mode competition between the free-running cavity modes and the Stokes lines. Hence if the Raman pump power is low enough to reduce the free-running cavity modes, we can obtain wider tuning for the system. On the other hand, the tuning range broadens as the BP power increases, which results in the higher Brillouin gain that suppresses the free-running cavity modes. This makes it possible for SBS to be generated at a wider spectral range.

The tuning characteristics are shown in Fig. 7 with the absence of free-running cavity modes at 264 mW Raman pump power and 5 mW BP power. In this case, the highest tuning range of 12 nm with an average of 14 output channels (10 Stokes lines, 3 anti-Stokes lines and BP) is obtained. Our experimental findings are better than 11-nm tuning range in the C-band region with 5 Stokes lines as reported in [19]. This is owing to the fact that our PCF was pumped bidirectionally by the BP, resulting in the higher Brillouin gain efficiency.

The magnified output spectrum of the two corner wavelengths at 1603 and 1615 nm at 264 mW Raman pump power and 5 mW BP power is shown in Fig. 8. The magnified output spectrum is obtained by reducing the optical spectrum span to 3 nm, from 1602 to 1605 nm in Fig. 8(a). In Fig. 8(b), the decreased span is from 1614 to 1617 nm. It is evident from Fig. 8(a) and (b), that the 14 output channels' peak powers are well above −30 dBm and the OSNR values are above 20 dB. The peak powers of the first, second, third, and fourth Stokes lines are respectively 0.88, 0.57, 0.34, and 0.22 mW at 1603 nm wavelength. Similarly at 1615 nm wavelength, the corresponding peak powers of the first four Stokes lines are 0.87, 0.53, 0.30, and 0.21 mW.

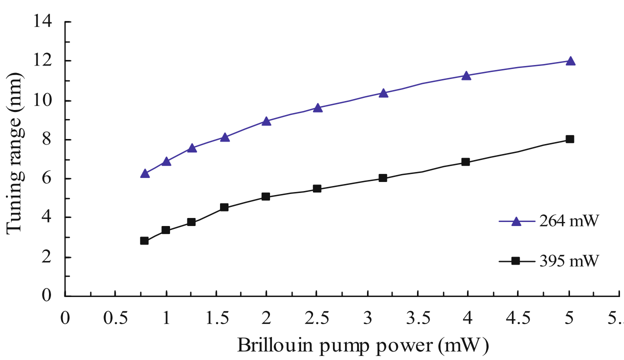


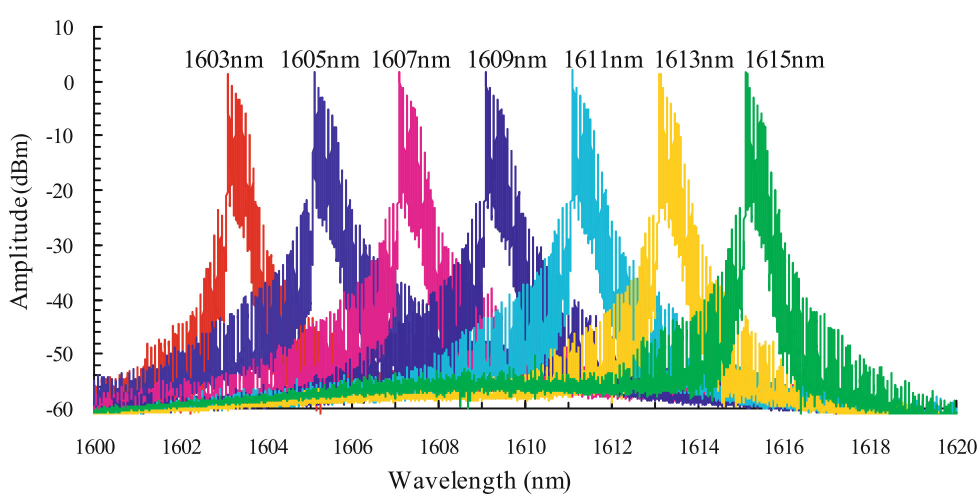
Fig. 6 Tuning range versus Brillouin pump power at different Raman pump powers of 264 and 395 mW

Lastly, it is of great importance to test the stability of our laser system. Figure 9 shows the variation of the Stokes lines peak power over a period of 60 minutes. Over this duration, the multiwavelength BEFL output is scanned at intervals of 5 minutes, keeping the Raman pump power, BP power and BP wavelength at 264 mW, 5 mW, and 1608 nm, respectively. Referring to Fig. 9, the multiple Stokes lines show a good stability over the duration of 60 minutes. While the Stokes lines from the first order to the eight order fluctuate within ±0.2 dB, the ninth and tenth Stokes lines have larger power fluctuations. The ninth Stokes line power fluctuates at ±0.4 dB and the tenth Stokes line shows the highest fluctuation of ±0.5 dB. The higher fluctuation of the tenth Stokes is because the line has not reached its saturation level, thus making its peak power to be sensitive to the fluctuation of the net gain in the laser cavity.

4 Conclusion

A multiwavelength Brillouin-erbium fiber laser utilizing a 50 m PCF as a nonlinear gain medium and a bismuth-oxide EDF as the linear gain medium pumped by a 1455 nm Raman pump laser has been demonstrated. The effects of Raman pump power, BP power and BP wavelength on the number of generated Stokes lines are studied. A total number of 38 output channels is obtained at an averagely low Raman pump power of 264 mW and 1.0 mW BP power. The

Fig. 7 Tunable output spectra of Stokes and anti-Stokes lines at 264 mW Raman pump power and 5 mW Brillouin pump power



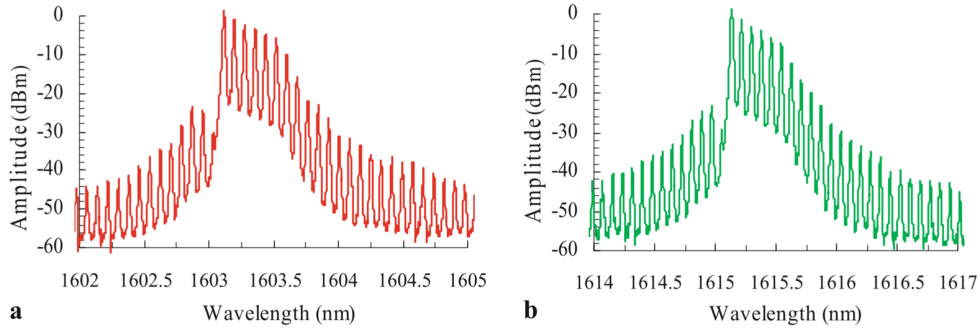


Fig. 8 Magnified output spectrum at (**a**) 1603 nm, (**b**) 1615 nm of 264 mW Raman pump power and 5 mW BP power

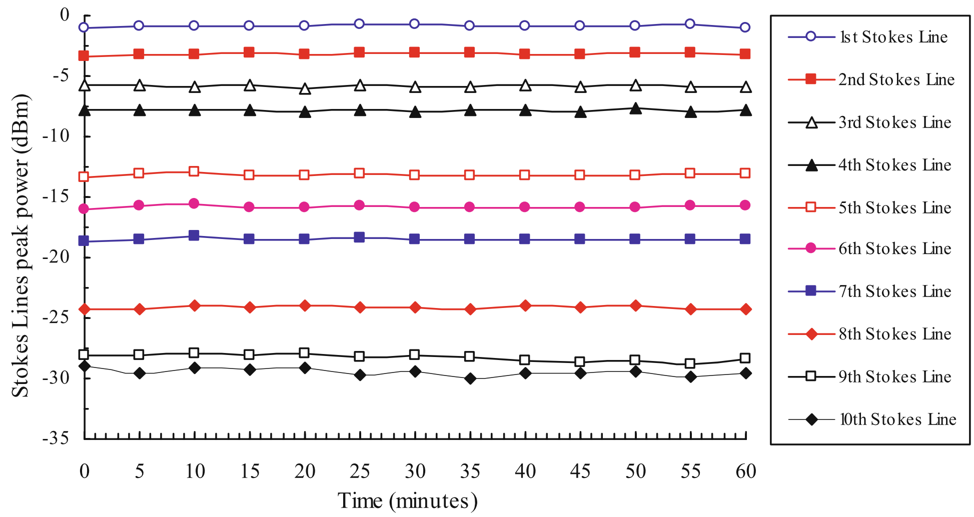


Fig. 9 Spectral stabilities of the generated Stokes lines at 264 mW Raman pump power and 5 mW BP power

Stokes and anti-Stokes lines' OSNR are around 15 dB and more with the peak power above −30 dBm. This multiwavelength BEFL exhibits a wide tuning range of 12 nm and a high count of 38 channels although the unidirectional configuration is deployed. The same number of 14 channels, each with an OSNR above 20 dB is maintained throughout the region of 1603 to 1615 nm. These are achieved when the Raman pump and BP powers are set at 264 and 5 mW respectively.

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