Seamless tuning range based-on available gain bandwidth in multiwavelength Brillouin fiber laser

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Abstract: We experimentally demonstrate a simple widely tunable multiwavelength Brillouin/Erbium fiber laser that can be tuned over the entire C-band, thereby greatly improving the tuning range limitation faced by the previous Brillouin-erbium fiber laser architectures. Tuning range of 39 nm from 1527 nm to 1566 nm, which is only limited by the amplification bandwidth of the erbium gain was successfully achieved. At Brillouin pump wavelength of 1550 nm and 1480 nm laser pump and Brillouin pump powers of 130 mW and 2 mW respectively, all the generated output channels have peak power above 0 dBm, with the first output channel having a peak power of 8.52 dBm. The experimental set up that consists of only 4 optical components, is simple, devoid of the complex structure employed previously to enhance the tunability and feedback mechanism normally associated with multiwavelength Brillouin-erbium fiber laser sources. The generated output channels are stable, rigidly separated by 10 GHz (0.08 nm).

OCIS codes: (140.3500) Lasers, erbium; (290.5900) Scattering, stimulated Brillouin; (060.4370) Nonlinear optics, fibers.

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1. Introduction

The ever–increasing demand for bandwidth in optical communication systems, resulting from the spread of the internet and other multimedia technology makes the dense wavelength division multiplexing (DWDM) a system of choice. The DWDM system requires a laser with multiple wavelengths for its successful operation [1]. This, among several other reasons fuelled the interest of scientist and engineers in to the development of laser sources that are capable of generating multiwavelength from a single wavelength light source. Apart from supporting DWDM systems, multiwavelength lasers found applications in sensors such as in laser gyroscope [2], optical spectroscopy [3], microwave signal processing [4], the generation of short optical sources and millimeter-wave carriers [5], and current monitors [6].

Researchers have adopted different approach to the methods of generating multiwavelength lasers. Prominent among these methods are; multiwavelength Brillouin/Raman fiber lasers (MWBRFLs) [7], multiwavelength Brillouin fiber lasers (MWBFLs) [8], multiwavelength erbium doped fiber lasers (MWEDFLs) [9] and multiwavelength Brillouin/Erbium fiber lasers (MWBEFLs) [10]. Among these technologies, the MWBRFLs and MWBEFLs have the inherent advantage of maintained Stokes signal spacing of about 10 GHz (0.08 nm) [7,10]. MWBEFLs however can produce better optical signal to noise ratio (OSNR) than that of the MWBRFLs. MWBEFLs utilizes the hybrid integration of two gain mediums, the nonlinear Brillouin gain due to stimulated Brillouin scattering (SBS) in optical fibers and the linear gain from erbium doped fiber [11]. This technique took advantage of the narrow bandwidth of the Brillouin amplification in optical fiber and the high gain from the erbium–doped fiber to create the MWBEFL. On the other hand however, MWBEFLs have the disadvantage of limited tuning range due to the gain competition imposed by its cavity gain characteristics. The tuning range is defined as the range of Brillouin pump (BP) wavelength which produces the Stokes lines in the absence of self–oscillations cavity modes [12].This means the Brillouin pump wavelength of the MWBEFL must be chosen near the wavelength at which the cavity has the highest gain in order to suppress the cavity modes. Several attempts were made to overcome this problem with a view to improve the tunability of MWBEFL.

By inserting a Sagnac loop filter into the fiber resonator, tunable range of MWBEFL was improved to 14.5 nm. However, the highest peak power of the 12 generated Brillouin wavelength is -25 dBm [13]. A wider tuning range of 60 nm was achieved in [12] but at the expense of a very high BP power that reduces the number of the output channels. . Tunable range of 14.8 nm at 20 mW of pump power with only one output channel with its peak power at -20 dBm was achieved in [14]. However, when the pump power was increased to 156 mW the tuning range dropped to 5 nm although the output channels increased to seven with the first Stokes having a peak power of 5.64 dBm. Most recently, a method of BP pre-amplification before being injected into the Brillouin gain medium was shown to produce 10 nm tuning range in the L–band at low pump power of 100 mW [15]. In addition to this, the tuning range was further improved by forcing the BP to propagate bi-directionally in the

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Erbium-doped fiber dubbed as double-pass BP amplification [16]. Even though that the tuning range can be improved by having higher Brillouin pump powers in the laser cavity, the self-lasing cavity modes cannot be effectively eliminated. This problem has motivated us to find alternative solutions in order to achieve the widest tuning range possible of multiwavelength generation in MWBEFL.

In this paper, we report experimental demonstration of a MWBEFL that can freely be tuned over the entire C-band window. Tuning range of 39 nm, from 1527 nm to 1566 nm, which is only limited by the amplification bandwidth of the erbium gain was experimentally achieved. Our technique suppresses other potential modes to circulate in the laser cavity, thus the self-lasing modes are eliminated and hence rectifies the tuning range limitations faced by the previous MWBEFL architectures. Also, our structure that consists of only 4 optical components in the resonator is simple, cost effective and devoid of the complexity normally associated with enhancement of feedback mechanism found in the previous MWBEFL studies [11,13-14]. At BP power of 2 mW and a pump power of 130 mW, all the 4 generated output channels have power above 0 dBm, with the first channel having a peak power of 8.52 dBm.

2. Experimental Setup

The configuration of the proposed setup is as shown in Fig. 1. The structure consist of an Erbium-doped fiber (EDF) gain block in a ring cavity resonator with four optical components, a circulator, an isolator and two 3-dB optical couplers, designated C1 and C2 in Fig. 1. The Brillouin gain media is provided by 11 km long dispersion compensating fiber (DCF).

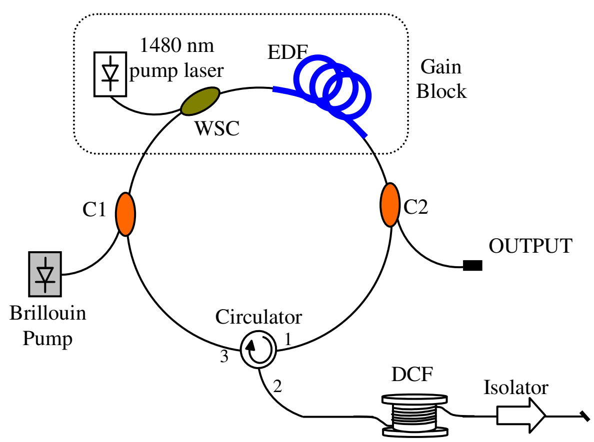

Fig. 1. Experimental setup of the enhanced multiwavelength BEFL.

The gain block that made up an erbium doped fiber amplifier (EDFA) consists of 8 meters long EDF and a 1480 nm wavelength division multiplexing (WDM) coupler. A 1480 nm pump laser with a maximum power of 130 mW was used as the primary light source for the EDF. The WDM coupler was used to multiplex the laser pump and lights signal. An external cavity tunable laser source (TLS) provided the Brillouin pump power. It was coupled to the ring cavity resonator through coupler C1 as shown in Fig. 1. The output of the resonator was connected to an optical spectrum analyzer (OSA) via coupler C2, which provided the channel through which the backward propagating Stokes (also called Brillouin Stokes, BS) signals are monitored. The optical circulator was utilized to provide unidirectional movement of both the BP and the BS signals. The forward transmitted BP signal is terminated with an isolator to guard against any unwanted back reflection. The injected BP signal from the TLS will first be amplified by the EDFA. It will then be transported to the coupler C2 where 50% power will

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thereafter be guided into the Brillouin gain media by the optical circulator. When the BP power exceeds the threshold power of the Brillouin gain media, SBS will be initiated and thus the BP signal will create a Brillouin gain in the Brillouin gain media, (i.e. the dispersion compensating fiber). This effect will create the first order Stokes signal which will propagate in the opposite direction to the direction of the BP signal. This first order Stokes signal will again be guided into the ring cavity resonator by the optical circulator where it will be amplified by the EDFA and follow the same progression as the BP. When it exceeds the threshold condition, it will then create the second order Stokes signal. In the same way, the second order Stokes signal will create the third order Stokes signal. The process will continue until the next higher order Stokes signals power is too small to exceed the threshold condition and hence creation of subsequent Stokes order signal will diminish. In our proposed setup, the generation of Stokes signal in the DCF is denoted as the process to reflect the oscillating modes. For a conventional fiber laser, the oscillating modes are reflected back into the laser cavity at their own wavelengths. However, in our research work, the oscillating modes are reflected back into the laser cavity by their lower order Brillouin Stokes. Thus the reflectivity is determined by the Brillouin gain in the DCF. The resolution of the OSA was set at 0.015 nm for all observation and measurements in the experiment.

3. Results and discussion

Firstly, the lasing threshold of the generated output channels was investigated in this research work. The BP wavelength was fixed at 1550 nm and its power was varied from 0.08 mW to 2 mW. For each of the BP power, the required 1480 nm laser pump power (threshold power) to get the lasing of the first-order Stokes signal is recorded. Figure 2 shows the plot of threshold power of the first-order Stokes signal against the BP power at 1550 nm BP wavelength. The lasing threshold grows exponentially in good agreement with theory. It can be seen from Fig. 2 that higher BP powers require smaller 1480 nm pump powers, to create the first order Stokes signal.

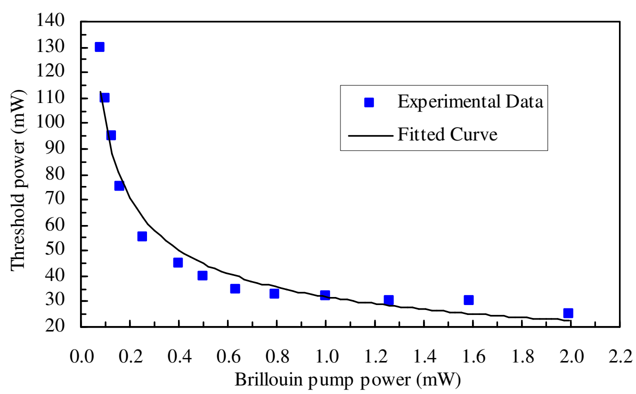

Fig. 2. Threshold power of the 1st Stokes signal at different BP power at BP wavelength of 1550 nm.

At the maximum 1480 nm laser pump power (PP) and BP powers of 130 mW and 2 mW respectively, up to 4-output channels were observed. As depicted in Fig. 3, all the generated output channels have peak powers above 0 dBm, with first and forth channels having a peak power of 8.52 dBm and 0.84 dBm respectively. This is much higher than the Stokes peak power of about -15 dBm as reported in [11] and around -25 dBm as reported in [13]. Furthermore, the Stokes signals are equally spaced, separated by 10 GHz (0.08 nm) as can be seen in Fig. 3.

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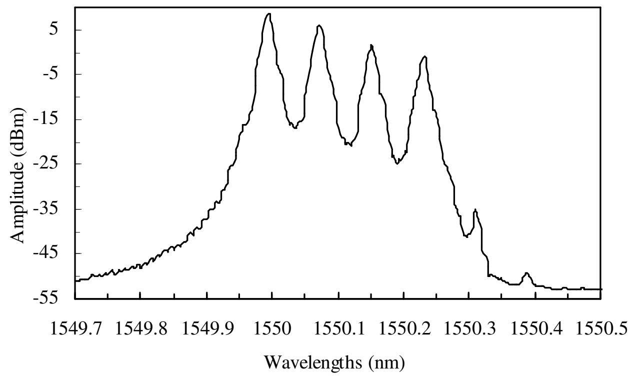

Fig. 3. Output Spectrum of the MWBEFL at BP power of 2 mW and 1480 nm pump power of 130 mW.

The peak power of the output channels increased with increase of PP and the BP power. Figure 4 shows the peak power of the output channels at BP power of 2 mW and different PP. The peak powers of all the generated Stokes signals were found to grow linearly with the increment in PP. At zero PP power, the BP line has a peak power of -10.44 dBm. At the maximum PP power of 130 mW, the peak power of the first output channel grows to 8.52 dBm. The second output channel that appears at 25 mW PP at a peak power of -11.19 dBm also grows to a peak power of 6.05 dBm at the maximum PP power. In the same way, the third and fourth output channels grows from -11.90 dBm to 2.20 dBm and -7.23 dBm to 0.84 dBm respectively as clearly depicted in Fig. 4. Since the PP is limited to 130 mW, the amount of injected energy into the fiber laser cavity is inadequate to saturate the forth Stokes signal and consecutively the fifth-order Stokes cannot be generated.

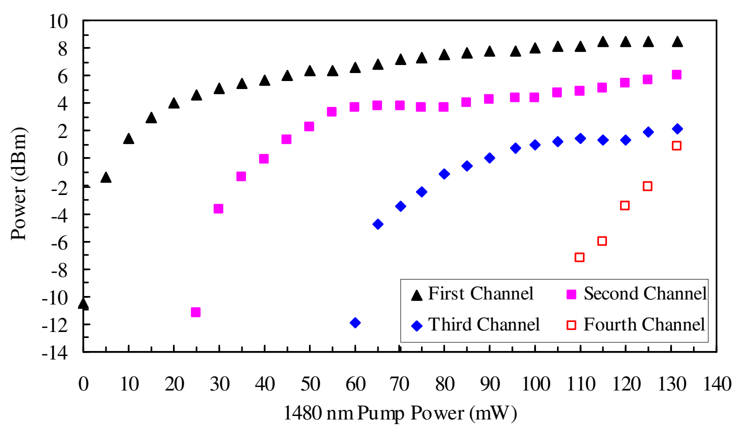

Fig. 4. Variation of output channels peak power with PP power at BP power of 2 mW.

The spectral stabilities of the MWBEFL were also investigated at maximum PP of 130 mW and BP power of 2 mW at 1550 nm wavelength. Figure 5 shows the fluctuations of the output channels peak power over an observation of a period of 60 minutes. Over this period of time, the MWBEFL was scanned at every 5 minutes interval, keeping the input power and wavelength constant. The first, second and third output channels show a very good stability with the maximum power fluctuations of 0.22 dB, 0.40 dB 0.65 dB, and wavelength shifts 0 nm, 0.002 nm and 0.002 nm respectively. The fourth output channel however has an average power fluctuation of 1.85 dB. This is owing to the fact that the forth Stokes signal has not

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reached its saturation level. Therefore, its peak power is sensitive to the fluctuation of the net gain in the fiber laser cavity.

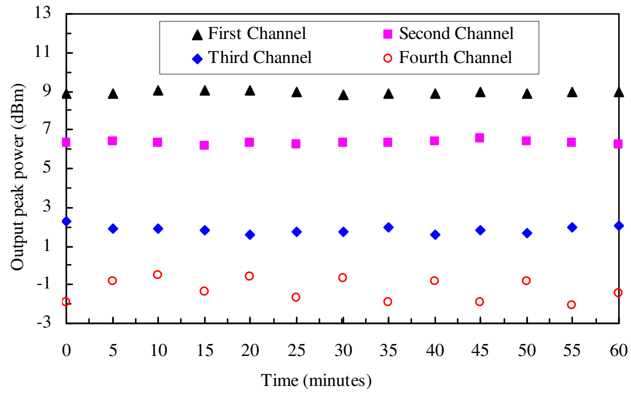

Fig. 5. Output peak power fluctuation at 130 mW pump power and, 2 mW BP power.

We also investigated the optical signal to noise ratio (OSNR) of the generated output channels at maximum BP power of 2 mW as depicted in Fig. 6. The measured experimental results are limited to the resolution bandwidth of the OSA which is set at 0.015 nm. The analysis of OSNR is performed by comparing the peak power and the highest noise floor level (by comparing both sidebands) after the lasing condition is achieved. For PP greater than 50 mW, the average OSNR is recorded at 25.7 dB, 22.4 dB, 22.0 dB, and 22.0 dB for the first, second, third and fourth channels respectively. In this research work, the first channel has higher OSNR of about 3.5 dB compared to the other three channels. This discrepancy is related to the lasing process; the first channel is generated from external-cavity laser diode and the higher order channels are generated from the SBS process.

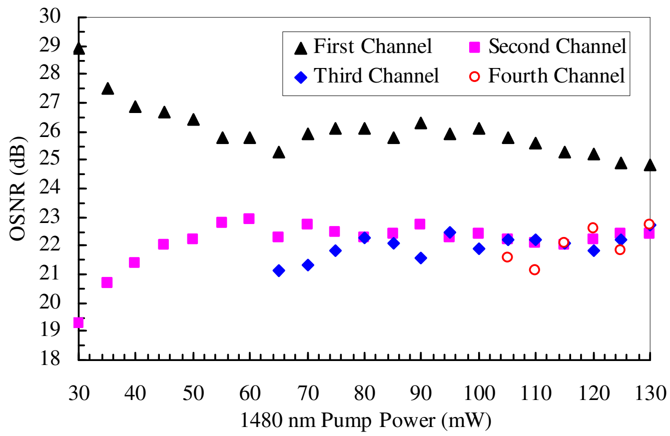

Fig. 6. Variation of the OSNR with pump power at 2 mW BP power.

Due to homogeneous effects in EDF, multiwavelength generation is difficult to achieve in a wider wavelength range. This is because oscillating modes within the peak gain of the laser cavity, also known as lasing cavity modes, potential modes or self-lasing cavity modes are intrinsically generated and they are always dominant [13]. To investigate this effect, the BP wavelength was tuned from 1525 nm to 1575 nm with a step of 2 nm at 130 mW and 2 mW of the 1480 nm pump and BP powers respectively. We found out that the 4 generated output channels are tuned over 39 nm from 1527 nm to 1566 nm as depicted in Fig. 7.

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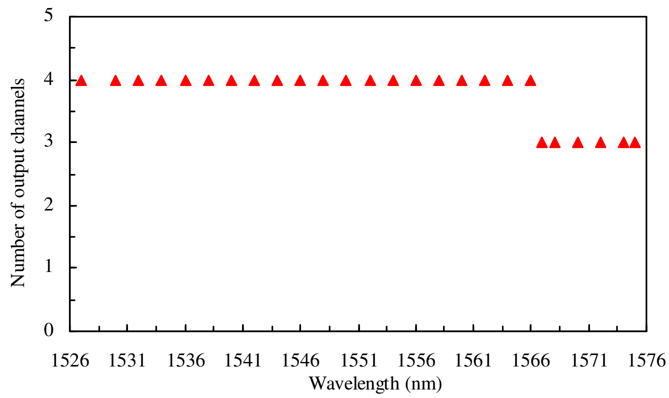

Fig. 7. Tunable spectra of the generated output channels at 130 mW and 2 mW of the 1480 nm PP and BP powers respectively.

At 1567 nm, as can be seen in Fig. 7, the output channels dropped to three channels. This observation has resulted from the reduction of the erbium gain for BP wavelength higher than 1566 nm. The wide tunability obtained is attributed to the fact that the stimulated Brillouin scattering effect has selected its bandwidth reflection which is based on the injected BP wavelength. Since there is no physical reflector at the end of DCF, the source of reflection could be due to the Rayleigh scattering in this fiber section. However, this weak reflectivity is much lower compared to the effect of SBS. Therefore, it suppresses other potential modes to circulate in the laser cavity, thereby eliminating the self-lasing modes within the amplification bandwidth of Erbium gain. Also, the total power of the generated output channels was investigated against the BP wavelength as depicted in Fig. 8.

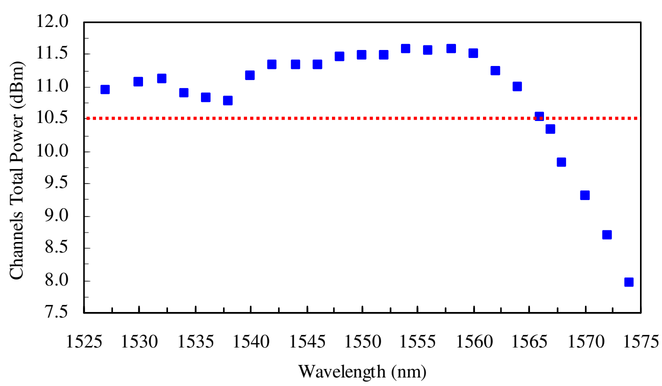

Fig. 8. Total power of the Stokes signals against BP wavelength.

Referring to Fig. 8, the total output power of the four channels is more than 10.5 dBm for the whole tuning range from 1527 nm to 1566 nm. The maximum output power of 11.6 dBm occur around 1554 nm and 1558 nm which indicate the highest gain from the Erbium gain block. Based on the experimental results, there is no significant gain peaking due to lasing conditions. Therefore, the response of the findings indicates that the proposed technique is highly dependent on the type of gain block. In addition to this, the tuning range can be expanded by designing wideband optical amplifiers that can support bigger amplification bandwidths.

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The output spectra of the tunable MWBEFL at some selected BP wavelength is given in Fig. 9, while the corresponding magnified view of the output channels at 1530 nm, 1540 nm, 1550 nm and 1566 nm of BP wavelengths are shown in Fig. 10. Referring to Fig. 9, the output spectrum is clean from any self-lasing cavity modes generated from the laser cavity for any BP wavelengths. On the other hand, Fig. 10 shows clearly that the output consists of four channels, the first channel is the BP and the rest of the output channels are generated from the SBS effect. The proposed technique of using SBS as the reflector can provide a wider tunability range which is only limited by the amplification bandwidth of the selected amplifier in the loop arm.

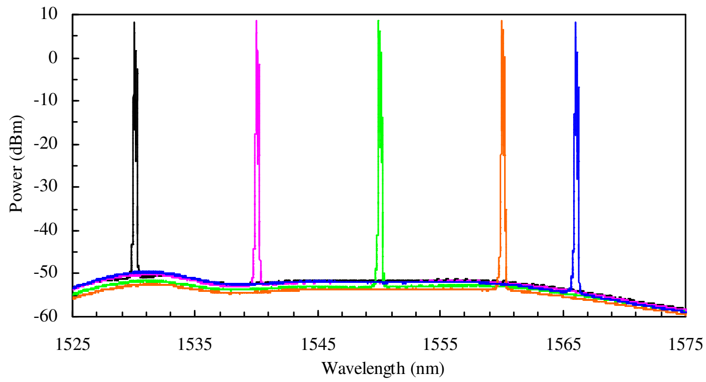

Fig. 9. Output Spectra of the tunable MWBEFL at 130 mW of 1480 nm pump and 3 dBm of BP powers.

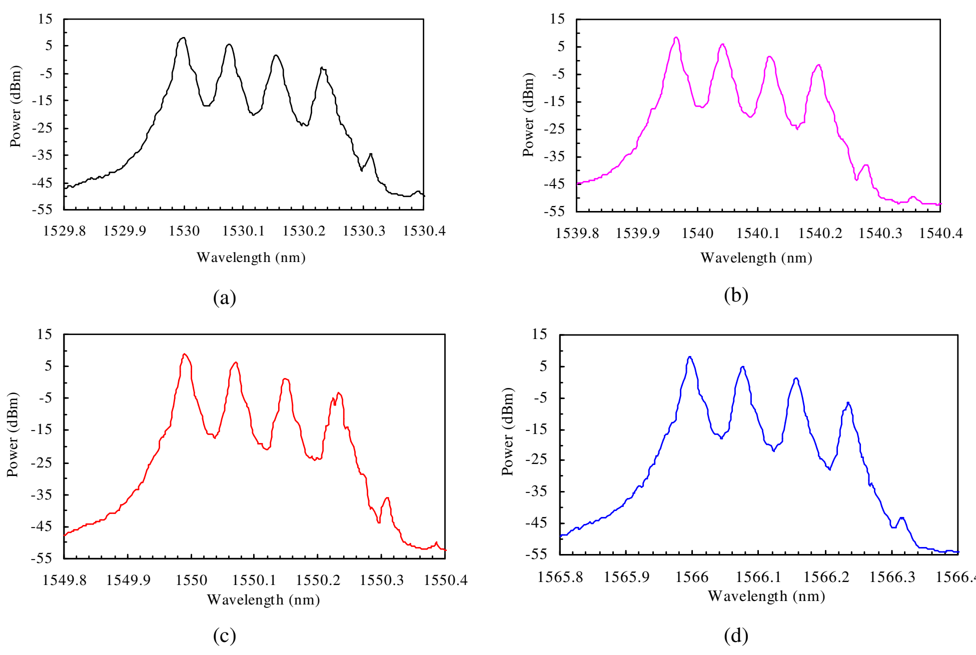

Fig. 10. Magnified view of the output channels at BP wavelength of (a) 1530 nm, (b) 1540 nm, (c) 1550 nm and (d) 1566 nm.

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4. Conclusion

We have successfully demonstrated a simple multiwavelength Brillouin/erbium fiber laser that suppresses other potential modes to circulate in the laser cavity. The proposed fiber laser structure does not have any physical mirror at one end of the laser cavity. The wavelength-selective reflection is only generated from the effect of stimulated Brillouin scattering in the dispersion compensating fiber. Owing to the weak reflectivity condition, the self–lasing modes are eliminated within the amplification bandwidth of Erbium gain, thus the tuning range limitation faced by the previous Brillouin-erbium fiber laser architectures are greatly improved. The tuning range over 39 nm from 1527 nm to 1566 nm with four output channels is experimentally obtained. The tuning range is only limited by the amplification bandwidth of the Erbium gain. Our technique is also cost effective because of the low numbers of component count in the resonator as opposed to the previous studies to eliminate the self-lasing cavity modes and increase feedback mechanisms in the multiwavelength BEFL.

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