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# Double-Brillouin Frequency Spacing Multi-Wavelength Brillouin Erbium Fiber Laser in Double Cavities Configuration

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**ABSTRACT**

Multi-wavelength fiber laser has great potential for use in dense wavelength-division multiplexing (DWDM) systems, sensors, and microwave photonics. This paper presents a multi-wavelength Brillouin erbium fiber laser (MW-BEFL) with double-frequency Brillouin spacing of approximately 0.176 nm between each adjacent Stokes. The proposed setup utilizes double cavities configuration for odd and even-order Brillouin Stokes to propagate separately in the system. This configuration is flexible as it can be transformed into a single-spacing MW-BEFL by swapping the ports of the circulator; it can also extract the odd-orders Brillouin Stokes by relocating the OSA in the cavity. Up to 25 double-spaced Brillouin Stokes are obtained with a tuning range of 30 nm. The first 8 Stokes have peak power variation within ± 3.7 dB and an average signal-to-noise ratio of 20 dB.

## 1. Introduction

Stimulated Brillouin Scattering (SBS) has been regarded as a promising solution for multi-wavelength comb generation due to the distinct characteristics such as low threshold, high Brillouin gain coefficient, narrow linewidth, low noise intensity, and stable operation at room temperature [1-3]. The generation of SBS in the fiber is based on the nonlinear interaction with the participation of acoustic phonons between the pump and Stokes field. Brillouin fiber lasers have generated great interest for various applications including multi-wavelength sources as well as optical sensors due to their extremely narrow linewidth. Many works have been carried out to generate a multi-wavelength comb with constant spacing of 0.09nm which is equivalent to 11 GHz in the frequency domain [4-7]. With the extension of 5G technology, wave bands of more than 28 GHz play an important role in facilitating the multiplexing process in 5G communication [8]. Hence, exploring multi-wavelength comb with frequency spacing higher than 20 GHz and their application in microwave signal generation has greatly gained research interest in the past few years [9-12].

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Several approaches have been demonstrated to achieve double Brillouin frequency spacing Brillouin erbium fiber laser (BEFL). One of the attempts is by adjusting the BP power distribution in a bi-directional pumping scheme through an optical coupler [13]. However, there are significant peak power discrepancies between the odd and even-order Stokes. Mamdoohi *et al.,* demonstrates a switchable Brillouin-Raman fiber laser by utilizing a nonlinear amplifying fiber loop, the switching was achieved by changing the optical coupling ratio in the cavity [14]. Another attempt to switch the Brillouin frequency spacing by incorporating a micro-air gap in the laser cavity, switching is achieved by adjusting the lateral misalignment of the micro-air-gap. However, the peak power discrepancy between the odd and even channels was high at 20 dB [15,16]. A double-frequency spacing Brillouin generation in the 1.3um region was reported using a Bismuth doped fiber as the laser gain medium, 20 Stokes are obtained with the tunability of only 19 nm [17]. Some other works required the reconstruction of the laser cavity from single loop cavity to double loop cavity and changing the length of the nonlinear medium in the loop [18,19].

In this paper, a multi-wavelength BEFL with double frequency spacing is demonstrated by using the double cavities configuration for odd and even-order Brillouin Stokes to propagate separately in the system. The flexibility of this configuration enables it to be transformed into a single-spacing MW-BEFL by swapping the ports of the circulator; odd-orders Brillouin Stokes can also be extracted by relocating the OSA in the cavity. A total of 25 double-spaced Brillouin Stokes is obtained with a tuning range of 30 nm. The first 8 Stokes have peak power variation within ± 3.7 dB and an average signal-to-noise ratio of 20 dB.

## 2. Experimental Setup

Figure 1 shows the schematic diagram of the double-frequency spacing (DF) MW-BEFL using a 2 km length of single mode fiber (SMF) as the Brillouin gain medium (BGM). A 50:50 optical coupler is used to inject the Brillouin pump (BP) into the cavity and allows the generated double-spaced Brillouin Stokes to oscillate in the cavity. Two optical circulators (C1 and C2) are incorporated in the cavity to direct the generated odd and even-orders of Brillouin Stoke travel in the separate cavities. A commercial erbium doped fibre amplifier (EDFA) and a 10 m length erbium doped fiber (EDF) which is pumped by a 980 nm laser diode are used to amplify the Stokes signal in the cavity thus generating multiple Stoke signals. The EDF has a cut-off wavelength at 970 nm and an absorption coefficient of 13 dB/m and 20 dB/m at 980 nm and 1531 nm respectively. The output of the Brillouin fiber laser is extracted through a 20:80 optical coupler and measured by an optical spectrum analyzer (OSA: Yokogawa AQ6360B).

A laser from an external cavity tunable laser source (TLS: AQ4321D) with a linewidth of 200 kHz is used as a BP. The BP is amplified by the EDFA before being injected into the SMF through port 1 to port 2 of an optical circulator (C1), a back-scattered Brillouin Stoke ($1^{st}$ Brillouin Stoke) with a Brillouin frequency shift of $\omega_{shift}$ is generated when the BP exceeds the SBS threshold in the SMF. The generated $1^{st}$ Brillouin Stoke will be re-injected into the other end of the same SMF through port 1 to port 2 of another optical circulator (C2). A 980 nm pumped EDF is added in between C1 and C2 to provide sufficient gain to the $1^{st}$ Brillouin Stoke, which acts as a BP at the other end of the SMF to generate the $2^{nd}$ Brillouin Stoke. The $2^{nd}$ Stoke will propagate in the clockwise direction and channelled from port 2 to port 3 of C2, extracted out by the 20:80 optical coupler into OSA. The residual light of the $2^{nd}$ Stoke will oscillate clockwise direction in the laser cavity and generate $3^{rd}$ Stokes when it re-enters the Brillouin gain medium. The cascading SBS process will continue when the SBS threshold is met each time the n-Brillouin Stokes gain sufficient power to induce Brillouin scattering in the gain medium. This configuration provides double cavities for odd and even-order

Stokes to propagate separately in the system. The OSA is positioned in the cavity where only even-order Stokes are extracted as output. As a result, a double-frequency spacing Brillouin fiber laser with up to 25 Brillouin Stokes is generated and detected with equal spacing of 0.176 nm. The same configuration can be transformed into a single-spacing MW-BEFL by just swapping port 2 and port 3 of C2. The odd-order Brillouin Stokes of the DF-MWBEFL can also be extracted by placing an OSA in between the C1 (port 3) and C2 (port 1).

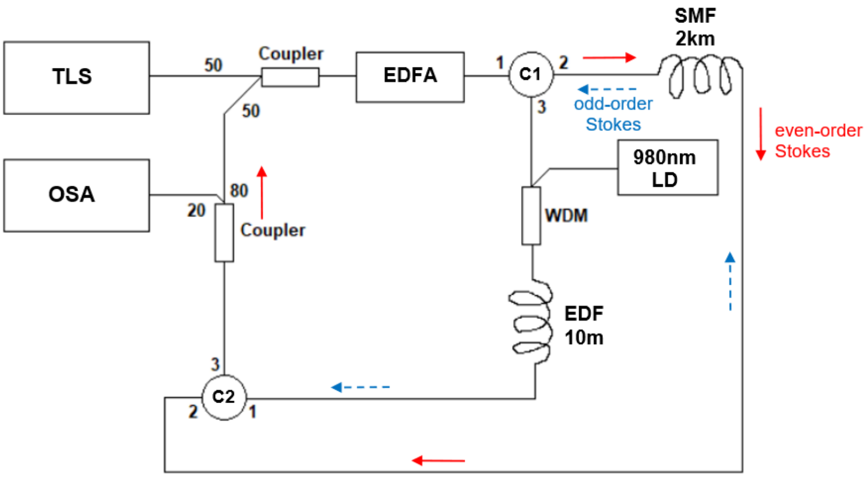
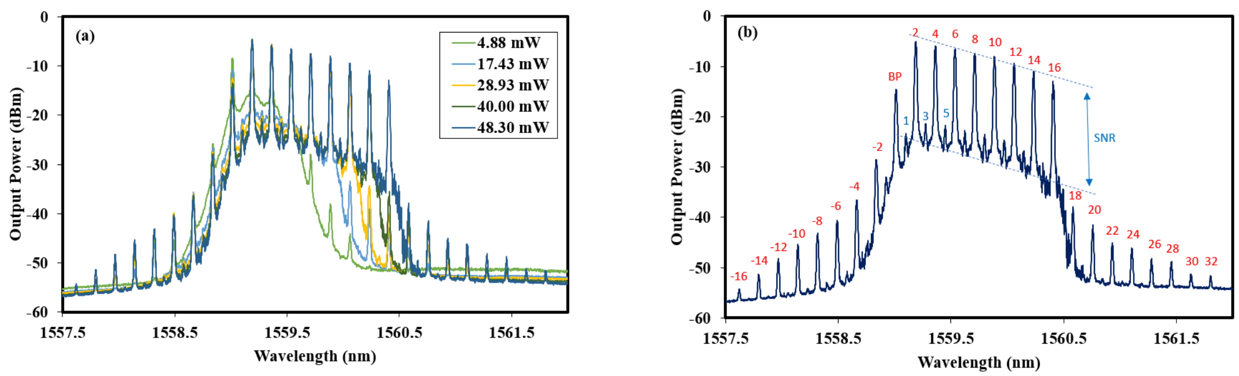



**Fig. 1.** Schematic of the double-frequency spacing BEFL

## 3. Results and Discussion

The spectra of the multi-Stokes DF-MWBEFL at various 980 nm pump power are shown in Figure 2(a). The injected laser signal power from the TLS unit is fixed at 6 dBm at a wavelength of 1559 nm, close to the EDF laser peak gain to generate maximum numbers of Brillouin Stokes. An optical comb with equal double-frequency spacing is observed at the output, the average frequency spacing between each Stoke is approximately 0.176 nm in the wavelength domain and 20.6 GHz in the frequency domain. At a pump power of 48 mW, up to 25 double-spaced Brillouin Stokes are produced, including the anti-Stokes. The generation of the anti-Stokes lines was due to the relaxation of the excited molecules which were previously excited from the non-base vibration state as described in Figure 3. With the increase in the fiber temperature, these previously excited molecules will be encountered more frequently [20]. As shown in Figure 2(a), the number of Brillouin Stokes increased with the increment of 980 nm pump power. The Brillouin Stokes peak power of the DF-MWBEFL and the number of simultaneous Stoke lines is apparently limited by the BP power and 980 nm pump power. The peak power of the first Brillouin Stoke is always higher compared to the subsequent Stokes because it was generated when the incident BP intensity is at its highest. As the intensity of the subsequent Stokes decreases due to scattering, the amplitude of the acoustics wave also decreases, leading to lower power for the subsequent Stokes.

The output spectrum of the DF-MWBEFL with a maximum number of generated Brillouin Stokes lines is shown in Figure 2(b). It is observed that the peak power of the 18th Brillouin Stoke reduces rapidly due to the insufficient power of the secondary Brillouin pump to generate the next Brillouin Stokes. The balance between the EDF gain and the Brillouin pump plays an important role in achieving MWBEFL. The peak power variation between the first 8 Stokes stays within ± 3.7 dB, this flatness could be due to both odd and even-order of the Brillouin Stokes are being amplified once before entering the BGM in the laser cavity. The first 8 Stokes lines ($2^{nd}$ – $16^{th}$) have signal-to-noise ratio (SNR) values of between 19 dB to 21 dB, which were measured from the peak of each Stoke to their corresponding noise level.




(a) (b)

**Fig. 2.** (a) Optical spectra of the DF- MWBEFL at various 980nm pump power (b) DF-MWBEFL spectrum with maximum number of generated Brillouin Stokes lines

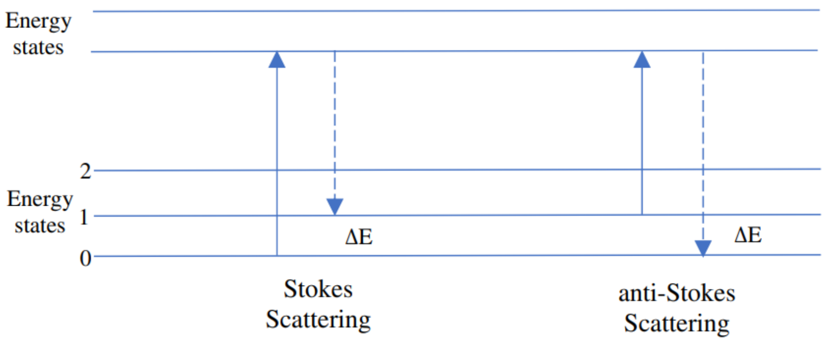



**Fig. 3.** The relaxation of the excited molecules for Stokes and anti-Stokes scattering [20]

Figure 4(a) shows the number of generated double-frequency Brillouin Stokes at different 980 nm pump powers. The BP is fixed at a wavelength of 1559 nm with peak power of 0 dBm and 6 dBm, respectively. Only the Stokes lines which fall within 30 dB from the highest peak are considered, as the other lower Stokes that fall beyond the optical power are not significant. It is observed that the number of Stokes increased with the power of both the 980 nm pump and BP. When the 980 nm pump power is below 17 mW, a higher BP power is required to generate multiple Brillouin Stokes. However, as the pump power increased beyond 23 mW, a BP power of 0 dBm is sufficient to generate the equivalent number of Brillouin Stokes. More Stokes lines could be generated if the power of the amplified Stokes is further increased or alternatively reducing the SBS threshold. The SBS threshold is defined as the input pump power at which the backscattered Stokes power is equal to the pump power at the fiber output, which can be expressed as [21]:

$$P_{th} = \frac{21 A_{eff} \alpha}{g_B[1 - \exp(-\alpha L)]} \tag{1}$$

where $A_{eff}$ and $L$ are the effective core area and the length of the gain medium respectively, $\alpha$ is the optical attenuation coefficient along the fiber, and $g_B$ is the Brillouin gain coefficient. The output power characteristics of the first 8 positive Brillouin Stokes at various BP power are illustrated in

Figure 4(b). The BP wavelength is fixed at 1559 nm and its power is varied from 0 dBm to 6 dBm. The peak power of each generated Brillouin Stokes is observed to increase with the BP power.

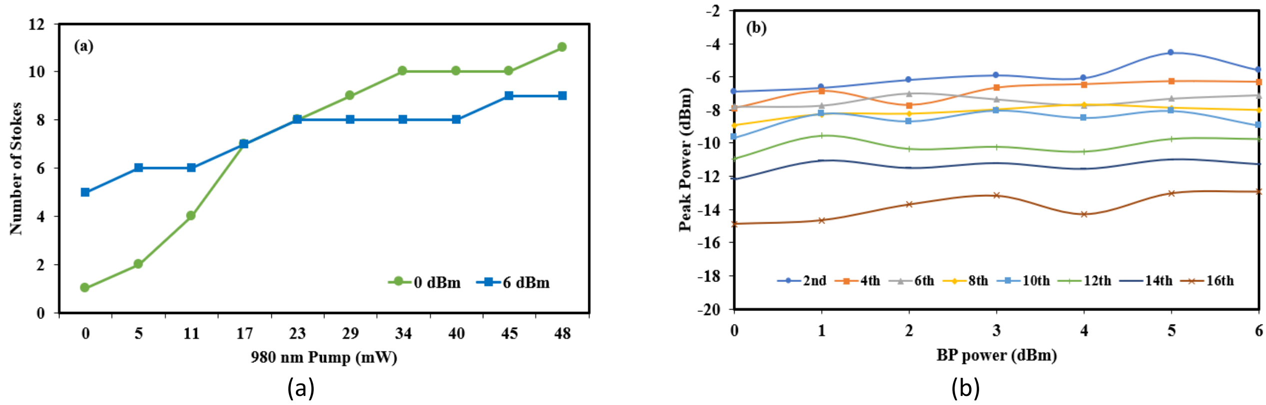



**Fig. 4.** (a) Number of generated double-frequency spacing Brillouin Stoke at various 980 nm pump power and BP power (b) Brillouin Stokes power of the DF- MWBEFL at different BP power

Tunability is one of the important criteria as it provides flexibility for the system. Figure 5(a) shows the tuning characteristics of the first 3 positive Stokes of the double-frequency spacing MWBEFL. The BP and the 980 nm pump power were fixed at 6 dBm and 48 mW respectively. The BP wavelength was tuned near and over the whole spectral range of the free running EDF laser gain region from 1544 nm to 1589 nm. When the wavelength is fall off the gain region of EDF, the Stokes will experience insufficient gain to lase and terminate the process of multiple Stokes generation. The peak power of the 2$^{nd}$ Stokes is flat over the wavelength range from 1549 nm to 1579 nm which results in a tuning range of 30 nm. Follow by a tuning range of 20 nm and 15 nm for 4$^{th}$ Stoke and 6$^{th}$ Stoke, respectively. The broad tuning range allows a robust operation of the MWBEFL as the BP does not need to be accurately wavelength matched if it generates sufficient Brillouin gain. Figure 5(b) shows the number of generated Brillouin Stokes lines at various BP wavelengths. At a BP wavelength of 1559 nm, a maximum of 8 lines is obtained and the number of Stoke lines is reduced when the BP wavelength shifts beyond the peak of the EDF gain curve.

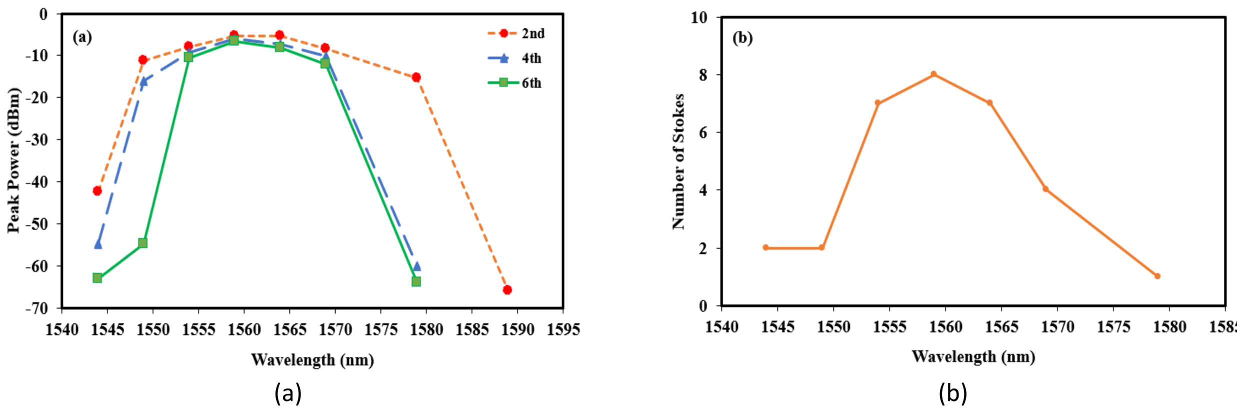



**Fig. 5.** (a) Tuning Characteristics of the DF-MWBEFL (b) number of generated Brillouin Stokes lines against BP wavelength

## 5. Conclusions

We demonstrated a double frequency spacing multi-wavelength Brillouin erbium fiber laser. The proposed setup utilizes double cavities configuration for odd and even-order Brillouin Stokes to propagate separately in the system. A maximum of 25 even-order Brillouin Stokes is obtained with the first 8 positive Stokes having flat optical peak power with a variation of ± 3.7 dB. The flexibility of this MWBEFL design has potential for future research on narrow linewidth as well as multi-wavelength sources for DWDM applications.

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