

Multiwavelength/Brillouin Generation in Bismuth-doped Fiber Laser with Single- and Double-Frequency Spacing

Harith Ahmad, Muhamad Z. Samion, Aizuddin A. Kamely, Siyi Wang, Yu Wang, and Jayanta K. Sahu

Abstract—Multiwavelength fiber lasers operating in the 1.3 μm wavelength region are of great interest as they complement existing systems in the conventional optical communication band of 1.55 μm . In this work, a multiwavelength Brillouin fiber laser with single- and double-Brillouin frequency spacings operating in 1.3 μm is proposed and demonstrated using a dispersion compensating fiber (DCF) as the Brillouin gain medium. A bismuth-doped fiber serves as the laser gain medium. At the maximum pump power of 1021 mW and with the Brillouin pump set at 11 dBm, up to 13 Brillouin Stokes lines with a wavelength spacing of 0.074 nm are obtained in the single-spaced configuration. In the case of the double-spaced configuration, 20 Stokes lines are generated with a wavelength spacing of 0.15 nm between the even Stokes lines. By tuning the central wavelength of the Brillouin pump, both laser configurations are wavelength-tunable with a range of 93 nm and 19 nm for the single-spaced and double-spaced Brillouin lasers respectively. This is, to the best of the author's knowledge, the first demonstration of a multiwavelength/Brillouin laser using a bismuth-doped fiber as the laser gain medium.

Index Terms — Bismuth-doped fiber laser; multiwavelength; stimulated Brillouin Scattering; single-frequency spacing, double-frequency spacing.

I. INTRODUCTION

The advent of multiwavelength laser sources has prompted a revolution in telecommunication [1], [2], sensing applications [3], [4], optical signal processing and microwave photonics technology [5], [6]. Among them, multiwavelength fiber laser sources have attracted substantial attention ascribed to their flexible wavelength tuning capabilities [7], [8], high signal-to-noise ratios (SNRs) [9], small power fluctuation as well as long operational lifetimes [10]. Additionally, their ease of fabrication has yielded various inventive designs and approaches to realize multiwavelength operation in fiber laser systems. These include the use of optical nonlinear

mirrors [11], fiber Bragg gratings (FBGs) [12], Mach-Zehnder interferometers (MZIs) [13], and also the exploitation of nonlinear effects such as four-wave mixing (FWM) [14], and stimulated Brillouin scattering (SBS) [15]. Among these, the use of the SBS effect in optical fibers is particularly interesting for multiwavelength generation as the lasers would exhibit extraordinarily narrow linewidth, low intensity noise and a stable operation at room temperature [16]–[18]. This was favored for applications in the dense-multiwavelength-division multiplexed (DWDM) systems.

To date, a number of studies have developed the SBS based multiwavelength fiber lasers with improving performances in terms of number of channels, frequency spacing, operating wavelength and Brillouin Stokes tuning capability. For instance, in 2011, Tang *et al.* [19] demonstrated a multiwavelength Brillouin-erbium fiber laser in a simple ring cavity configuration with an operating wavelength range from 1564 to 1576 nm. Later, Alimi *et al.* [20] successfully demonstrated a multiwavelength Brillouin-erbium fiber laser in a linear cavity structure with a wide Brillouin Stokes lines tuning capabilities, covering from 1532 to 1572 nm. Meanwhile, Wang *et al.* [21] reported an SBS-based multiwavelength generation in 2.0 μm region with the thulium-doped fiber laser, obtaining a wavelength spacing of 0.10 nm. Soon after, Hu *et al.* [22] reported a switchable single and double Brillouin frequency spacing multiwavelength fiber laser based on a dual scheme consisting of a Brillouin gain medium and a thulium-doped fiber. A wavelength tunability of 1.3 nm is also realized by shifting the Brillouin pump wavelength. Recently, Ahmad *et al.* [23] successfully demonstrated a multiwavelength Brillouin fiber laser operating in the 1.3 μm region, utilizing a praseodymium-doped fluoride fiber as the amplifying gain medium. As for now, this was the only reported work on the generation of multiwavelength Brillouin output in the 1.3 μm region using a rare earth-doped fiber as the active

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mode area of $55 \mu\text{m}^2$ and a dispersion slope of about $0.045 \text{ ps nm}^{-2} \text{ km}^{-1}$ at 1550 nm . A 90/10 coupler is then connected to the Port 3 of the circulator, where 90% of the signal will circulate back into the cavity while 10% of the signal is used for optical analysis. A Yokogawa AQ6370C optical spectrum analyzer (OSA) with a resolution of 0.02 nm is used to record the optical spectrum of the signal.

Fig. 1 (b) shows the operation principle to generate a single-spacing Brillouin Stokes in the proposed setup. As the BP signal enters the ring cavity through the 50% port of the coupler, it will then propagate towards the DCF by propagating from Port 1 to Port 2 of the circulator. The interaction of the BP signal with the BGM, which in this case the 10-km DCF, will generate the 1st Brillouin stoke (BS_1) since the BP at this point exceeds the SBS threshold. BS_1 will then travel in the opposite direction as opposed to the BP, which will continue to propagate in the forward direction towards the FM. Both BS_1 and the BP will eventually propagate in the laser cavity through Port 3 and towards the 90/10 coupler, where the multiwavelength output can be observed at the 10% port of the coupler. As BS_1 continues to circulate in the cavity through the 90% port of the coupler, the 2nd Brillouin stokes (BS_2) will be generated when BS_1 propagates in the DCF. This process will be repeated and will continue to produce subsequent Stokes where $\text{BS}_{n,(n=2,3,4,\dots)}$ through the cascaded SBS process as long as the Stokes power exceed the SBS threshold. The Brillouin Stokes will be generated at a certain frequency downshift from its preceding signal, which is the BP for BS_1 and BS_{n-1} for BS_n . The Brillouin frequency shift, ν_B can be calculated by the following equation as in [28],

$$\nu_B = 2nv_a/\lambda \quad (1)$$

where n is the refractive index at the operating wavelength, v_a is the acoustic velocity and λ is the operating wavelength of the signal. Taking values that are applicable for silica fibers [29], $n = 1.44$ and $v_a = 5.83 \text{ km/s}$, ν_B is calculated to be $\sim 12.77 \text{ GHz}$ at $\lambda = 1314 \text{ nm}$.

Fig. 2 shows the evolution of the optical spectrum when the power of the 1200 nm pump laser diodes was increased. The BP is set at a center wavelength of 1313.998 nm with an output power of 11 dBm . This wavelength is chosen since it coincides closely with the peak of the gain curve of this laser cavity. As can be seen from the figure, the number of Stokes generated is dependent on the pump power. Without the pump from the 1200 nm laser diodes, one Brillouin Stokes can be observed at 1314.072 nm , implying that the power of the BP itself is already sufficient and has exceeded the SBS threshold of the BGM to generate BS_1 . The average wavelength spacing between the adjacent Stokes lines was measured to be 0.074 nm , which tallies to the theoretical frequency shift of $\sim 12.77 \text{ GHz}$ at about 1314 nm . When the pump power was increased to 362 mW , the 2nd Brillouin Stokes could be observed since BS_1 has now been amplified and has enough power to generate BS_2 . As the pump power is further increased to 482 mW , 3 Stokes lines (BS_1 , BS_2 and BS_3), and 1 anti-Stokes line were now observed. The generation of anti-Stokes waves can usually be attributed to the

interaction between the co-propagating BP and the Stokes waves in the laser cavity, through the FWM effect [30]. More Stokes and anti-Stokes lines are generated as the pump power increases, and the maximum number of Stokes could be observed when the pump power reaches its maximum total value at 1021 mW .

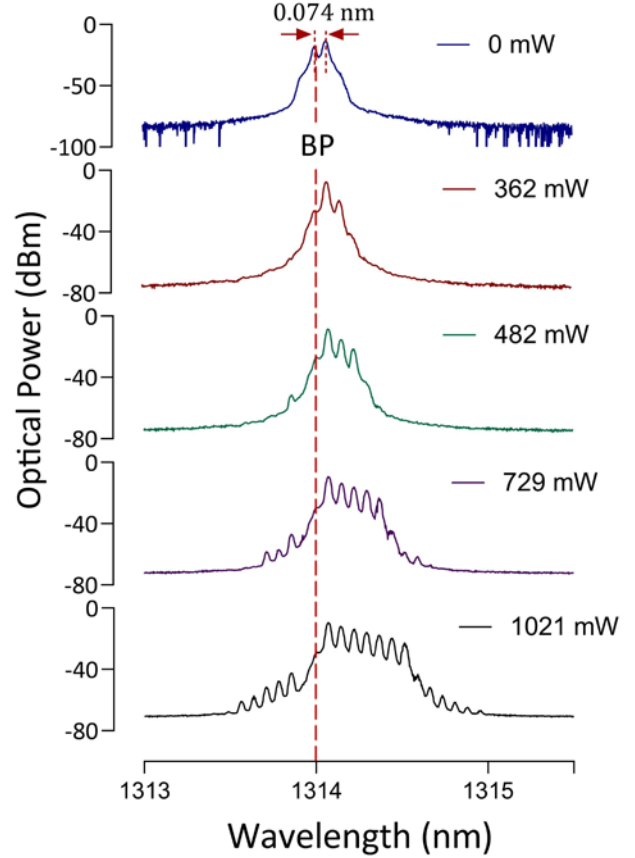


Fig. 2. Evolution of the generated single-spacing Brillouin Stokes with increasing 1200 nm pump laser diode powers.

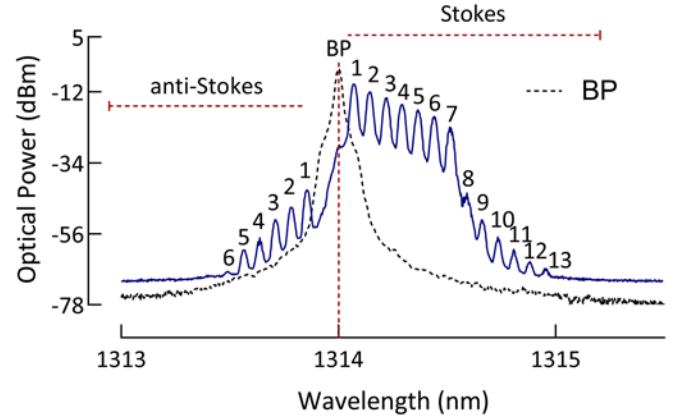


Fig. 3. Optical spectrum of the single-spacing Brillouin frequency at the maximum pump power of 1021 mW .

The output spectrum of the MWBBFL with the maximum number of generated Brillouin stokes is given in Fig. 3. At the maximum pump power of 1021 mW , and without the BP being injected into the cavity, only the amplified spontaneous emission (ASE) was obtained at the output without any lasing. When the BP was launched into the cavity, a total of 13 Brillouin Stokes and 6 anti-Stokes were generated. The

separation between each anti-Stokes lines was also 0.074 nm, similar to the separation between the Brillouin Stokes. Only the first 7 Stokes generated have SNR values of more than 47 dB, which was calculated from the peak of each Stokes to the noise floor at approximately -70 dBm. The SNR was determined as such because each Stokes has actually its own sharp, distinctive lines when recorded using a high resolution OSA of 0.16 pm as reported in [31]. However, we are unable to obtain the high-resolution spectrum at 1.3 μm as we do not have a suitable equipment to carry out the measurement at this wavelength region. From the figure, it can be seen that the BP is not as evident as compared to the other Stokes. This could be attributed to the pump depletion after which the Brillouin gain begins to saturate [28].

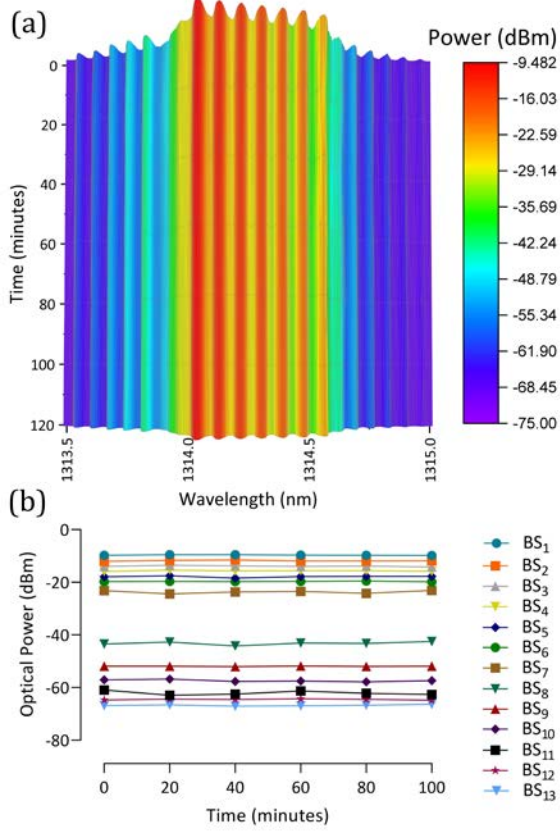


Fig. 4. Stability measurement of the multiwavelength Brillouin fiber laser in terms of the (a) optical spectrum, and (b) the peak power of each single-spaced Brillouin Stokes.

The stability measurement for the single-frequency spacing MWBBFL is recorded and depicted in Fig. 4, with the pump power being fixed at 1021 mW. The output spectrum is taken at every 20-minute interval for a period of 100 minutes. Over the whole period, the MWBBFL shown in Fig. 4 (a) is stable with no major signs of wavelength shifts and power fluctuations. Fig. 4 (b), meanwhile, shows a more detailed analysis of the optical power stability of each Stokes lines. From the graph, the maximum power fluctuations recorded are for BS₈ and BS₁₁, which is about 1.7 dB and 1.9 dB respectively. Other Stokes lines meanwhile, recorded lower fluctuations of only between 0.25 dB to 1.37 dB. This implies that the MWBBFL could operate stably for a long period of time.

The tunability of the single-spaced MWBBFL was also investigated by tuning the center wavelength of the BP, where the results are depicted in Fig. 5 (a). The tuning range of the single-spaced MWBBFL covers a broad wavelength span of 93 nm, ranging from 1272 nm to 1365 nm. Although, it is worthy to note that when the BP is set from 1260 nm to 1271 nm, only BS₁ is observed regardless whether the pump power is at its maximum or even at zero. As mentioned earlier, this is because the power of the BP itself is already sufficient to induce the generation of BS₁. The power of BS₁ however, does not exceed the SBS threshold and the BiDF could not provide enough amplification for BS₁ to generate BS₂. Therefore, the tuning range that is considered in this case was when there is more than one Brillouin Stokes being generated.

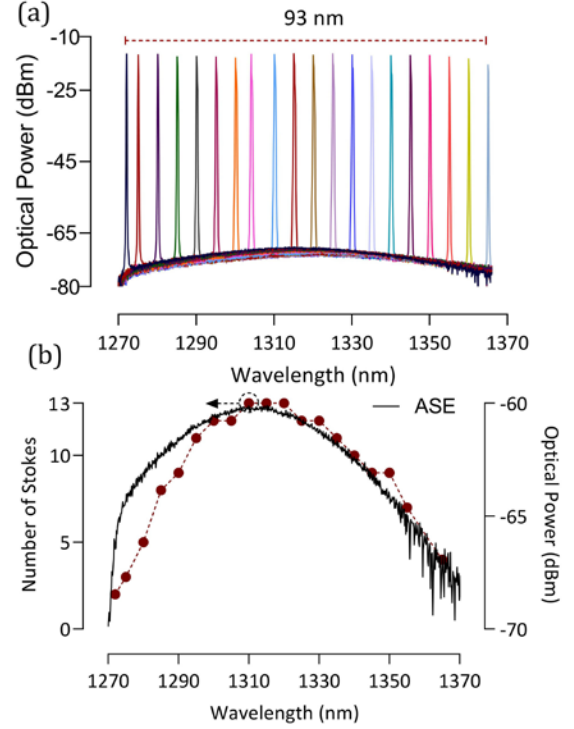
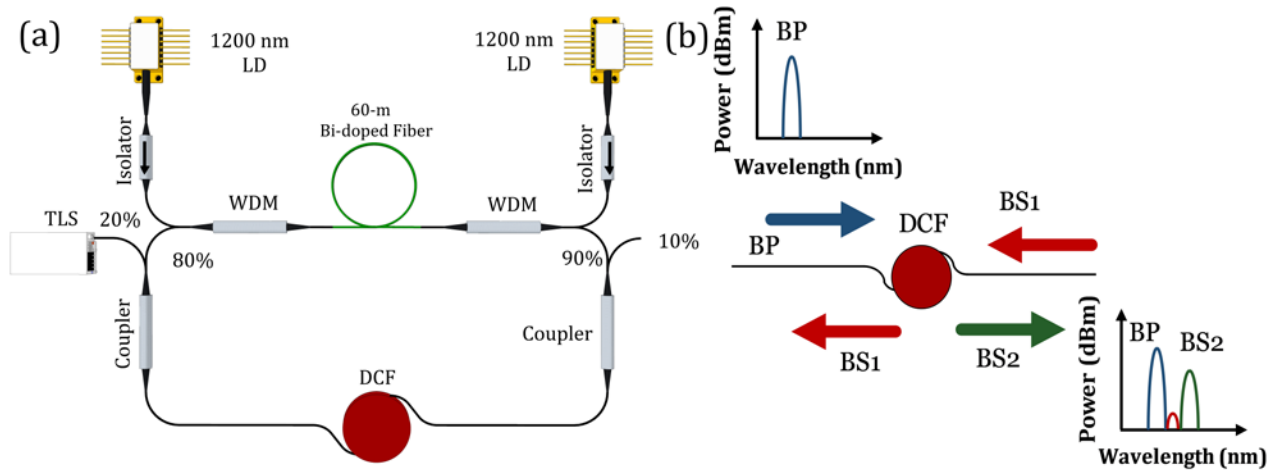


Fig. 5. (a) Tunability spectra of the single-spaced multiwavelength Brillouin fiber laser, and (b) number of generated Brillouin Stokes lines against the BP wavelength.

The number of Brillouin Stokes lines generated at each BP wavelength when the pump power was fixed at 1021 mW is given in Fig. 5(b). At 1272 nm, there only 2 Stokes lines generated, implying that the BiDF was able to provide enough amplification for BS₁ to generate BS₂. As the wavelength was tuned towards the longer wavelength, the number of Stokes lines increased gradually until the maximum of 13 Stokes lines were obtained between 1310 nm to 1320 nm. This is where the peak of the gain curve is located. Tuning the BP wavelength beyond 1320 nm causes the number of Stokes to decrease until the longest possible wavelength of 1365 nm is reached, which produced only 4 Stokes. It can be inferred that the trend for the number of Stokes lines generated matches the amplified spontaneous emission (ASE) curve of the BiDF. This indicates that the amplification provided by the BiDF greatly influence the cascading SBS effect for the generation of multiple Stokes lines.



B. Double Frequency spacing in Brillouin/Bismuth doped Fiber Laser

The experimental configuration is now modified to generate a double-spaced Brillouin output as given in Fig. 6 (a). The setup mainly comprises of the same components, that was the 1200 nm LDs, two 1200 nm ISOs, two 1200/1310 nm WDMs and a 60-m long of BiDF as the gain medium. No isolator is used in the main cavity for this proposed setup, as to allow a bi-directional signal propagation. For this setup, the BP was injected into the ring cavity through the 20% port of an 80/20 coupler. This coupler was chosen instead of a 3-dB coupler as to allow a higher circulating signal in the laser cavity. The DCF was placed between the 80/20 and 90/10 couplers. The output signal would be extracted at the 10% port of the 90/10 coupler.

From Fig. 6 (b), 20% of the BP signal will be injected into the cavity through the 80/20 coupler and it will travel towards the DCF. The interaction of the BP signal and the DCF would cause a frequency downshift of the oscillating signal thereby generating the 1st Stokes line, BS₁ provided the BP power exceeded the SBS threshold. BS₁ will propagate in the backward direction as opposed to the BP, whereas the BP will continue to travel towards the 90/10 coupler and would be extracted at the 10% output port. When BS₁ oscillates in the clockwise direction in the ring cavity, it would be amplified by the BiDF and continue to oscillate towards the other end of the DCF. BS₁ now acts as the new BP and can generate BS₂ if its power also exceeded the SBS threshold. The generated Stokes line, BS₂ will have a wavelength upshift of about 0.074 nm with respect to BS₁ and will travel in the anti-clockwise direction. This process will continue to generate additional Stokes lines as long as each new Stokes line can exceed the SBS threshold. This cavity setup allows the anti-clockwise propagating Stokes lines to be extracted at the 10% port of the 90/10 coupler. The signals propagating in the clockwise direction will be heavily attenuated as compared to the signals propagating in the anti-clockwise direction. This makes the BP and even Stokes to be clearly defined in the extracted optical spectrum at the output, while the odd Stokes were significantly suppressed.

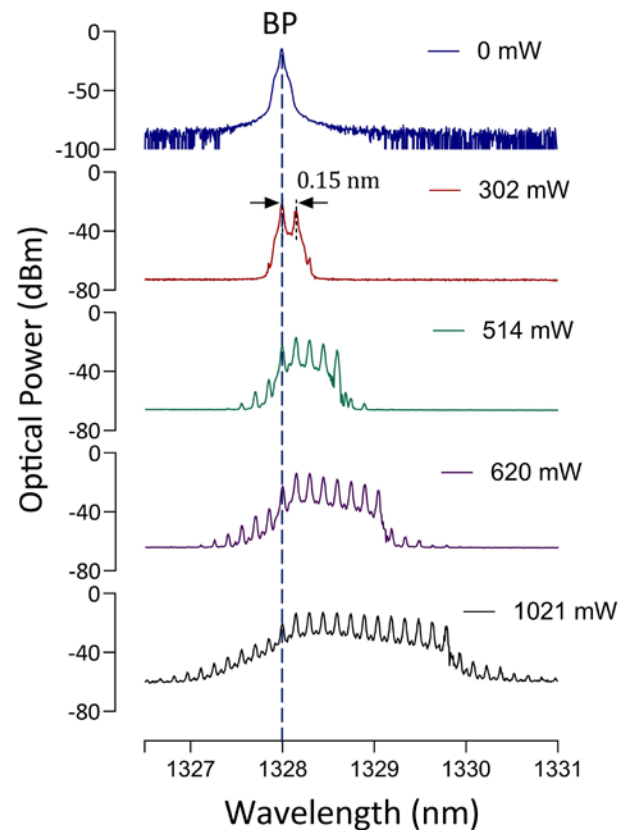


Fig. 7. The evolution of the generated double-spaced Brillouin Stokes lines against the increasing 1200 nm laser pump power.

The obtained optical spectrum against the increasing 1200 nm pump power was given in Fig. 7. For the case of the double-spaced MWBBFL, the BP output power was maintained at 11 dBm, with the center wavelength being set at 1328 nm since it is around the peak of the gain curve for this configuration. Similar to the single-spaced MWBBFL, the number of Stokes lines generated is also dependent on the pump power of the pump laser. When both the 1200 nm pump lasers

are off, only the BP is observed at the wavelength of 1327.99 nm. As the pump power was increased to 302 mW, BS₂ was observed at 1328.14 nm with a spacing of 0.15 nm with respect to the BP. This augurs well with the calculated double frequency spacing, which is ~ 25.3 GHz at around 1328 nm. As the pump power was further increased, more Stokes lines were generated since higher amplification was provided to cascade the SBS effect in the BGM. The pump power was then further increased until a maximum power of 1021 mW, thereby producing the maximum number of double-spaced Brillouin Stokes and anti-Stokes lines.

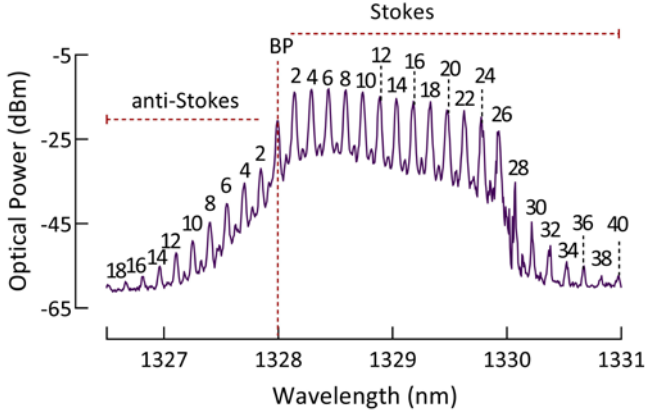


Fig. 8. Optical spectrum of the double-spacing Brillouin Stokes and anti-Stokes lines at the maximum pump power of 1021 mW.

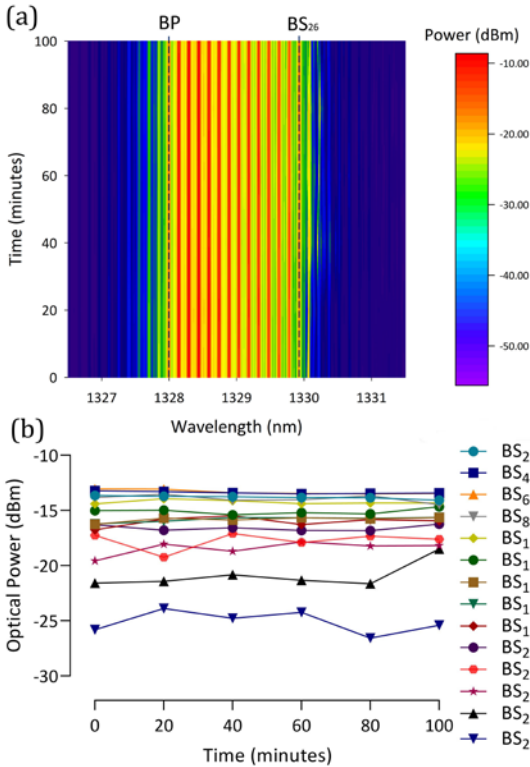


Fig. 9. Stability of the double-spaced MWBBFL in terms of (a) the optical spectrum (top view), and (b) the peak power of each double-spaced Brillouin Stokes lines against time.

Fig. 8 shows the optical spectrum of the MWBBFL with a double frequency spacing taken at the maximum pump power of 1021 mW, where up to 20 Brillouin Stokes and 9 anti-Stokes lines, which were labeled as 2,4,6... were generated. The odd

Stokes are still marginally visible, although they have been greatly attenuated since the position of the output coupler only allow the even Stokes to be extracted from the cavity. The first 13 even Stokes (BS₂ to BS₂₆) have SNRs of between 37 dB up to 46 dB, while the last 7 even Stokes (BS₂₈ to BS₄₀) have SNRs of less than 24 dB. Although the Stokes at longer wavelengths have lower SNRs, the number of Stokes lines generated in this work that have SNRs more than 30 dB are still higher as compared to that of previously reported works in generating double-spaced Brillouin Stokes [22], [32].

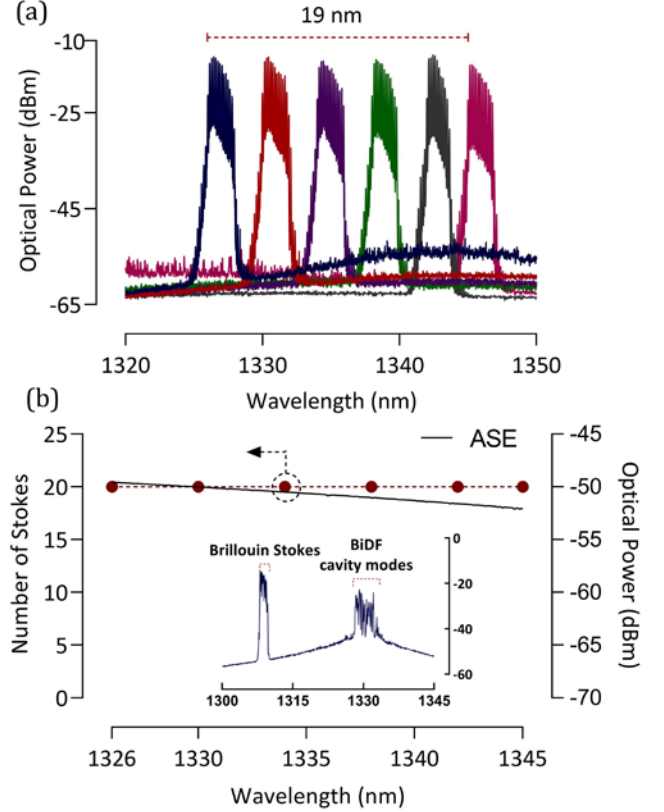


Fig. 10. (a) Tunability spectra of the double-spaced MWBBFL, and (b) the number of generated Brillouin Stokes lines against wavelength. Inset: Appearance of the BiDF cavity modes when the BP wavelength is tuned beyond the 19 nm tuning range (1326 nm to 1345 nm).

The stability of the double-spaced MWBBFL is also investigated for a period of 100 minutes. The optical spectrum was taken when the BP wavelength and the pump power was fixed at 1328 nm and 1021 mW, respectively. The results were recorded at every 20-minute interval and the stability result is illustrated in Fig. 9 (a). The double-spaced MWBBFL is stable for the first 13 even Stokes (BS₂ to BS₂₆), in which there is no shift in the wavelengths and no major fluctuations in the peak power of these Stokes lines. The higher order Stokes are less stable, where slight variations in the wavelengths and the peak power could be observed. This could be explained by observing that the lower orders Stokes has actually reached saturation and thus becomes stable. Higher fluctuations were observed for higher order Stokes because the Stokes have not yet reached their saturation levels. This is due to their peak powers being less than 5% than the peak powers of the stable lower order Stokes. For the peak power analysis of the double-spaced MWBBFL, only even Stokes with peak power of more than -30 dBm were selected. Thus, only the peak power of the

TABLE I
DEVELOPMENT OF MWBBFLS IN THE 1.3-MICRON WAVELENGTH REGION.

Amplifying medium	Operating wavelength (nm)	Generated Stokes (Single / Double)	Tuning Range (nm)	Reference
SOA	1310	20 / -	Fixed	[33]
SOA	1320	11 / -	Fixed	[34]
PDFF	1296 – 1304	24 / 16	8 / 8	[23]
BiDF	1272 – 1365	13 / 20	93 / 19	[This work]

first 14 even Stokes, BS₂ to BS₂₈, ranging from 1328.14 nm to 1330.0741 nm were recorded in Fig. 9 (b). The minimum and maximum fluctuations of BS₂ to BS₁₆ were measured to be only 0.28 dB and 0.74 dB, respectively, while the remaining Stokes lines, BS₁₈ to BS₂₈, have average fluctuations of about 1.9 dB.

The tunability spectrum of the double-spaced MWBBFL is shown in Fig. 10 (a). The total tuning range for the double-spaced MWBBFL is 19 nm, ranging from 1326 nm to 1345 nm. A total of 20 even spaced Brillouin Stokes lines were generated at each tuned wavelength, and is the same throughout the whole wavelength span as seen in Fig. 10 (b). This is due to the ASE power being at about the same level from 1326 nm to 1345 nm, providing enough amplification to only generate 20 Stokes lines. However, the unwanted lasing of the cavity oscillating modes were observed at around the peak of the gain curve as seen in the inset of Fig. 10 (b) when the BP was tuned outside of this 19 nm-wavelength span, causing instability to the generated Brillouin Stokes lines. This phenomenon is common in multiwavelength fiber lasers utilizing the SBS effect [35], [36]. Therefore, we only limit the tuning range of the BP so that the lasing of the BiDF cavity modes was suppressed.

III. DISCUSSIONS

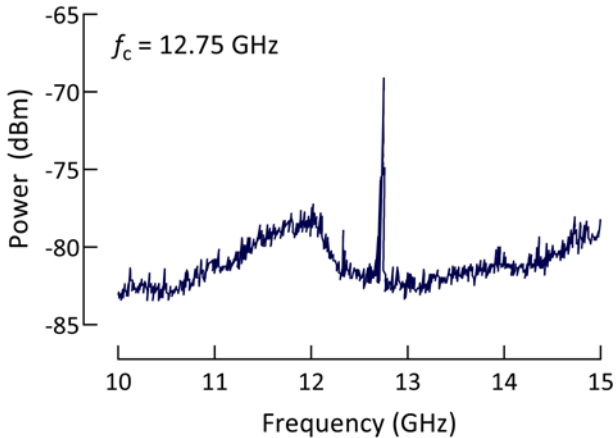


Fig. 11. Frequency beating of the single-spaced MWBBFL

The frequency beating of the MWBBFL was obtained by inputting the output of the laser into a high-speed photodetector (PD). Fig. 11 shows the generated microwave signal after the single-spaced MWBBFL was amplified by an 1.3 μm amplifier, and was sent into a Newport 818-BB-35F InGaAs PD. The PD has a bandwidth of 15 GHz and a responsivity is 0.65 AW^{-1} at around 1.31 μm . The output of the laser needed to be amplified

as the frequency response of the PD was relatively low beyond 10 GHz. The generated signal has a center frequency of 12.75 GHz as observed in an Anritsu MS2667C Spectrum Analyzer. This is in good agreement with the earlier calculated value of ~ 12.77 GHz. The peak was the result of the superposition of the frequency beatings between the BP and BS₁, BS₁ and BS₂, BS_n and BS_{n+1} ($n=2,3,\dots,13$), where their measured wavelength spacings were identical at about 0.074 nm (~ 12.7 GHz). Previous works on multiwavelength fiber lasers based on the SBS effect have also reported similar frequency spacings between adjacent Stokes lines. The previously demonstrated works on multiwavelength Brillouin fiber lasers operating in the 1.3 μm wavelength region are given in Table I.

The demand for multi-wavelength Brillouin laser sources operating at 1.3 μm is expanding at a significant pace, owing to the increasing demand for a broad bandwidth in DWDM systems. Different types of amplifying medium were explored to provide the necessary gain for the multi-wavelength generation in 1.3 μm region, including semiconductor optical amplifiers (SOAs) and praseodymium-doped fluoride fiber (PDFF). Table I compares the performances of multi-wavelength Brillouin lasers operating in the 1.3 μm region. From the table, it can be seen that the previous works on SOAs are able to provide gain for the generation of single-spacing multi-wavelength Brillouin lasers, centered at 1310 nm and 1320 nm, respectively. As in [33], 20 Stokes lines were obtained in a ring cavity configuration, while in reference [34] 11 Stokes lines were generated in a linear cavity configuration. The number of generated Stokes lines is nevertheless quite low as compared to that in the PDFF laser cavity, as demonstrated in [23]. Although the number of generated single-spaced Stokes in this work is not as high as that was obtained by Ahmad *et al.* [23] using PDFF as the gain medium, this would be the first time that Stokes lines are obtained in a cavity using BiDF as the gain medium. This BiDF, unlike the PDFF, can be easily spliced to silica based fibers that are commonplace in optical networks. Furthermore, the BiDF is not hygroscopic as compared to the PDFF which needs extreme care when handling. Additionally, a broader tuning range is observed for both frequency spacings in the BiDF laser cavity as compared to the PDFF, which could be attributed to the broader amplification bandwidth of the BiDF across the 1.3 μm region. In this work, the single- and double-spacing multi-wavelength Brillouin lasers can be tuned around 93 nm and 19 nm, respectively. This is about double the tuning range of the single-spacing Brillouin and about 11 times higher for double-spacing

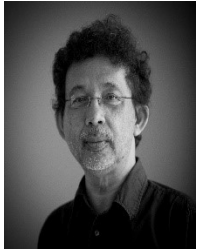
Brillouin than that previously reported [23], which makes this laser suitable for various applications especially in DWDM systems.

IV. CONCLUSION

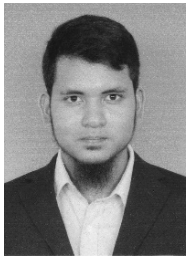
We have successfully demonstrated the generation of multiwavelength fiber lasers by stimulated Brillouin scattering using bismuth-doped fiber as the laser gain medium. The Brillouin frequency spacing of the multiwavelength laser was switchable between a single- and double-frequency spacing of ~12.75 GHz and ~25.3 GHz respectively. Up to 13 single-spaced and 20 double-spaced Brillouin Stokes lines were generated by placing the BGM in different arrangements in the laser cavity. The MWBBFL can be tuned by varying the central wavelength of the Brillouin pump, where a broad tuning range of 93 nm was achieved in the single-spaced configuration and up to 19 nm in the double-spaced configuration respectively. The laser would find potential application in DWDM communication and fiber sensing.

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