Flat amplitude multiwavelength Brillouin-Raman comb fiber laser in Rayleigh-scattering-enhanced linear cavity

A. K. Zamzuri[1]*, M. A. Mahdi[2], A. Ahmad[1], M. I. Md Ali[1], and M. H. Al-Mansoori[3]**

[1] *Lightwave Systems Unit, TM Research & Development Sendirian Berhad, Idea Tower, Universiti Putra Malaysia-Malaysian Technology Development Corporation, 43400 Serdang, Selangor, Malaysia.*
*zamzuri@tmrnd.com.my
[2] *Photonics and Fiber Optic Systems Laboratory, Department of Computer and Communication Systems Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Malaysia.*
**adzir@ieee.org
[3] *Centre for Photonics Research Innovation & Applications, Faculty of Engineering, Multimedia University, 63100 Cyberjaya Selangor, Malaysia.*
mansoori@ieee.org

Abstract: We investigate the amplitude flatness of Rayleigh-assisted Brillouin-Raman comb laser in a linear cavity in which feedbacks are formed by high-reflectivity mirror. The optimization of Brillouin pump power and wavelength is very crucial in order to obtain a uniform power level between Stokes lines. The Brillouin pump must have a relatively large power and its wavelength must be located closer to the Raman peak gain region. The flat-amplitude bandwidth is also determined by the choice of Raman pump wavelengths. A flat-amplitude bandwidth of 30.7 nm from 1527.32 to 1558.02 nm is measured when Raman pump wavelengths are set to 1435 and 1450 nm. 357 uniform Brillouin Stokes lines with 0.086 nm spacing are generated across the wavelength range. The average signal-to-noise ratio of 17 dB is obtained for all the Brillouin Stokes lines.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (290.5900) Scattering, stimulated Brillouin; (290.5910) Scattering, stimulated Raman; (290.5870) Scattering Rayleigh.

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1. Introduction

Multiwavelength fiber lasers are one of the attractive solutions to support dense wavelength division multiplexed systems. There are two common techniques commonly utilized; external channel filtering and internal channel generation. The former technique is based on slicing a broadband spectrum from a supercontinuum source [1]. The latter technique is to produce multiple channels using any means of filtering within a laser cavity internally. A physical narrowband filter can be utilized as one of the options in this technique [2]. On the other hand, a group of laser lines can be generated from a seed channel. This approach is commonly known as hybrid-gain configuration which manipulates narrow bandwidth of Brillouin gain in optical fibers.

The idea is first demonstrated in Brilloun-erbium fiber laser cavity [3]. Later, it is extended to incorporate the nonlinear Brillouin scattering in Raman fiber laser cavity [4]. Since the Raman amplification has wide gain bandwidth, the generation of Brillouin Stokes lines is higher compared to its counterpart of Brillouin-erbium fiber lasers. Brillouin-Raman fiber laser requires a relatively long nonlinear fiber owing to the nature of Raman amplification. In addition, the proposed laser structure in Ref. 4 based on linear cavity in which the signal travels bidirectionally in the amplifying fiber. Therefore, the generation of Brillouin Stokes lines is assisted by Rayleigh scattering. This complicated nonlinear interaction is well explained in the follow-up research work [5]. Referring to the proposed laser structure, only one high reflectivity mirror is used and at the other cavity end, a virtual mirror is formed taking advantage of Rayleigh double-scattering. Owing to the process of Rayleigh scattering, this virtual mirror has weak reflectivity compared to the physical mirror. Thus, the proposed laser cavity is driven into deep saturation to push Rayleigh component to reach the same saturation level set by the Brillouin components. On the other hand, the distinctive power level discrepancy is clearly observed when the Brillouin-Raman fiber laser cavity is constructed from two virtual mirrors (no physical mirror at both cavity ends) [6].

Based on this literature review, we proposed a linear cavity formed by the high-reflectivity element at both ends of the laser cavity [7]. In the research work, the problem of power level discrepancy is successfully resolved. Furthermore, the optical signal-to-noise ratio (OSNR) of the Stokes lines is higher than those achieved from the previous research works. However, all the experimental results obtained with the expense of the amplitude flatness which has been superiorly demonstrated in Ref. 5 and 6.

In this paper, we concentrate on the amplitude flatness issue based on the Brillouin-Raman linear-cavity fiber laser. The behavior of Stokes lines that produces flat power level is investigated in details for single-wavelength and dual-wavelength pumping schemes. In this work, a counter measure to produce flat-amplitude Stokes lines in a wider wavelength range is suggested.

2. Experimental set-up

The proposed fiber laser architecture for the generation of multiwavelength Stokes lines is depicted in Fig. 1. The laser architecture is constructed by incorporating a high-reflectivity mirror for each cavity end. The Raman amplification is obtained from the dispersion compensating fiber (DCF) pumped in a counter-directionally by a Raman pump unit (RPU). The length of DCF is 11 km with total insertion loss of 5 dB. Its nonlinear coefficient is 7.31 $(\mathrm{Wkm})^{-1}$ and the effective area is 20 $\mu\mathrm{m}^2$. The pump lasers at wavelength of 1435 and 1450 nm are utilized in the RPU. For each pump wavelength, two laser diodes with wavelength locker are multiplexed through a polarization beam combiner. Then, these pump wavelengths are multiplexed using a pump combiner before integrating with a wavelength selective coupler (WSC). The Brillouin pump (BP) is injected directly via a 3-dB coupler obtained from an external-cavity tunable laser source. Finally, the laser output is taken from the other

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arm of the 3-dB coupler. The operating principle of the proposed laser structure is similar to our previous experiment [7].

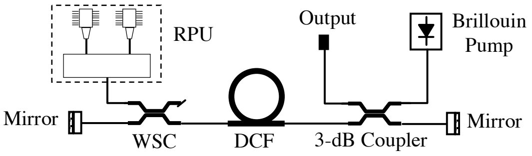
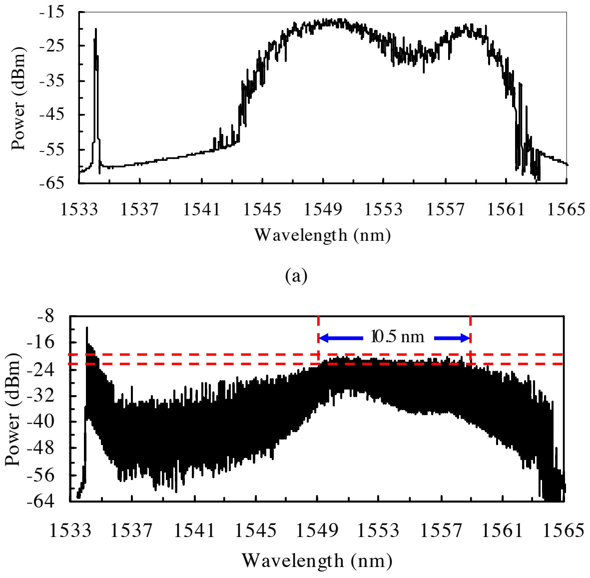


Fig. 1. Multi-wavelength Brillouin-Raman fiber laser architecture in a linear cavity.

3. Results and discussion

In the first experiment, single pump wavelength at 1450 nm is activated in order to investigate the impact of BP wavelength and power on the generation of multiple Brillouin Stokes lines. The 1450 nm pump power is tuned to 300 mW and the BP wavelength is fixed to 1534 nm. The BP power is varied from 1 to 10 mW and the laser output is measured using the optical spectrum analyzer with the resolution bandwidth set to 0.01 nm. For 1.8 mW BP power, the output spectrum is measured as depicted in Fig. 2(a). In this case, only two Brillouin Stokes lines are obtained from the experiment owing to the nature of fiber nonlinearity in the DCF. Since the BP wavelength is detuned away from the cavity peak gain that occurs around 1546-1561 nm as depicted in Fig. 2(a), the subsequent Brillouin Stokes lines cannot be generated in this low gain regime. Even though that the laser architecture is also supported by the Rayleigh scattering effect, the BP has low gain to compete with the cavity modes under this condition. When the BP power is increased to 10 mW, the combination effect of Brillouin gain and Rayleigh scattering is also increased and thus, the generation of Brillouin Stokes lines with 0.086 nm spacing from 1534 to 1564 nm is obtained as depicted in Fig. 2(b).



(a)

(b)

Fig. 2. Measured output spectrum for 1534 nm BP wavelength at (a) 1.8 mW and (b) 10 mW power, the pump power is fixed to 300 mW.

The processes of Raman amplification, Brillouin shift and Rayleigh scattering are blended in the proposed laser structure. For BP wavelengths far away from the laser cavity gain, the

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generation of cascaded Brillouin Stokes lines is dominated by Rayleigh scattering and these Stokes lines are relatively weaker than other Stokes lines within the laser cavity bandwidth as shown in Fig. 2(b). As a result, the output power is also not flat over the whole wavelength range owing to this low saturation effect. The flat-amplitude Stokes lines are defined by 3-dB peak power fluctuation across the whole spectrum regardless of the Stokes lines location. Referring to Fig. 2(b), the flat-amplitude bandwidth is obtained from 1549.5 to 1558.6 nm, which is about 10.5 nm bandwidth. It is also important to note that the flat-amplitude region is occurred in the range of Raman peak gain. In addition, the noise envelope follows exactly like the Raman gain spectrum which indicates that the oscillating Brillouin Stokes lines are not strong enough to suppress the noise generation from the stimulated Raman scattering.

In order to obtain the flat-amplitude Stokes lines, the optimization of BP wavelength and power is critical as also suggested in Ref. 4. For the laser structure pumped by single wavelength at 1450 nm; the RPU power, BP power and wavelength must be optimized in order to obtain the widest bandwidth of the flat-amplitude Stokes lines. In the following experiment, the pump power is fixed to a few values of 215, 250 and 300 mW, and then the BP power is fixed to either 1.8 or 10 mW. After that the BP wavelength is varied from 1534 to 1559 nm. For each measurement, the same experimental procedure and results analysis as described in the previous experiment are repeated. The 3-dB bandwidth of the flat-amplitude Stokes lines is analyzed as shown in Fig. 3. At low pump power and BP power (215 mW and 1.8 mW), the Raman gain in the laser cavity is low and inadequate to provide enough energy for modes amplification to oscillate in the cavity. Therefore, the 3-dB bandwidth of flat-amplitude Stokes lines is found around the region closer to the BP wavelength only. An abrupt increase in the flat-amplitude bandwidth is observed when the BP wavelengths are set shorter than the Raman peak gain around 1551 nm as depicted in Fig. 3. The generation of these Stokes lines that dominating the wavelength region between the BP wavelength and the Raman peak gain is due to the contributions from the Rayleigh scattering. The peak power of these Stokes lines increases when pumped by higher powers of BP and RPU thus the generated Stokes lines experience saturation and the flat-amplitude bandwidth is extended.

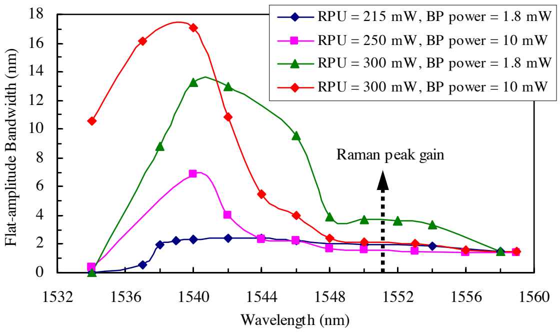


Fig. 3. The 3-dB bandwidth of the flattened Stokes lines at different pump powers, BP powers and wavelengths.

Since the Raman amplification is gradually increased from short wavelengths to longer wavelengths (until its peak gain around 1551 nm), thus the amplification of Brillouin Stokes lines is also increased within this wavelength range. Therefore, the injection of BP into the laser cavity gets this benefit by selecting its wavelength lower than the Raman peak gain. Based on the optimization process as depicted in Fig. 3, the optimum BP wavelength is found at 1540 nm. The widest flat-amplitude bandwidth is obtained when the BP wavelength is set at 1540 nm and its power is cranked up to 10 mW. The measured flat-amplitude bandwidth is from 1542.8 to 1559.2 nm, which is about 17.1 nm bandwidth as shown in Fig. 4. The noise floor is also improved to almost flat across this bandwidth. The BP is effectively amplified since its wavelength is moved closer to the high gain region. The laser cavity is forced into deep saturation by Brillouin effect and the creation of flat-amplitude Stokes lines is also partly contributed by the inhomogeneous nature of the Raman gain [4]. Since the laser cavity is formed by high reflectivity mirror at both ends of the cavity, most of the energies for amplification are concentrated within the peak gain range of Raman bandwidth. Therefore, the BP wavelength must be tuned closer to this region and its power must be adequately high in order to suppress the noise generation from the stimulated Raman scattering. Referring to the published work in Ref. 5, the generated Stokes lines is flat across wider bandwidth however, low OSNR values are measured and not uniform for the entire flat-amplitude region. In addition, based on the experimental results obtained in Ref. 6, the peak powers of lines are not uniform owing to the different optical properties between Brillouin and Rayleigh mechanisms in the laser cavity. Thus, the OSNR of the lines is also not equal between the Brillouin and Rayleigh components. Both experimental results are generated by exploiting the property of Rayleigh backscattering effect (virtual mirror) which has weak reflectivity. However, the OSNR is measured of higher than 16 dB across the wavelength range in this research work. The most noticeable difference between our results and other published results is the complete oscillation experienced by each individual Stokes line in the laser cavity.

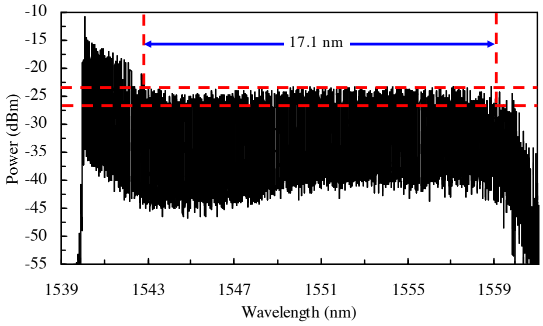
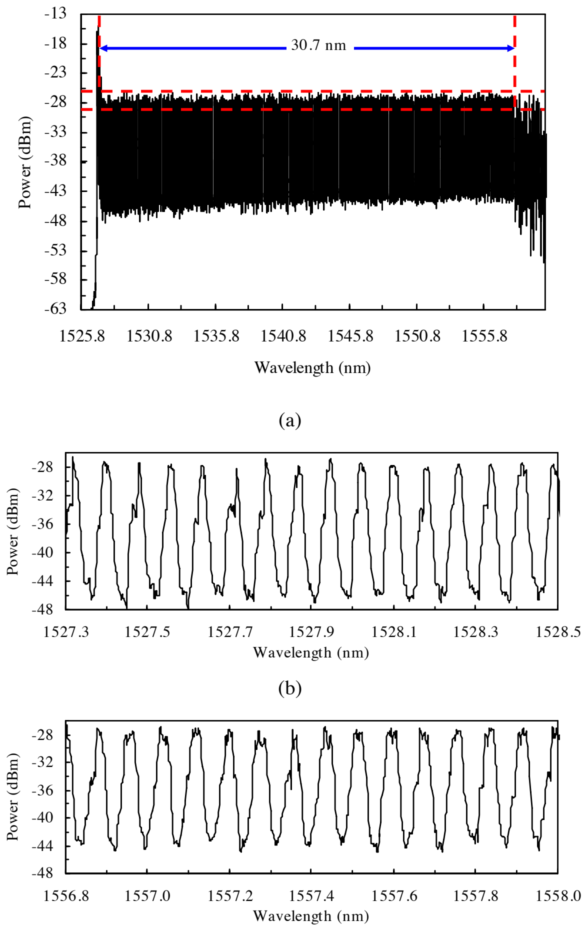


Fig. 4. Output spectrum following a proper optimization of BP wavelength (1540 nm) and power (10 mW), the Raman pump power is fixed to 300 mW.

Based on the findings, the Stokes lines can have uniform peak power within the Raman peak gain bandwidth from the linear-cavity fiber laser. This is owing to the fact that the generated Stokes lines achieve their saturation level faster because of their higher gain in the laser cavity. Even though that the BP and RPU powers are pushed to their maximum value, the flat-amplitude region cannot be extended owing to the limited gain bandwidth by the Raman amplification especially in the short wavelength range. Therefore, the saturation level of the generated Rayleigh-assisted Stokes lines is not achieved under this condition. In order to widen the flat-amplitude bandwidth, the laser cavity must be pumped by another Raman pump wavelength to improve its Raman gain bandwidth. Based on our results analysis, another Raman pump lasers at 1435 nm are activated to achieve the aforementioned objective. The pump power from the RPU is carefully adjusted concurrently with the optimization of BP wavelength and power. As a result, the optimized output spectrum is obtained which has flat-amplitude Stokes lines as depicted in Fig. 5(a). Under this condition, the BP wavelength is set at 1527 nm and its power is tuned to 4.14 mW. In addition, the RPU is configured as follows; 1435 nm (200 mW) and 1450 nm (120 mW). The flat-amplitude bandwidth is obtained from 1527.32 to 1558.02 nm, which is about 30.7 nm bandwidth (357 Stokes lines with 0.086 nm spacing). Fig. 5(b) and 5(c) represent a magnified view of the Stokes lines at both edges (short and long wavelengths) of the flat bandwidth. From both figures, it is clearly seen that the peak power of Stokes lines is flat within the 3-dB range. The measured OSNR values are averaged around 18 and 16 dB for the low and high cut-off wavelength range respectively.

These results show that the average OSNR value across the flat-amplitude bandwidth is about 17 dB, which supersedes the OSNR values reported in Ref. 5 and 6.



(a)

(b)

(c)

Fig. 5. The optimized flat-amplitude spectrum (a) the whole spectrum, (b) magnified span at the low cut-off wavelengths and (c) magnified span at the high cut-off wavelengths.

4. Conclusion

In conclusion, we have investigated the amplitude flatness of Rayleigh-assisted Brillouin-Raman linear-cavity fiber laser. High-reflectivity mirrors used at both ends of the laser cavity create strong oscillation of cavity modes (without the injection of BP) around the Raman peak gain. In order to have a reasonable flat-amplitude Stokes lines, the BP wavelength must be located closer to the Raman peak gain region. The optimization of BP power and wavelength has great influence in determining the uniformity of the Stokes lines amplitude. The flat-amplitude bandwidth is also governed by the number of Raman pump wavelength used in the laser structure. The widest bandwidth of 30.7 nm is obtained when the laser cavity is pumped by dual-wavelength pumping scheme at 1435 and 1450 nm with total pump power of 320 mW. Owing to the high-reflectivity feedbacks, the average OSNR value of 17 dB across the flat-amplitude bandwidth is successfully measured. The flexibility and scalability of Raman-pumped laser cavity has great promise to provide multiple channels in larger bandwidths.