Multi-wavelength Brillouin Raman Erbium Fiber Laser utilizing Captured Residual Raman Pump Power

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***Abstract*—We experimentally demonstrate a multi-wavelength Brillouin Raman Erbium fiber laser (MBREFL) by using captured residual Raman pump to pump an erbium doped fiber. Results show that our MBREFL is capable of producing up to 48 Brillouin Stokes lines (BSL) at Brillouin and Raman pump power of +6 dBm and 600 mW, respectively. The proposed MBREFL is tunable free of self-lasing modes for 14.5 nm from 1574.5 with BSLs between 33 and 48.**

Keywords—Multi-wavelength Brillouin fiber laser, residual Raman pump, erbium-doped fiber laser

I. Introduction

Multi-wavelength fiber laser generated based on non-linear scattering attracted interests from many researchers due to its application in sensors, optical communications and microwave generation [1]–[5]. Conventional multi-wavelength Brillouin fiber lasers (MBFL) however are limited by the low Brillouin gain, hence additional amplification are employed to generate higher number of channels [6]. Typically, erbium doped fiber amplifiers are used in Multi-wavelength Brillouin Erbium Fiber Lasers (MBEFL) [7]–[9], or Raman amplifiers are used in Multi-wavelength Brillouin Raman Fiber Lasers (MBRFL), respectively [10], [11].

While most reported works on combining the usage of both Raman and erbium effects are in amplifier design [12]–[14], there are a few reports of such technique in multi-wavelengths Brillouin Raman erbium fiber lasers (MBREFL) [15]–[18]. Ahmad et al. utilizes a 1420 nm Raman Pump Unit (RPU) with a 7.7 km DCF to amplify the Brillouin Pump (BP) and the subsequent Brillouin Stokes Lines (BSL), as well as bi-directionally pumped 30-m Depressed Cladding Erbium Doped Fiber (DC-EDF) to achieve significant amplifications in S-band region [15]. The authors reported up to 17 channels with 3-nm tuning range when BP was set between 1499nm and 1502 nm. Shirazi et al. used two 1425 nm RPUs to bi-directionally pump a 7.7 km Dispersion Compensated Fiber (DCF), which simultaneously functions as Brillouin and Raman gain medium [16]. The authors also used a 3 m EDF, pumped by a 980 nm laser diode (LD), to pre-amplify the BP and generated BSLs propagating into the DCF. The laser set up resulted in 34 Stokes lines when BP is 6.5 dBm at 1530 nm and total pump power (Raman and erbium) is 400 mW. Shirazi et al. later another set up with 0.45 m bismuth-based EDF (Bi-EDF) where resulted in 38 Stokes lines by improving amplification in L-band region [17]. One common drawback in all these design is that they require two or more LD as pump.

In this paper, a new MBREFL operating in L-band is proposed where a wavelength selective coupler (WSC) was used to capture residual Raman pump power (RPP) [19] to pump a 10 m EDF gain medium. The new design generates higher number of BSLs as well as reduces complexity of previous MBREFL.

II. Experimental Setup of MBREFL

Fig. 1 shows the experimental set up of proposed MBREFL consisting of a tunable laser source (TLS), an isolator (ISO), a 3-dB optical coupler (OC), two wavelength division multiplexer (WDM1, WDM2), a Raman pump unit (RPU), a 7.1 km dispersion compensated fiber (DCF), a wavelength selective coupler (WSC), two Faraday mirror (FM) and a 10-m erbium-doped fiber (EDF).

BP is provided by the TLS, which outputs up to +6 dBm between 1540 and 1610 nm. The ISO is used to protect the TLS from back reflections. The DCF works as both Raman and Brillouin gain medium, where a RPU with 2 Watt maximum power at 1480 nm provides the Raman pump power (RPP). Two FMs at both ends of the cavity allow the BP and generated BSLs to oscillate within the cavity. The laser output is measured at one of the OC port using an Optical Spectrum Analyzer (OSA).

BP injected by the TLS propagates to the OC through the isolator. Half of the BP power will be measured by OSA at output and the other half will be amplified by the Raman pumped DCF (when Raman pump power (RPP) when it is adequate to initiate Stimulated Raman Scattering (SRS)). The amplified BP will generate first-order BSL (BSL1) in the opposite direction when stimulated Brillouin scattering (SBS) threshold is exceeded. BSL1 travels through the OC again before passing through the EDF pumped by residual Raman pump power (R-RPP), twice. Half of BSL1 power will propagate back to the DCF generating second-order BSL, while the other half is measured by OSA as output. This whole oscillation process continues, generating higher order BSLs until the amplifiers reached saturation point. The BP is fixed to +6 dBm at 1580 nm during the experiments except for tuning range experiment.

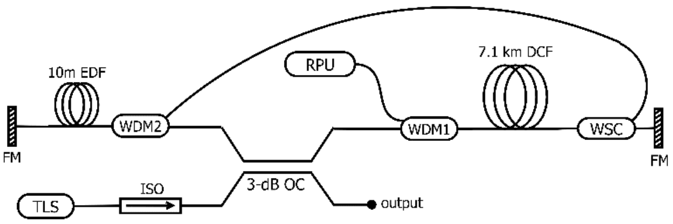

Fig. 1. Proposed MBREFL Setup

III. Results and Discussions

Self-lasing modes in absence of BP of the proposed MBREFLwas first investigated. Fig. 2 shows the measured output at selected RPP. At low RPP, self-lasing modes shows peak near 1563 nm, contributed by the EDF gain. As the RPP increases, the peak is shifted towards longer wavelength as the SRS effect increase until SRS dominates when RPP is near 400 mW. Increasing the RPP further will eventually resulted in red-shift effect, as discussed in detail in [20], [21].

The number of generated BSLs with varying RPP is then investigated. Fig. 3 shows the number of BSLs generated by the MBREFL versus varying RPP in 25 mW steps. The first BSL for the MBREFL appears at RPP of as low as 50 mW. This low SBS threshold is contributed by amplification provided by the EDF, pumped by residual RPP. The number of BSLs grows steadily up to 48 BSLs at RPP of 600 mW. The maximum number of BSL is higher compared to Abass' MBRFL and earlier MBREFL designs [15]–[17], [19]. Fig. 4 shows output of the MBREFL with maximum number of BSLs, with RPP of 600 mW. At RPP beyond 600 mW, the higher-order Stokes line becomes noisy and eventually distorts the signal at RPP of 725 mW as shown in Fig. 5, as a result of self-lasing modes competition [19].

Careful observation of the output spectrum however shows that, at low RPP, self-lasing modes appears at around 1565 nm region, as shown in Fig. 6(a), since BP at 1580 nm is unable to suppress generated self-lasing modes. As the RPP increases, the self-lasing modes shifts to longer wavelength and are suppressed when RPP is more or equal to 250 mW. Fig. 6(b) depicts the output spectrum at RPP of 250 mW.

Tuning range of the MBREFL was also investigated with BP wavelength swept, at fixed power of +6 dBm and RPP at 600 mW. Here, tuning range is defined by BP wavelength range where self-lasing modes are insignificant. Fig. 7 shows that the MBREFL is tunable for BP range of 1574.5 to 1594 nm. Varying the BP wavelengths however, shows fluctuations in the number of BSLs generated. The number of BSLs for the proposed MBREFL at selected BP wavelengths was recorded to be between 33 to 48 within its tuning range, as summarized in Fig. 8.

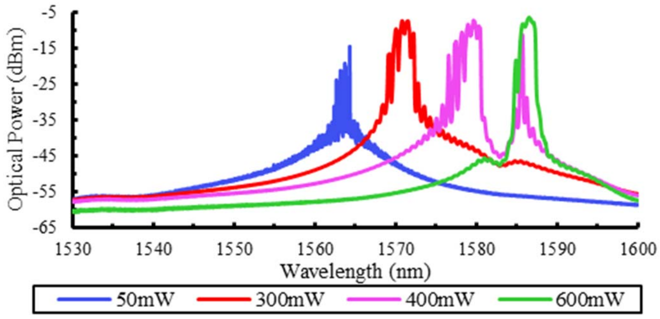

Fig. 2. Self-lasing cavity modes spectrum of MBREFL

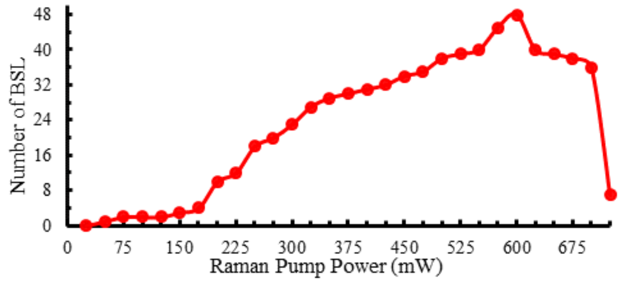

Fig. 3. Number of generated Brillouin Stokes Lines versus Raman pump power of proposed MBREFL, with fixed BP power of +6 dBm and wavelength of 1580 nm.

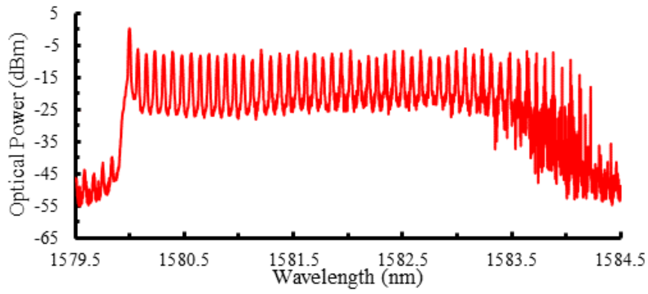

Fig. 4. MBREFL output for BP of +6 dBm at 1580 nm and RPP of 600 mW.

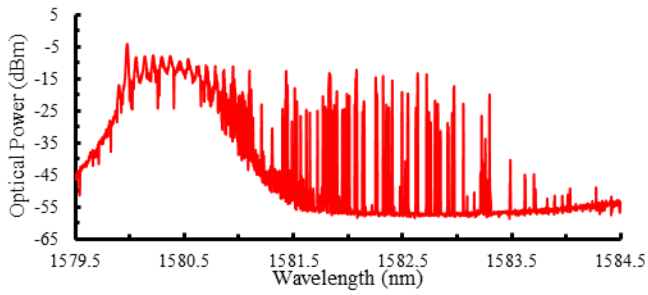

Fig. 5. MBREFL output for BP of +6 dBm at 1580 nm and RPP of 725 mW.

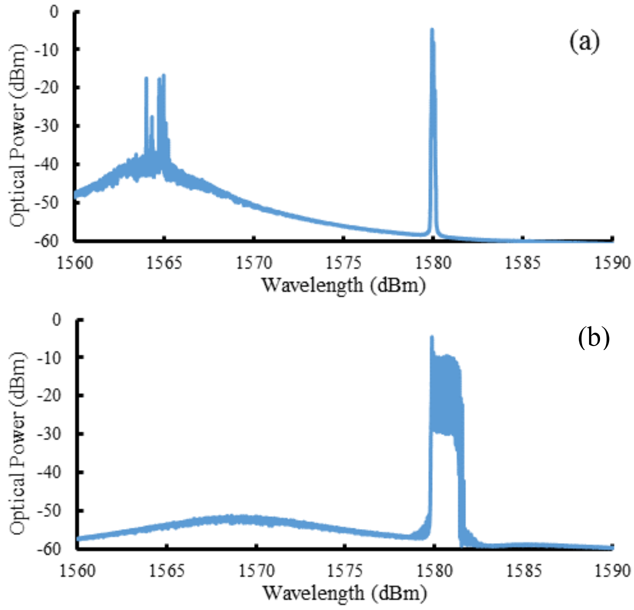

Fig. 6. Output spectrum of proposed MBREFL at different RPP of (a) 75 mW and (b) 250 mW, with BP power of +6 dBm and wavelength of 1580 nm.

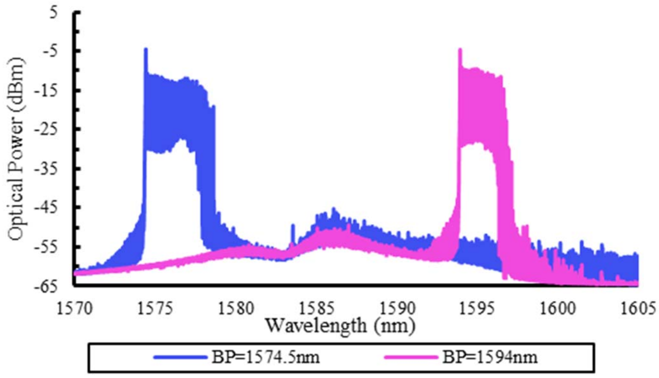

Fig. 7. Tuning range of proposed MBREFL

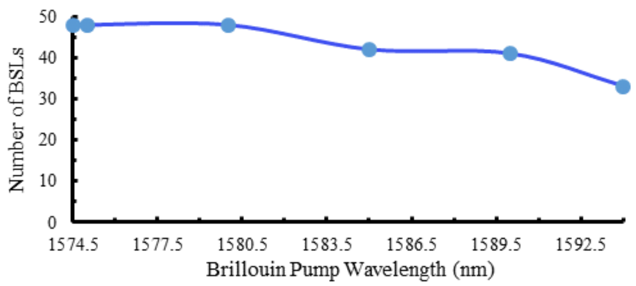

Fig. 8. Number of BSLs versus BP wavelengths with free of self-lasing modes. BP is fixed at +6 dBm while RPP at 600 mW.

IV. Conclusion

A MBREFL utilizing residual Raman pump was experimentally demonstrated in this paper. The MBREFL utilizes the captured RPP to pump a 10 m EDF, which eliminates the need for multiple EDF and Raman pump as suggested by earlier MBREFL designs, hence reduces complexity. The proposed MBREFL is able to generate up to 48 BSLs at BP power and RPP of +6 dBm and 600 mW, respectively, which is higher than other MBREFL designs reported. The MBREFL has tuning range of 19.5 nm (1574.5 and 1594 nm), with its number of BSLs varies from 33 to 48 at the same BP power and RPP.

Acknowledgment

The authors would like to extend their appreciation to Universiti Tenaga Nasional for supporting the work through the UNITEN BOLD grant numbered 10289176/B/9/2017/38 and UNIIG numbered J510050695.

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