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Effective use of an EDFA and Raman pump residual powers via a Bi-EDF in L-band multi-wavelength fiber laser generation

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Abstract

Residual powers of an erbium-doped fiber amplifier (EDFA) and a Raman pump are utilized effectively for pumping a 0.45 m long bismuth-based EDF (Bi-EDF) in linear-cavity L-band multi-wavelength fiber laser generation. A 7.7 km dispersion compensating fiber (DCF) operates as both Brillouin and Raman gain media and a 6.5 dBm fixed-power tunable laser source (TLS) amplified by an EDFA works as a Brillouin pump (BP). By inserting the Bi-EDF in the linear cavity and using the EDFA and the fixed Raman pump residual powers 13.6 mW and 64 mW, at wavelengths 978.8 nm and 1490.6 nm respectively, the gain spectrum is inhomogeneously broadened so that linewidth of the gain spectrum is expanded from 3.4 to 12.3 nm. As a result, the number of lines of an L-band multi-wavelength fiber laser (MFL) is increased noticeably. In addition, the number of lines at a BP wavelength 1590.6 nm decreased from 38 to 32 by using the maximum EDFA pump residual power of 44 mW due to a reduction in the quantum coefficient efficiency. However, flatness and stability characteristics of the MFL are improved. The MFL can be generated in the wavelength region 1570–1610 nm with the signal to noise ratio of about 42.

Keywords: stimulated Brillouin scattering, fiber lasers, Raman amplifier, EDFA

(Some figures may appear in colour only in the online journal)

1. Introduction

Multi-wavelength fiber lasers (MFLs) are low cost, compactly structured and compatible with optical fibers and so consequently attract widespread interest in applications such as wavelength-division-multiplexing (WDM) systems, light detection and ranging (LiDAR), microwave photonics, imaging, optical component testing, fiber-optical sensing, metrology and spectroscopy [1–17]. Multi-wavelength Brillouin fiber lasers (MBFLs) can be generated by cascaded stimulated Brillouin scattering (CSBS) as a simple, accurate and consistent method with flexible wavelength tuning [18–20]. Brillouin Stokes power is dependent on Brillouin pump (BP) power in a SBS process, so it is customary to use hybrid gains such as Brillouin–erbium and Brillouin–Raman gains to increase the number of Brillouin Stokes lines generated in CSBS processes in multi-wavelength Brillouin–erbium fiber lasers (MBEFLs) and multi-wavelength Brillouin–Raman fiber lasers (MBRFLs) respectively [21–27]. Although MFLs can be generated by erbium gain media with advantages of power conversion efficiency and low threshold, such lasers are normally unstable and suffer gain competition among different lasing wavelengths at room temperature due to the homogenous line broadening and cross-saturation gain of EDF [28]. One method to achieve a stable and uniform MFL source using EDF gain is to employ a nonlinear fiber as a Raman gain medium [28–30]. In order to utilize more available bandwidth in optical fibers, some works have been designated to generate L-band MBEFL by using a Bi-EDF pumped by laser diodes (LDs) at a wavelength of 1480 nm [23, 31, 32].

In this work, we use residual pump powers of a Raman pump and an EDFA, at wavelengths 1490.6 nm and 980 nm

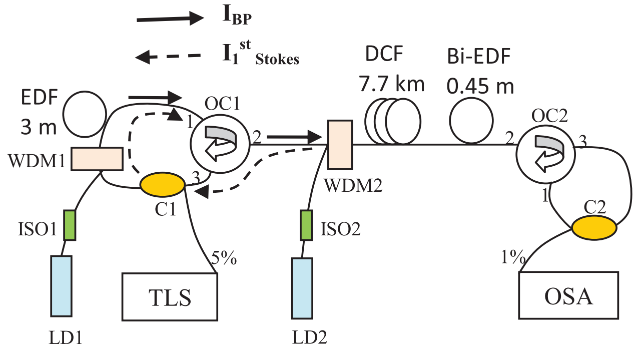

Figure 1. Experimental setup for the proposed multi-wavelength fiber laser generation after inserting the Bi-EDF.

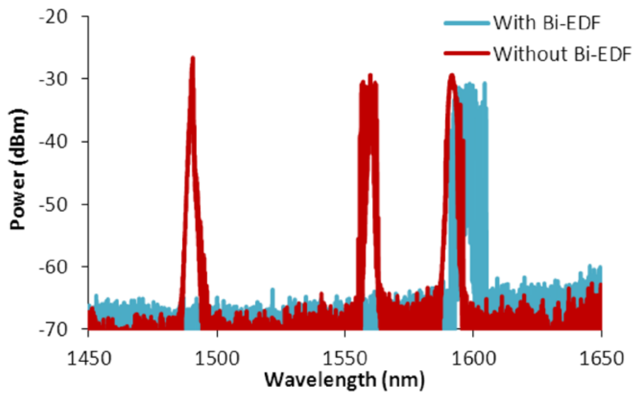

Figure 2. The generated ASE or free-running gain spectrum in the output with and without using the Bi-EDF.

respectively, for pumping an inserted 0.45 m long Bi-EDF. Surprisingly, there is a noticeable expand in the gain spectrum of amplification so that the number of Brillouin Stokes lines are increased effectively in the L-band MFL generation. In Raman amplification at the Raman pump wavelength region 1480–1490 nm, this work also proposes that the linewidth of the gain spectrum can be expanded effectively by inserting a Bi-EDF pumped a few mW at a wavelength 980 nm.

2. Experimental set-up

The proposed linear cavity configuration for MFL generation is demonstrated in figure 1. The 7.7 km long DCF, used as both the Brillouin and the Raman gain media, has a mode effective area of 15 μm^2, with an attention loss of 0.65 dB km^{-1} at the wavelength region 1550 nm and with a dispersion value of −584 ps nm^{-1}. Brillouin pump (BP) is an external-cavity tunable laser source (TLS) amplified by an EDFA. Therefore, the TLS with a 6.5 dBm fixed power is connected to a 3 m EDF through the 5% ratio port of the input coupler C1 (5/95) and the wavelength division multiplexing coupler WDM1. The EDF has absorption of about 12.2 dB m^{-1} at 97.80 nm and 18 dB m^{-1} at 1550 nm. This EDF furthermore possesses a mode field diameter (MFD) of 3.7 μm at 980 nm and 6.2 μm at 1550 nm. The TLS1 is set according to manufacturer's specifications to have the narrow linewidth of about 20 MHz. An EDF amplifier (EDFA) is produced by pumping the EDF with a laser diode (LD1), with a maximum 160 mW pump power at an operational wavelength of 980 nm. BP is emitted into DCF through port 1 and port 2 of an optical circulator (OC1) and a WDM coupler, WDM2. The DCF is also pumped in a forward direction by another laser diode (LD2) acting as a Raman pump (RP) at a 1490.6 nm wavelength with 300 mW fixed pump power through the WDM coupler, WDM2. The Raman pump power injected into the DCF is measured as 246 mW via a power meter. Subsequently, LD2 with 64 mW residual power and LD1 with 13.6 mW maximum residual power both emit into a 0.45 m long Bi-EDF. The Bi-EDF is employed as an erbium gain in the L band wavelength region (1565–1625 nm) and is characterized by a nonlinear coefficient 60 (W·km)$^{-1}$, an erbium concentration of 3250 ppm, a MFD of about 6.2 μm at 1550 nm, a cut-off wavelength of 1440 nm and peak absorption around 73 dB m^{-1} and 83 dB m^{-1} at 978.8 nm and 1490.6 nm respectively. OC1 and OC2 are two optical circulators, where upon port 3 is connected to port 1 through couplers C1 and C2 respectively, used as reflectors at both ends of the linear cavity. The isolators (ISOs) protect the LDs from any reflected power. The 1% port of a 1/99 coupler C2 is employed to tap output power characterized by an optical spectrum analyzer (OSA) with a resolution 0.02 nm. This configuration allows production of the greatest number of Brillouin Stokes lines and minimal round trip loss.

After the BP is injected into the linear cavity via C1 and OC1, it is amplified by the EDFA and routed into the DCF. The first Brillouin Stokes signal is generated at this time if the BP power surpasses or equals the first Stokes threshold power. The first Brillouin Stokes signal, propagating in the opposite direction to the BP signal, is also amplified by the EDFA and re-circulated back into the DCF via OC1. This re-circulated signal acts as the BP to generate the second Brillouin Stokes signal and is later reflected from OC2 such that the signal completes a round trip oscillation. The second Stokes signal is generated when the first Brillouin Stokes power reaches the second Brillouin Stokes threshold power and this second Stokes signal also begins to oscillate in the cavity to generate a higher-order Brillouin Stokes signal under the same mechanism. The subsequently cascaded Brillouin Stokes signal can be generated as long as the total gain is equal to or larger than the cavity loss. The *N*th Stokes line is generated at the frequency $\omega_{\mathrm{NS}} = \omega_{\mathrm{BP}} - N\Omega_B$ where Ω_{B} is the Brillouin shift in the DCF.

3. Results and discussion

The amplified spontaneous emission (ASE) which is also called the free-running gain spectrum is obtained when the TLS power is set in the 'Off' state whereas the EDF pump and the Raman pump are set in the 'On' state. Figure 2 shows the wavelength region of the gain spectrum around 1590.6 nm with the linewidth 3.4 nm due to Raman gain region. The peak around 1560 nm is due to EDFA and it is suppressed completely by using the Bi-EDF. After the residual pump powers 13.6 mW and 64 mW of the EDFA and the Raman

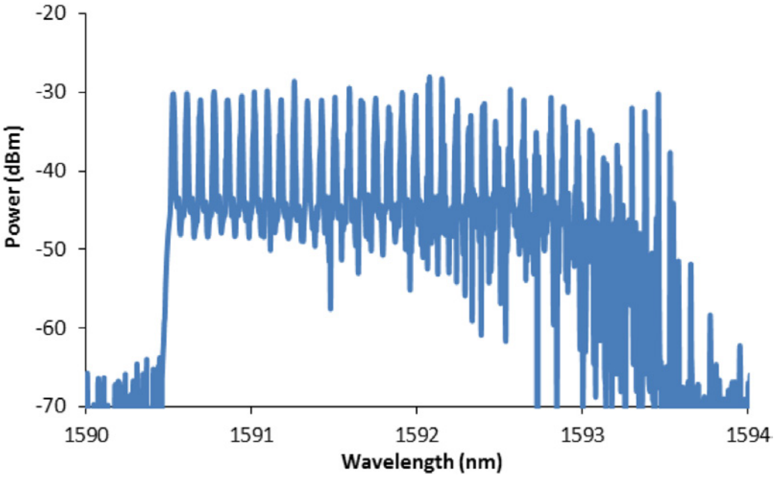

Figure 3. The generated MFL spectra having 38 Brillouin Stokes lines with a 0.08 nm line spacing via using the Bi-EDF, TLS pump power of 6.5 dBm, EDFA pump power of 44 mW and Raman pump power of 300 mW.

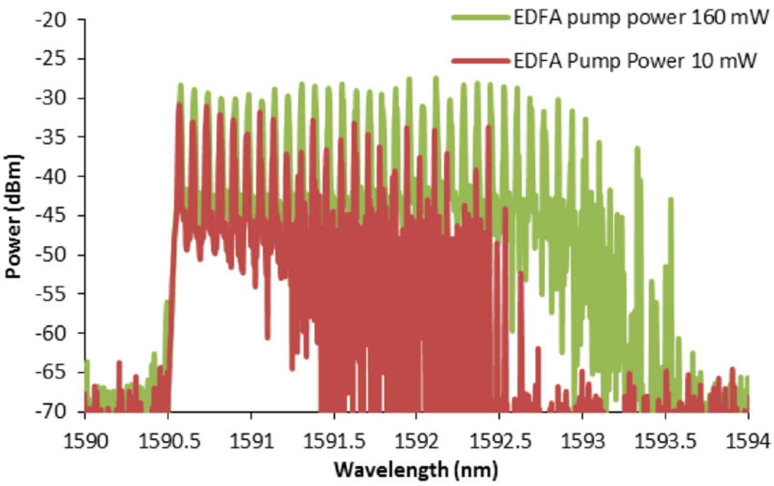

Figure 4. The effect of the pump power of the EDFA used in the BP on flatness and number of lines of the generated MFL in the output.

pump at wavelengths 978.8 nm and 1490.6 nm respectively, are injected into the inserted Bi-EDF, the gain spectrum is expanded so that its linewidth is increased to 12.3 nm. The self-lasing cavity modes oscillate around the peak gain in the gain region, whereupon the difference between total gain and cavity loss is maximal. Figure 2 also shows that both the residual Raman pump power at a wavelength 1490.6 nm and the EDFA gain around 1560 nm are suppressed in the output after inserting the Bi-EDF in the linear cavity. The L-band gain wavelength region between 1590 and 1605 nm is detected by injecting the residual Raman pump power at 1490.6 nm wavelength and the residual pump power of the EDF at the wavelength 978.8 nm into the 0.45 m long Bi-EDF. The residual Raman pump at the wavelength 1490.6 nm and the EDF gain around 1560 nm are eliminated by using the inserted Bi-EDF. The free-running region determines the operational wavelength of the MFL, so that the BP wavelength should be close to this free-running region in order to make use of the total gain. By emitting the BP as a seed signal near to the free-running wavelength region, a MFL can be generated by using a cascading stimulated Brillouin scattering process. A MBRFL with a few Brillouin Stokes lines is generated by using TLS power of 6.5 dBm at a wavelength 1590.6 nm, EDFA pump power 44 mW and 300 mW Raman pump power. However, after inserting the Bi-EDF following the DCF in the cavity and using the residual powers, 38 Brillouin Stokes lines are produced in the MFL, as demonstrated in figure 3. The power level of lines is about −30 dBm, which is the same as the free-running power level shown in figure 2. Fluctuation in the power levels of the lines is due to the mode competition in the Bi-EDF and an inhomogeneous broadening gain characteristic is demonstrated by inserting the Bi-EDF.

The BP power and residual EDFA pump power are boosted by increasing the EDFA pump power, such that the mode competition is suppressed efficiently and flatness of the MFL is improved as shown in figure 4. Stability of the MFL is also improved by increasing the EDFA pump power. Enhancing the EDFA pump power from 10 to 160 mW allows the number of lines in the generated MFL to increase from 20 to 32 and stability and flatness of the MFL is also improved. Using

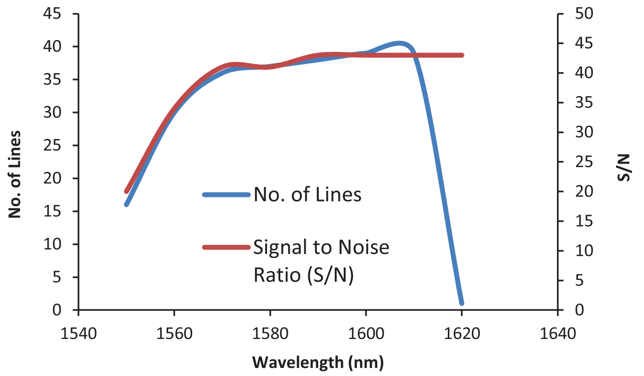

Figure 5. The number of lines and the signal to noise ratio obtained, against the BP wavelength. These two factors have maximal values when BP wavelength is in the free-running region.

160 mW EDFA pump power, the number of lines is lower than that obtained by using 44 mW EDFA pump power as shown in figure 3. This situation is explained by a significant increase in the quantum conversion efficiency (QCE) of the 978.8 nm and 1490 nm pumped Bi-EDFA when the EDFA pump power of 44 mW is used [33]. The QCE factor is defined as the ratio between the amplified signal photons and the total launched pump photons [33, 34]:

$$\mathrm{QCE} = \frac{\lambda_S\left(P_S^{\mathrm{out}} - P_S^{\mathrm{in}}\right)}{\lambda_{978.8}P_{978.8} + \lambda_{1490.6}P_{1490.6}} \tag{1}$$

where λ_s, $\lambda_{978.8}$ and $\lambda_{1490.6}$ are Brillouin seed signal, EDFA pump and Raman pump wavelengths, respectively. P_S^{out} and P_S^{in} are the output and input Brillouin signal power of the Bi-EDFA. $P_{978.8}$ and $P_{1490.6}$ represent EDFA pump and Raman pump power in the input of the Bi-EDFA respectively. Only a small amount of 978.8 nm pump power is required to reach the optimum QCE in the case where most of the Bi-EDFA power is supplied by 1490.6 nm pump power [34]. The QCE factor is calculated to be about 16% when the input and output signal powers at the wavelength 1590.6 nm are measured to be 38.72 μW and 10.85 mW, respectively and the residual powers 13.6 mW and 64 mW of the EDFA and the Raman pump respectively, are employed for pumping the inserted Bi-EDFA as used in the MFL generation in figure 3.

Impact of the BP wavelength on the number of lines and the signal to noise ratio in the MFL generation is also studied. Figure 5 shows that the MFL can be generated by using the BP wavelength between 1550 nm and 1610 nm, while the number of lines and the signal to noise ratio are increased when the BP wavelength is close to the free-running gain region determined at the output.

In summary, a MFL with 38 Stokes lines arises via inserting a 0.45 m long Bi-EDF in the linear cavity and satisfying several conditions: TLS power of 6.5 dBm, EDFA pump power of 44 mW and Raman pump power of 300 mW. The residual EDFA and Raman pump power 13.6 mW and 64 mW respectively, are used for pumping the Bi-EDF to generate a hybrid Raman/Bi-EDF amplifier. This work also suggests that a linewidth of the gain spectrum can be expanded effectively by inserting a Bi-EDF and using an EDFA pumped a few mW at a wavelength 980 nm when there is a Raman amplification in the wavelength region 1480–1490 nm.

4. Conclusions

A multi-wavelength fiber laser (MFL) source is generated via Brillouin seed signals and a compacted single-pump hybrid Raman/Bi-EDFA in a linear cavity. A Bi-EDF of only 0.45 m length is inserted in the setup. This causes the gain spectrum to be inhomogeneously broadened so that the linewidth of the gain spectrum is expanded from 3.4 to 12.3 nm. The Bi-EDF is pumped by the residual pump powers at the wavelengths 978.8 and 1490.6 nm and an L-band gain in the 1590–1605 nm wavelength region is prepared. A MFL possessing 32 Stokes lines is produced by using the EDFA pump power at 160 mW, the fixed TLS power of 6.5 dBm and the fixed Raman pump power of 300 mW. Decreasing the EDFA pump power to 44 mW causes an increase in the number of lines to 38. Such a result is due to an increase in the quantum coefficient efficiency, although the flatness and stability of the MFL are reduced due to mode competition in the Bi-EDF.

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