An enhanced S-band brillouin/erbium fiber laser with an additional EDFA in sub-loop

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Abstract: An enhanced short wavelength band brillouin erbium fiber laser (S-band BEFL) is demonstrated using an additional erbium-doped fiber amplifier (EDFA) in the sub-loop of the laser system. Compared with the conventional BEFL without the EDFA, the enhanced BEFL has improved the number of channels as well as the tuning range which are determined by the re-injected signal power. The incorporation of the EDFA also reduces the power difference between the first Stokes and the second Stokes from 17.2 dB in conventional BEFL to 3.8 dB in the proposed BEFL. A stable output laser comb with 8 channels was obtained with Brillouin pump of 5 mW and signal at 1502 nm. The BEFL has the potential to be used in the future dense wavelength division multiplexing communication system.

Keywords: S-band, optical fiber devices, brillouin scattering, BEFL, EDFA, optical fiber laser

Classification: Photonics devices, circuits, and systems

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1 Introduction

Dense wavelength division multiplexed (DWDM) system, which consists of a large number of wavelength sources spaced at 100 GHz, 50 GHz and lately 12.5 GHz is vital technology to increase the total information bit rate transmitted over long communication links [1]. Multi-wavelength source is an important component in this DWDM system. Brillouin/erbium-doped fiber laser (BEFL) is one of the possible approaches to reduce the cost of the optical sources and maintaining the inter-channels spacing [2, 3]. It utilizes both the nonlinear Brillouin gain in the single-mode fiber (SMF) and a linear gain in erbium-doped fiber (EDF) to generate multiple wavelengths operation with equal channel spacing. The BEFL based sources can be implemented by incorporating a demux unit and modulating it externally.

Most of the BEFL systems are focused in conventional band (C-band) and long wavelength band (L-band) due to the bandwidth limitation of an erbium-doped fiber amplifier (EDFA). Recently, a new S-band amplification technique, which utilises erbium-doped fiber with depressed cladding design and a 980 nm pump laser to generate EDF gain extension effect, has been reported [4]. In our previous work, a S-band BEFL was demonstrated using this S-band amplifier [5]. In this letter, an enhanced S-band BEFL is demonstrated by incorporating additional S-band EDFA in sub loop. The optimum balancing of cavity gain profile and Brillouin injection signal has effectively increased the number of Stokes in the new BEFL.

2 Configuration of the S-band BEFL

Fig. 1 shows the schematic diagram of the S-band BEFL with additional EDFA in sub loop. An optical circulator is used to inject Brillouin pump (BP) into the main cavity and to force unidirectional operation of the laser in the cavity. Two optical couplers (C1 and C2) are incorporated in the resonator and joined in a reverse S arrangement to act as looping arm in order to generate multiple stokes signal. A forward pumped EDF 2 is placed in the sub loop to increase the number of comb line. The length of SMF, EDF 1 and EDF 2 are fixed at 500 m, 15 m and 15 m, respectively. Both EDFs have a depressed cladding design and peak absorption of 7.6 dB/m in the 980 nm region. A 90/10 coupler is also included inside the cavity to extract the output.

A narrow linewidth laser from an external cavity tunable laser source (TLS) is used as a BP. The BP signal which closed to the peak gain of the free-running EDF laser is injected into the SMF through port 1 to port 2 of an optical circulator in the clockwise direction of the system. This signal will generate a nonlinear Brillouin gain in the counter-clockwise direction at a frequency shifted from the Brillouin pump by the Stokes shift in SMF. The Brillouin gain is then routed into the forward pumped EDF 1 through port 2 to port 3, to generate Stokes at a frequency of approximately 11 GHz away from the BP. A portion of the BEFL signal traveling in counter-clockwise direction is then amplified by EDFA2 in the sub loop and re-injected at the

Fig. 1. Configuration of the enhanced S-band BEFL

other end of the SMF in the clockwise direction to acts as a BP to generate additional frequencies. The output is measured and characterized by an optical spectrum analyzer (OSA) with a resolution of 0.015 nm. The BEFL performance is compared with the conventional BEFL [5], which is obtained by removing EDFA2.

3 Result and discussion

Fig. 2 shows the BEFL output comb against wavelength for the BEFLs with and without EDFA2. The BP power is fixed at 5 mW while 980 nm pump powers of P1 and P2 are fixed at optimum powers of 94 mW and 200 mW respectively. As shown in the figure, both spectra are located at different center wavelength due to the different in the total cavity loss between both systems. The first Stokes for the BEFLs with and without EDFA2 is obtained at wavelength of 1502.3 and 1502.7 nm, respectively. The simultaneous laser lines separated by 0.084 nm is also observed in the both BEFLs. The homogeneous nature of the EDF gain within the limited bandwidth enables the multi-line BEFL operation through the combination of travelling waves generated by EDF and Brillouin gain. Fig. 2 also shows that the incorporation of EDFA2 increases the number of Stokes from 4 to 5 lines. The number of Stokes increases due to the stronger feedback signal via sub-loop, which increase the spectral width of free-running EDF laser without the Brillouin pump. In both systems, 3 anti-Stokes lines are generated as depicted in Fig. 2, which is due to the four-wave mixing effect and bi-directional transmission in the SMF.

The optimum balancing of cavity gain profile and Brillouin injection signal plays an important role in achieving multiple wavelength generations to the higher order Stokes line over wide spectral width. Therefore, the incorporation of EDFA2 in the sub-loop, which increases the Brillouin injection signal power improves the balancing and resulted in higher number of Stokes

line. The power difference between the first and second Stokes for the enhanced BEFL is obtained at about 3.8 dB, and it is much lower than 17.2 dB obtained for the conventional BEFL without EDFA2. This is observed due to the BP power being almost similar to the re-injected power in the enhanced BEFL. Without EDFA2, generated Stokes lines are not strong enough to suppress the ASE, ceasing the generation of the higher order Stokes line. The number of lines generated in the proposed BEFL system is limited to 8 lines because of the resonator configuration and the available pump power. This is not an intrinsic limitation, and more available pump power and a lower loss resonator will increase the number of lines.

Fig. 2. BEFL output comb against wavelength.

Figs. 3 (a) and (b) show the tuning range of the BEFLs with and without EDFAs, respectively for the first few Stokes and anti-Stokes. Tuning range of a BEFL is determined by how far the wavelength can be tuned without obvious variation of Stoke's peak power. In the experiment, the pump powers of BP, EDFA1 and EDFA2 are fixed at 5 mW, 94 mW and 200 mW respectively. BP wavelength was tuned over the spectral range of the free running EDF laser gain region and output power for various lines are measured. As shown in both Figs. 3 (a) and (b), the tuning range is better in the enhanced BEFL compared with in the conventional BEFL with the tuning range for the first Stokes usually is larger than other Stokes. This is due to when the wavelength is fall off the gain region of EDF laser, only the 1st Stokes can be generated and the other Stokes will experience insufficient gain to lase and terminate the process of multiple Stokes generation. For instance, the tuning range of the first Brillouin Stokes increases from 1 nm to 1.8 nm as depicted in Fig. 3. The broad tuning range allows a robust operation of the BEFL as the BP does not need to be accurately wavelength matched, provided that

it generates sufficient Brillouin gain. From these results, the BEFL with additional EDFA in the sub-loop is expected to play an important role in development a practical BEFL with a large number of Stokes line and broader tuning range. This BEFL has the potential to be used in the future DWDM communication system.

(a) with EDFA2

(b) without EDFA2

Fig. 3. Tuning range for the BEFLs for several Stokes and anti-Stokes (a) with EDFA2 (b) without EDFA2. Minus symbols indicate anti-Stokes.

4 Conclusion

An enhanced S-band BEFL is obtained with additional EDFA2 at the sub-loop of the laser system. Compared with the conventional S-band BEFL without the additional EDFA, this BEFL has improved the power difference between the first Stokes and the second Stokes from 17.2 dB to 3.8 dB. The enhanced BEFL system also increases the number of channels as well as the tuning range by increasing the re-injected signal power. A stable output laser comb with 8 channels was obtained with Brillouin Pump of 5 mW and BP signal at 1502 nm. The BEFL has constant spacing of 0.084 nm or 11.1 GHz which has a potential application in DWDM system.