Optical Fiber Technology 41 (2018) 21–26

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte

Widely tunable multiwavelength Brillouin-erbium fiber laser with triple Brillouin-shift wavelength spacing

M.H. Al-Mansoori[a,*], A. Al-Sheriyani[a], M.A.A. Younis[a], M.A. Mahdi[b]

[a] Electrical and Computer Engineering, Faculty of Engineering, Sohar University, Sohar, PO Box 44, PC 311, Oman
[b] Wireless and Photonic Networks Research Centre, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

ARTICLE INFO

Keywords:
Multiwavelength fiber laser
nonlinear stimulated Brillouin scattering
Brillouin fiber laser
Laser tunability

ABSTRACT

In this paper, we demonstrate a widely tunable multiwavelength Brillouin-erbium fiber laser (MBEFL) having a wavelength spacing of 0.25 nm (triple Brillouin-shift wavelength spacing). The proposed laser structure overcomes the need for Brillouin pump wavelength to be closed to the self-lasing cavity modes region. The laser exhibits a wide tuning range of 40 nm (from 1530 nm to 1570 nm) at Brillouin pump and 980 nm pump powers of 25 mW and 350 mW, respectively. Four stable output channels are produced within this wavelength range with all the channels having a peak output power greater than 1.58 mW. The laser has the potential to be used as a multiwavelength laser source for dense wavelength division multiplexing communication.

1. Introduction

Multiwavelength laser sources have attracted great attention owing to their various applications in optical communication systems such as wavelength division multiplexing (WDM) systems, microwave and millimeter wave generation, microwave photonic filter and fiber sensors [1–7]. Different techniques were demonstrated to generate multiwavelength fiber laser sources by utilizing the nonlinear effect of optical fibers, such as four-wave mixing [8], stimulated Brillouin scattering (SBS) [9], and stimulated Brillouin-Raman scattering [10]. However, the efficiency and capacity of lasers based on only the use of the nonlinear effect of optical fibers are relatively low. Therefore, to improve the laser performance, another rare-earth gain medium, such as erbium-doped fiber amplifier (EDFA), was integrated with the Brillouin effect in the same laser cavity [11–12]. The so-called multiwavelength Brillouin-erbium fiber laser (MBEFL) has several advantages such as low threshold power, large gain, and narrow linewidth characteristics [13–17].

Although the efficiency and capacity of the laser were improved by this integration, the output wavelength suffers from a limitation in the tunability and power instability owing to laser mode competitions and a narrow wavelength spacing of ~11 GHz (~0.08 nm), which limits the real use of the laser in communication systems. Various efforts were made to extend the tuning range and stabilize the laser using polarization-maintaining fiber Sagnac loop filters [18], high external Brillouin pump (BP) powers [19], tunable band pass filters [20–21], BP preamplification techniques [22–24], virtual mirrors [25], and a passive EDF absorber section [26]. However, for narrow line spacing, much effort has been made to expand the spacing between the laser lines to ~20 GHz [27–30]. In the earlier work [27], an MBEFL with wavelength spacing of 10 GHz and 20 GHz is reported. Only six laser lines were generated with a variation of the output power between the spectral lines. The number of 20 GHz laser lines was improved to 10 using a four-port circulator in [28] with a tuning range of only 9 nm. In another work [29], a double-frequency shifter was used to demonstrate an MBEFL with up to fifteen laser lines, a wavelength spacing of 0.173 nm and a tuning range of 10 nm from 1552 to 1562 nm. An effort was made to enhance the generation of double-spaced multiwavelength Brillouin fiber laser using four wave mixing and a tunable optical bandpass filter as demonstrated in [30]. The laser can generate up to eighteen Stokes lines at input signal power of 190 mW. In a more recent work, two ring cavities were used to generate MBEFL with switchable wavelength spacing by toggling an optical switch [31]. The laser can generate up to five laser lines with double spacing of 0.178 nm and a tuning range of 15 nm. Although extensive experiments were conducted on MBEFL development to improve the laser output lines and tunability and expand the spacing between the laser lines from 10 GHz to 20 GHz, the majority had a channel spacing of either 10 GHz or 20 GHz.

Thus far, few works were reported on MBEFLs with triple (~33 GHz) Brillouin wavelength spacing [32–36]. A MBEFL with tunable wavelength and switchable frequency with only two Stokes lines with triple Brillouin wavelength spacing was reported in [32]. Three cascaded sections of single mode fiber (SMF) were utilized to generate MBEFL with triple wavelength spacing. The tuning range of Stokes

* Corresponding author.
E-mail address: mmansoori@soharuni.edu.om (M.H. Al-Mansoori).

https://doi.org/10.1016/j.yofte.2017.12.012
Received 7 October 2017; Received in revised form 11 December 2017; Accepted 17 December 2017

signals was 22 nm only with peak power below −3.5 dBm. In addition, the peak laser difference between the third- and second-order Stokes lines was around 25 dB. A long SMF length of 50 km has been recently utilized in two ring laser cavities to generate MBEFL with triple Brillouin wavelength spacing [33]. Up to ten laser lines having low output power (below −4 dBm) were produced using high 980 pump power of 600 mW. However, at 1525.5 nm only three triple Brillouin frequency Stokes signals were produced with the self-lasing cavity modes observed at the laser cavity peak gain around 1559 nm. Therefore, the tuning range of Stokes signals without self-lasing cavity modes was only limited to 35 nm only. Moreover, the peak laser difference between the third- and second-order Stokes lines was only 18 dB. Another method of utilizing cascaded SMFs in a ring cavity to produce switchable multi-wavelength laser output was reported in [34]. The feature of switchable frequency spacing was achieved by adding or removing the SMF sections manually. A long cascaded SMF length of 70 km with two EDFAs having two high pump powers were used to produce three Stokes lines with triple wavelength spacing. However, the use of three lengths of SMF as the Brillouin gain medium to realize triple-spaced Brillouin Stokes lines make the laser source relatively large and limit the potential applications of the laser. In order to mitigate the drawbacks from previous laser structures, we have proposed a structure that able to produce six triple-spaced Stokes lines with more than 27 dB peak power difference between neighboring lines [35]. However, for the proposed structure, the inclusion of EDFA to amplify the third-order Stokes line limits its tunability characteristic to 19 nm wavelength range only.

In recent work, a MBEFL with switchable frequency spacing by using a modular structure and the generation of beating frequency microwave signals have been reported [36]. Nine output lines with triple wavelength spacing of 0.259 nm at BP wavelength of 1565 nm were generated using two erbium-ytterbium-doped fiber amplifiers with high power of 29.5 dBm and 28 dBm, respectively. However, when the BP wavelength was tuned away from 1565 nm the number of output lines reduced. At 1550 nm BP wavelength, only three Stokes lines were generated and free-running cavity modes were observed around 1565 nm. In this case, the proposed setup was not able to suppress these unwanted modes which limited its tuning range. In addition, the peak power of Stokes lines was below −15 dBm and the peak laser difference between the third- and second-order Stokes lines was around 20 dB. Therefore, in all proposed structures of MBEFL with triple Brillouin wavelength spacing [32–36], the mode competition limits the laser tuning range and impacts the power stability of the Stokes signals.

In this paper, a widely tunable MBEFL with a wavelength spacing of 0.25 nm (33 GHz) is proposed and experimentally demonstrated. We overcome the need for BP wavelength to be matched with the self-lasing cavity modes region by putting the EDFA outside the lasing cavity. Therefore, the BP wavelength can be placed at any wavelengths within the EDFA gain bandwidth. Four output channels are produced and can be broadly tuned in the range of 40 nm (limited by the EDFA gain profile) in the C-band region without appearance of free-running cavity modes. The proposed laser structure does not use any filtering techniques to tune the output channels and eliminate the laser cavity modes. The laser lines exhibit a wide tunability, high peak power, and high optical signal to noise ratios (OSNRs). The developed laser structure has enhancement in wavelength tuning, OSNRs, channels peak output power, peak power difference between the 33 GHz and 22 GHz Stokes signals than previously reported works [32–36].

2. Experimental setup and operating principles

The experimental setup of the proposed laser structure is shown in Fig. 1. The laser structure consists of three-port broadband optical circulator, four-port broadband optical circulator, four-port optical coupler having a splitting ratio of 50/50, SMF with a length of 10 km, dispersion-compensating fiber (DCF) with a length of 12 km, optical isolator (ISO), and EDFA gain block.

The EDFA gain block is comprised of an erbium-doped fiber (EDF) with a length of 3 m, pump laser with a wavelength of 980 nm, and WDM coupler. The WDM coupler is used to multiplex the pump power at 980 nm wavelength and the C-band signals. The Brillouin gains are provided by the SMF and the DCF. The DCF is chosen because of the fact that the effective core area is smaller than SMF, Rayleigh back scattering coefficient of the DCF is higher than that of a standard SMF and the nonlinear coefficient of DCF is five times higher than that on standard SMFs [37]. The ISO is used to remove any back reflection lights that perturb the laser operation. A tunable laser source with power of 25 mW is used to provide the BP signal. The BP signal is forwarded into the laser cavity through port 3 of the 3-dB optical coupler. After the 3-dB coupler, the BP signal propagates to the Brillouin gain medium (DCF) through the three-port optical circulator. In the DCF, the 1st Stokes signal shifted 11 GHz (~0.08 nm) down from the original BP signal is initiated when the Brillouin threshold of the DCF is achieved. The 1st Brillouin Stokes line (BS1) propagates in the reverse direction to the EDFA through port 3 of the three-port circulator.

Then the Stokes signal accumulates more energy through optical amplification in the EDFA. Afterwards, it passes the SMF through port 1 and port 2 of the four-port circulator (CIR). In the SMF, the second Brillouin Stokes signal (BS2) with a spacing of 0.17 nm (22 GHz) will be produced when the 1st Brillouin Stokes signal power exceeds the Brillouin threshold of SMF. Then, the generated 22-GHz-shifted Brillouin Stokes signal propagates in the opposite direction through port 2 and port 3 of the CIR to another end of the DCF. In the DCF, once the 0.17 nm-shifted signal power reaches the Brillouin threshold conditions, it experiences another 11 GHz shift (in the opposite direction) that generates a Stokes signal (BS3) with 33 GHz shifted from the original signal (BP). The 33-GHz-shifted signal propagates from port 3 to port 4 of the CIR and travels to the 3-dB coupler. The laser output is recorded through output port (port 4) of the 3-dB optical coupler using an optical spectrum analyzer (OSA) with a resolution of 0.02 nm (fixed throughout the experiment). In the same way, the process of high-order Stokes signal generation continues until the higher-order Brillouin Stokes line falls below the Brillouin threshold condition in the gain medium.

3. Results and discussion

The threshold power of the MBEFL with a wavelength spacing of 0.25 nm was investigated first. The threshold power was measured by fixing the BP power at its maximum value (25 mW) and wavelength of 1550 nm. Then, the 980 nm pump power was varied until the Stokes signal generated. The evolution of the first and second Brillouin Stokes signals with a channel spacing of 0.25 nm is depicted in Fig. 2.

Referring to Fig. 2(a), the threshold power of the first 0.25 nm Brillouin Stokes signal was 50 mW. As the pump power was increased further, the peak power of the first 0.25 nm Brillouin Stokes signal increased, which leads to the generation of the second 0.25 nm channel that could clearly be seen at a pump power of 160 mW. Fig. 2(b) shows the output spectrum of the first and second Stokes signals with a spacing of 0.25 nm at a pump power of 160 mW.

To generate higher-order Stokes signals, the 980 nm pump power of the EDFA was increased. The third 0.25 nm Brillouin Stokes signal was produced when the 980 nm pump power was pushed to 280 mW. Fig. 3 shows the output spectrum of the laser at a pump power of 350 mW. Four output channels were generated with peak powers greater than 1.6 mW and the OSNRs were measured to be larger than 45 dB. Since the maximum available 980 nm pump power was limited to 370 mW, the amount of the power injected into the laser cavity was insufficient to saturate the third 33 GHz Stokes signal, and consecutively the fourth 33 GHz Stokes signal could not be oscillated as depicted in Fig. 3.

Fig. 4 depicts the change in the threshold power (the 980 nm pump) at different BP powers and different wavelengths. When the BP power