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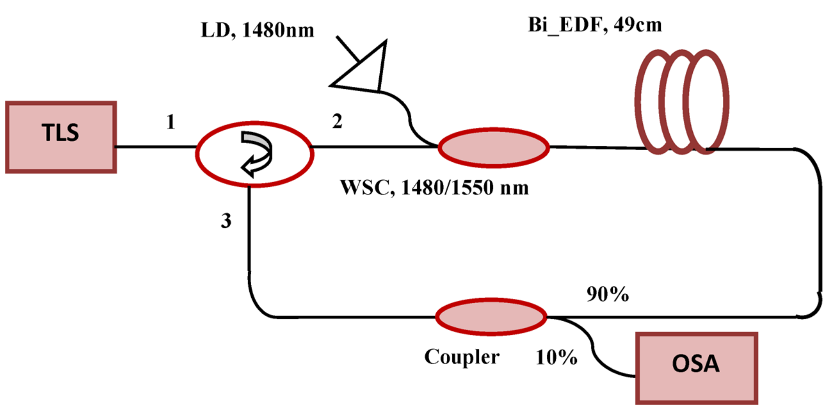

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Compact Bi-EDF-Based Brillouin Erbium Fiber Laser Operating at the 1560-nm Region

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Abstract: A single-frequency Brillouin erbium fiber laser (BEFL) is demonstrated operating at the 1560-nm region using a simple ring resonator with a very short piece of bismuth-based erbium-doped fiber (Bi-EDF) for the first time. A 49-cm-long Bi-EDF is used to provide both nonlinear gain and linear gain to generate a stimulated Brillouin scattering (SBS) and to amplify the generated SBS, respectively. The BEFL operates at 1559.49 nm with a peak power of −4 dBm and a side-mode suppression ratio of 14 dB when the Brillouin pump (BP) and 1480-nm pump powers are fixed at 6 dBm and 144 mW, respectively. The BP wavelength is also tunable within a wavelength range from 1558.8 to 1560.0 nm.

Index Terms: Bismuth-based erbium-doped fiber, brillouin fiber laser, stimulated Brillouin scattering, ring cavity.

1. Introduction

Stimulated Brillouin scattering (SBS) is a nonlinear process in fiber optics that occurs due to the interaction of light with acoustic waves or vibration phonons. Most efficient Brillouin scattering manifested in a backward-propagating narrow-linewidth Stokes wave with its frequency downshifted from that of the incident light [1]. This unique phenomenon has attracted significant interest for decades to the study of the narrow-linewidth (single-wavelength and multiwavelength) fiber laser sources [2], [3]. The Brillouin fiber laser (BFL) is generated by the SBS and has many potential applications in instrument testing and sensing, as well as an optical source for dense wavelength division multiplexing (DWDM) systems [4]. The BFL device is desirable to use a gain medium with a large Brillouin gain coefficient to lower the power requirements and to shorten the length of the device [5]–[7]. In a Brillouin erbium fiber laser (BEFL), an erbium gain medium is incorporated in the BFL setup to generate amplified spontaneous emission as well as to assist in the Brillouin Stokes generation.

Recently, the advance in optical fiber fabrication technology has resulted in the production of bismuth-based erbium-doped fiber (Bi-EDF) with an erbium ion concentration of more than 3000 ppm [8]. This fiber acts as an effective gain medium for realizing the compact optical amplifier. Another striking feature of the Bi-EDF is its ultrahigh nonlinear coefficient, which is 100 times larger than that of silica-based highly nonlinear fiber (HNLF) [9]. Therefore, it can offer strong nonlinear effect in a relatively very short length ($\sim$0.5 m) of fiber for realizing a compact BFL or BEFL. To date, many works have been reported on compact BFLs using a reduced length of nonlinear fiber [10]. In our earlier work, a compact BEFL has been demonstrated using a 215-cm-long Bi-EDF as the gain

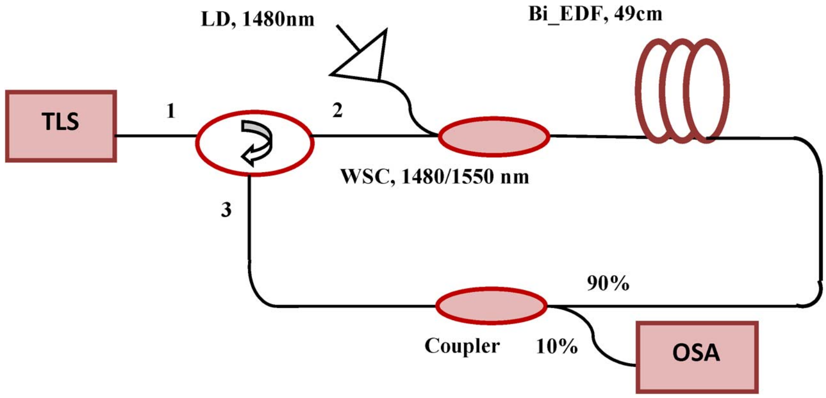

Fig. 1. Configuration of ring-cavity-based Bi-EDF.

medium [11]. In this paper, a BEFL is demonstrated using a further reduced length of Bi-EDF (49 cm) as the gain medium. The BEFL uses an almost similar setup with the previous work but with a proper optimization of the cavity loss and output coupler ratio. This is the first demonstration of the BEFL with such a very short length of gain medium. Although the maximum peak power obtained is just approximately −4 dBm, the BFL has a very narrow linewidth and low relative intensity noise (RIN), and therefore, it is useful for many applications [12].

2. Experimental Setup

Fig. 1 illustrates the architecture of the proposed BEFL, which consists of an optical circulator, output coupler and Bi-EDF in a ring configuration. The Brillouin gain medium is provided by a piece of 49-cm-long Bi-EDF with effective area of 29.4 μm^2, nonlinear coefficient of 60 $(\text{Wkm})^{-1}$, erbium concentration of 3,200 ppm, cutoff wavelength of 1440 nm, and a pump absorption rate of 130 dB/m at 1480 nm. The Bi-EDF is pumped by a 1480-nm laser diode to also provide amplification in C-band region from 1525 to 1570 nm so that it can amplify the SBS Stokes. The circulator used in this ring cavity laser system acted also as an isolator to direct the propagation of Brillouin–Stokes into a counterclockwise direction. The measured results were extracted from the laser system by using 90/10 coupler where 10% power is used for monitoring and measurement purpose while the 90% power is circulated back into the laser cavity. An external tunable laser source (TLS) with a linewidth of approximately 20 MHz is used as a Brillouin pump (BP) that can be tuned from 1520 nm to 1620 nm with maximum power of 6 dBm. The 1480-nm pump is injected into the Bi-EDF via the 1480/1550-nm wavelength selective coupler (WSC). An optical spectrum analyzer (OSA) with a resolution of 0.015 nm is used for all measurement and observation in the experiment. Compared with the ring configuration in our previous work [11], optical isolator is removed and output coupler ratio is changed in this setup to reduce the cavity loss so that the SBS can be achieved in a very short piece of Bi-EDF.

3. Result and Discussion

Fig. 2 shows the output spectrum of the BEFL at various 1480-nm pump powers. In the experiment, the BP power and wavelength is fixed at 6 dBm and 1559.40 nm, respectively. As shown in the figure, the BEFL operates at 1559.49 nm, which is 0.09 nm shifted from the BP wavelength at the maximum 1480-nm pump power of 144 mW. The 0.09-nm difference between the wavelengths of the BEFL and BP is the Brillouin frequency shift of the Bi-EDF. The operating wavelength of the BEFL is determined by the Bi-EDF gain and cavity loss in the ring, and therefore, the BP wavelength should be adjusted to match the peaks of the free-running Bi-EDF laser. The inset of Fig. 2 illustrates a free-running Bi-EDF laser (without the BP) spectrum of the BEFL system which shows multiple peaks at 1559-nm region. The multiple peaks are obtained due to the mode competition in the Bi-EDF, which has an inhomogeneous broadening gain characteristic. Due to the small Brillouin gain, the

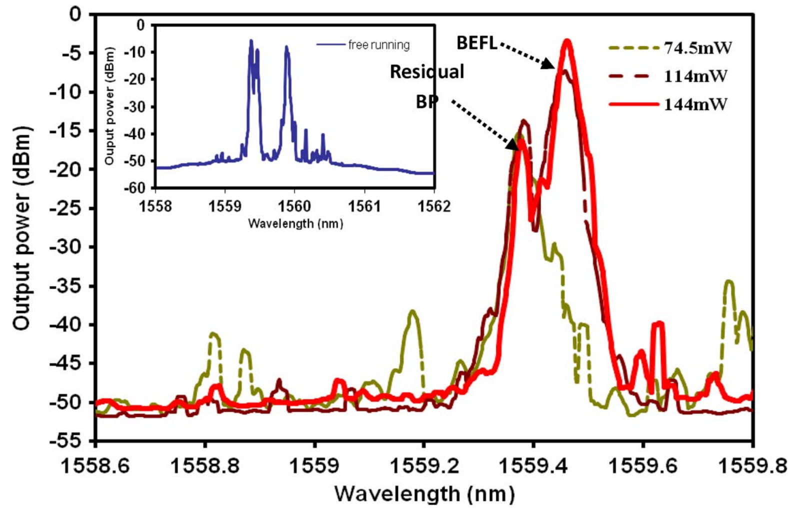

Fig. 2. Brillouin spectra at 1559.4 nm and free-running spectrum of Bi-EDFA.

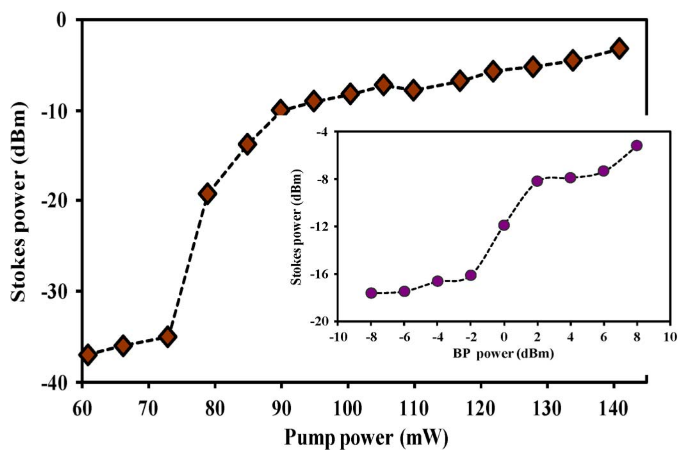

Fig. 3. Brillouin Stokes power against the pump power. Inset shows the Stokes power against the BP power.

wavelength of operation of the BEFL must be close to the peak of Bi-EDF free-running laser. Therefore, the BP signal is launched at this wavelength region to make use the Bi-EDF gain. The 3-dB bandwidth of the BEFL is measured to be approximately 0.02 nm limited by the OSA resolution. At the maximum 1480-nm pump power, the side-mode suppression ratio (SMSR) is obtained at approximately 14 dB. In this work, the SMSR is defined as the power difference between the BEFL's peak and the second highest peak, which is the residual backscattered BP signal. The SMSR reduces with the reduction of the 1480-nm pump power as shown in Fig. 2.

Fig. 3 shows the Stokes power against the 1480-nm pump power. As shown in the figure, the 1480-nm pump power threshold is approximately within 80 to 90 mW. Below this pump power, the amplifier gain is very low and cannot sufficiently compensate for the loss inside the laser cavity, and thus, no Stokes is observed. After the threshold power, the Stokes power is observed to linearly increase with the 1480-nm pump power. Compared with the earlier report which uses 215-cm Bi-EDF to generate BEFL [11], this BFL has a lower threshold power. This is attributed to a lower cavity loss in this setup, which is obtained by removing an optical isolator and optimization of the output coupler by allowing more power to oscillate in the ring cavity. Inset of Fig. 3 shows the curve of Stokes power against BP power. The BP power threshold is approximately within 0 to 2 dBm. Below this pump

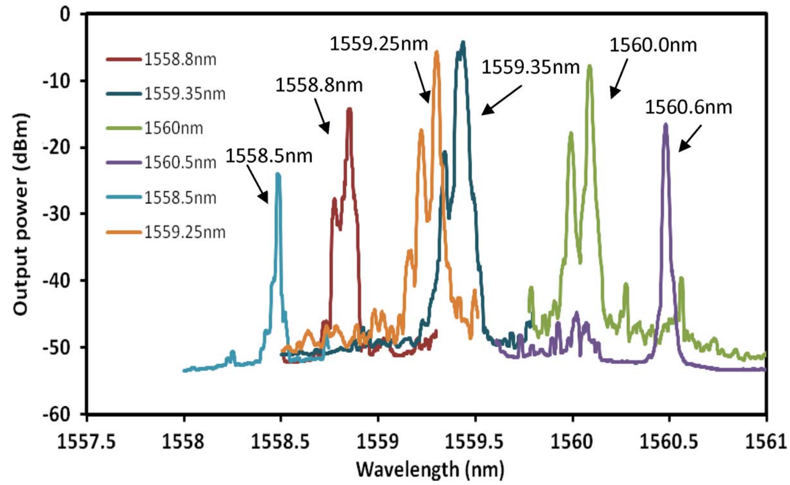

Fig. 4. Output spectrum of the BEFL at various BP wavelengths.

power, the Brillouin gain is very small and cannot support the SBS process in the cavity. The use of optical circulator in the ring cavity allows the unidirectional operation of the BEFL. This suppresses the four-wave mixing process in the cavity and therefore no anti-Stokes is observed.

Fig. 4 shows the output spectrum of the BEFL at various BP wavelengths. In this experiment, the BP and 1480-nm pump power are fixed at 6 dBm and 144 mW, respectively. As shown in the figure, the BP can be tuned from 1558.8 nm to 1560.0 nm and the maximum power of the generated BEFL is approximately −4 dBm. As the BP scans across the spectrum, different spectral shape results from SBS interaction with some peaks more distinct than other at different locations of the spectrum. This is attributed to the amplification characteristic of the Bi-EDF as well as the cavity loss, which determine the optimum operating wavelength of the BEFL. The tuning range is smaller compared to our previous work [11] due to the use of a shorter gain medium (Bi-EDF), which resulted in a smaller Brillouin gain. The increase of BP power is expected to increase the tuning range. The proposed BEFL operates at 1560 nm as opposed to 1613 nm in the previous report [11]. This is attributed to the peak wavelengths of the Bi-EDF lasers, which depends on the length of the Bi-EDF used as well as the emission characteristics of the erbium ion. The operating wavelength can be slightly tuned within the width of the free-running Bi-EDF laser by varying the BP wavelength. The further reduction of the Bi-EDF section will reduce the erbium gain and prevents the BEFL generation due to the emission cross section of the Bi-EDF peaks at 1530 nm. The single-wavelength BEFL is expected to have a very narrow linewidth as well as low RIN and frequency noises, which makes it suitable for sensing application.

4. Conclusion

A single wavelength BEFL is successfully demonstrated using only a 49-cm Bi-EDF as a gain medium. The BEFL is achieved by reducing and optimization of the cavity loss in the ring configuration. At the BP power of 6 dBm and 1480-nm pump power of 144 mW, the BEFL operates at 155.49 nm, which is upshifted by 0.09 nm from the BP with a peak power of approximately −4 dBm and an SMSR of 14 dB. The BP wavelength is also tunable within a wavelength range from 1558.8 nm to 1560.0 nm. The generated BEFL has a narrow linewidth, as well as low RIN and frequency noises, which makes it suitable for sensing applications.

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