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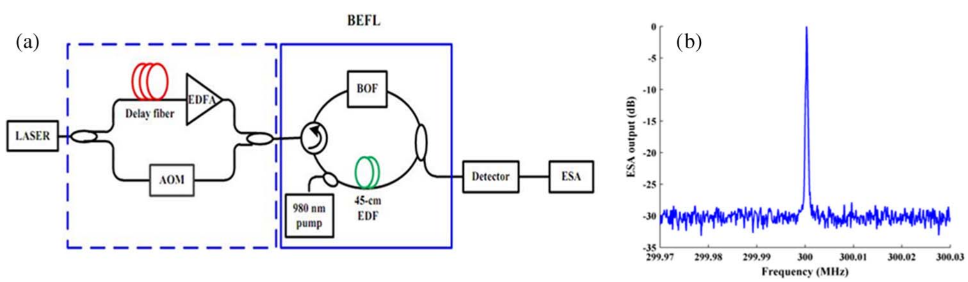

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Ultranarrow-Linewidth Brillouin/Erbium Fiber Laser Based on 45-cm Erbium-Doped Fiber

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Abstract: We demonstrate an ultranarrow-linewidth Brillouin/erbium fiber laser (BEFL), in which 45-cm commercialized erbium-doped fiber (EDF) acts as both the Brillouin and linear gain media. The Brillouin pump threshold of the BEFL is in submilliwatts. Its 980-nm pump threshold is only 15 mW. The BEFL presents an ultranarrow linewidth of 40 Hz. This single-frequency BEFL presents a number of applications in many high-coherence fields.

Index Terms: Ultranarrow linewidth, Brillouin/Erbium fiber laser, stimulated Brillouin scattering.

1. Introduction

Stimulated Brillouin scattering (SBS), the dominant nonlinear process in optical fibers, has drawn much research attention for decades [1]. It has been widely used in many applications like narrowband optical amplification, distributed Brillouin optical fiber sensing, and so forth [2], [3]. One of the most significant applications is narrow-linewidth laser emission. The first Brillouin fiber laser (BFL) was reported in 1976 [4]. It can emit linewidth at Hertz and even sub-Hertz magnitude theoretically [5], [6]. Experiments demonstrated that the BFL presented an intrinsic linewidth of 30 Hz [7], [8]. Unfortunately, they required critically pump coupled resonators or very high pump threshold powers [7]–[9]. Brillouin/Erbium fiber lasers (BEFLs) overcome these critical requirements by using an intra-cavity erbium-doped fiber amplifier (EDFA) to compensate for the cavity losses [10]. Long single-mode fibers ($>$100 m) are required to provide sufficient Brillouin gain since the Brillouin gain coefficient of these fibers is weak ($\sim 2 \times 10^{-11}$ m/W) [11]. But the lasing mode of the BEFL hops frequently in the long cavity. It is desirable to use short gain medium to reduce the cavity length for single-frequency operation. Some short-cavity BEFLs with high-nonlinearity fibers were studied [12]. A length of 49 cm Bismuth-based erbium-doped fiber (Bi-EDF) was used as both the Brillouin gain and the linear gain media for a

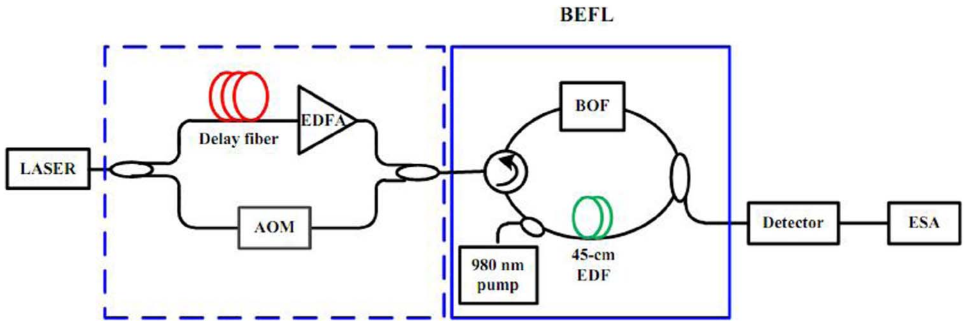

Fig 1. Experimental setup.

compact BEFL [13]. Nevertheless, the pump power requirement was high (> several hundreds of milliwatts or even more) and the output power was limited due to the severe fiber attenuation. It is desirable to use all commercialized standard fiber [14].

Recently, a novel compact BEFL has been proposed and studied, which uses 4 m commercialized erbium-doped fiber (EDF) as both the Brillouin gain and the linear gain media [15]. It presents low threshold, low phase noise, and stable fast-tuning output [16], [17]. In this paper, we further shorten the EDF to only 45 cm. The characteristics of this BEFL are studied in detail, including the optical spectrum, the longitudinal mode, the output power characteristics, and the laser linewidth. Particularly, we theoretically study the Brillouin pump (BP) threshold of a short length of EDF, and we derive an analytical relation for the BP threshold of the compact BEFL for the first time, to the best of the authors' knowing.

2. Experimental Setup

The configuration of the proposed BEFL is depicted as shown in the solid rectangular in Fig. 1. A 1550-nm laser source (~20 MHz) provides the BP for the BEFL through an optical circulator. A length of 45 cm commercialized EDF (CorActive), pumped by a 980 nm laser diode through a 1550 nm/980 nm wavelength-division multiplexer (WDM), acts as both the Brillouin and linear gain media in the laser. The BP excites SBS in the EDF and provides the Brillouin gain for the Brillouin Stokes. The 980 nm pump generates the linear gain in the EDF, which compensates for the round-trip optical losses and eases the difficulty for SBS excitation. A 1550-nm bandpass (~0.3 nm) optical filter (BOF) suppresses the amplified spontaneous emission (ASE) outside its passband and ensures the operation wavelength of the BEFL near the Brillouin Stokes wavelength. The BEFL output is extracted out by a 20/80 optical fiber coupler. This output coupling ratio is optimized so that considerable BEFL power is generated with the short gain medium.

The BEFL linewidth is measured by heterodyne beat technique. The laser source is split into two beams through a 3-dB coupler and generates two uncorrelated light with different frequencies, as in the dashed rectangular. One beam is 300 MHz frequency shifted by an acousto-opto modulator (AOM). The other one is delayed through a coil of 50 km fiber. An EDFA is adopted after the delay fiber to compensate for the severe light attenuation due to the long-haul fiber. The two beams are recombined through another coupler and injected into the BEFL. The two beams are uncorrelated with 300 MHz frequency discrepancy. They generate two Brillouin Stokes light in the BEFL and the two Brillouin Stokes beat with each other in the output coupler. The beat notes are received by the photo-electric detector and analyzed by an electrical spectrum analyzer (ESA).

3. Experimental Results and Discussions

We measured the optical spectrum of the BEFL with an optical spectrum analyzer (OSA). The measured results are shown in Fig. 2(a), when the BP power is 1 mW. The spectrum consists of only BP-induced Rayleigh scattering at 8 mW 980 nm pump power since the 980 nm pump power is below the threshold. With the increase of the 980 nm pump power, the accurately

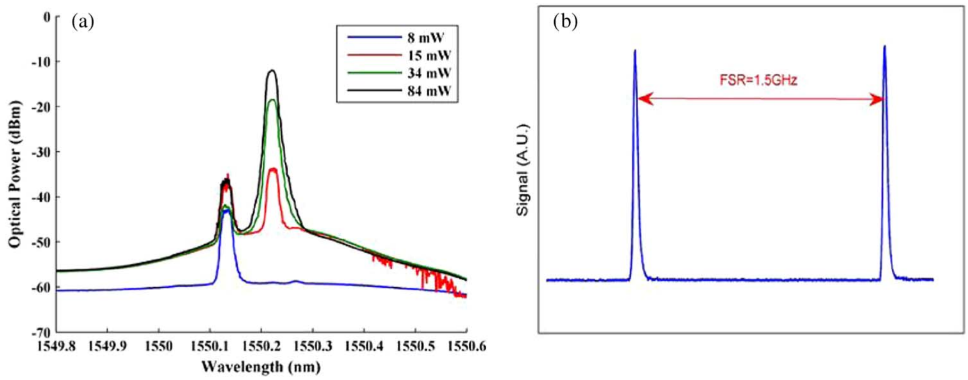

Fig. 2. (a) Optical spectra of the BEFL. (b) Single-mode operation of the BEFL.

Brillouin-frequency-downshifted BEFL is gradually excited. The wavelength difference between the BEFL and the BP is about 0.089 nm, corresponding to the Brillouin frequency shift of the EDF [18]. The longitudinal mode of the BEFL was measured by a scanning Fabry–Pérot interferometer ($\sim$1.5 GHz free spectrum range), as shown in Fig. 2(b). The BEFL is single-mode. No mode hopping was observed during the measurement. The free spectrum range of the BEFL cavity is about 100 MHz, much broader than the width of the Brillouin gain spectrum. Hence, only one longitudinal mode is allowed in the Brillouin gain spectrum, and no mode hopping occurs without severe environmental perturbations.

The output optical powers of the BEFL against the BP powers were measured and shown in Fig. 3(a). The BEFL output power decreases linearly with the BP power. It vanishes when the BP power exceeds a certain value, for example, about 2 mW in the situation with 33 mW 980 nm pump power. This phenomenon resulted from the EDF gain depletion by the BP [15]. The BEFL output powers against the 980 nm pump powers were shown in Fig. 3(b). The BEFL was measured with different BP powers ranging from 0.37 mW to 10 mW, respectively. The 980 nm pump threshold is only about 15 mW with 0.37 mW BP. The low 980 nm pump threshold is caused by the low round-trip losses of the BEFL cavity. The BEFL power increases linearly with the 980 nm pump power above the threshold. It reaches about 6 mW at 0.37 mW BP power and 383 mW 980 nm pump power.

The characteristic of the BEFL power against the 980 nm pump power is similar to that of the free running erbium-doped fiber laser (i.e., when BP power is zero) as the yellow curve with crosses in Fig. 3(b) shows. The BEFL power is dominantly transferred from the 980 nm pump power. The function of the BP is to excite SBS in the EDF. The increase of BP power not only decreases the BEFL power but also increases the 980 nm pump threshold. Therefore, a BP with high power is unnecessary in this kind of BEFL, especially when the gain medium is very short. On the other hand, this BEFL operates stably with 0.37 mW BP, demonstrating that the BP threshold is no more than 0.37 mW. Sub-milliwatt BP power is sufficient to excite SBS in the compact BEFL even when the hybrid gain medium is reduced to only 45 cm.

Compared with the previous compact BEFL using short Bi-EDF, the BEFL proposed here presents a rather low EDF pump threshold and relatively high output power. This is because this BEFL is based on commercialized EDF whose fiber attenuation and pump absorption is much lower than the specially manufactured Bi-EDF, and the operating wavelength of the Bi-EDF is in the extended L-band region, while the normal EDF operates in the C-band region. Hence, the BEFL in our study can find applications in the nowaday telecommunication and optical fiber sensing.

The linewidth of this BEFL was measured by the heterodyne beat technique. We did not use the delayed self-heterodyne technique, because its instrument-resolution is limited to about 1 kHz. And the measured heterodyne spectrum is actually a Voigt profile, which is the convolution of the Lorentzian lineshape of the laser under test and the Gaussian lineshape of the$1/f$ frequency noise induced by the long delays. The self-heterodyne technique is more suitable for

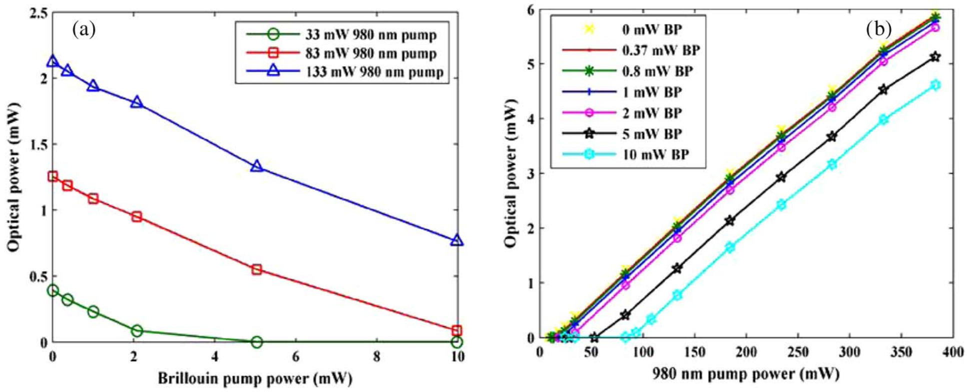

Fig. 3. (a) BEFL output powers against the BP powers and (b) against the 980 nm pump powers.

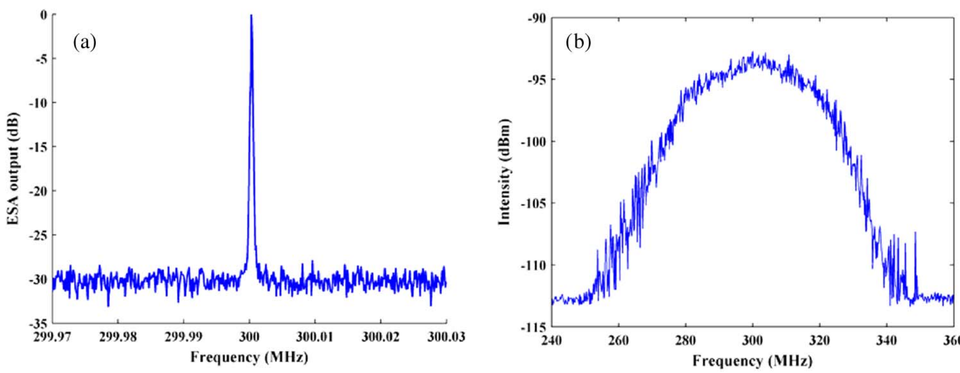

Fig. 4. (a) Heterodyne beat spectra of the BEFL and (b) delayed self-heterodyne spectrum of the BP.

the broadband lasers with over megahertz linewidth. In contrast, heterodyne beat technique could be conveniently carried out for the Brillouin laser by injecting two uncorrelated Brillouin pump with close frequencies [19]. The measured result is shown in Fig. 4(a), at 0.5 mW BP power and 200 mW 980 nm pump power. The 20-dB width of the beat spectrum is about 800 Hz. The full width at half maximum (FWHM) of the BEFL lineshape is derived to be 40 Hz [20]. The narrow linewidth of the BEFL is not a result of using narrow linewidth BP. The BP linewidth is about 20 MHz, measured by 25-km-delayed self-heterodyne method, shown in Fig. 4(b). The spectrum of the BP is much broader than that of the BEFL. And it is very unsmooth which is perhaps caused by frequency jitter in the BP. The BEFL is insensitive to the BP frequency jitter when the width of the BP jitter is much less than the SBS gain bandwidth. The BEFL linewidth is reduced by 5 orders of magnitude than that of the BP, which is caused by the intrinsic strong linewidth reduction in the BEFL [21].

Finally, we analyze the BP threshold of the BEFL. Although there were studies on both threshold and efficiency of the original BEFL laser configuration [22], there have been no theoretical analysis on the BP threshold for the newly proposed BEFL before. Here, we theoretically investigate on this issue. Starting from the case of a length of EDF, the Brillouin pump threshold P_{th} of an EDF is estimated according to the following equation [1]:

$$P_{th} = \frac{21 A_{eff}}{g_B L_{eff}} \tag{1}$$

where A_{eff} is the effective mode area, g_B is the Brillouin gain coefficient of the fiber, and L_{eff} is the effective fiber length. When the fiber length L is short, the effective fiber length L_{eff} can be replaced by L. The Brillouin gain coefficient g_B is 5×10^{-11} m/W and the effective area A_{eff} of the used EDF is 12×10^{-12} m^2. Hence, the Brillouin pump threshold is 11.2 W in the 45 cm EDF.

When the EDF is pumped by 980 nm light, the linear gain in the EDF should be taken into consideration. The Brillouin Stokes power P_S, the BP power P_{BP}, and the linear gain G satisfy the following relation in the threshold condition [23]:

$$\ln \frac{P_s(L)}{P_s(0)} = -\ln G - \frac{g_B L}{A_{eff} \ln G} P_{BP}(0)(G-1). \tag{2}$$

The above equation can be recast to provide greater insight into the BP threshold power in the following form:

$$\left[\ln\left(\frac{\eta G P_{th}}{P_N}\right) - \ln G\right] \frac{\ln G}{g_B} \frac{A_{eff}}{1 - G^{-1}} = G L P_{th} \tag{3}$$

where P_N is the power of one noise photon, η is the number that sets Stokes-to-signal ratio that defines the threshold ($\eta = P_{Stokes}(0)/P_{th}$). After numerically solving the above equation, the BP threshold power of the 45 cm pumped EDF is estimated to be about 2.4 W supposing the EDF gain is 10 dB, η is 0.01, and P_N is the typical 0.5 nW. The BP threshold of the pumped EDF is much reduced than that of the unpumped one.

As to the BP threshold of the BEFL, the cavity feedback should be taken into consideration as the boundary condition. Substituting $P_S(L) = RP_S(0)$ into (3), the BP threshold is expressed as the following:

$$P_{th} = \frac{\ln(RG)}{1 - G} \frac{A_{eff}}{g_B L} \tag{4}$$

The expression of (4) is similar to (1). But the coefficient in (4) is not a constant. It is associated with the cavity feedback and the linear gain of the EDF. And by comparing (4) with that in [21], it can be found that the BP threshold and the linewidth narrowing are affected by the same factors. The linewidth narrowing factor here is 5×10^5, deducing that the value of RG is 0.999 according to the relation in [21]. The power reflection ratio R is 0.8. Hence, the EDF gain G is 1. 25. Putting the values of R and G into (4), the Brillouin pump threshold is estimated to be about 0.48 mW, which agrees well with our experimental result. Compared (4) with (1), the coefficient 21 is replaced by the value of 0.0009 for our BEFL. The BP threshold of the BEFL is dominantly determined by the linear gain instead of the fiber length. Hence, it is as low as sub-milliwatt despite of so short gain medium length.

The low BP threshold in the BEFL can also be qualitatively explained in view of resonator finesse enhancement caused by the linear gain of the EDF [24]. SBS lasing threshold is very low in high-finesse resonators [25]. The EDF gain of the BEFL enhances the cavity finesse and therefore reduces the BP threshold. The enhancement of cavity finesse also leads to strong linewidth narrowing in the BEFL. Therefore, both of the low BP threshold and the narrow linewidth are inner connected by the EDF gain through the BEFL-finesse enhancement.

4. Conclusion

In conclusion, we study the BEFL in which 45 cm EDF acts as both the Brillouin and linear gain media. This BEFL is in stable single-mode operation for its ∼2 m cavity length. The 980 nm pump threshold is only about 15 mW. Its output power reaches about 6 mW at 383 mW 980 nm pump power. The BEFL presents an ultra-narrow linewidth of only 40 Hz although it is excited by 20-MHz BP. An analytical relationship for the BP threshold of the BEFL is derived, which indicates the BP threshold is dominantly determined by the linear gain of the EDF. Despite of the short Brillouin gain medium length, the BP threshold of the BEFL reaches sub-milliwatt. This BEFL can find many applications in highly coherent fields.

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