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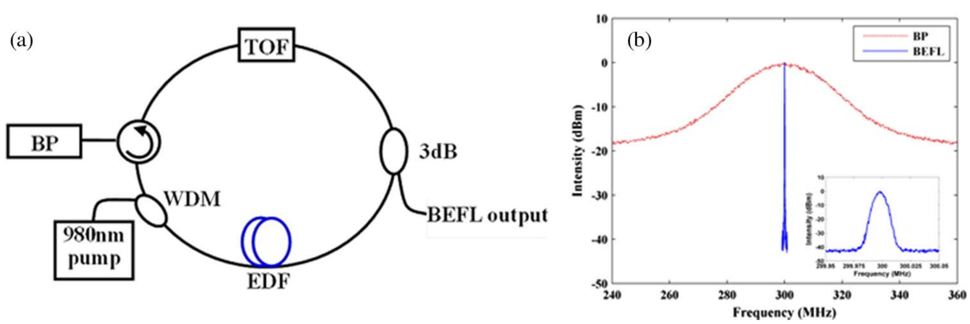


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# Strong Linewidth Reduction by Compact Brillouin/Erbium Fiber Laser

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**Abstract:** We demonstrate the strong linewidth reduction by a compact Brillouin/erbium fiber laser (BEFL), in which 4-m erbium-doped fiber (EDF) acts as both the Brillouin and linear gain media. Due to the assistance of the linear gain in the EDF with the acoustic damping and the cavity feedback in the resonator, the proposed BEFL transferred the 20-MHz Brillouin pump (BP) into the 950-Hz Brillouin Stokes laser emission, demonstrating that the laser linewidth is reduced by over $2 \times 10^4$ times through this BEFL. The linewidth reduction is independent of the 980-nm pump power or the BP wavelength. The BEFL keeps strong linewidth reduction over the whole C-band. This effect of the BEFL provides a simple but effective way to obtain highly coherent light for many applications.

**Index Terms:** Linewidth reduction, Brillouin/erbium fiber laser, stimulated Brillouin scattering.

## 1. Introduction

Ultra-narrow-linewidth lasers are of great importance for many applications, such as in LIDAR, coherent optical communications, and sensors [1]–[3]. Many techniques have been studied to reduce the linewidth of lasers, and great developments have been achieved on narrowing the linewidth of lasers. The technique of distributed Bragg reflector and distributed feedback can reduce the linewidth of a semiconductor laser to less than 100 kHz [4], [5]. Especially in recent years, the planar-waveguide external-cavity laser technology is able to squeeze the linewidth of laser diodes to as narrow as about 3 kHz, which is approaching the performance of a typical fiber laser [6]. Several methods are generally adopted in erbium-doped fiber lasers (EDFLs) to stabilize the lasing mode and achieve narrow linewidth, such as the Pound–Drever–Hall technique, distributed Bragg reflector, incorporating a saturable absorber, and external injection locking [7]–[10]. The linewidths of these EDFLs are able to be as narrow as about 1.5 kHz. Stimulated Brillouin scattering (SBS) in fibers is an intrinsic linewidth reduction mechanism for Brillouin fiber lasers (BFLs) [11]. BFLs present the application of laser linewidth narrowing without the use of a fast feedback loop [12]. Unfortunately, BFLs require critically pump coupled resonators, which makes them complicated to established and hard to apply.

Brillouin/erbium fiber lasers (BEFLs) have drawn much attention since 1996 because they overcome the disadvantages of a critical resonator and low output power in the BFLs [13], [14]. Their too-long cavities ($>$ 100 m), however, cause the lasing modes hop easily. Recently, a

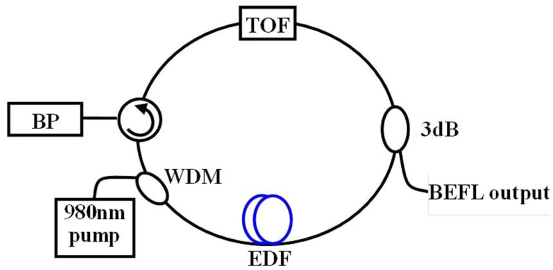


Fig. 1. Configuration of the compact BEFL: BP, Brillouin pump; WDM, wavelength-division multiplexer; EDF, erbium-doped fiber; TOF, tunable optical filter.

class of compact BEFLs has been reported, which uses a short length of commercialized erbium-doped fiber (EDF) as both the Brillouin gain and the linear gain media [15]–[18]. It has been demonstrated that these BEFLs present low phase noises, low pump threshold powers, large output powers ($\sim$10 mW), and wide-range stable fast-tuning output. However, the questions related to the linewidth of these novel BEFLs have not been attentively examined, and although there have been previous work on linewidth narrowing in BFLs, to the best of the authors' knowledge, there has been no related research on BEFLs. Contrary to the BFLs, the BEFL operates with population inversion, which determines that not only the spontaneous scattering but also the spontaneous emission should be taken into consideration when the fundamental limit of the temporal coherence of the BEFL is studied. Hence, the issue of linewidth narrowing in the BEFL shall be very interesting and worthy of being studied.

In this paper, we study the linewidth reduction by this novel compact BEFL. Strong linewidth reduction is observed. The effects of the Brillouin pump (BP) linewidth, the 980 nm pump powers, and the BP wavelength on the BEFL linewidth are also investigated. The study here demonstrate a new application for the novel compact BEFL. It provides a simple but effective optical method to reduce the laser linewidth and achieve high-coherence light for many optical fields.

## 2. Configuration and Principle of Compact BEFL

The configuration of the proposed BEFL is depicted in Fig. 1. The components of the laser cavity are all polarization-maintaining (PM), which guarantees the single-polarization state of the laser. A 1550-nm laser source provides the BP for the BEFL through an optical circulator. It is worth noting that this laser source is unnecessary to be polarization-maintaining, for the PM optical circulator also has the effect as a polarizer. A length of 4 m commercialized PM EDF (SCF-ER30-5/125-25-PM by Coractive Co.), 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 by the BP. Due to the combined influence of the Brillouin gain and the linear gain of the EDF, milliwatt or even sub-milliwatt magnitude of Brillouin pump power is capable of exciting SBS lasing in this short EDF. If without the 980 nm pump power, the resonator becomes very lossy, and then the injected BP cannot excite SBS in the EDF or generate lasing in the cavity. A narrow-band ($\sim$0.3 nm) tunable optical filter (TOF) is set with its passband covering the Brillouin Stokes wavelength. This narrow-band TOF suppresses the amplified spontaneous emission (ASE) outside its passband and ensures the operation wavelength of the BEFL near the Brillouin Stokes wavelength. Meanwhile, once the wavelength of the BP and the TOF changes together, it allows the BEFL to operate in a wide wavelength range besides that where the peak EDF gain locates. The BEFL output is extracted out by a 3 dB optical fiber coupler.

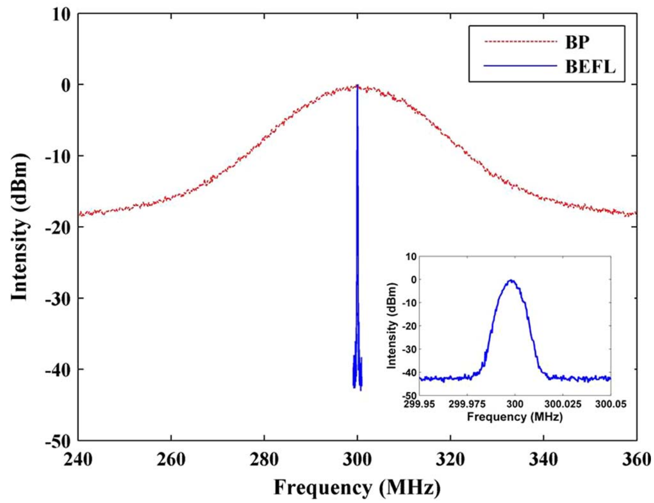


Fig. 2. Self-heterodyne spectra of both the BP (the red line) and the BEFL (the blue line). The inset shows the zoomed image of the self-heterodyne spectrum for the BEFL.

## 3. Experimental Results and Discussions

The output optical power of the 1550-nm light source is 8.8 mW, and the light injected into the EDF as the BP is about 4.4 mW after the optical circulator. The driving current of the 980 nm pump of the EDF is set to 300 mA (corresponding to 170 mW 980 nm pump power). The linewidths of both the BEFL and the BP were measured by delayed self-heterodyne technique with 25 km delay fiber. The frequency shift of the acousto-optic modulator is 300 MHz. The bandwidth resolution of the electric spectrum analyzer (ESA) is set to 100 Hz. The delayed self-heterodyne spectra of the BP and BEFL are shown in Fig. 2, in which strong linewidth reduction can be observed. The linewidth of the BP is about 20 MHz. To more accurately determine the ultra-narrow linewidth of the BEFL, it is estimated from the 20-dB width in the self-heterodyne spectrum [19]. The zoomed image of the heterodyne spectrum for the BEFL is presented in the inset of Fig. 2. The 20-dB spectrum width is about 19 kHz, demonstrating that the linewidth of the BEFL is 950 Hz. The BEFL linewidth is reduced by $2 \times 10^4$ times compared with the BP linewidth.

Theoretical study on the linewidth narrowing effect in the BFL has been presented in [20] and [21] within the framework of the usual three-wave model of SBS. The modeling of the linewidth reduction effect in the BEFL requires to add dynamical equations governing the physics of the erbium amplifier to SBS equations. It is much complicated work to establish the modeling. A simple analytical relation connecting the linewidth of the Stokes to that of the BP was derived in [20], [21]. Analogously, we here propose a phenomenological modification to fit for the compact BEFL. The proposed phenomenologically modified relationship between the linewidth of the BEFL $\Delta\nu_L$ and the linewidth of the BP $\Delta\nu_p$ is as follows:

$$\Delta\nu_L = \frac{\Delta\nu_p}{\left(1 + \frac{\gamma_A}{\Gamma_c}\right)^2} \tag{1}$$

where $\gamma_A$ and $\Gamma_c$ represent the damping rate of the acoustic wave and the cavity loss rate, respectively. $\gamma_A$ equals to $\pi\Delta\nu_B$, where $\Delta\nu_B$ is the bandwidth of the Brillouin gain spectrum. $\Gamma_c$ equals to $-c\ln R/nL$ where $c/n$ is the light velocity in the fiber of length $L$ and $R$ is the light amplitude feedback parameter. From the above relation, to achieve a large linewidth reduction ratio, it needs a large $R$. It should be noted that the above theory is for a BFL. In the proposed BEFL, the gain fiber provides both the Brillouin and linear gain. Hence, the above equation should be modified by taking into the linear gain into consideration. In the BEFL, the cavity loss

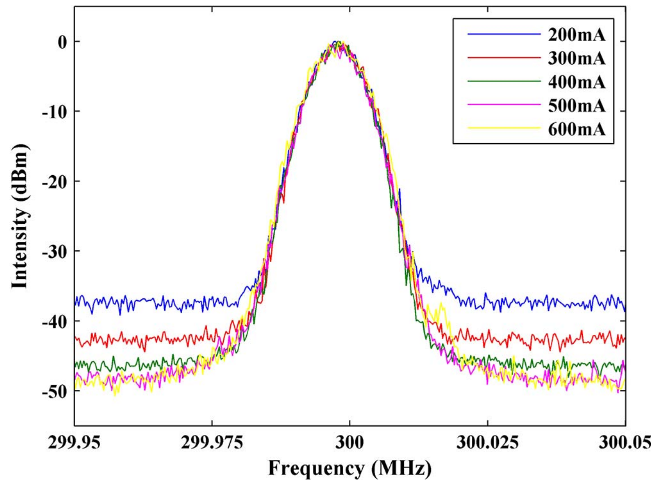


Fig. 3. Self-heterodyne spectra of the BEFL with the driving current of the 980 nm pump scanned from 200 mA to 600 mA at a step of 100 mA.

rate turns to $-c\ln RG/nL$ where the amplitude gain parameter $G$ is contributed by the linear gain of the EDF. And it is found that the key to strong linewidth reduction by the BEFL is the assistance of the linear gain of the EDF. Without the assistance of the EDF gain, the linewidth reduction is contributed by the cavity feedback parameter $R$. To reach the linewidth reduction ratio of $2 \times 10^4$, a BFL needs a cavity feedback parameter $R$ as large as about 0.97. With the assistance of the erbium gain, the experimental result shows that over 4 orders of magnitude of linewidth reduction is obtained with a 3-dB coupler used in the BEFL. Compared with the proposed BEFL and the traditional BFLs, they both present property of laser linewidth reduction. However, on the premise of realizing the same linewidth reduction performance, the BEFL is suited to operate with large output coupling, which leads to the advantage of the large output power in the BEFL. It also should be mentioned that unlike a BFL, the BEFL needs no critical pump coupled resonator. Hence, the linewidth reduction by the BEFL presents great priority to that by the BFLs in practical applications.

It is worth noting that Eq. (1) does not include Brillouin gain coefficient $g_B$, which means the linewidth narrowing effect does not depend on the strength of the Brillouin gain. The linewidth reduction is caused by the narrowband Brillouin gain spectrum (typically 20 MHz), in which the interaction between the pump, the acoustic wave, and the backscattered Stokes occurs. The narrowband Brillouin gain spectrum acts as a narrowband filter which selects lasing mode and narrows the laser linewidth. Although the strength of the Brillouin gain is very weak, it still generates strong linewidth narrowing effect after continuous cavity feedback and oscillation in the resonator.

We measured the linewidths of the BEFL with different 980 nm pump powers, as shown in Fig. 3. The driving current of the 980 nm pump was varied from 200 mA to 600 mA at a step of 100 mA, corresponding to the 980 nm pump powers from 112 mW to 347 mW. There are almost no differences between the linewidths of these five spectra, demonstrating that the linewidth of this BEFL is not affected by the 980 nm pump power. The experimental results can be explained as following. It is demonstrated that the linewidth narrowing effect is independent of the intracavity Stokes power or equivalently of the Brillouin pump power [20], [21]. Analogously, the variation of the 980 nm pump power changes the intracavity Brillouin Stokes power without affecting the linewidth reduction of the BEFL. It can also be explained by Eq. (1). Once the 980 nm pump power reaches the threshold and the BEFL starts to operate, the multiply of the optical loss $R$ and the optical gain $G$ for the Brillouin Stokes is constant, which closely approaches 1. Therefore, the factor $(1 + \gamma_A/\Gamma_c)^2$ keeps constant. With a certain BP, the linewidth of the BEFL stays unchanged with different 980 nm pump powers over the threshold. The

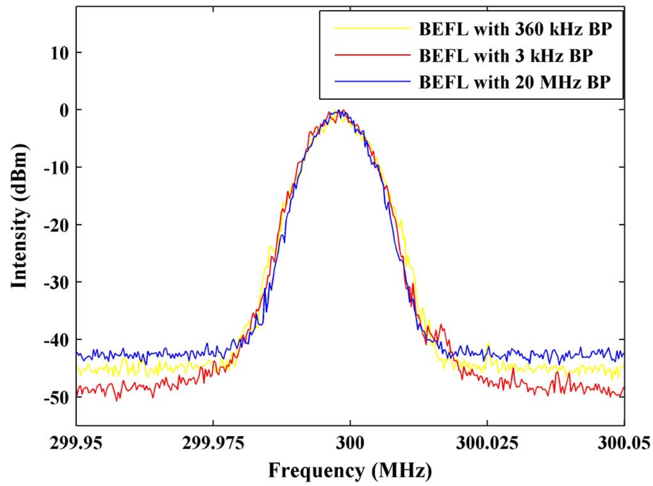


Fig. 4. Self-heterodyne spectra of the BEFL with 360 kHz (the yellow line), 3 kHz (the red line), and 20 MHz (the blue line) BP.

experimental results can be explained in view of the ratio of signal to ASE as well [22]. Just varying the 980 nm pump power of the EDF, the ratio of signal to ASE is not changed. As a result, the spectrum of the light is not broadened.

We used different light sources with 360 kHz and 3 kHz linewidth to provide the BP, respectively. The optical powers of the light sources are both adjusted to about 8.8 mW before injected into the BEFL cavity. The driving current of the 980 nm pump is set to 300 mA. The corresponding linewidths of the BEFL were measured, as shown in Fig. 4. The yellow line and the red line represent the result of the BEFL with 360 kHz and 3 kHz linewidth BP, respectively. For comparison, the result of the BEFL with 20 MHz BP is also presented in Fig. 4, as the blue curve shows. The measured self-heterodyne spectra are nearly the same in the three different situations. Interestingly, the linewidth of the BEFL is not further reduced with the decrease of the BP linewidth as we expected from Eq. (1). We infer that the linewidth reduction in the BEFL now stays in a "saturation region", where the BEFL linewidth can be no longer reduced with the decrease of the BP linewidth. The linewidth of the BEFL has been suppressed to the limit already due to its large linewidth reduction ratio. It is noted that the above three BP have different wavelengths, which are 1548.20 nm, 1550.15 nm, and 1555.05 nm, respectively. The experimental results in Fig. 4 indicate that the linewidth of the BEFL is unchanged with the BP wavelength. To further validate this result, we used a widely tunable laser source (over the whole C-band) as the BP and measured the corresponding BEFL linewidth. The experimental results demonstrate that the BEFL keeps its narrow linewidth when tuning the BP wavelength. The BEFL preserves strong linewidth reduction effect over the whole C-band.

To discuss the fundamental linewidth of the BEFL, several factors should be taken into consideration, such as the spontaneous emission, the spontaneous scattering, thermal fluctuations and environmental perturbations. The thermal and mechanical perturbations result in fluctuations of the BEFL cavity characteristics, and their bandwidth is typically of the order of 100 Hz. They are responsible for slow frequency drifts of the BEFL, and in practical use, lasers are usually packaged with temperature stabilization to avoid these two kinds of perturbations. The intrinsic linewidth of the BEFL is associated with both the spontaneous scattering and the spontaneous emission, since not only the Brillouin gain but also the linear gain is incorporated in this laser cavity. Spontaneous scattering is described by a Langevin noise term $f$, and it is in the order of $10^{-6}$ when the amplitude of the optical fields is in the order of unity [20]. It can be neglected if the linewidth of the Brillouin pump is larger than 40 kHz considering the free spectrum range of this BEFL is about 20 MHz [20]. This means that the measured spectra with 20 MHz and 360 kHz BP are determined by the spontaneous emission, and from Fig. 4 even when the BP linewidth is further decreased to 3 kHz, whereas the Langevin term $f$ is comparable with the phase diffusion of the BP, the spontaneous scattering is still neglectable compared with the spontaneous emission. Thus, the spontaneous scattering plays a determining role in the initiation of Brillouin Stokes in the BEFL, but it is neglectable in the contribution to the BEFL linewidth for its weak intensity. The degree of the fundamental linewidth of the BEFL is predominately determined by the spontaneous emission.

Finally, it is necessary to emphasize two points. The first is that the 4-m EDF is chosen for high 980 nm pump conversion efficiency and BEFL output power as discussed in [16]. It is perhaps very interesting to study the relationship between the EDF length and the BEFL linewidth, which shall be our next work. The second and very important point is that the theoretical anaylsis here is based on the phenomenological modification of the analytical relation for a BFL. The proposed modified relation can explain the strong linewidth reduction by the BEFL pretty well to some extent. Nevertheless, the limitation of the modification is obvious that accurately quantitative analysis are hard to be carried out. For example, the erbium gain brings only gain compensating cavity losses according to the modified Eq. (1). However, whether the erbium amplification influences the phase dynamics of the Stokes wave is left unknown through this equation. Hence, the modeling of the linewidth narrowing in the BEFL is stringently needed to precisely analyze the phenomenon. By then, the problem that to what extent the phenomenological modification is validate shall be solved. As a result, the future work is to accomplish the theoretical modeling for the proposed BEFL.

## 4. Conclusion

In conclusion, we demonstrate the strong linewidth reduction by a compact BEFL. The linewidth of the BP is transferred to the emitted Brillouin Stokes after being strongly reduced by the combined influence of the acoustic damping, the cavity feedback, and the linear gain of the EDF. The BEFL, which uses 4 m PM EDF as both the Brillouin and linear gain media, transfers the 20 MHz BP to 950 Hz BEFL output, achieving over 4 orders of magnitude of linewidth reduction. The linewidth reduction by the BEFL is unchanged with various 980 nm pump powers or different BP wavelengths, and due to the strong linewidth reduction, the BEFL reaches its fundamental linewidth limit which is predominately determined by the spontaneous emission. The proposed compact BEFL provides a useful and effective way to reduce laser linewidth. It can find a number of applications in many highly coherent fields.

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