Effects of modulation amplitude and frequency of frequency-modulated fiber lasers on the threshold of the stimulated Brillouin scattering in optical fiber

Wei Chen (陈 伟) and Zhou Meng (孟 洲)*

College of Optoelectronic Science and Engineering, National University of Defense Technology, Changsha 410073, China

**E-mail: zhoumeng6806@163.com*

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Stimulated Brillouin scattering (SBS) is a key problem with the increasing power of fiber transmission systems. In this letter, a frequency-modulated fiber laser with an ultra-narrow linewidth is chosen as a light source. The SBS threshold is increased from 4.1 to 6.2 mW at 13-MHz frequency modulation amplitude for a 50-km G652 fiber. We also show that the SBS threshold increases with not only the frequency modulation amplitude, but also the modulation frequency. The modulation frequency should be high enough for effective modulation.

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Stimulated Brillouin scattering (SBS) is a significant nonlinear effect in optical fibers caused by the interaction between optical and acoustic waves. Once the input power exceeds a specific critical value, i.e., the SBS threshold, the backscattering power increases dramatically. Recently, wavelength division multiplexing (WDM) combined with erbium-doped fiber amplifiers (EDFA) has been widely used to achieve high-capacity and long-haul optical communication, which has increased the power in the fiber sufficiently to consider SBS. Given that SBS is harmful to the system as it limits the power that can be coupled into the fiber, studying the SBS threshold is particularly significant. Smith presented a well-known formula to evaluate the SBS threshold[1]. Aoki *et al.* considered the influence of laser linewidth on the threshold[2]. Küng showed a more accurate expression of the threshold gain coefficient[3]. Le Floch *et al.* derived a more precise threshold evaluation through a non-localized fluctuating source model[4]. Shimizu *et al.* analyzed different methods for evaluating the SBS threshold and gave their suggestions[5]. The SBS threshold can be as small as 1 mW in a long fiber[6], which necessitates an increase in the threshold. Several methods can be used to realize this. For example, the laser linewidth can be broadened through frequency dithering or the spectrum of the input signal can be broadened using phase modulation[7−9]. Variations in fiber parameters, such as temperature[10], stress[11], core diameter[12], or the Brillouin shift frequency[13], can also be imposed along the fiber. In addition, the acoustic properties of the fiber can be varied in the transverse direction[14]. Recently, Mitchell *et al.* reported a laser chip that provides significant linewidth broadening by modifying a dither current[15], which is helpful in reducing the effects of SBS.

In this letter, a frequency-modulated fiber laser was used with an ultra-narrow linewidth (∼kHz) that we developed as a light source. This type of laser is used in many applications. For example, the phase-generated carrier (PGC) scheme has often been used in high-precision fiber-sensing systems such as a fiber-optic hydrophone system[16]. In such systems, high-frequency-modulated fiber lasers have always been indispensable. However, few papers have studied SBS using this type of laser. The frequency modulation amplitude of the frequency-modulated fiber laser was changed to study the variance of the SBS threshold and compared with the theoretical computing results. Furthermore, the variance of the threshold with modulation frequency was studied and explained.

SBS can be described as the interaction among the forward pump light wave, the backward Stokes light wave, and the forward acoustic wave. In this process, most of the power from the input pump is transferred to the low-frequency Stokes light; the corresponding frequency difference is called the Brillouin shift, which depends on the material of the fiber. For silica fibers, the shift is about 11.1 GHz at a pump wavelength of 1.55 μm[6].

The SBS threshold can be evaluated using methods[5]. In this letter, the input power when the backscattering Stokes power reaches about 0.5% of the input pump power was defined as the SBS threshold. Considering the linewidth of the light source, the threshold can be expressed as[5]

$$P_{\text{th}} = 21\frac{KA_{\text{eff}}}{g_{\text{B}}L_{\text{eff}}}\Big(1+\frac{\Delta\nu_{\text{s}}}{\Delta\nu_{\text{B}}}\Big), \tag{1}$$

where $L_{\text{eff}} = \frac{1}{\alpha}[1-\exp(-\alpha L)]$, α is the attenuation coefficient of the fiber, L is the fiber length, g_B is the peak value of the Brillouin gain, A_{eff} is the effective area of the core of the fiber, $\Delta\nu_{\text{s}}$ is the linewidth of the light source, and $\Delta\nu_{\text{B}}$ is the spontaneous Brillouin bandwidth. We supposed that $\Delta\nu_{\text{B}}$=50 MHz, and K is the polarization factor, which accounts for the polarization scrambling between the pump and Stokes waves. If their polarizations are identical, $K = 1$; meanwhile, for complete polarization scrambling in conventional single-mode fibers, $K = 2$[2]. For the narrow-linewidth laser, $\Delta\nu_{\text{s}}$ is quite small compared with $\Delta\nu_{\text{B}}$, thus the second term in the bracket can be ignored.

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For a frequency-modulated laser, the frequency can be written as

$$\nu = \nu_0 + \Delta\nu \cos 2\pi f t, \tag{2}$$

where ν_0 is the central frequency, which was about 193.55 THz in our experiments, $\Delta\nu$ is the frequency modulation amplitude, and f is the modulation frequency. As mentioned above, a frequency-modulated fiber laser with an ultra-narrow linewidth (~kHz) was chosen. The frequencies in these lasers are modulated by varying resonant cavity length. As a fiber several meters long is wound around a piezoelectric transducer (PZT) in the fiber laser, the fiber and cavity lengths are modulated when an electrical signal is applied to the PZT[17]. From Eq. (2), the frequency of the laser changes between $\nu_0 + \Delta\nu$ and $\nu_0 - \Delta\nu$, thus $2\Delta\nu$ is roughly regarded as the linewidth of the laser. As a result, the linewidth can be widened when a modulation signal is present and the variance of the SBS threshold can then be studied.

Experiments were performed to validate the theories above. The experimental setup is shown in Fig. 1. The source was the ultra-narrow-linewidth fiber laser (FL) with a wavelength of 1550 nm that we developed, which was connected to a signal source (AFG 3022B, Tektronix, USA) to realize the frequency modulation. Two EDFAs (EDFA1 and EDFA2) were used to ensure that the power was high enough to reach the SBS threshold. We developed the EDFA2, in which the gain could be adjusted so that the power in the fiber is easily changed. Circulator1 was connected with a tunable filter (SOTMTF, Shanghai Synet Optics Technology Corporation) whose bandwidth was about 0.3 nm to suppress the amplified spontaneous emission (ASE) noise and ensure the monochromaticity of the laser after EDFA amplification. Using circulator2, the power could not only be launched into the 50-km single-mode fiber (G652, Wuhan Research Institute of Post and Telecommunication), but the backscattering power could also be examined with the power meter (PM1) connected to it. The input power was measured after circulator2 (at point "A" in Fig. 1), and PM2 was used to measure the output power.

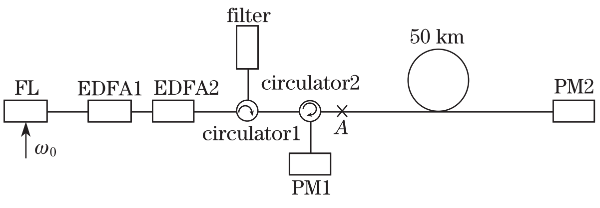

Fig. 1. Experimental setup.

The output versus input power at different modulation voltages are shown in Fig. 2, where the real and dashed lines denote the forward and backward output powers, respectively. The frequency modulation amplitude varied with the modulation voltage and the coefficient was about 1.3 MHz/V, which was derived from the experimental data of our laboratory. The lines marked with squares, circles, and triangles correspond to 0 (without modulation), 5-, and 10-V modulation voltages, respectively, with their corresponding frequency modulation amplitudes at about 0, 5 × 1.3, and 10 × 1.3 MHz. The modulation frequency f was 12.5 kHz. The SBS threshold clearly increases with the frequency modulation amplitude. The linewidth is widened when the frequency of the laser is modulated, this phenomenon is accounted for by Eq. (1). When modulation was not applied, the SBS threshold was as small as 4.1 mW and was increased to 6.2 mW at a modulation voltage of 10 V. The SBS threshold would clearly increase more if a higher modulation voltage was used. However, this was not possible with our limited apparatus. For the ultra-narrow-linewidth fiber laser, compared with $\Delta\nu_B$, $\Delta\nu_s$ is quite small without modulation (~kHz), leading to $\Delta\nu_\mathrm{s}/\Delta\nu_\mathrm{B} \approx 0$. If $A_\mathrm{eff} = 80\ \mu\mathrm{m}^2$, $g_\mathrm{B} = 4 \times 10^{-11}$ m/W, and α=0.2 dB/km, then $P_\mathrm{th} \approx 4.3$ mW using Eq. (1), which is very close to the experimental result (4.1 mW). Furthermore, at a modulation voltage of 5 V, the frequency modulation amplitude is 5×1.3 MHz and $\Delta\nu_\mathrm{s} = 2 \times 5 \times 1.3$=13 MHz. Using Eq. (1), we obtain $P_\mathrm{th} \approx 5.4$ mW, which is also in agreement with the result in Fig. 2 (5.3 mW). Accordingly, this trend can be verified at a modulation voltage of 10 V.

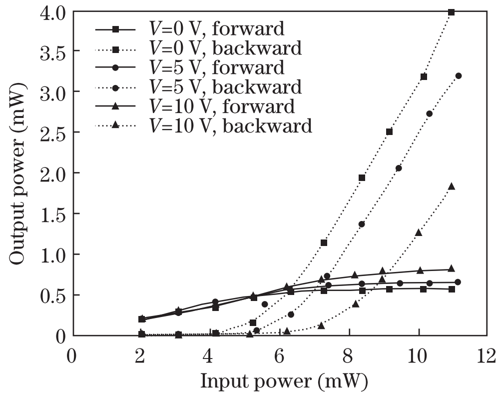

Fig. 2. Output power versus input power at 12.5-kHz modulation frequency.

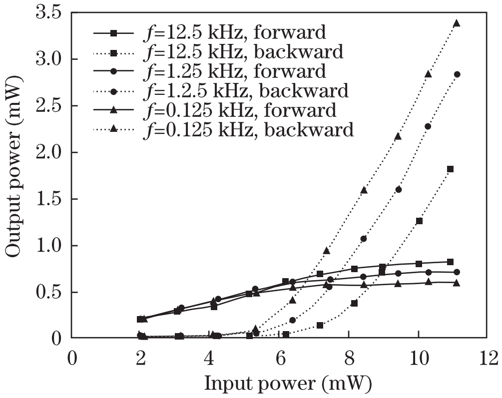

Fig. 3. Output power versus input power at 10-V modulation voltage.

The variance of the SBS threshold was also studied with modulation frequency, as shown in Fig. 3. The lines marked with squares, circles, and triangles correspond to the modulation frequencies f at 12.5, 1.25, and 0.125 kHz. The modulation voltage was 10 V, corresponding to a frequency modulation amplitude of 10×1.3 MHz. The SBS threshold clearly increases with the modulation frequency. Unlike in Fig. 2, the SBS threshold is close to that without modulation when f is 0.125 kHz. This can be attributed to ineffective modulation of the fiber laser frequency when the modulation frequency is low enough. Considering the extreme situation, the linewidth of the laser is not broadened if the modulation frequency decreases to zero. Consequently, the SBS threshold is almost the same with or without modulation. Therefore, the modulation frequency should be high enough for effective modulation.

In conclusion, frequency-modulated fiber lasers are useful in many applications, such as in fiber-optic hydrophone system using the PGC technique. Hence, studying the SBS threshold of this type of laser is particularly significant. The SBS threshold is increased from 4.1 to 6.2 mW at 13-MHz frequency modulation amplitude for a 50-km G652 fiber. We also show that the SBS threshold increases with not only the frequency modulation amplitude, but also the modulation frequency. In addition, the modulation frequency should be high enough for effective modulation. Furthermore, the increase of the SBS threshold can be also realized by phase modulation, which will be disussed in detail in our next paper.

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