Forward and backward intensity noises induced by stimulated Brillouin scattering in optical fiber

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The characteristic of intensity noise is degraded when stimulated Brillouin scattering (SBS) occurs in the fiber transmission systems. We use the localized fluctuating model to study SBS and obtain the curves of intensity fluctuations versus the single-pass gain. Corresponding experiments are also conducted. For the forward light, the relative intensity noise (RIN) dramatically increases at first and gradually stabilizes when the input power is above the SBS threshold. For the backward light, the RIN increases dramatically with the input power near the threshold. As the input power continues to increase, the RIN decreases quickly at first and subsequently decreases slowly. This observation is attributed to the lower frequencies.

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Stimulated Brillouin scattering (SBS) is a significant nonlinear effect in optical fiber, which is caused by the interaction between the optical and acoustic waves. Once the input power exceeds the SBS threshold, most of the power is transferred to the backscattered Stokes light, and the backward power begins to increase significantly. Previous works have indicated that SBS is initiated from the spontaneous Brillouin scattering (SpBS) caused by the thermal fluctuations in the density of the medium. As a result, the backward Stokes power exhibits stochastic dynamics, and the intensity noise is induced[1,2]. The noisy Stokes light also induces intensity noise in the forward transmitted light due to the depletion of the input pump light. Numerous research groups have studied the characteristics of the transmitted intensity noise[3−5]. As a result of the research undertakings on the SBS, several SBS models have been proposed, including the localized non-fluctuating model, localized fluctuating model, and distributed fluctuating model[1,6−8].

The localized fluctuating model was used to investigate the fluctuations in the Stokes output intensity[6]. The fluctuations decrease with the single-pass gain. However, the fluctuations in the forward output intensity were not considered and the corresponding experiments were not carried out to verify the theory. The forward transmitted intensity noise induced by the SBS may be the dominant noise in the receiver[3]. Unfortunately, the relevant SBS model was not offered and the relations between the intensity noise and the input power were not presented.

In our past research, we investigated the phase noise induced by SBS[9] and proposed methods of SBS suppression[10,11]. In this letter, we focus on the forward and backward intensity noises induced by SBS in optical fiber. The localized fluctuating model is used and the corresponding experiments are conducted. Furthermore, the variances of the intensity noise with the input power are exhibited. The experimental results are in good agreement with the theoretical results. Considering that intensity noise is an important factor that affects the performance of the fiber transmission systems, our research on the SBS-induced intensity noise plays a key role in the application of such systems.

The localized fluctuating model of SBS was proposed by Boyd *et al.*[6]. They supposed that SBS was under steady state conditions, and it was based on the following equations:

$$\begin{aligned} \mathrm{d}I_\mathrm{p}/\mathrm{d}z = -g_\mathrm{B}I_\mathrm{p}I_\mathrm{s} \\ \mathrm{d}I_\mathrm{s}/\mathrm{d}z = -g_\mathrm{B}I_\mathrm{p}I_\mathrm{s} \end{aligned}, \tag{1}$$

where I_p and I_s denote the pump and Stokes intensities, and g_B denotes the Brillouin gain factor. They also assumed that SpBS, which initiated SBS, occured at the rear of the fiber. Using the boundary condition $I_\mathrm{s}(L) = fI_\mathrm{p}(L)$, where f represents the fraction of the backscattered and transmitted intensity at $z = L$, to solve Eq. (1), and ignoring the terms of order f, it can be determined that

$$G = \frac{\ln R - \ln f}{1 - R}, \tag{2}$$

where $G = g_\mathrm{B}I_\mathrm{p}(0)L$ is the single-pass gain and $R = I_\mathrm{s}(0)/I_\mathrm{p}(0)$ is the reflectivity. To describe the stochastic dynamics of SpBS, they assumed that the probability distribution of f is a characteristic of a thermal source with a mean value equal to f_0:

$$P(f) = \frac{1}{f_0}\exp(-f/f_0). \tag{3}$$

Thus, f is a stochastic quantity and its mean value f_0 is approximately 10^{-12}. Using Eq. (2), the probability distribution of R can be obtained as

$$Q(R) = \frac{1}{f_0}\exp\left(\frac{-R\mathrm{e}^{GR-G}}{f_0}\right)(1+GR)\exp(GR-G). \tag{4}$$

Equation (4) indicates that the reflectivity produces fluctuations, which are induced by the fluctuating seed, and expressed by Eq. (3). As a result, all the functions of reflectivity have fluctuations and their corresponding mean values can be derived.

Generally, relative intensity noise (RIN) is used to describe the intensity fluctuations. RIN can be expressed as

$$\begin{aligned}\mathrm{RIN} &= 10\,\mathrm{lg}(<\delta P^2> / <P>^2) \\ &= 20\,\mathrm{lg}[(<\delta P^2>)^{1/2} / <P>],\end{aligned} \tag{5}$$

where $<P>$ is the average power and $<\delta P^2>$ is the mean-square power fluctuation spectral density. In the localized fluctuating model, the normalized standard deviation of intensity $\Delta I = (<I^2> - <I>^2)^{1/2} / <I>$ is used as a measurement of RIN. The mean values of R and R^2 can be obtained by Eq. (4) when G and f_0 are given. Considering that the backward Stokes intensity is $I_\mathrm{s}(0) = RI_\mathrm{p}(0)$ and the forward output intensity is $I_\mathrm{p}(L) \approx (1-R)I_\mathrm{p}(0)$, the forward and backward intensity fluctuations expressed by ΔI can be finally obtained.

The values of forward and backward ΔI versus G at $f_0 = 10^{-12}$ are shown in Fig. 1. For the forward light, ΔI is zero when the input power is below the SBS threshold ($G \approx 24$). The value dramatically increases at first and subsequently becomes almost constant when the input power is above the threshold. For the backward light, ΔI quickly decreases at first and slowly decreases when the input power is above the threshold. Although the variations of ΔI below the threshold are not shown in Fig. 1(b), we can infer that the corresponding ΔI is zero in the absence of SBS, which is the same case as with the forward light.

Based on these results, we can state that the localized fluctuating model can describe different intensity noise characteristics of the forward and backward lights when SBS occurs. Thus, the localized fluctuating model is effective and can be used to study SBS. The backward intensity fluctuations obtained by the localized and distributed fluctuating models were compared[6]. The fluctuations were found to be similar when SBS occurs. Furthermore, since the localized fluctuating model considers only the pump and the Stokes wave, it is simpler than the distributed fluctuating model which incorporates the influence of the acoustic wave.

We conduct the experiments to verify the theory. Experimental setup is shown in Fig. 2. The light from a TUNICS-Plus tunable external cavity laser with 1 550-nm wavelength is amplified by an erbium-doped fiber amplifier (EDFA) whose gain is tunable. Its amplified light is filtered by an optical filter (~0.3-nm bandwidth). With the use of a circulator (circulator 2), the light can be launched into the 50-km single-mode fiber (SMF), and the backscattered light can be examined. The response of the detector depends on its input power; thus, a variable optical attenuator (VOA) is placed before the detector to ensure the same input power. An analog-to-digital converter (A/D) is also applied and the RIN spectra are measured using a computer program.

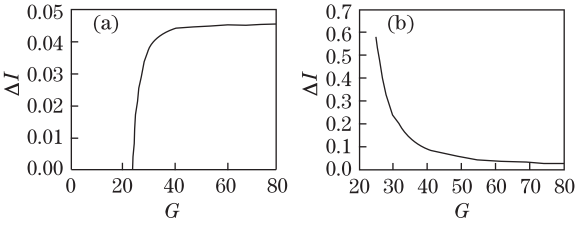

Fig. 1. (a) Forward and (b) backward ΔI versus G.

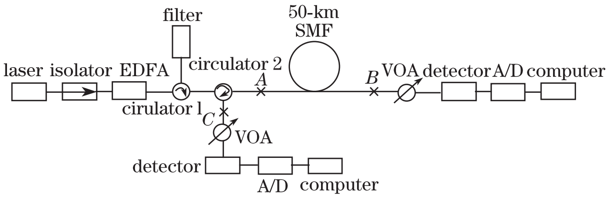

Fig. 2. Experimental setup for measuring the forward and backward intensity noises.

In the experiments, the output of the laser is adjusted to 10 mW and the gain of the EDFA is varied to achieve different input powers. In spite of this, the RIN values induced by the EDFA at different gains remain almost the same (~−100 dB/(Hz)$^{1/2}$ at 1-mW normalized received power of the detector). This is caused by the considerable suppression of the amplified spontaneous emission (ASE) of the EDFA when the output of the laser is as high as 10 mW. Hence, we can neglect the influence of the ASE noise induced by the EDFA.

Figure 3 shows the forward and backward output powers (measured at points B and C in Fig. 2) versus the input power (measured at point A in Fig. 2). The input power is defined as the threshold of SBS when the backscattered power reaches approximately 0.5% of the input power. The SBS threshold is approximately 6 mW. The curves of the RIN versus the input power for different frequencies are shown in Fig. 4.

In the case of the forward light, it is apparent that the RIN is low when the input power is below the SBS threshold. From the low level, it dramatically increases and gradually stabilizes when the input power is above the threshold. As mentioned before, RIN can be also expressed by ΔI in the simulation and both can be used to describe the intensity fluctuations. At the same time, the variations of the input power are the same with G when $G = g_\mathrm{B}I_\mathrm{p}(0)L$. Based on these two points, the result presented in Fig. 4(a) agrees well with Fig. 1(a) although the corresponding axes are different. Similar experimental results are also presented in Ref. [12]. As mentioned, SBS is initiated from SpBS which has the characteristic of thermal fluctuations. Thus, intensity noise is introduced into the backscattered Stokes light due to the amplification of the thermal noise when SBS occurs. Considering that the input pump power is mainly transferred to the backward Stokes power and to the forward output power, the intensity noise in the forward light is inevitably induced by the noise in the backward light. The intensity noise in the forward light was also attributed to multiple Brillouin scattering processes[3]. Figure 4(a) shows that the RIN at 1-kHz frequency is the highest, whereas the RIN at 20 kHz is the lowest, and the RIN at the mean value between 0 and 20 kHz is the middle value. It should be noted that in practical applications, we should ensure that the input power is below the threshold to prevent SBS-induced intensity noise. This is crucial for a fiber system because the noise decides its sensitivity. To increase the SBS threshold, several methods are used, such as frequency modulation and phase modulation[10,11].

For the backward light, as shown in Fig. 4(b), RIN increases dramatically with the input power near the SBS

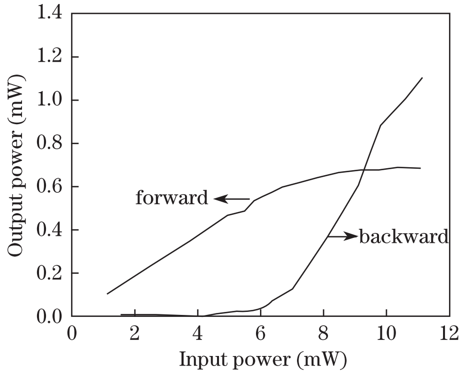

Fig. 3. Forward and backward output powers versus input power.

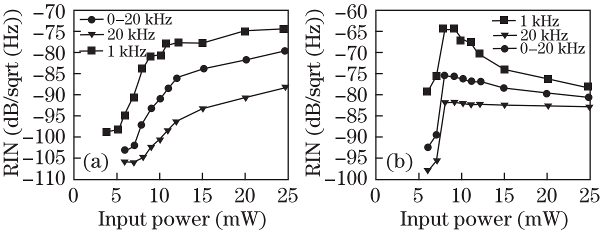

Fig. 4. (a) Forward and (b) backward RINs versus input power for 1, 20, and 0–20 kHz frequencies.

threshold. This indicates that excessive RIN is induced by SBS. When the input power exceeds the threshold (higher than 8 mW), the RIN quickly decreases at first and slowly decreases with the lower frequencies (e.g., 1 kHz). This accords with Fig. 1(b). This phenomenon results from the saturation of the Brillouin amplification process with the increasing input power[6]. However, for the higher frequencies (e.g., 20 kHz), RIN remains constant above the threshold, which implies that the decrease of RIN with the input power above the threshold is mainly due to the lower frequencies of the backward light.

In conclusion, the localized fluctuating model is used to study SBS. The intensity fluctuations versus the single-pass gain have been presented for both forward and backward lights based on the model. In addition, experiments have been conducted to measure RIN at different input powers. When the input power is above the SBS threshold, the forward RIN dramatically increases at first and gradually stabilizes, indicating that the excessive intensity noise is caused by the SBS. Thus, measures must be taken to prevent the occurrence of SBS in practical applications. On the contrary, the backward RIN decreases quickly at first and then decreases slowly in the presence of SBS. This is due to the saturation of the Brillouin amplification process. Furthermore, the decrease of the backward RIN with the input power is mainly due to the lower frequencies. The results and conclusions in the present letter present a good reference for the practical design of fiber transmission systems. Based on these, measures must be taken to suppress SBS as well as the intensity noise that it induces.

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