Stimulated Brillouin scattering-induced phase noise in an interferometric fiber sensing system*

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Stimulated Brillouin scattering-induced phase noise is harmful to interferometric fiber sensing systems. The localized fluctuating model is used to study the intensity noise caused by the stimulated Brillouin scattering in a single-mode fiber. The phase noise structure is analyzed for an interferometric fiber sensing system, and an unbalanced Michelson interferometer with an optical path difference of 1 m, as well as the phase-generated carrier technique, is used to measure the phase noise. It is found that the phase noise is small when the input power is below the stimulated Brillouin scattering threshold, increases dramatically at first and then gradually becomes flat when the input power is above the threshold, which is similar to the variation in relative intensity noise. It can be inferred that the increase in phase noise is mainly due to the broadening of the laser linewidth caused by stimulated Brillouin scattering, which is verified through linewidth measurements in the absence and presence of the stimulated Brillouin scattering.

Keywords: stimulated Brillouin scattering, phase noise, interferometric fiber sensing, intensity noise

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1. Introduction

Interferometric fiber sensing systems have been extensively used for a wide rang of measurands, including acoustic and magnetic fields, and acceleration.[1−3] It is significant to study the phase noise characteristics as they decide the resolution of such systems. Stimulated Brillouin scattering (SBS) is an important nonlinear effect in the fiber,[4−6] and is caused by the interaction between the optical and acoustic waves. SBS occurs easily, as its threshold can be as low as 1 mW for long-haul fiber transmission.[7] In previous work, many models have been proposed to describe the effects of SBS, including the localized non-fluctuating model, the localized fluctuating model and the distributed fluctuating model.[8] It has also been shown that SBS is initiated from spontaneous Brillouin scattering (SpBS) and has stochastic dynamics,[9] and as a result intensity noise is introduced into both the backward Stokes light and the forward transmitted light. Furthermore, excessive phase noise is also brought into the fiber system due to SBS. In order to measure the phase noise, an unbalanced interferometer, as well as the phase-generated carrier (PGC) technique, have been used.[10−12]

In this paper, we investigate SBS with the localized fluctuating model and obtain the relation between intensity fluctuation and input power. We analyze the phase noise structure for an interferometric fiber sensing system, and use an unbalanced Michelson interferometer with a 1 m optical path difference (OPD) to measure the phase noise and present the curves of phase noise versus input power. In addition, we measure the laser linewidths in the absence and presence of SBS. Compared with our last conference paper, which is a simplified version of this one,[13] we extend things by including an analysis of the SBS threshold, a more detailed introduction of the localized fluctuating model, a description of the phase noise structure in the system, the experimental setup, the results of laser linewidth measuring and the practical solutions in application.

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2. Theory

2.1. SBS threshold

Considering the linewidth of the light source, we can give the SBS threshold as[14]

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

where $L_{\rm eff} = [1-\exp(-\alpha L)]/\alpha$, α is the attenuation coefficient of the fiber, L is the fiber length, $g_{\rm B}$ is the peak value of the Brillouin gain, $A_{\rm eff}$ is the effective area of the fiber core, $\Delta\nu_{\rm s}$ is the linewidth of the light source, $\Delta\nu_{\rm B}$ is the spontaneous Brillouin bandwidth and we assume $\Delta\nu_{\rm B} = 50$ MHz, and K is the polarization factor, which accounts for the polarization scrambling between the pump and the Stokes waves. If their polarizations are identical, $K = 1$; while for the complete polarization scrambling in the conventional single-mode fiber (SMF), $K = 2$.[15] For a narrow-linewidth laser, $\Delta\nu_{\rm s}$ is quite small compared with $\Delta\nu_{\rm B}$, so the second term in the bracket can be ignored. Given that $\alpha = 0.2$ dB/km, $L = 50$ km, $g_{\rm B} = 4\times10^{-11}$ m/W, and $A_{\rm eff} = 80$ μm^2, we obtain $P_{\rm th} \approx 4.3$ mW.

2.2. The localized fluctuating model of SBS

The localized fluctuating model of SBS was proposed by Boyd, Rzazewski and Narum.[8] Here, we give a detailed introduction of this model. We assume that SBS is under steady-state conditions and can be described based on the following equations:

$$\begin{aligned} {\rm d}I_{\rm p}/{\rm d}z &= -g_{\rm B}I_{\rm p}I_{\rm s},\\ {\rm d}I_{\rm s}/{\rm d}z &= -g_{\rm B}I_{\rm p}I_{\rm s}, \end{aligned} \tag{2}$$

where $I_{\rm p}$ and $I_{\rm s}$ denote the pump and the Stokes intensities, respectively. It is also assumed that the SpBS, which initiates the SBS, occurs in the rear of the fiber. Using the boundary condition $I_{\rm s}(L) = fI_{\rm p}(L)$ (where f represents the fraction of the backscattered and transmitted intensity at $z = L$) to solve Eq. (2) and ignoring the terms of order f, we obtain

$$G = \frac{\ln R - \ln f}{1-R}, \tag{3}$$

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

$$P(f) = \frac{1}{f_0}\exp(-f/f_0). \tag{4}$$

Thus, f is a stochastic quantity, and its mean value f_0 is about 10^{-12}. Using Eq. (3), we obtain the probability distribution of R as

$$Q(R) = \frac{1}{f_0}\exp\left(\frac{-R\,{\rm e}^{GR-G}}{f_0}\right)(1+GR)\exp(GR-G). \tag{5}$$

Generally, relative intensity noise (RIN) is used to describe the intensity fluctuation, and it can be expressed as

$${\rm RIN} = 10(\langle\delta P^2\rangle/\langle P\rangle^2) = 20((\langle\delta P^2\rangle)^{1/2}/\langle P\rangle), \tag{6}$$

where $\langle P\rangle$ is the average power, and $\langle\delta P^2\rangle$ is the mean-square power fluctuation spectral density. In the localized fluctuating model, we use the normalized standard deviation of the intensity, $\Delta I = (\langle I^2\rangle - \langle I\rangle^2)^{1/2}/\langle I\rangle$, as a measurement of the RIN. The mean values of R and R^2 can be obtained by using Eq. (5) when G and f_0 are given. Considering that the forward output intensity is $I_{\rm p}(L) \approx (1-R)I_{\rm p}(0)$, we can finally obtain the forward intensity fluctuation expressed by ΔI.

The forward ΔI versus G at $f_0 = 10^{-12}$ is shown in Fig. 1. It shows that ΔI is zero when the input power is below the SBS threshold ($G \approx 24$) and increases dramatically at first and then becomes almost constant when the input power is above the threshold.

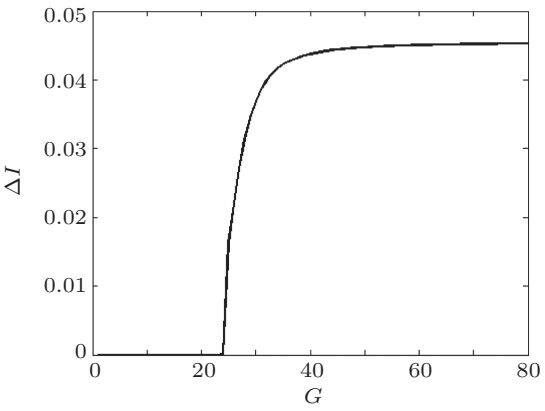


Fig. 1. Forward ΔI versus G at $f_0 = 10^{-12}$.

2.3. The source of phase noise

For an interferometric fiber sensing system, the phase noise mainly results from the following two aspects.

1) The phase noise converted from the RIN, which is also called the Gordon–Mollenauer noise.[16] The

linear part of this phase noise is given by $\langle\delta\varphi^2\rangle = 1/(2Q)$, where $\langle\delta\varphi^2\rangle$ is the phase noise variance, and Q is the signal-to-noise ratio. It can be inferred from the above relation that RIN-induced phase noise is 3 dB lower than RIN. Generally, the nonlinear part of this phase noise is much lower than the linear part and can be neglected for the interferometric fiber sensing system.

2) The phase noise due to the laser linewidth. For an unbalanced interferometer with an OPD of ΔL, this phase noise can be expressed as $\delta\varphi = (2\pi\Delta L/c)\delta\nu$, where c is the speed of light in free space, and $\delta\nu$ is the laser linewidth. It can be easily found that this phase noise is proportional to the laser linewidth.

Based on the above theory, when the input power is below the SBS threshold, the phase noise is mostly due to the RIN and the linewidth of the laser source itself. However, when SBS occurs, SBS-induced RIN can be transferred to the phase noise. Furthermore, since the variance of the laser linewidth can be caused by SBS, the corresponding phase noise will inevitably be introduced.

In order to measure the laser linewidth, many methods have been proposed, including heterodyne,[17] self-heterodyne[18] and self-homodyne.[19] In this paper, self-homodyne is used as the acoustic-optic modulator (AOM) is not needed for this method, which makes the experimental setup simpler than that of the self-heterodyne.

3. Experiments

The experimental setups used to measure the intensity and phase noise are shown in Figs. 2 and 3, respectively. The light from a laser diode (LD) with a 1550 nm wavelength and $\sim$ 10 kHz linewidth is amplified by an erbium-doped fiber amplifier (EDFA) and attenuated by a variable optical attenuator (VOA). So the power launched into the 50 km SMF can be adjusted. Another VOA is placed before the detector to ensure that the same power is detected. An analog-to-digital convertor (A/D) is applied, and the intensity and phase noise are measured with our programs in the computer. Compared with the measuring of the intensity noise, the measuring of the phase noise is a little more complicated. An unbalanced Michelson interferometer with an OPD of 1 m is introduced before the detector, which is encapsulated in a housing design to suppress the environmental noise. As a result, the phase noise is mainly due to the laser and the SBS when the input power is below and above the SBS threshold. Faraday rotators are used to suppress the polarization noise. Furthermore, a piezoelectric transducer (PZT) modulated by a voltage signal (with the other port connected to A/D) is indispensable in measuring the phase noise that uses the PGC technique.

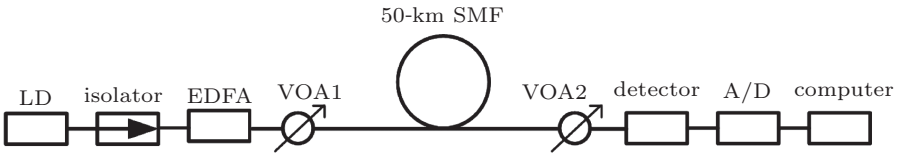


Fig. 2. The experimental setup for measuring intensity noise.

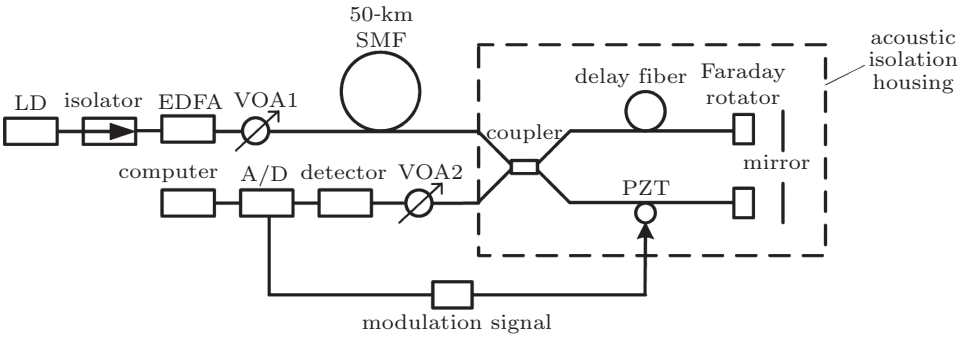


Fig. 3. The experimental setup for measuring phase noise.

The experimental setup used to measure the laser linewidth with the self-homodyne method is shown in Fig. 4. The light from the LD is coupled into an unbalanced Mach–Zehnder interferometer by a 1:1 coupler after 50 km fiber transmission. In one arm of the interferometer, the 25 km delay fiber is followed by an EDFA and an optical filter composed of a circulator and a fiber Bragg grating (FBG), which are used to compensate for the power loss introduced by the delay fiber. The output of the interferometer is received by a detector, and the spectrum is recorded by an electric spectrum analyzer (ESA). According to the self-homodyne method, the half width at half maximum (HWHM) of the spectrum displayed by the ESA, which has a Lorentzian shape, is just the laser linewidth of the LD.

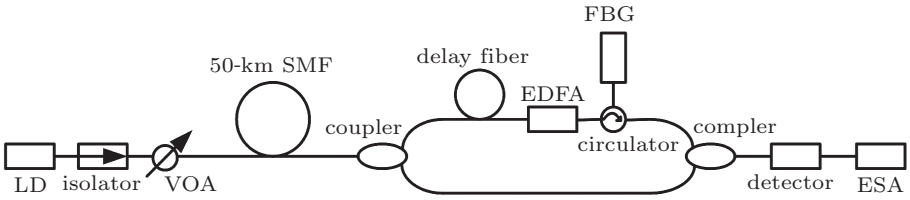


Fig. 4. The experimental setup for measuring laser linewidth.

4. Results and discussion

4.1. SBS-induced intensity noise

The output power versus the input power for the 50 km SMF is shown in Fig. 5. It can be found that the SBS threshold is about 5 mW, which is very close to the theoretical result obtained in the theory part. Figure 6 shows the RIN at frequencies of 3, 4 and 5 kHz versus the input power, and the received power of the detector has been normalized to 5 μW. Obviously, the RIN increases from about −100 to −80 dB/Hz$^{1/2}$ as a result of SBS. In other words, when SBS is present, excessive intensity noise is firstly introduced into the backscattered Stokes light due to the amplification of the thermal noise from the SpBS, and this has the characteristic of a thermal source. Then the intensity noise in the forward light is inevitably induced because of the interactions among the input pump light, the backscattered Stokes light and the forward output light. As shown in Fig. 6, the RIN is small when the input power is below the SBS threshold, and increases dramatically at first and then gradually becomes flat when the input power is above the threshold. As mentioned before, RIN can also be expressed by ΔI in the simulation, and both of them can be used to describe the intensity fluctuation. At the same time, the variations in input power are the same as those of G, as $G = g_{\mathrm{B}} I_{\mathrm{p}}(0) L$. Based on the above two points, the results shown in Figs. 1 and 6 agree well with each other, although the corresponding axes are different.

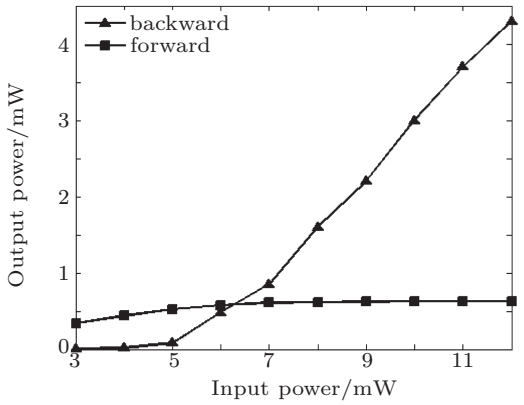


Fig. 5. Output power versus input power for a 50 km SMF.

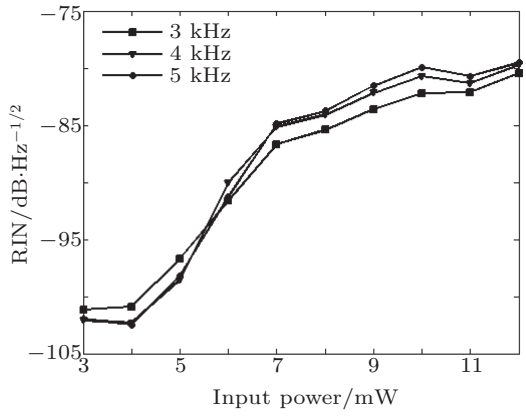


Fig. 6. RIN at frequencies of 3, 4 and 5 kHz versus input power.

4.2. SBS-induced phase noise

The phase noise spectra between 0.1 and 5 kHz are shown in Fig. 7, and the red, green and blue lines correspond to the input powers of 5, 7 and 9 mW, respectively. The frequency of the modulation signal is 12.5 kHz, and the normalized received power of the detector is 5 μW. It can be found that the phase noise is lowest when the input power is 5 mW, and highest when the input power is 9 mW. Figure 8 shows phase noise at frequencies of 3, 4 and 5 kHz versus input power. Due to SBS, the phase noise increases from about −95 dB/Hz$^{1/2}$ to nearly −65 dB/Hz$^{1/2}$. Compared with Fig. 6, it is apparent that the variance in phase noise with input power is similar to that of the RIN. When the input power is below the SBS threshold, the phase noise is small, originating from the laser itself. When the input power exceeds the threshold, the phase noise increases at first and then stabilizes around 11 mW. Similar results can also be found in Ref. [20]. As discussed before, the phase noise in the presence of SBS results mainly from the transfer of SBS-induced RIN and the variance of the laser linewidth caused by SBS. And the RIN-induced phase noise is 3 dB lower than the RIN. However, comparing Fig. 8 with Fig. 6, we find that the phase noise is higher than the RIN when SBS occurs, e.g. the phase noise is about 10 dB higher than the RIN at an input power of 12 mW. So we can conclude that the increase in phase noise is mainly due to the broadening of the laser linewidth caused by SBS. In other words, when SBS occurs, both the RIN transfer and the linewidth broadening lead to the increase in phase noise, however, the latter dominates the process.

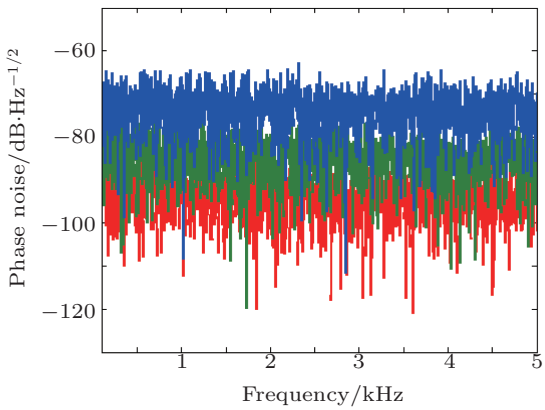


Fig. 7. (colour online) Phase noise spectra at input powers of 5 (red), 7 (green) and 9 mW (blue).

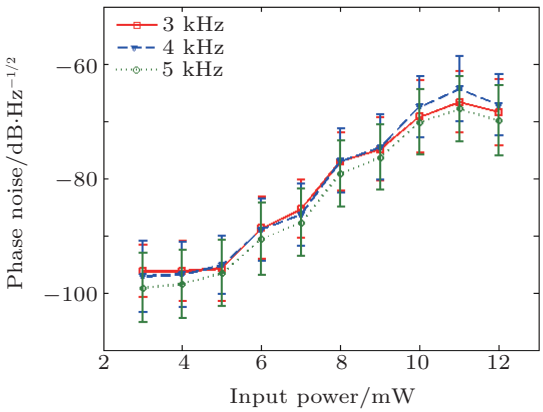


Fig. 8. (colour online) Phase noise at frequencies of 3, 4 and 5 kHz versus input power. Error bars indicate standard deviations.

4.3. Linewidth broadening due to SBS

In order to verify the above conclusion, the laser linewidth in the absence and presence of SBS are measured, and the results are shown in Fig. 9. As the starting frequency of the ESA used in the experiment is 9 kHz, spectra with frequencies lower than 9 kHz can not be observed. Through curve fitting, we obtain the curves, which have an approximately Lorentzian shape. When the input power is 3 mW, SBS does not occur, and the corresponding linewidth is about 11 kHz. However, when the input power is 6 mW, SBS occurs, and the corresponding linewidth is about 17 kHz. The laser linewidth is broadened as a result of SBS, which confirms the above conclusion.

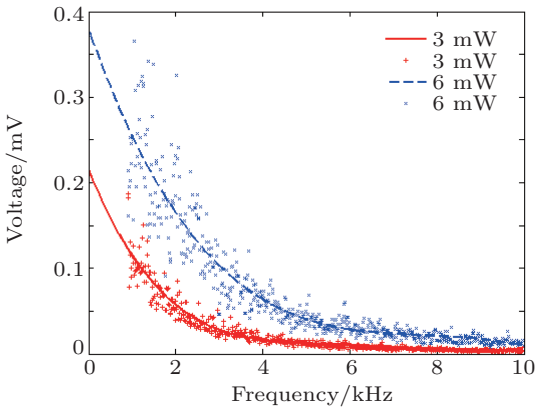


Fig. 9. (colour online) Linewidth measurement at input powers of 3 and 6 mW.

4.4. Solutions in applications

From the above results, it can be found that when SBS occurs, excessive phase noise is induced, giving rise to a sharp increase in the total noise of the system. As a result, the sensitivity of the interferomet-

ric fiber sensing system is reduced, and therefore SBS needs to be suppressed in the practical applications of such systems. To realize this, we have used many methods, including the frequency[21] and the phase[22] modulations. In the frequency modulation, a high-performance laser source whose frequency can be fast-tuned is necessary. In our previous paper,[21] the SBS threshold was only increased from 4.1 to 6.2 mW, as it was limited by our laser source. Compared with the frequency modulation, the phase modulation seems to be more effective, as the threshold can be improved by ~ 7 dB.[22] It is noticed that both methods are based on laser linewidth broadening, which will also induce additional phase noise. Thus the parameters, such as the modulation index and the modulation frequency, should be selected carefully to achieve a balance between SBS suppression and laser linewidth broadening. The relevant contents can be found in our previous paper.[23]

5. Conclusion

In conclusion, the RIN versus the input power is measured, and it is found that the RIN is small when the input power is below the SBS threshold, and increases dramatically at first and then gradually becomes flat when the input power is above the threshold, which is consistent with the theoretical result. The curves of phase noise versus input power at different frequencies are also presented, and they are similar to those of the RIN. The phase noise increase is seen to be mainly due to the broadening of the laser linewidth caused by SBS, and it is found that the linewidth increases from 11 to 17 kHz as the input power increases from 3 to 6 mW for the 50 km fiber transmission, which verifies the above conclusion. Therefore, it is necessary to pay attention to SBS-induced phase noise when we develop a practical long-haul interferometric fiber sensing system.

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