A simple model of suppressing stimulated Brillouin scattering in optical fiber with frequency-modulated laser*

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A simple model is developed to study the mechanism of stimulated Brillouin scattering (SBS) suppression with frequency-modulated laser in optical fiber. By taking into account the laser frequency distribution along the fiber induced by frequency modulation, the average effective Brillouin gain is calculated to determine the SBS threshold. Experimental results show agreement with the numerical analysis. The application for SBS suppression in interferometric fiber sensing system is also discussed in this paper. The results show that the maximum input power can be increased effectively by frequency modulation method.

Keywords: stimulated Brillouin scattering, frequency modulation, interferometric fiber sensing

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1. Introduction

The stimulated Brillouin scattering (SBS) is a very important nonlinear effect in long-haul fiber transmission systems.[1] When the input power is higher than the SBS threshold, the forward transmission power converts to the backscattering Stokes power successively. Owing to this, SBS limits the maximum input power and transmission length of the system. What is worse, SBS brings massive phase noise, which leads to the system performance degradation.[2] So SBS suppression gained much interest in the past years and many SBS suppression methods have been proposed, such as phase modulation,[3] frequency modulation,[4,5] changing Brillouin frequency shift distribution,[6–8] etc. Above all, frequency modulation method is a low-cost and convenient method, for it does not add excess instrument to the system.

Hirose studied the suppression of SBS by frequency modulation in optics communication systems and proposed a model to analyze the mechanism by the effective gain length.[4] In this paper, a simple model based on effective Brillouin gain calculation is proposed to study SBS suppression by frequency modulation. The numerical analysis shows that the SBS suppression factor is related to the modulation frequency and modulation amplitude, which is confirmed by the experiment results. The results show that the frequency modulation method is effective to increase the maximum input power and suppress the phase noise in interferometric fiber sensing systems.

2. Theory

When a single frequency laser is frequency-modulated by a cosine signal, the output frequency of the frequency-modulated laser can be expressed as:

$$\upsilon(t) = \upsilon_0 + \Delta\upsilon \cos(\omega_{\rm m} t), \tag{1}$$

where υ_0 is the output frequency of the laser without frequency modulation, $\Delta\upsilon$ presents the frequency modulation amplitude, and $\omega_{\rm m}$ is the angular frequency of the modulation signal.

When the frequency-modulated laser is launched into a long-haul optical fiber, the laser frequency shows different distributions when the modulation frequencies are different,

$$\upsilon(z,t) = \upsilon_0 + \Delta\upsilon \cos(\omega_{\rm m} nz/c + \omega_{\rm m} t), \tag{2}$$

where z presents a location in the fiber, c is the light velocity in free space, and n is the refractive index. Figure 1 shows the laser frequency distribution along 50-km fiber with different modulation frequencies when the modulation amplitude is 150 MHz at $t = 0$. The vertical coordinate in Fig. 1 presents the laser frequency deviation of $\upsilon(z,0) - \upsilon_0$. It is shown that

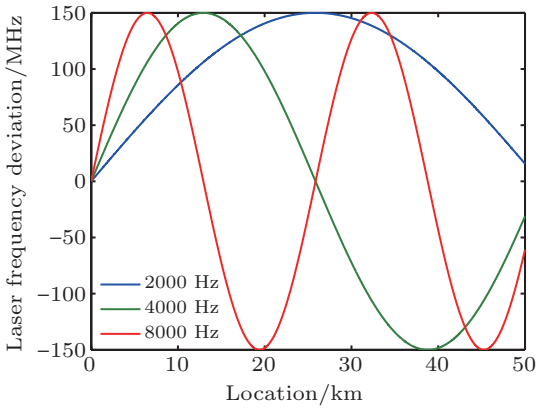


Fig. 1. (color online) The laser frequency distribution along 50-km fiber with different modulation frequencies.

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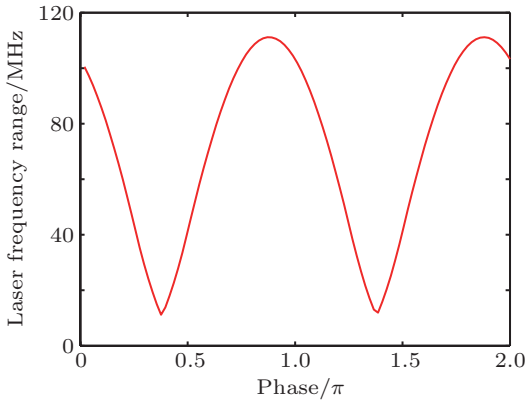


Fig. 2. (color online) The existing laser frequency range in 50-km fiber with modulation frequency 500 Hz in one modulation period.

The existing laser frequency range in the fiber changes with the modulation frequency. Figure 2 shows the laser distribution range versus the modulation phase in a modulation period when the modulation frequency is 500 Hz and the modulation amplitude is 150 MHz, it means that the frequency distribution range also varies with the modulation phase. In a single mode fiber with uniform Brillouin frequency shift, the laser frequency distribution in the fiber determines the Brillouin gain. When the laser frequency distribution range increases, the effective Brillouin gain bandwidth increases, and the Brillouin gain peak decreases. Theoretical analysis shows that the laser frequency distribution range increases with the modulation frequency when the modulation frequency is below c/nL, and keeps nearly constant when the frequency is over c/nL, where L is the fiber length.

In practical applications of frequency modulation in interferometric fiber sensing systems, the modulation frequency is usually less than 1 MHz. Compared to the acoustic damping constant, which is on the order of 10 ns,[9] the frequency modulation period is much longer. So the Brillouin gain can be treated as a Lorentz profile around $\upsilon(z,t)$ as the steady state,[9] which can be obtained from the optical frequency distribution as follows:

$$g_{\mathrm{B}}(\upsilon,z,t)=\frac{(\Delta\upsilon_{\mathrm{B}}/2)^2}{(\upsilon-\upsilon_0-\Delta\upsilon\cos(\omega_{\mathrm{m}}nz/c+\omega_{\mathrm{m}}t)+\upsilon_{\mathrm{B}})^2+(\Delta\upsilon_{\mathrm{B}}/2)^2}g_{\mathrm{P}}, \tag{3}$$

where $\Delta\upsilon_{\mathrm{B}}$ is the natural Brillouin gain linewidth, υ_{B} is the Brillouin frequency shift, g_{P} is the natural Brillouin gain peak. The distribution of $g_{\mathrm{B}}(\upsilon,z,t)$ determines the effective Brillouin gain in the fiber. From Eq. (3), it is suggested that the Brillouin gain profile shows a periodic vibration with the modulation signal, correspondingly, the Brillouin gain pumped by a frequency-modulated laser vibrates periodically.

In a long-haul fiber, the input light acts as the pump light of the SBS. The Stokes light $I_{\mathrm{S}}(\upsilon,z,t)$ can be expressed as:[10]

$$\frac{\mathrm{d}I_{\mathrm{S}}(\upsilon,z,t)}{\mathrm{d}z}=-g_{\mathrm{B}}(\upsilon,z,t)\frac{I_{\mathrm{p}}(z)}{A_{\mathrm{eff}}}I_{\mathrm{S}}(\upsilon,z,t)+\alpha I_{\mathrm{S}}(\upsilon,z,t), \tag{4}$$

where α is the linear loss coefficient of the fiber, $I_{\mathrm{p}}(z)$ is the pump light power at the location z. If the pump depletion is neglected, the pump light can be expressed as follows when the input power is $I_{\mathrm{P}}(0)$:

$$I_{\mathrm{P}}(z)=I_{\mathrm{P}}(0)\exp(-\alpha z). \tag{5}$$

By solving Eq. (4), the Stokes light can be expressed as

$$I_{\mathrm{S}}(\upsilon,0,t)=I_{\mathrm{S}}(\upsilon,z,t)\cdot\exp\left\{-\alpha z+\frac{I_{\mathrm{P}}(0)}{A_{\mathrm{eff}}}\times\int_0^L g_{\mathrm{B}}(\upsilon,z,t)\exp(-\alpha z)\,\mathrm{d}z\right\}. \tag{6}$$

In this paper, $G(\upsilon,t)=\int_0^L g_{\mathrm{B}}(\upsilon,z,t)\exp(-\alpha z)\,\mathrm{d}z$ is defined as the effective Brillouin gain at t. As we all know, SBS occurs first at the frequency where $G(\upsilon,t)$ is the maximum, so the Brillouin gain peak is the key factor to determine the SBS threshold.[8] Generally speaking, we measure the average backscattering power to determine the SBS threshold. So by taking into account the fact that $G(\upsilon,t)$ vibrates with t periodically, an average of $G(\upsilon,t)$ in a modulation period is reasonable to determine the effective Brillouin gain in the numerical calculation. The average effective Brillouin gain which determines the SBS threshold is expressed as:

$$G_{\mathrm{eff}}=\int_0^{2\pi/\omega_{\mathrm{m}}}\max\left\{\int_0^L g_{\mathrm{B}}(\upsilon,z,t)\times\exp(-\alpha z)\,\mathrm{d}z\right\}\mathrm{d}t/(2\pi/\omega_{\mathrm{m}}). \tag{7}$$

For the laser without frequency modulation, the Brillouin gain distribution is constant and the average effective Brillouin gain is shown by

$$G_{\mathrm{eff0}}=g_{\mathrm{p}}L_{\mathrm{eff}}, \tag{8}$$

where $L_{\mathrm{eff}}=(1-\exp(-\alpha L))/\alpha$ is the effective length. The SBS threshold pumped by continuous single frequency laser can be calculated as the following equation[9]

$$P_{\mathrm{th}}=21\frac{KA_{\mathrm{eff}}}{G_{\mathrm{eff}}}. \tag{9}$$

SBS suppression factor is defined as the ratio of SBS threshold with frequency modulation and without modulation. So the SBS suppression factor of frequency modulation method can be expressed as

$$S=\frac{G_{\mathrm{eff0}}}{G_{\mathrm{eff}}}, \tag{10}$$

3. Experiment

The SBS threshold measurement setup is shown in Fig. 3. The semiconductor laser (LD) used in the experiment operates at 1.55 μm with a linewidth of 5 kHz which can be frequency-modulated in hundreds MHz frequency range. The laser is amplified by an erbium-doped fiber amplifier (EDFA) and launched into the 50-km single mode fiber (SMF) through a coupler and a circular, and the fractional ratio of the coupler (CP) is 1:99 to measure the input power by the 1% port. The backscattering power is detected at the circular port 3 by a detector (D2). In the experiment, an arbitrary waveform generator (AWG) is used to generate the sine frequency modulation signal and the Fabry–Perot interferometer (F-P) to measure the average spectrum bandwidth of the forward propagating light.

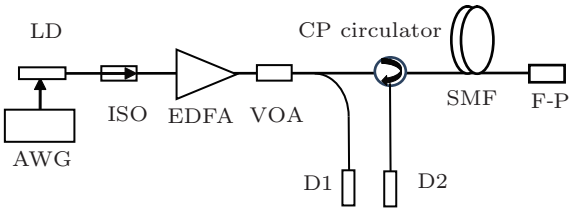


Fig. 3. The experimental setup for SBS threshold measurement.

Figure 4 shows the SBS suppression factor of frequency modulation versus modulation amplitude. In the numerical simulation, the natural Brillouin gain linewidth is 40 MHz, the fiber length is chosen as 50 km, and the modulation frequency is 10 kHz. The experimental and simulation results both show that the suppression factor increases with modulation amplitude. When frequency modulation is applied to the laser, the laser frequency distribution of Eq. (2) makes the effective Brillouin gain linewidth broadened and Brillouin gain peak decreased, which leads to the SBS suppressed.

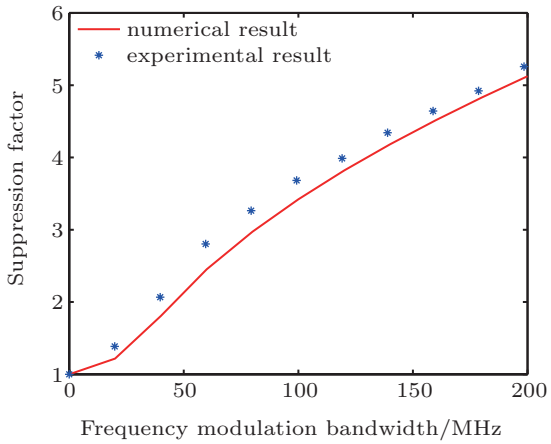


Fig. 4. (color online) SBS suppression factor versus modulation amplitude: theory and experiment.

Figure 5 shows the SBS suppression factor of frequency modulation versus modulation frequency in 50-km SMF. In the numerical simulation, the natural Brillouin gain linewidth is 40 MHz and the modulation amplitude is chosen as 200 MHz. The simulation result shows that when the modulation frequency is less than 4 kHz, the SBS suppression factor increases with the modulation frequency rapidly, and when the modulation frequency is beyond 4 kHz, the SBS suppression factor shows a periodic vibration with the modulation frequency, which tends to be stable at high modulation frequency. The experimental result shows a similar tendency with the numerical result, but the periodic vibration with modulation frequency is not observed clearly, and the reason may be the measurement error and the modulation efficiency of the laser.

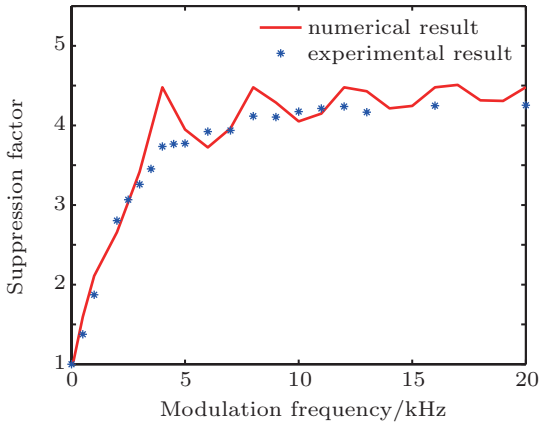


Fig. 5. (color online) SBS suppression factor versus modulation frequency: theory and experiment.

From Fig. 2, the existing laser frequency range in the fiber vibrates with time, which leads to the Brillouin gain peak changing correspondingly. Figure 6 shows the Brillouin gain peak in a modulation period by numerical simulation, in which two peaks of the effective Brillouin gain in a modulation period are shown. The two gain peaks result in two power peaks of the backscattering Stokes light, which is observed by the experiment in Fig. 7. It is observed that the two power peaks of the Stokes light is not equal and there is a phase deviation between the forward propagating light power and the Stokes light power, which is well-founded. For the semiconductor laser used in the experiment, the blue line in Fig. 7 shows that an excess amplitude modulation is applied to the forward propagating light by the frequency modulation. On the other hand, figure 6 shows that Brillouin gain has two equal peaks in a period at the top and bottom, respectively. The two peaks of the Stokes power indicates the two Brillouin gain peaks in a modulation period, and the inequality is induced by the excess amplitude modulation. The phase deviation between the forward propagating power and Stokes power is owing to the optics delay between them. The experimental results confirmed that the theoretical analysis of average Brillouin gain is effective to determine the SBS threshold.

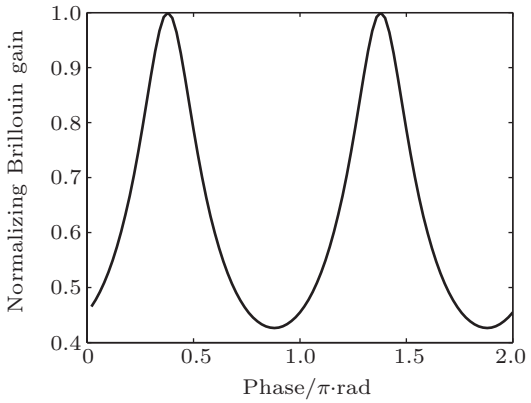


Fig. 6. The numerical Brillouin gain in a modulation period.

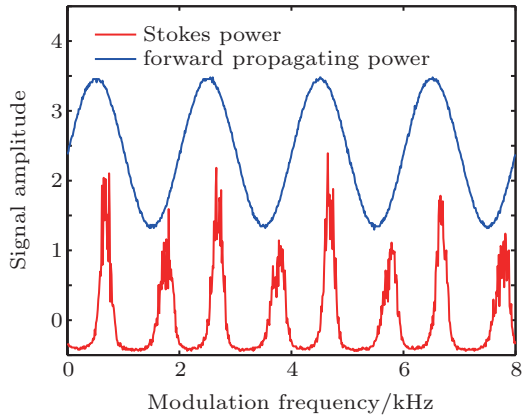


Fig. 7. (color online) The observed backscattering Stokes power and forward propagating power.

In practical application of SBS suppression by frequency modulation, it is reasonable to choose the modulation frequency above c/nL and the modulation amplitude as high as possible.

In PGC-based interferometric fiber sensing systems, the frequency modulation method is widely used to generate PGC carrier, which can increase the maximum input power simultaneously. Phase noise is a key factor to determine the performance of the system. So we measured the phase noise versus input power when the PGC carrier is generated by laser frequency modulation and PZT modulation respectively. The experimental result in Fig. 8 shows that the laser frequency modulation suppresses SBS and phase noise effectively. The result is meaningful in designing remote interferometric fiber sensing systems. According to the results in the previous sections, the SBS suppression factor increases with frequency modulation amplitude. However, the modulation amplitude is determined by the following equation

$$C = \frac{4\Delta\upsilon}{\upsilon_{\mathrm{m}}} \sin(\omega_{\mathrm{m}}\Delta L/2c), \tag{11}$$

where ΔL represents the path difference of the interferometer, and $\upsilon_{\mathrm{m}} = \omega_{\mathrm{m}}/2\pi$. In PGC-based interferometric fiber sensing systems, C is usually chosen as a constant for the accurate demodulation of the signal, ω_{m} is a factor that determines the measurement bandwidth, so we can choose $\Delta\upsilon$ and ΔL to obtain a higher SBS suppression factor. Because the SBS suppression factor increases with modulation amplitude, so a shorter path difference is better for a higher SBS suppression factor. In the other word, a shorter optical path difference leads to a lower phase noise, which can enhance the sensitivity of the system. But the SBS suppression factor is limited by the maximum modulation amplitude which is determined by the modulation performance of the laser. This gives some reference in designing the interferometric fiber sensing systems.

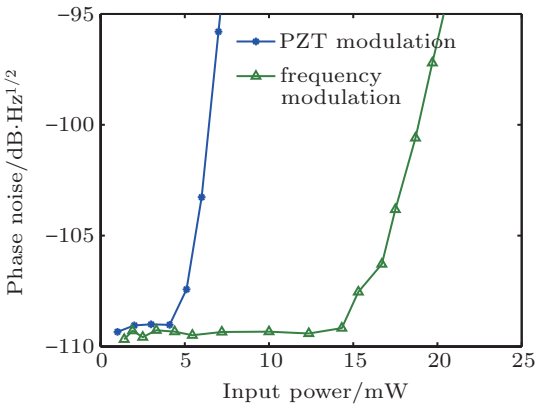


Fig. 8. (color online) Phase noise versus input power.

4. Conclusion

In the paper, SBS suppression mechanism by frequency modulation is studied in theory and experiment. A simple model is proposed and verified by the experiment. The results show that the SBS suppression factor can be calculated by the average effective Brillouin gain owing to the frequency distribution. We found that the SBS suppression factor is related to the modulation frequency and amplitude. To suppress SBS effectively, the modulation frequency should be chosen above c/nL and modulation amplitude as high as possible. In PGC-based interferometric fiber sensing systems, frequency modulation method is effective to suppress SBS and phase noise, it is better to choose a shorter path difference interferometer and a higher modulation amplitude to obtain a higher SBS suppression factor.

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