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An optical modulation method to suppress stimulated Brillouin scattering and the phase noise in a remote interferometric fiber sensing system

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ABSTRACT

A novel optical modulation method for stimulated Brillouin scattering (SBS) and the phase noise suppression in a remote interferometric fiber sensing system is proposed. Compared to the conventional phase modulation method to suppress SBS with only one phase modulation signal, another phase modulation signal with π shift is applied at the output end of the fiber, which converts the generated multi-frequency light to single-frequency light. Therefore the method can suppress not only SBS but also the phase noise induced by linewidth broadening owing to the first phase modulation. As a result, the method can keep the system a low phase noise level with a higher input power, which overcomes the conventional drawback of linewidth broadening. The results show a good reference to the design of remote interferometric fiber sensing systems.

1. Introduction

Interferometric fiber sensing systems have been widely applied in the fields such as oil exploration, seismic wave test and underwater signal detection [1,2]. However, with the increased transmission length of the systems, varieties of nonlinear effects become significant and lead to the phase noise increasing. Stimulated Brillouin scattering is the most significant for its lowest threshold power [3]. Various methods have been proposed to suppress SBS, among which phase modulation is an effective and convenient method [4–9]. Chen et al. studied the effects of phase modulation on SBS for phase noise suppression in a remote interferometric fiber sensing system. The results show phase modulation suppresses SBS and SBS induced phase noise effectively, but the linewidth broadening induced by phase modulation leads to the excess phase noise increasing [10]. The linewidth broadening induced by phase modulation sets a limit to the further suppression of the phase noise.

To overcome the linewidth broadening induced by phase modulation, a novel optical modulation method for SBS and phase noise suppression in remote interferometric fiber sensing systems is presented. A phase modulation signal is applied at the input end of the transmission fiber to generate multi-frequency light, and another phase modulation signal with a phase shift of π is applied at the output end of the fiber to convert the multi-frequency light to the single-frequency light [11]. Compared to the conventional phase modulation method, the novel method suppresses not only SBS but also the phase noise induced by linewidth broadening due to phase modulation. The research is meaningful in the design of remote interferometric fiber sensing systems.

2. Theory

SBS is a nonlinear effect caused by the interaction between the optical and acoustic waves in the fiber [12]. The backscattered power increases massively when the input optical power exceeds the SBS threshold. The SBS threshold P_t in the optical fiber is given by [13]:

$$P_t = 21\frac{KA_{eff}}{g_B L_{eff}}\left(1+\frac{\Delta\upsilon}{\Delta\upsilon_B}\right), \quad (1)$$

where K is the polarization factor($1 \leqslant K \leqslant 2$), A_{eff} is the fiber effective core area, g_B is the peak Brillouin gain coefficient, L_{eff} is the effective fiber length, $L_{eff} = (1-\exp(-\alpha L))/\alpha$ (α is the attenuation coefficient of the fiber and L is the fiber length), $\Delta\upsilon$ is the linewidth of the light and $\Delta\upsilon_B$ is the spontaneous Brillouin gain bandwidth. More precisely, the SBS threshold can be determined by the acoustic-optic effective area rather than the fiber effective core area [14].

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However, the difference is negligible in the step-index single mode fiber used in the experiment, so we still calculate the SBS threshold by equation (1), by which the calculated SBS threshold can be lower than 5 mW in 50 km single mode fiber (SMF). In an interferometric fiber sensing system, once the input power exceeds the SBS threshold, SBS initiates massive phase noise and leads to a serious decrease in sensitivity [15].

By single-frequency cosinusoidal phase modulation, a single-frequency light (Fig. 1a) can be converted to multi-frequency light (Fig. 1b), which can be expressed as:

$$E = E_0 \cos(\omega_0 t + \delta \cos(\omega_1 t) + \varphi_0), \quad (2)$$

where E_0 is the electric amplitude of the input light, δ is the modulation index which can be expressed by $\delta = V\pi/V_\pi$ (where V is the amplitude of the modulation signal and V_π is the half wave voltage

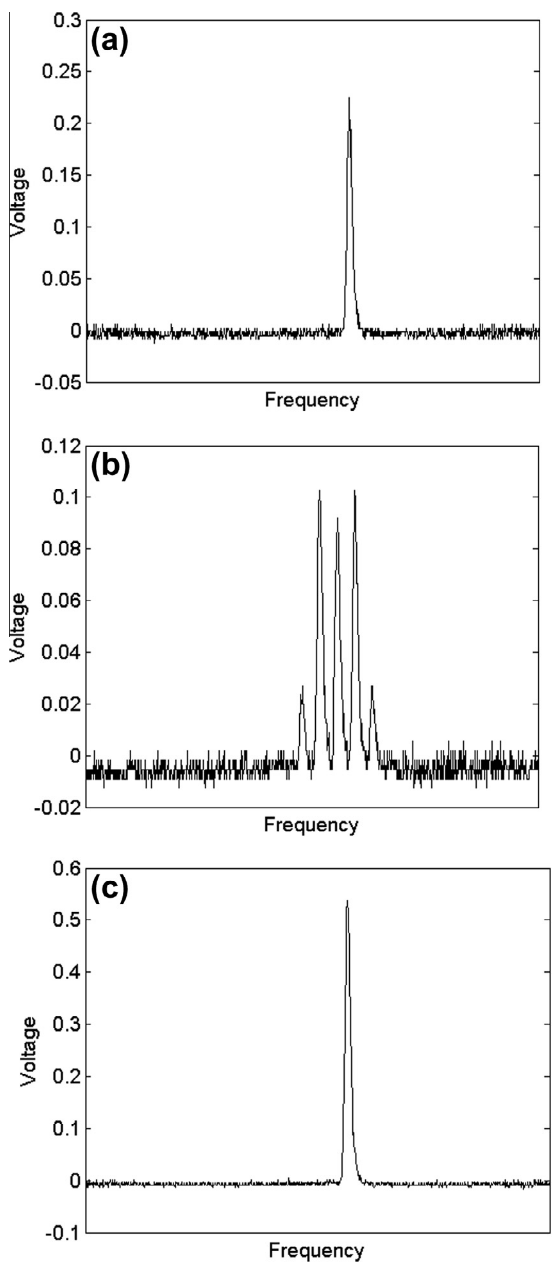

Fig. 1. The light spectrum detected by a Fabry–Perot interferometer (a) Original single frequency light, (b) Modulated light with the first phase modulation, (c) Light with the pi-shifted phase modulation.

of the phase modulator), ω_1 is the angular frequency of the modulation signal, ω_0 and φ_0 are the angular frequency and initial phase of the input light, respectively. Equation (2) can be expressed in Bessel function form as follows:

$$E = E_0 \cdot \left(\sum_{k=0}^{\infty} A_k(\delta) \cos(\omega_0 t + k\omega_1 t + \varphi_1 + \varphi_0) \right), \quad (3)$$

where $A_k(\delta) = (-1)^k J_k(\delta)$, $\varphi_1 = \pi/4 + (-1)^{k+1} \cdot \pi/4$. It can be shown that phase modulation broadens the input light linewidth by generating sidebands around the optical frequency. So the energy of the input light transfers from the original single-frequency to all sidebands. If the modulation frequency is over the Brillouin gain linewidth, the SBS threshold is determined by the maximum optical sideband power, and the threshold power of SBS can be increased by $1/\max|A_k(\delta)|^2$ [9].

However, in a remote interferometric fiber sensing system, phase noise is a key factor that determines the sensitivity of the system. The phase noise increases with the linewidth of the light according to equation (4) [16]:

$$\Delta\varphi = \frac{2\pi\Delta L}{c}\Delta\upsilon, \quad (4)$$

where ΔL represents the optical path difference of the Michelson interferometer and c is the light velocity in free space.

The modulated light has a wider linewidth than the single-frequency light, which leads to phase noise increasing. To suppress the phase noise induced by linewidth broadening, another phase modulation with a phase shift of π compared to the previous one is applied to the modulated light at the output end of the fiber. Then the light is obtained as equation (5):

$$\begin{aligned} E &= E_0 \cos(\omega_0 t + \delta\cos(\omega_1 t) + \delta\cos(\omega_1 t + \pi) + \varphi_0 + \varphi_d) \\ &= E_0 \cos(\omega_0 t + \varphi_0 + \varphi_d) \end{aligned} \quad (5)$$

where φ_d represents the phase delay induced by the transmission fiber. Hence, the single-frequency light is obtained again by the second phase modulation (Fig. 1c). The light propagating in the transmission fiber is the modulated light to suppress SBS, and the input light of the interferometer is the single-frequency light, which avoids the linewidth broadening induced phase noise. The novel method overcomes the drawback of linewidth broadening induced by phase modulation.

3. Experimental setup

The experimental setup for the measurement of the phase noise is shown in Fig. 2.

The single-frequency light from a laser diode (LD) with 1550 nm wavelength is modulated by a $LiNbO_3$ phase modulator (PM1) after the isolator (ISO). Then the modulated light is amplified by an erbium-doped fiber amplifier (EDFA) and attenuated by a variable optical attenuator (VOA1) to obtain different powers before entering the 50 km SMF. The forward propagating light is modulated by another phase modulator (PM2) at the output end of the SMF. The Michelson interferometer with 1 m optical path difference is encapsulated in a box to suppress the environmental noise and two Faraday rotation mirrors (FRM1/2) are used to suppress the polarization noise [17]. The piezoelectric transducer (PZT) is wrapped with fiber to be modulated by a 32 kHz cosinusoidal signal for phase generated carrier (PGC) demodulation technique [18]. Another variable attenuator (VOA2) is placed at the output port of the interferometer to keep a constant power to the detector (D). The signal is detected by a detector and converted to digital form by an analog-to-digital converter (A/D) to be proceeded with the