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Signal-to-noise ratio improvement in Brillouin optical correlation domain analysis combining Brillouin gain and loss effects

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ABSTRACT

A novel scheme is proposed to measure Brillouin gain spectrum in an optical fiber combining Brillouin gain and loss effects. A dual-parallel Mach-Zehnder modulator is used to generate upshifted afterward downshifted single sideband with suppressed carrier by periodically chopping the dc bias. The two successive single sidebands serve as Brillouin pump and probe waves to amplify and absorb the carrier wave for lock-in detecting of the net Brillouin gain between Brillouin gain and loss effects. The signal-to-noise ratio of the cost-effective measurement system with fewer optical devices is twofold enhanced. Distributed strain sensing ability with a nominal spatial resolution of 1.6 cm is experimentally demonstrated by utilization of this scheme into a Brillouin optical correlation domain analysis system.

Keywords: Stimulated Brillouin scattering, fiber optic distributed sensors, BOCDA, single sideband modulation

1. INTRODUCTION

Distributed optical fiber sensors based on Brillouin scattering have been studied for decades because they can be used for distributed temperature or/and stain measurements [1-5] in smart materials and smart structures. There has been a challenge to achieve high spatial resolution in the time-domain pulse-based distributed sensing system [6, 7]. This is because the spatial resolution determined by the pulse width is limited to be meter order due to the narrow-bandwidth nature of the Brillouin gain [6] or loss [7] effect. Recently, new proposals [8, 9] were presented to achieve time-domain cm-order distributed sensing ability, which needs sophisticated control of optical/electronic devices. Thanks to continuous-wave mechanism, in contrast, Brillouin optical correlation-domain analysis (BOCDA) [10-13] can provide cm-order or even mm-order spatial resolution, and the high spatial resolution can be easily tuned by the parameters of the frequency modulation to the laser source. In a traditional BOCDA system [10-13], frequency-modulated Brillouin pump and probe waves serve as two counter-propagating beams in a sensing optical fiber, respectively. The frequency difference between the pump and probe waves is generated by a single-sideband modulation technique. The localized Brillouin gain spectrum (BGS) in a short fiber segment (i.e., the spatial resolution) is interrogated by lock-in detecting of the Brillouin interaction (i.e., only the Brillouin gain), which needs assistance of an intensity modulator and high-cost erbium-doped fiber booster [12, 13].

In this work, we demonstrate a novel method of measuring the net BGS in a short fiber segment by successive combination of the Brillouin gain and loss effects. Comparing the usual method by only measuring Brillouin gain or loss effect, this novel method can improve the signal-to-noise ratio (SNR) by 3 dB. It is experimentally demonstrated that a simple component of a dual-parallel Mach-Zehnder modulator (DMZM) is sufficient to generate the waves working for both Brillouin gain and loss effects, which enables the measurement system superior and more cost-effective. The distributed strain sensing ability with a nominal spatial resolution of 1.6 cm is also experimentally verified by use of this method into a BOCDA system.

2. PRINCIPLE AND EXPERIMENTAL SETUP

Stimulated Brillouin scattering (SBS) occurs when two lightwaves, called the Brillouin pump and the probe waves, counter-propagate in an optical fiber and the probe frequency is downshifted with respect to that of the pump by the Brillouin frequency shift (ν_B). The SBS interaction not only causes strong gain to the probe wave but also generates

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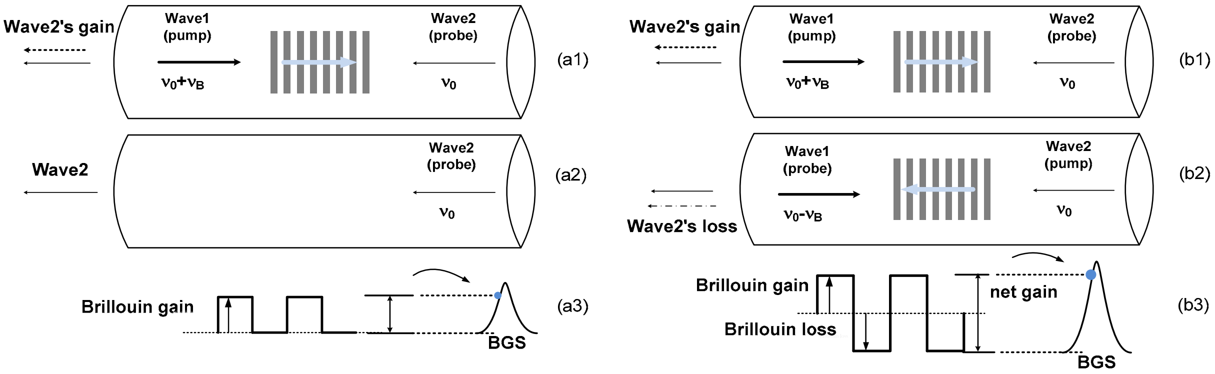

Fig. 1. Schematic comparison of the traditional BGS measurement only using Brillouin gain (a1, a2, a3) and the novel BGS measurement of the net gain combining Brillouin gain and loss effects (b1, b2, b3).

corresponding loss to the pump wave, which are called Brillouin gain and loss effects, respectively. Figure 1 illustrates a schematic comparison between the traditional BGS measurement scheme and the proposed novel scheme. In Figs. 1(a1, a2, a3), the wave2 (probe) is downshifted in frequency with respect to the wave1 (pump) by a magnitude of around the ν_B, and their interference generates an acoustic grating moving in the same direction as the wave1. The BGS is precisely lock-in detected when the wave1 is periodically turned on and off by an additional intensity modulator [12, 13]. In contrast, as shown in Figs. 1(b1, b2), if the optical frequency of the wave2 is fixed while that of the wave1 is upshifted afterwards downshifted, the wave1 and wave2 alternatively exchange between Brillouin pump and probe waves and thus they generate acoustic grating in two opposite directions, respectively. During the alternative exchange of the two waves, the net Brillouin gain between Brillouin gain and loss effects shown in Fig. 1(b3) can be extracted by lock-in detection, which is twofold improved in the SNR (i.e., by 3dB) in comparison with Fig. 1(a3).

The experimental setup of the proposed novel scheme of the BGS measurement is depicted in Fig. 2. A 1553 nm distributed-feedback laser diode (DFB-LD) was used as the laser source, and its output was divided into two beams by a 30/70 optical coupler. One beam (30%, wave2) with ~6 dBm optical power was directly injected into a 5-m-long single-mode fiber under test (FUT) after passing through a 5-km delay fiber, which was used to generate a higher-order correlation peak laid in the FUT for distributed BGS measurement in the modified BOCDA system explained below. The other beam (70%, wave1) was modulated by a 20-GHz $LiNbO_3$ dual-parallel Mach-Zehnder modulator (DMZM) driven by a microwave generator (ν).

The DMZM comprises two parallel Mach-Zehnder modulators and a parent Mach-Zehnder modulator that is biased at the third bias [14]. When the third bias is alternatively set by a low-level or high-level voltage, the parent Mach-Zehnder modulator is zero-biased or π-biased. In consequence, the optical output from the DMZM is a suppressed-carrier single-sideband signal with the suppression ratio of more than 25 dB, which is upshifted or downshifted in frequency as illustrated in Fig. 3 for ν =10.85GHz. The wave1 of the upshifted or downshifted single-sideband signal was amplified by an erbium-doped fiber amplifier (EDFA) to ~23 dBm and launched into the FUT through a circulator. The counter-propagating wave1 and wave2 generate acoustic grating moving along the FUT in the counterclockwise or clockwise direction, which depends on the wave1 being the upshifted or downshifted single sideband. The wave2 suffering Brillouin gain or loss from the wave1 was circled towards a variable optical attenuator (VOA) by the circulator, and then transformed to electronic domain by a 100 MHz photo-detector (PD). We applied a 10 kHz electronic square wave into the third bias of the DMZM, introducing a periodical switching of the wave1 from the upshifted to downshifted single-sideband signal. The amplified or absorbed wave2 was demodulated by a lock-in amplifier (LIA) at the chopping frequency of 10 kHz, which was recorded by a personal computer via a data-acquisition card (DAQ).

3. EXPERIMENTAL RESULTS

First, we verified the feasibility of the proposed scheme for the BGS measurement in an entire 5-m-long FUT. The microwave generator was swept from 10.7 GHz to 11GHz. The experimental results are shown in Fig. 4. It can be seen that when the high-level or low-level voltage of the electronic square wave applied to the third bias of the DMZM is increased, the peak of the net BGS is approximately linearly enhanced or weakened. This is because the detuned voltages vary the extinction ratio of the upshifted or downshifted single sideband to the other sideband as well as the carrier, changing the magnitude of the Brillouin gain or loss effects and consequently altering the net gain or the peak of the

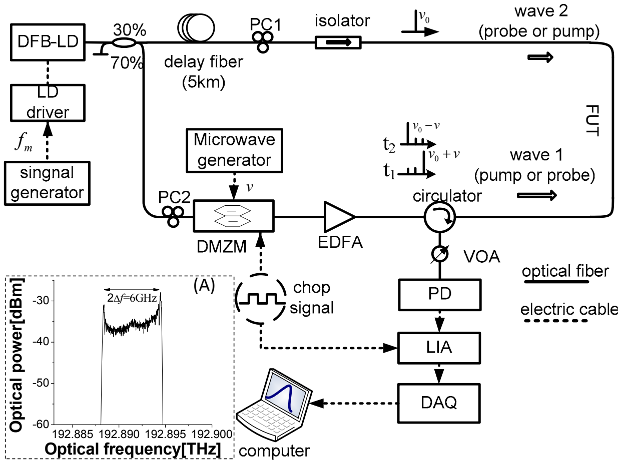

Fig. 2. Experimental setup of the novel BGS measurement scheme combing Brillouin gain and loss effects. The novel scheme can be used as a modified BOCDA system if a sinusoidal frequency modulation is introduced into a distributed-feedback laser (DFB-LD) with the measured optical spectrum shown in the inset of "A". PCs, polarization controllers; EDFA, erbium-doped fiber amplifier; DMZM, dual parallel Mach-Zehnder modulator; FUT, fiber under test; VOA, variable optical attenuator; PD, photo-detector; LIA, lock-in amplifier; DAQ, data-acquisition card.

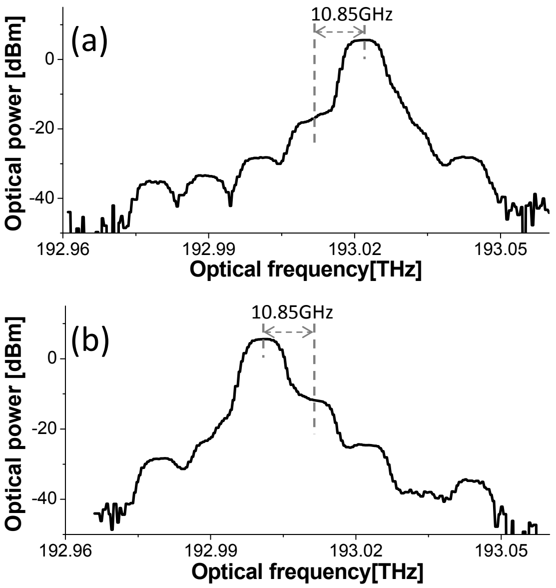

Fig. 3. Measured optical spectrum of the wave1 launched from the DMZM biased by a high-level voltage for Brillouin pump (a) or a low-level voltage for Brillouin probe (b).

measured BGS. Note that the SNR of the proposed scheme is twofold improved due to the combination of Brillouin gain and loss effects when compared to the traditional scheme [12, 13].

Next, we adopted the proposed scheme into a BOCDA system by introducing a sinusoidal frequency modulation to the laser source. The inset (a) of Fig. 2 indicates the optical power spectrum of the frequency-modulated laser source giving a modulation depth Δf=3 GHz. The modulation frequency (f_m) was scanned within the range of 19.993-20.0134 MHz for distributed measurement of BGS along the FUT. The measurement range (d_m) and the spatial resolution (Δz) are defined by [10]:

$$d_m = \frac{c}{2n_{eff} f_m}, \quad \Delta z = \frac{c}{2n_{eff} f_m} \frac{\Delta \nu_B}{\pi \Delta f}, \qquad (1)\ \&\ (2)$$

where c is the light speed in vacuum, n_{eff} = 1.446 the effective refractive index of the FUT, and $\Delta\nu_B$ = 30MHz the Brillouin bandwidth. According to Eqs. (1) and (2), the nominal performances of the modified BOCDA can be estimated to be d_m = 5.2 m and Δz = 1.6 cm.

The 5-m FUT was constructed by applying axial strain upon a 5-cm portion. We measured the BGS distribution by the combination of Brillouin gain and loss effects. An example of the 3-dimentional (3D) BGS distribution around the strained portion is depicted in Fig. 5(a) for an axial strain of $\Delta\varepsilon$ = 820 με. The Brillouin frequency shift ν_B distribution is extracted through Lorentzian fitting to the measured BGS distribution. The results for three different axial strains are summarized in Fig. 5(b), which clearly identify the strained portions and the applied strains. The accuracy of the ν_B measurement was estimated to be about ±1 MHz for the current setup.

4. CONCLUSIONS

We have demonstrated a novel scheme of the BGS measurement combining the Brillouin gain and loss effects and utilized it into a BOCDA system. The novel scheme is more cost-effective with fewer optical devices when compared to the traditional system [12, 13] since one DMZM and one EDFA are sufficient for the generation of Brillouin pump/probe waves and the lock-in detection. The feasibility of the novel scheme with a twofold SNR improvement has been principally analyzed and experimentally verified. Besides, the distributed strain sensing ability with the 1.6-cm nominal spatial resolution in the modified BOCDA system has been also confirmed. It is expected that the novel scheme will enable the distributed BOCDA system with more feasibility and cost-effectiveness as a fiber-optic nerve system in smart materials and smart structures.

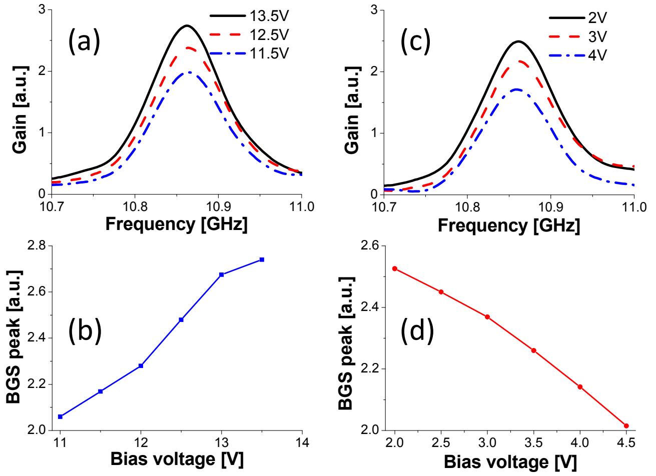

Fig. 4. Measured BGS (above) and peak (below) of the net gain when increasing the high-level (a,b) or low-level (c,d) voltage of the electronic square wave on the third bias of DMZM.

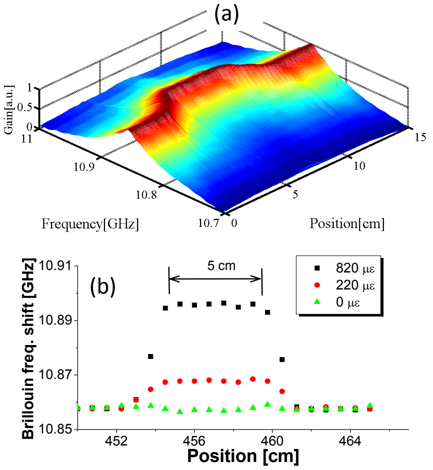

Fig. 5. (a) 3D plot of the distributed BGS and (b) measured Brillouin frequency shift (ν_B) distribution around strained fiber portion.

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REFERENCES

[1]. T. Horiguchi, T. Kurashima, and M. Tateda, "Technique to measure distributed strain in optical fibers," IEEE Photon. Technol. Lett. 2(5), 352-354 (1990).

[2]. T. Kurashima, T. Horiguchi, and M. Tateda, "Thermal effects of Brillouin gain spectra in silica optical fibers," IEEE Photon. Technol. Lett. 2(10), 718–720 (1990).

[3]. W. Zou, Z. He, and K. Hotate, "Investigation of strain- and temperature-dependences of Brillouin frequency shifts in GeO_2-doped optical fibers," J. of Lightwave Technol. 26(13), 1854-1861 (2008).

[4]. W. Zou, Z. He, and K. Hotate, "Complete discrimination of strain and temperature using Brillouin frequency shift and birefringence in a polarization-maintaining fiber," Opt. Express 17(3), 1248–1255 (2009).

[5]. W. Zou, Z. He, and K. Hotate, "One-laser-based generation/detection of Brillouin dynamic grating and its application to distributed discrimination of strain and temperature," Opt. Express 19(3), 2363-2370 (2011).

[6]. M. Niklès, L. Thévenaz, and P. A. Robert, "Simple distributed fiber sensor based on Brillouin gain spectrum analysis," Opt. Lett. 21(10), 758-760 (1996).

[7]. X. Bao, A. Brown, M. DeMerchant, and J. Smith, "Characterization of the Brillouin-loss spectrum of single-mode fibers by use of very short (<10ns) pulses," Opt. Lett. 24(8), 510–512 (1999).

[8]. W. Li, X. Bao, Y. Li, and L. Chen, "Differential pulse-width pair BOTDA for high spatial resolution sensing," Opt. Express 16(26), 21616-21625 (2008).

[9]. K. Y. Song, S. Chin, N. Primerov, and L. Thévenaz, "Time-domain distributed fiber sensor with 1 cm spatial resolution based on Brillouin dynamic grating," J. Lightwave Technol. 16(26), 21616-21625 (2010).

[10]. K. Hotate and T. Hasegawa, "Measurement of Brillouin gain spectrum distribution along an optical fiber using a correlation-based technique—Proposal, experiment and simulation," IEICE Trans. Electron. E83-C(3), 405-412 (2000).

[11]. K. Hotate, and M. Tanaka, "Distributed fiber Brillouin strain sensing with 1-cm spatial resolution by correlation-based continuous-wave technique," IEEE Photon. Technol. Lett. 14(2), 179-181 (2002).

[12]. K. Y. Song, Z. He, and K. Hotate, "Distributed strain measurement with millimeter-order spatial resolution based on Brillouin optical correlation domain analysis," Opt. Lett. 31(17), 2526–2528 (2006).

[13]. W. Zou, Z. He, M. Kishi, and K. Hotate, "Stimulated Brillouin scattering and its dependences on temperature and strain in a high-delta optical fiber with F-doped depressed inner cladding," Opt. Lett. 32(6), 600–602 (2007).

[14]. A. Loayssa, R. Hernández, D. Benito, and S. Galech, "Characterization of stimulated Brillouin scattering spectra by use of optical single-sideband modulation," Opt. Lett. 29(6), 638-640 (2004).