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## Distributed Strain Sensing Based on Combination of Brillouin Gain and Loss Effects in Brillouin Optical Correlation Domain Analysis

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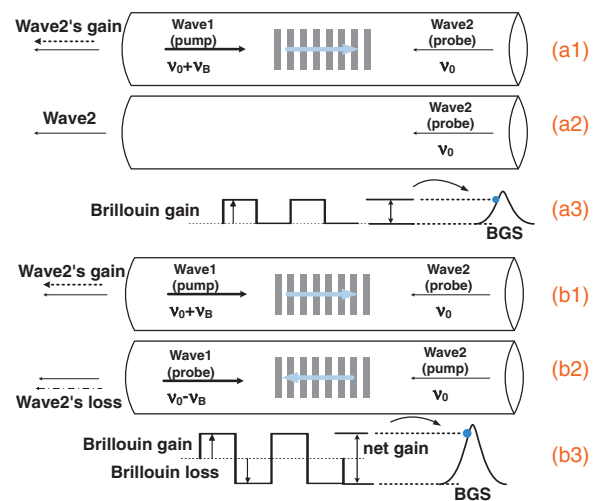
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We propose a novel scheme to improve the Brillouin optical correlation domain analysis (BOCDA) system by combining Brillouin gain and loss effects. Periodical chopping of the dc bias of a dual-parallel Mach-Zehnder modulator is used to successively generate upshifted or downshifted single-sideband signal with suppressed carrier. The successively generated signal serves as a Brillouin pump (probe) to amplify (absorb) the carrier for lock-in detection of the net gain between Brillouin gain and loss effects. The signal-to-noise ratio of the novel scheme is twofold enhanced and the feasibility of distributed strain sensing with a nominal spatial resolution of 1.6 cm is experimentally demonstrated.

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**B**rillouin-scattering-based distributed optical fiber sensors have been studied for decades because they can be used for distributed temperature or/and strain measurements<sup>1-5</sup> 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.<sup>6,7</sup> 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<sup>6</sup> or loss<sup>7</sup> effect. Recently, new proposals<sup>8-10</sup> have been presented to achieve time-domain centimeter-order distributed sensing ability, which needs sophisticated control of optical/electronic devices. Thanks to a continuous-wave mechanism, in contrast, Brillouin optical correlation-domain analysis (BOCDA)<sup>11-14</sup> can provide centimeter-order or even millimeter-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,<sup>11-14</sup> frequency-modulated Brillouin pump and probe waves serve as two counter propagating beams in a sensing optical fiber. 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 detection of the Brillouin interaction (i.e., only the Brillouin gain), which needs the assistance of an intensity modulator and a high-cost erbium-doped fiber booster.<sup>13,14</sup>

This paper demonstrates a novel scheme of measuring the net BGS in a short fiber segment and its application to a BOCDA system by successive utilization of the Brillouin gain and loss effects. In comparison with the usual method of measuring the Brillouin gain effect,<sup>13,14</sup> this novel method can improve the signal-to-noise ratio (SNR) by about 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 when compared with the scheme demonstrated in ref. 10 where optical dividing and filtering were needed for Brillouin optical time-domain analysis system. The novel scheme is utilized into a BOCDA system, which is more cost-effective than the traditional BOCDA system.<sup>13,14</sup> Its distributed strain-sensing ability with a nominal spatial resolution of 1.6 cm is also experimentally verified.



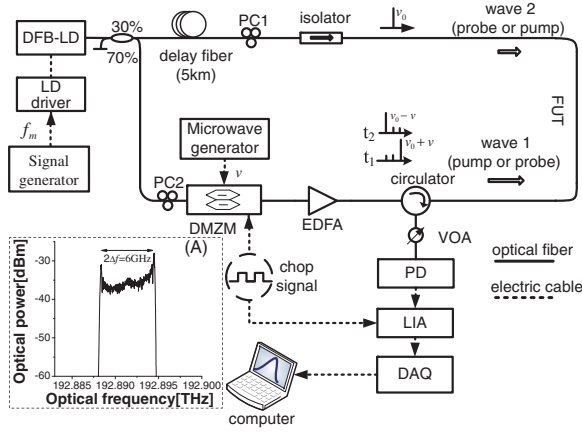
**Fig. 1.** Schematic comparison of the traditional BGS measurement using only Brillouin gain (a1–a3) and the novel BGS measurement of the net gain combining Brillouin gain and loss effects (b1–b3).

Figure 1 illustrates a schematic comparison between the traditional BGS measurement scheme<sup>13,14</sup> and the proposed novel scheme. In Figs. 1(a1)–1(a3), Wave2 (probe) is downshifted in frequency with respect to the Wave1 (pump) by a magnitude of around the  $\nu_B$ , and their interference generates an acoustic grating moving in the same direction as Wave1. The BGS is precisely lock-in detected when Wave1 is periodically turned on and off by an additional intensity modulator.<sup>13,14</sup> In contrast, as shown in Figs. 1(b1) and 1(b2), if the optical frequency of Wave2 is fixed while that of Wave1 is upshifted then downshifted, Wave1 and Wave2 alternately exchange between Brillouin pump and probe waves and thus they generate acoustic grating in two opposite directions, respectively. As a result, Wave2 suffers the Brillouin gain afterwards loss effects from Wave1, which can be expressed by

$$\Delta P_2^i = \text{sgn}^i \cdot g^i \cdot P_1 \cdot P_2 \cdot L, \quad (1)$$

where  $\Delta P_2$  is the power change of Wave2, the superscript  $i = 1$  or  $2$  corresponds to the Brillouin gain or loss effect,  $\text{sgn}^1 = +1$  or  $\text{sgn}^2 = -1$  denotes Wave2 being amplified or depleted by Wave1,  $P_1$  or  $P_2$  is the optical power of Wave1 or Wave2,  $g^i$  is the Brillouin gain (approximately loss as well) spectrum, and  $L$  is the optical fiber length.

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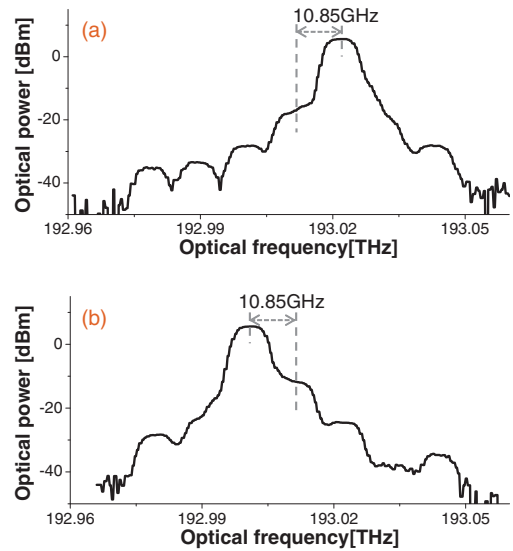


**Fig. 2.** Experimental setup of the novel BGS measurement scheme combining Brillouin gain and loss effects. The novel scheme can be used as a modified BOCDA system if a sinusoidal frequency modulation is introduced into a DFB-LD with the measured optical spectrum shown in the inset of “A”. PCs, polarization 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.

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, i.e.,  $\Delta P_2^{\text{net}} = \Delta P_2^1 - \Delta P_2^2 = 2\Delta P_2^1$ , which is twofold improved in the SNR (i.e., by 3 dB) in comparison with Fig. 1(a3).

The experimental setup of the proposed scheme 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 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 optical power of Wave2 launched into the FUT is ~5 dBm.

The other beam (70%, Wave1) was modulated by a 20 GHz LiNbO<sub>3</sub> DMZM, which is driven by a microwave generator ( $\nu$ ). The DMZM comprises two parallel Mach-Zehnder modulators and a parent Mach-Zehnder modulator that is biased at the third bias.<sup>15)</sup> When the third bias is alternately set at a proper low-level or high-level voltage, the parent Mach-Zehnder modulator can be zero-biased or  $\pi$ -biased.<sup>15)</sup> Consequently, 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  $\nu = 10.85$  GHz. 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 Wave1 being the upshifted or downshifted single sideband. Wave2 suffering Brillouin gain or loss from Wave1 was circled towards a variable optical attenuator (VOA) by the circulator, and then transformed to electronic domain by a photo detector (PD). A 10 kHz electronic square wave was applied into the



**Fig. 3.** Measured optical spectrum of Wave1 launched from the DMZM biased by a proper low-level voltage for Brillouin pump (a) or a proper high-level voltage for Brillouin probe (b).

third bias of the DMZM, introducing a periodical switching of 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). Note that the chopping frequency is limited to be about tens of kHz due to the frequency limitation of the DMZM’s bias electrodes.

First, we verified the feasibility and SNR improvement ability of the proposed scheme for the BGS measurement in the entire 5 m FUT. The microwave generator was swept from 10.7 to 11.0 GHz. When only the low-level or high-level voltage of the electronic square wave to the third bias of the DMZM is properly set at 2 or 13.5 V, the BGS is attributed to Brillouin gain or loss effect, respectively. When both voltages are simultaneously set, the net BGS is contributed by the combination of Brillouin gain and loss effects. The experimental results are shown in Fig. 4. It is clearly seen that the SNR of the proposed scheme is approximately twofold improved due to the combined Brillouin gain and loss effects when compared with the traditional scheme based on only the Brillouin gain effect.

Besides, we investigated the dependence of the peak of the net BGS on both bias voltages, which is depicted in Fig. 5. The peak is approximately linearly weakened [see Figs. 5(a) and 5(b)] or enhanced [see Figs. 5(c) and 5(d)]. This is because the low- or high-level bias voltage varies the extinction ratio of the upshifted (or downshifted) single sideband to the other sidebands, changes the power of Wave1 being amplified by the EDFA and consequently alters magnitude of the Brillouin gain or loss effects (i.e., the net Brillouin gain). The slight deviation from the ideal linearity is possibly attributed to the nonlinear response of the detuned bias voltages on the DMZM, leading to the nonlinear amplification of the power of Wave1 by the EDFA.

Next, we adopted the proposed scheme into a BOCDA system by introducing a sinusoidal frequency modulation to

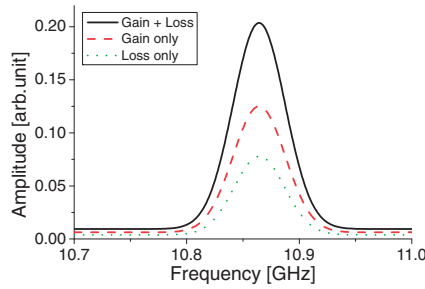


Fig. 4. Comparison of the measured BGS based on the proposed scheme (combination of gain and loss, solid curve) and the traditional scheme (gain or loss, dashed or dotted curve).

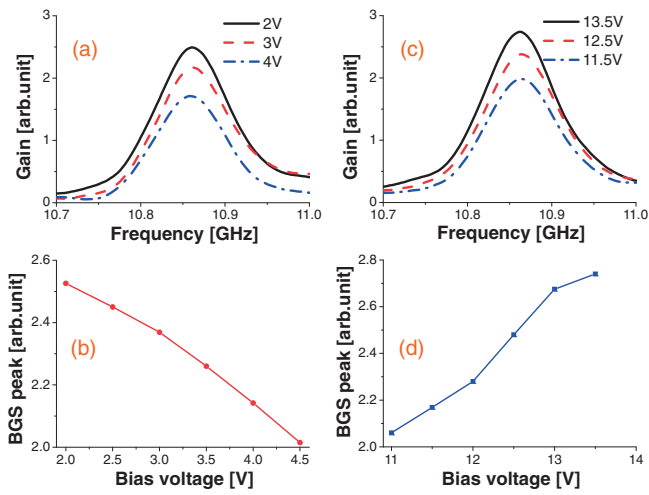


Fig. 5. Measured BGS (above) and peak (below) of the net gain when increasing the low-level (a, b) or high-level (c, d) voltage of the electronic square wave to the third bias of DMZM.

the laser source. The inset (A) of Fig. 2 indicates the optical power spectrum of the laser source giving a modulation depth  $\Delta f = 3$  GHz. The modulation frequency ( $f_m$ ) was scanned within the range of 19.993–20.0134 MHz for distributed BGS measurement. The measurement range ( $d_m$ ) and spatial resolution ( $\Delta z$ ) are defined by<sup>11)</sup>

$$d_m = \frac{c}{2n_{\text{eff}}f_m}, \quad (2)$$

$$\Delta z = \frac{c}{2n_{\text{eff}}f_m} \frac{\Delta\nu_B}{\pi\Delta f}, \quad (3)$$

where  $c$  is the light speed in vacuum,  $n_{\text{eff}} = 1.446$  the effective refractive index of the FUT, and  $\Delta\nu_B = 30$  MHz the Brillouin bandwidth. According to eqs. (2) and (3), the nominal performances of the modified BOCDA are estimated to be  $d_m = 5.2$  m and  $\Delta z = 1.6$  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 three-dimensional (3D) BGS distribution around the strained portion is depicted in Fig. 6(a) for an axial strain of  $\Delta\varepsilon = 820 \mu\varepsilon$ . The Brillouin frequency shift  $\nu_B$  distribution is extracted through Lorentzian fitting to the measured BGS distribution. The results for three different axial strains are summarized in Fig. 6(b), which clearly

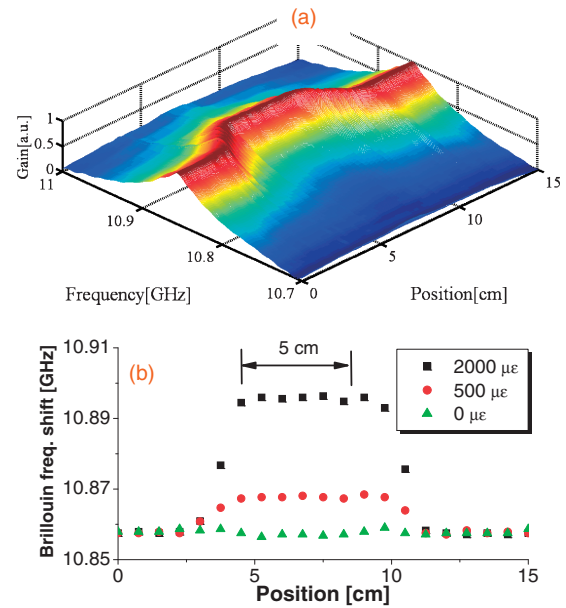


Fig. 6. (a) 3D plot of the distributed BGS and (b) measured Brillouin frequency shift ( $\nu_B$ ) distribution around the strained fiber portion.

identify the strained portions and the applied strains. The accuracy of the  $\nu_B$  measurement was estimated to be about  $\pm 1$  MHz for the current setup.

In conclusion, we have demonstrated a novel scheme of the BGS measurement combining the Brillouin gain and loss effects and utilized it in a BOCDA system. The novel scheme is more cost-effective with fewer optical devices when compared with the traditional BOCDA system<sup>13,14)</sup> 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. The distributed strain sensing ability with the 1.6 cm nominal spatial resolution in the modified BOCDA system has also been confirmed. It is expected that the modified BOCDA system can find potential applications to smart materials and smart structures.

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