Bidirectional measurement for Brillouin optical correlation domain analysis

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Abstract: We propose and experimentally demonstrate a bidirectional measurement for Brillouin optical correlation domain analysis as a novel and simple way of the performance enhancement. Brillouin gain and loss spectra of two adjacent correlation peaks are simultaneously and independently analyzed by applying midpoint attenuation in a fiber under test, which doubles both the speed and the range of the distributed measurement.

OCIS codes: (060.2310) Fiber optics; (060.2370) Fiber optics sensors; (060.4080) Modulation; (120.5820) Scattering measurements; (290.5900) Scattering, stimulated Brillouin.

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1. Introduction

Distributed fiber sensors based on Brillouin scattering has attracted great attention for a couple of decades as a strong candidate for health monitoring of civil structures and materials [1]. Various types of measurement schemes have been developed for the acquisition of local

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Brillouin gain spectrum (BGS) such as Brillouin optical time domain analysis (BOTDA), Brillouin optical time domain reflectometry (BOTDR), and Brillouin optical correlation domain analysis (BOCDA) [2–5]. Among them, the BOCDA is a kind of point sensor with random accessibility of the sensing position based on the synthesis of optical coherence function (SOCF), and has recently shown notable progresses in the performance like a spatial resolution of millimeter-order [6], a single-position sampling rate of 1 kHz [7], and a repetition rate as high as 20 Hz for obtaining a whole distribution map [8]. The main drawback of the BOCDA has been the limited measurement range originated from the periodic nature of the sensing position that is called correlation peak (CP) [5]. A couple of effective techniques have been introduced to enlarge the measurement range without deteriorating the spatial resolution such as double frequency modulation [9] and optical time-gating [10], where the range enlargement of up to 100 times has been reported with some additional complexity of the system [10].

In this paper, we newly propose bidirectional measurement for the BOCDA system as another simple way of both extending the measurement range and increasing the repetition rate of the distributed measurement. In our scheme, the Brillouin gain and loss spectra of two adjacent correlation peaks are simultaneously and independently analyzed, which effectively doubles both the measurement range and the acquisition speed of the distribution map of local BGS. In addition, the proposed scheme can be easily implemented on ordinary BOCDA systems without additional complexity of active controls, and possibly applied together with the established time-gating or double modulation scheme. In experiments, the bidirectional measurement is applied together with beat lock-in detection [7] to the BOCDA system for double extension of the measurement range from 100 to 200 m, keeping both the same spatial resolution and acquisition time of the whole distribution map as the confirmation of the proposed method.

2. Theory

As depicted in Fig. 1(a), in an ordinary BOCDA system, counter-propagating pump and probe waves generate a single CP within a fiber under test (FUT), where the stimulated Brillouin scattering (SBS) intensively takes place by SOCF.

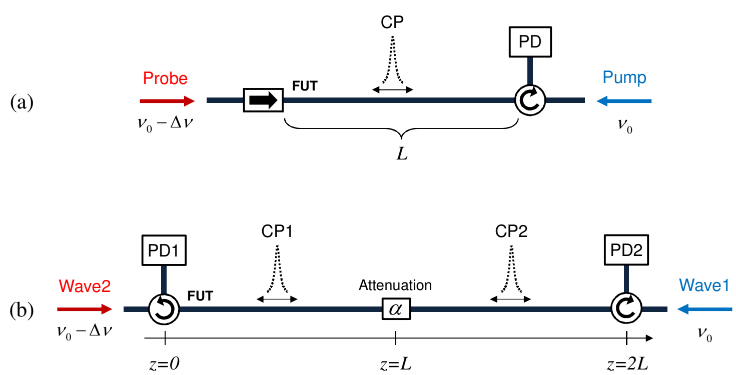

Fig. 1. Schematics of (a) ordinary BOCDA, and (b) BOCDA with bidirectional measurement.

The maximum length of the FUT is the interval between correlation peaks determined by the following equation:

$$L = \frac{V_g}{2 f_m} \tag{1}$$

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where V_g and f_m are the group velocity of light and the modulation frequency of the light source, respectively. After propagating through the FUT, the pump wave (with higher frequency, ν_o) is absorbed by an optical isolator, and the probe wave (with lower frequency, ν_o - $\Delta\nu$) is detected by a photo detector (PD) through a circulator for the analysis of the Brillouin gain spectrum (BGS) while sweeping $\Delta\nu$ around the Brillouin frequency ν_B of the fiber.

The operation scheme of the bidirectional measurement is shown in Fig. 1(b). Wave1 (with higher frequency, ν_o) and wave2 (with lower frequency, ν_o - $\Delta\nu$) are counter-propagated through a FUT with a length of $2L$ so that two correlation peaks (CP1, CP2) are generated within the fiber by the SOCF between two optical waves. An optical attenuator (attenuation: α) is inserted in the midpoint of the FUT by which the locations of CP1 and CP2 are separated, and wave1 and wave2 are detected by PD1 and PD2, respectively, after propagating through the FUT and circulators. For the formulation of the output intensity of wave2 detected by PD2, we assume following points for simplicity: 1. Propagation loss of the FUT and circulators is ignored except that of the midpoint attenuator. 2. Brillouin gain is small enough so that the intensity change of wave1 is ignorable within the fiber. These assumptions are validated considering the facts that the range is less than 1 km and the Brillouin gain is less than 1% in most cases of BOCDA measurement. The output intensity of wave2 (I_2) detected by PD2 is expressed as follows:

$$I_2 = \alpha \cdot I_{20} \cdot e^{\int_0^L g_B \cdot \alpha \cdot I_{10} \cdot dz} \cdot e^{\int_L^{2L} g_B \cdot I_{10} \cdot dz} = \alpha \cdot I_{20} \cdot e^{\left(\alpha \int_0^L g_B \cdot dz + \int_L^{2L} g_B \cdot dz \right) \cdot I_{10}} \tag{2}$$

where I_{10} and I_{20} are the input intensities of wave1 and wave2, respectively, and $g_B = g_B(z, \Delta\nu)$ is the Brillouin gain coefficient. If the midpoint attenuation is large enough (i.e. $\alpha << 1$), Eq. (2) is simplified to

$$I_2 \cong \alpha \cdot I_{20} \cdot e^{I_{10} \cdot \int_L^{2L} g_B \cdot dz} \tag{3}$$

Therefore, one can measure the Brillouin gain spectrum at CP2 by analyzing the output of PD2. In a similar way to the case of wave2, the output intensity of wave1 (I_1) detected by PD1 is formulated as follows:

$$I_1 = \alpha \cdot I_{10} \cdot e^{-\int_0^L g_B \cdot I_{20} \cdot dz} \cdot e^{-\int_L^{2L} g_B \cdot \alpha \cdot I_{20} \cdot dz} = \alpha \cdot I_{10} \cdot e^{-\left(\int_0^L g_B \cdot dz + \alpha \int_L^{2L} g_B \cdot dz \right) \cdot I_{20}} \tag{4}$$

where the amplification of wave2 by SBS is ignored for simplicity. Equation (4) is further simplified under the condition of small α as follows:

$$I_1 \cong \alpha \cdot I_{10} \cdot e^{-I_{20} \cdot \int_0^L g_B \cdot dz} \tag{5}$$

Equation (5) shows that the Brillouin loss spectrum at CP1 is obtained by analyzing the output of PD1. In this way, the bidirectional measurement enables simultaneous detection of the Brillouin frequencies of two adjacent correlation peaks by analyzing the output of PD1 and PD2, which effectively leads to the doubling of both the measurement range and the acquisition speed of distribution map of ν_B.

For the experimental implementation of the bidirectional measurement, the beat lock-in detection is preferable for the analysis of the output from each PD to remove large DC offset induced in ordinary lock-in detection [7]. Additionally, the chopping frequencies (f_{L1}, f_{L2}) of wave1 and wave2 are controlled according to the modulation frequency (f_m) of the light source in the following way to circumvent the rise of beat noise [11]:

$$f_{L1} = \frac{f_m}{2m}, \quad f_{L2} = \frac{f_m}{2n} \quad (m, n\text{: positive integer and } m \neq n) \tag{6}$$

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Consequently, the reference frequency of the lock-in amplifier is determined by difference of two chopper frequencies as follows:

$$f_{LB} = \left| f_{L1} - f_{L2} \right| = \left| \frac{f_m (m-n)}{2mn} \right| \tag{7}$$

3. Experimental results

The experimental setup of the BOCDA system for the bidirectional measurement is shown in Fig. 2. A 1550 nm distributed feedback laser diode (DFB-LD) was used as a light source to which a sinusoidal current modulation was applied to generate two CPs within a FUT, a 200 m single-mode fiber. The output of the LD was divided by a 3-dB fiber coupler, and one of the arms was connected to a single sideband modulator (SSBM) which was driven by microwave sweeper (Agilent 83620A), so that the first lower sideband (i.e., frequency $\nu_o - \Delta\nu$) was generated for wave2. A polarization switch (PSW) was inserted after the SSBM for suppressing the polarization dependence of the Brillouin signal [12], and the output was amplified by an Er-doped fiber amplifier (EDFA) to 23.5 dBm before entering the FUT through a circulator. The output from the other arm was amplified by another EDFA through a 10 km delay fiber to the same level as wave2, and propagated to the FUT for wave1 in the opposite direction to wave2 through another circulator.

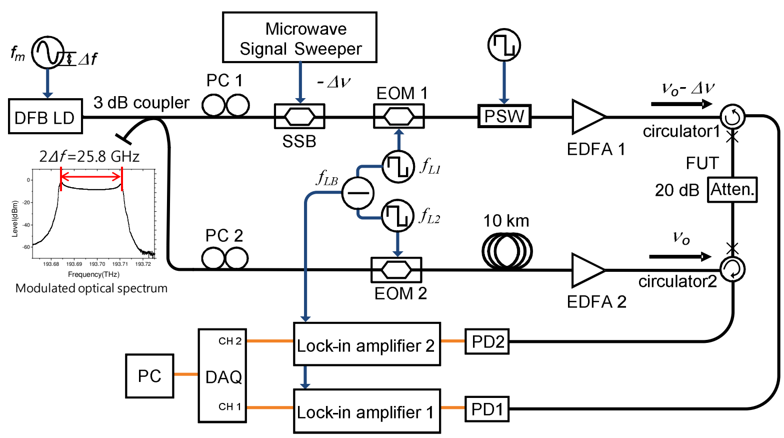


Fig. 2. Experimental setup of the BOCDA system for bidirectional measurement.

For simultaneous measurement of Brillouin signal (gain or loss) at two CPs, two 125 MHz photo detectors (PDs) and lock-in amplifiers were used. Since both waves are detected as probe waves in this bidirectional approach, the beat lock-in detection is the most suitable for the acquisition of the Brillouin signal to suppress the rise of large DC offset [6]. Both wave1 and wave2 are chopped at different frequencies (f_{L1} & f_{L2}) which were determined by Eq. (6) with m = 1 and n = 3, respectively, and the reference frequency of the lock-in amplifiers was set by Eq. (7). The modulation frequency f_m was controlled between 998 ~1000 kHz depending on the measurement position in the FUT, and the modulation amplitude Δf was about 12.9 GHz as shown in the inset of Fig. 2. From those parameters, the measurement range and the spatial resolution were calculated to be about 100 m and 7.6 cm, respectively [5]. However, note that in our bidirectional measurement, the length of the FUT was set twice of the calculated value. Additionally, a 20 dB optical attenuator was inserted in the midpoint of the FUT as a key component of this approach. The BGS was measured every 5 cm along the FUT, by sweeping $\Delta\nu$ from 10.3 to 11.3 GHz in the vicinity of ν_B of the FUT (10.86 GHz). We performed distributed measurements by imposing axial strain on 40 ~50 cm sections of the first and the second segments of the FUT as shown in Fig. 3. The locations of the strain applied points are 27, 67, and 129 m, where the strains of 3.86, 2.34, and 3.82 mε were applied, respectively.

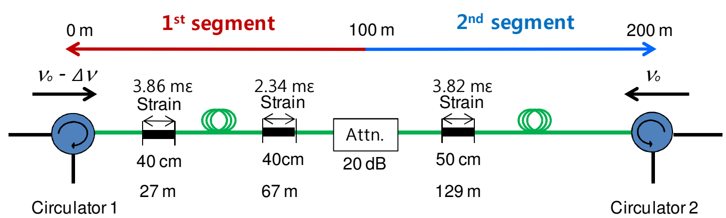
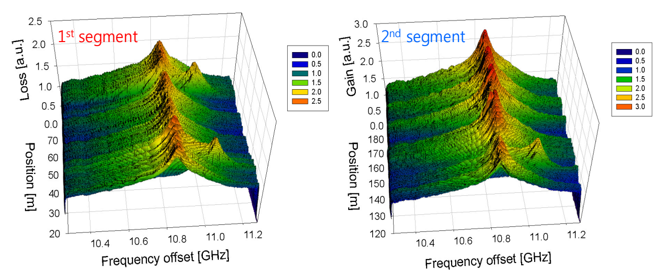
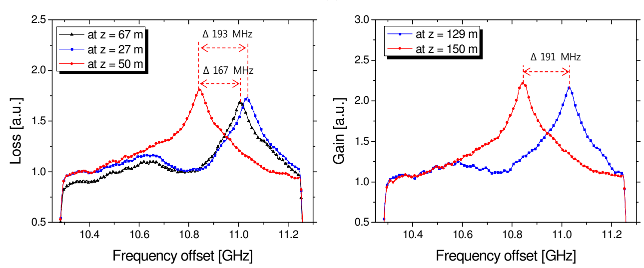


Fig. 3. Structure of the FUT with strain-applied segments.

Figure 4(a) shows 3D plots of the measurement results of the distribution of the Brillouin gain (2nd segment) and loss (1st segment) spectra along the FUT, where one can observe clear shift of the Brillouin spectrum at each strain-applied section. As depicted in Fig. 4(b), the frequency shifts are measured to be about 193, 167 and 191 MHz for each section, that match well to the reported slope of 0.05 MHz/με with the measurement error of ± 3.5 MHz.



(a)



(b)

Fig. 4. (a) 3D plots of the BGS distribution along the FUT. (b) Measured BGS at five sample points.

For comparison, we performed the same measurement without the optical attenuator in the FUT, and the measurement results of the 2nd segment are shown in Fig. 5. It is seen that the signals coming from two correlation peaks are added with similar amplitudes so that the shift of ν_B is not properly detected in strain-applied sections. For example, although there is no strain applied at positions z = 127, 167 m, one can observe abnormal BGS which leads to wrong measurement results. This result confirms the key role of the optical attenuation in the midpoint for bidirectional measurement.

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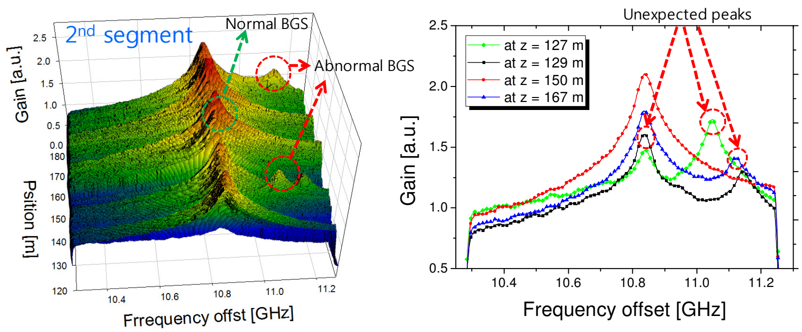

Fig. 5. (a) 3D plot of the measured BGS of the segment II. (b) BGS at sample positions of z = 127, 129, 150, and 167 m, respectively, without the midpoint attenuation applied.

Figure 6 is the measured distribution map of v_B obtained by fitting Fig. 4(a), where one can see the proper detection of the strain-applied sections within the 200 m FUT. This result clearly confirms the double extension of the measurement range by introduction of the bidirectional measurement.

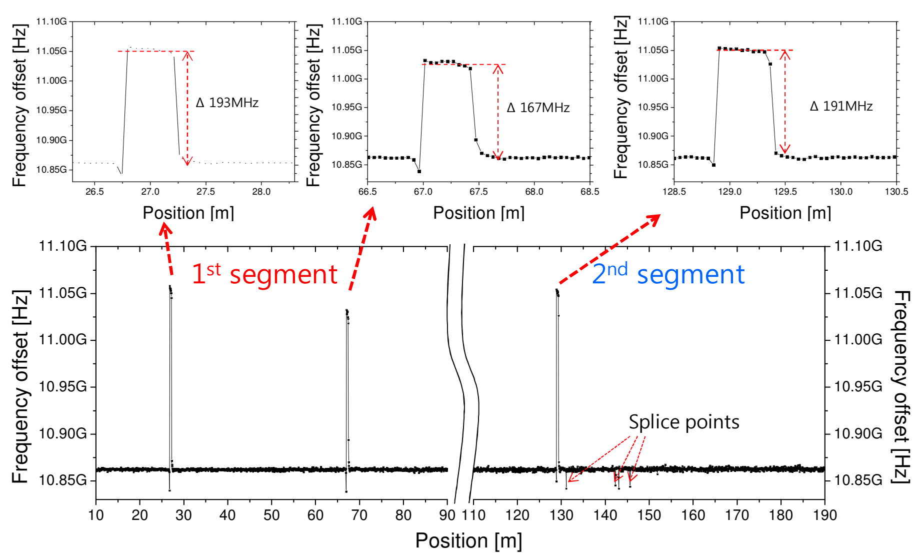

Fig. 6. Distribution map of the Brillouin frequency along the 200 m FUT.

4. Conclusion

We have proposed and experimentally demonstrated the bidirectional measurement for a BOCDA system. Our method could be easily applied to ordinary BOCDA system without additional frequency- or timing-control of former enlargement schemes, and effectively double both the measurement range (i.e. the number of sensing points) and the speed of acquiring whole distribution map, at the same time. We think the bidirectional measurement can be applied together with the time-gating or the double modulation scheme in parallel, providing an easy and practical tool to enhance the performance of BOCDA systems.

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