Single-ended distributed temperature or strain sensor based on stimulated Brillouin scattering

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ABSTRACT

We propose a single-ended distributed temperature or strain sensor based on stimulated Brillouin scattering (SBS) in a polarization-maintaining (PM) optical fiber. Pump and probe waves with orthogonal polarization states enter one fiber end and generate SBS assisted by a polarization beam splitter and a PM isolator at the other fiber end. Unlike the previously-reported method, neither an optical filter nor a sophisticated beat-lock-in detection is necessary. Single-ended distributed sensing of temperature or strain is experimentally demonstrated with the measurement range and the spatial resolution of 200 m/16 cm, 56 m/5 cm, or 5.6 m/5 mm, respectively.

Keywords: Stimulated Brillouin sensing, fiber optic sensors, polarization-maintaining fiber

1. INTRODUCTION

Fiber optic Brillouin distributed sensors [1-6] have been extensively studied during the past decades because they are regarded as powerful tools for diagnosing temperature or strain distribution in smart materials and smart structures. There are three important factors in Brillouin distributed sensors: (1) the interrogation of the temperature or strain information, (2) the way to resolve the position along the fiber length, and (3) the configuration of the optical fiber under test (FUT). All factors are related to Brillouin scattering phenomenon in the FUT, which is an interaction between light photons with acoustic phonons. The optical frequency of the scattered (or amplified) photons is downshifted from that of the incident (or pump) photons. The downshifted frequency is known as Brillouin frequency shift (BFS, ν_B) and it is proportional to the acoustic velocity. Either temperature or strain change alters linearly the acoustic velocity, so that the local temperature or strain information can be interrogated by monitoring the local BFS. Various laser technologies have been utilized to revolve the position information, for example, pulse-formation technology [1-3] or continuous-wave correlation-based technology [4-6]. The pulse-based technique has an advantage of long measurement ability (~tens of kilometers); the correlation-based technology has unique features of random-accessible ability and high spatial resolution (even sub-centimeter). Spontaneous Brillouin scattering (SpBS) in the FUT offers a way to build up single-ended distributed sensors [3,6]; besides, stimulated Brillouin scattering (SBS) is used to develop double-ended distributed sensors since pump and probe waves need to be counter-propagated [1,4-5]. The SpBS-based distributed sensors are more flexible in long-range application but with much weaker signal compared with the SBS-based distributed sensors.

In this paper, we demonstrate a novel proposal of single-ended SBS-based distributed sensor. The novel proposal offers several advantages over the previously-reported method based on a reflector at the far fiber end [7]. The measurement range is not be halved; neither an optical filter nor a sophisticated beat-lock-in detection is necessary; the frequency modulation depth is not limited to be a half of the BFS. We demonstrate experimentally single-ended distributed sensing of temperature or strain with the measurement range (d_m) and the spatial resolution (Δz) of 200m/16cm, 56m/5cm, or 5.6m/5mm, respectively.

2. PRINCIPLES

Figure 1 compares two different schemes of single-ended SBS-based distributed sensor. In Fig. 1(a), sinusoidally frequency-modulated pump and probe waves are launched into a single-mode optical fiber (SMF) from one end [7]. One forward wave is reflected back by a reflector at the far end and then encounters the other forward wave. Afterwards, they generate SBS at a particular position of the synthesized correlation peak. However, there are two similar cases of SBS interaction as shown in Fig. 1(a), which halves the measurement range with respect to the ordinary double-ended Brillouin optical correlation domain analysis (BOCDA) system [4].

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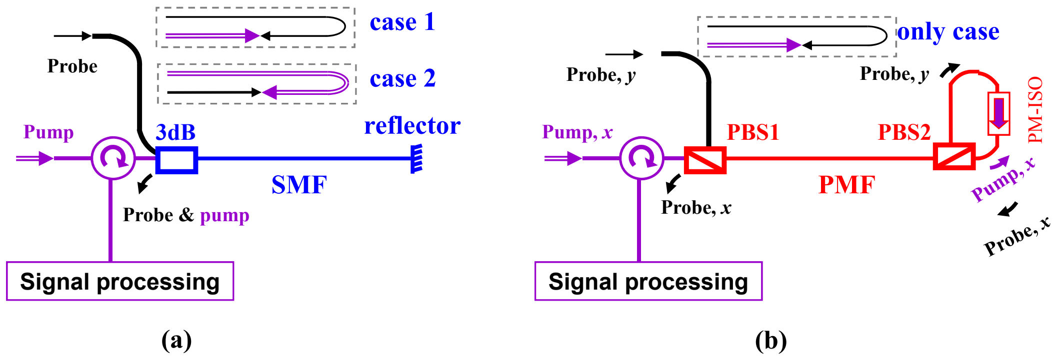


Fig. 1. Comparison of two different schemes of single-ended SBS-based distributed sensors based on (a) a reflector and (b) a combined PBS and PM-ISO at the far end of the fiber under test. There is only one case of Brillouin interaction in (b) but two cases in (a).

Our novel scheme is shown in Fig. 1(b). A polarization-maintaining optical fiber (PMF) is used as the sensing FUT. Sinusoidally frequency-modulated pump and probe waves are linearly polarized with orthogonal *x*-polarized and *y*-polarized states, respectively. The two waves are launched into a PMF through a polarization-beam splitter (PBS1). At the far end of the PMF, the two waves are divided by an additional PBS2. With the assistance of a polarization-maintaining isolator (PM-ISO), only the probe wave (*y*-polarized) is rotated back to the PMF with the orthogonal *x*-polarized state. Consequently, the probe wave encounters the pump wave with the same polarization state (*x*-polarized) and SBS occurs at the synthesized correlation peak. Since there is only one case of SBS interaction, the measurement range (d_m) and the spatial resolution (Δz) are exactly the same as the ordinary BOCDA system [4], given by following:

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

where c is the light speed in vacuum, n_{eff} (~1.446) is the effective refractive index of the fiber, $\Delta\nu_B$ is the Brillouin linewidth (~30 MHz), and f_m (Δf) is the modulation frequency (depth).

Furthermore, the novel configuration proposed in this paper [depicted in Fig. 1(b)] simplifies signal processing when compared to the scheme in Fig. 1(a). Since the forward pump wave is completely blocked by the PM-ISO, the pump wave and the Brillouin loss signal appearing in the output are only related to the cross-talk of the PMF (α<-25 dB/100m). The detected signal (P_d) of the novel proposal can be approximately expressed by:

$$P_d = P_s \mathrm{e}^{gP_p\Delta z} + \alpha(P_p - \mathrm{e}^{gP_p\Delta z}) \simeq P_s + \alpha P_p + (1-\alpha) g P_p P_s \Delta z \, , \tag{3}$$

where g is a normalized Brillouin gain coefficient, and P_s (P_p) is the optical power of the probe (pump) wave, respectively. A single lock-in detection as employed in the ordinary BOCDA system [4] is sufficient to demodulate the Brillouin interaction (gain) signal, i.e., the third component of the right hand side of Eq. (3). Eq. (3) further shows that it is not necessary to use any optical filter to cut down the Brillouin loss signal. Because of this, the modulation depth (Δf) can far exceed the half of the BFS (ν_B), which offers significant advantage over the SpBS-based single-ended distributed sensor [6].

3. EXPERIMENT AND RESULTS

The experimental setup is illustrated in Fig. 2. A 1549-nm distributed-feedback laser diode (DFB-LD) is used as a light source, and a sinsodinal frequency modulation is directly applied by a function generator. The inset of Fig. 2 shows the modulation depth Δf=~12 GHz, which is even greater than the BFS ν_B=~10.9 GHz of the PMF. The output of the DFB-LD is divided by a 3-dB coupler to generate pump and probe waves, respectively. A single-sideband modulator (SSBM) is used to downshift the optical frequency of the probe wave. The downshifted frequency around the BFS ν_B is swept by a mirowave synthesizer. A ~3-km SMF spool is laid in the probe arm to introduce a higher-order correlation peak in the PMF under test. Besides, an intensity modulator (IM) is employed to chop the pump power at a frequency of 123 kHz. Pump and probe waves are amplified by two erbium-doped fiber amplifers (EDFAs) to ~24 dBm and ~7 dBm, respectively. The probe wave is linearly polarized by a polarizer; the pump wave is also linearly polarized after passing a PM circulator (PM-CIR). Both linearly-polarized pump and probe waves are launched into the PMF through two orthogonal ports of a PBS1, so that pump and probe waves propagate along the PMF with orthogonal polarization states.

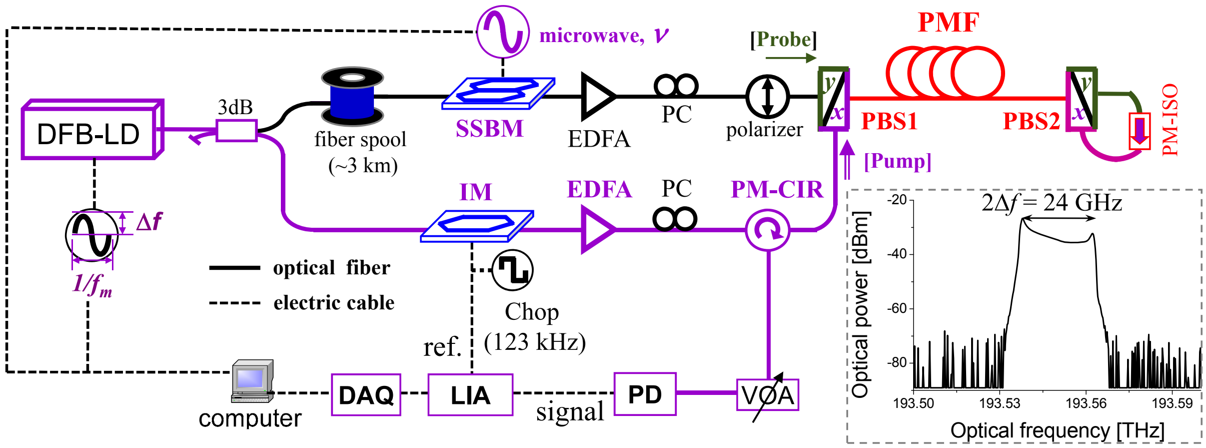
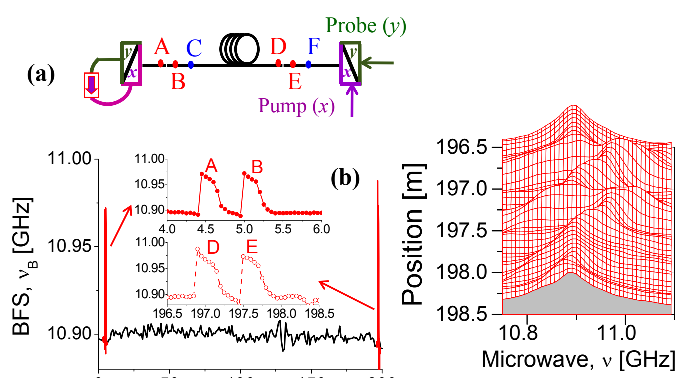


Fig. 2. Experimental setup of the novel single-ended SBS-based distributed temperature or strain sensor. The inset shows the optical power spectrum of the laser source with a modulation depth Δf=~12 GHz.

At the far PMF end, two ports of the PBS2 are spliced together with a PM-ISO. The output from the PM-CIR is attenuated by a variable optical attenuator (VOA) and detected by a photo-detector (PD). The electronic signal is demodulated by a lock-in amplifier (LIA) at the chopping frequency of 123 kHz. The demodulated signal is sampled by a data acqusition card (DAQ) as a function of the microwave frequency (ν) to collect the Brillouin gain spectrum (BGS).

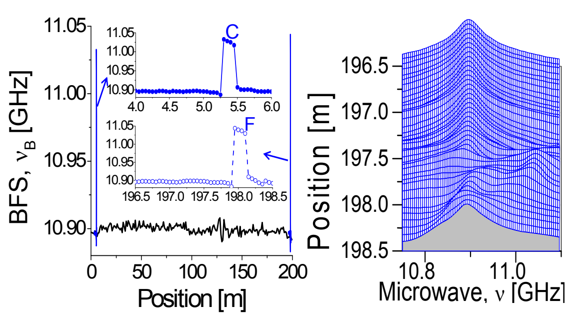
First, we set the modulation frequency f_m to 478.134 – 521.968 kHz, which corresponds to a nominal measurement range d_m = ~200 m and a nominal spatial resolution Δz =16 cm according to Eqs. (1) and (2). A 200-m PMF sample is prepared as shown in Fig. 3(a), which comprises four portions (A, B, D, and E) heated by a hot plate and two portions (C and F) strained by a set of *x*-stages. All heated or strained portions are ~16 – 20 cm in length. Fig. 3(b) depicts the characterized BFS distribution along the PMF when the temperature of the heated portions is set to T = 81°C. One example of 3-D plot of the distributed BGS around one end of the PMF is shown in Fig. 3(c) where the increased BFS in the heated D and E portions can be clearly seen. The magnified views of the heat-induced BFS are shown in the insets of Fig. 3(b). When ~0.3-% strain is applied to C and F portions, we measure the BFS distribution again, which is depicted in Fig. 4(a). 3-D plot of the distributed BGS around one end of the PMF is shown in Fig. 4(b) where the strain-increased BFS can be clearly recognized. The detailed views of the strain-induced BFS are included in the insets of Fig. 4(a). Additionally, we can realize 5-cm spatial resolution by setting the modulation frequency f_m to 1813.61 – 1856.98 kHz. The nominal d_m and Δz are calculated to be 56 m and 5 cm, respectively; experimentally, we succeed in measuring the strain- and temperature-induced BFS changes in ~5-cm portions.

Finally, we demonstrate distributed sensing of temperature or strain with the highest spatial resolution of 5 mm



(c)

Fig. 3. (a) Prepared 200-m PMF sample with four heated portions (A, B, D, and E) and two strained portions (C and F). (b) Measured BFS distribution when the temperature of the heated portions is T=81°C. The insets show the results around the heated portions. (c) 3-D plot of the distributed BGS around one end of the PMF.



(a) (b)

Fig. 4. (a) Measured BFS distributions when ~0.3-% strain is applied to the C and F portions. The insets show the results around the strained portions. (b) 3-D plot of the distributed BGS around one end of the PMF.

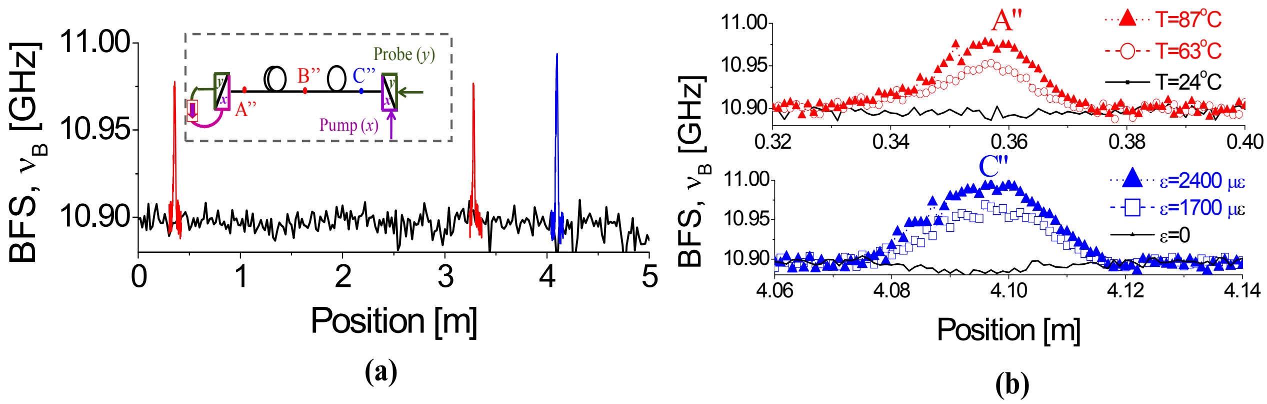


Fig. 5. (a) Measured BFS distributions along the 5-m PMF. The inset shows the PMF structure with two heated portions (A" and B") and one strained portion (C"). (b) Magnified plots of the BFS distributions around the heated A" portion (top) and the strained C" portion (bottom).

reported in all single-ended sensors to date. The largest Δf=~12 GHz of the DFB-LD is applied; the modulation frequency f_m is set to 18.476 – 18.516 MHz near the Brillouin linewidth $\Delta\nu_B$. The nominal d_m and Δz are calculated to be 5.6 m and 5 mm, respectively. The prepared 5-m PMF sample with two 5-mm heated portions (A" and B") and one 5-mm strained portion (C") are shown in the inset of Fig. 5(a). The BFS distribution along the entire 5-m PMF is measured when T=87°C and $\Delta\varepsilon$=0.24%, which is plotted in Fig. 5(a). The BFS increments are obviously visible. When different ΔT or $\Delta\varepsilon$ is applied, we repeat the measurements. The experimental results around the A" and C" portions are summarized in Fig. 5(b), from which different BFS change induced by different ΔT or $\Delta\varepsilon$ can be clearly derived.

4. CONCLUSIONS

We have demonstrated a novel single-ended SBS-based distributed sensor. By combining a PMF with two PBS and one PM-ISO as a FUT, both pump and probe waves can access the same end of the FUT to diagnose distributed temperature or strain information. Unlike the previously-proposed method [7], neither an optical filter nor a beat-lock-in detection is necessary; the frequency modulation depth can be larger than the half of the BFS. The measurement range is the same as the traditional BODDA system. We have experimentally demonstrated distributed sensing with $d_m/\Delta z$ of 200m/16cm, 56m/5cm, or 5.6m/5mm, respectively. In addition, the ratio of $d_m/\Delta z$ can be enlarged by employing a laser diode with a broader modulation depth or by using a temporal-gating technique. Further combination with our recent proposal of discrimination of strain and temperature [8] will enable potential application in single-ended distributed and discriminative sensing of strain and temperature.

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REFERENCES

1 X. Bao, D. J. Webb, and D. A. Jackson, "32-km distributed temperature sensor using Brillouin loss in optical fiber," Opt. Lett. **18**, 1561-1563 (1993).
2 M. Nikles, L. Thevenaz, and P. Robert, "Simple distributed sensor based on Brillouin gain spectrum analysis," Opt. Lett. **21**, 758-760 (1996).
3 M. N. Alahbabi, Y. T. Cho, and T. P. Newson, "150-km-range distributed temperature sensor based on coherent detection of spontaneous Brillouin backscatter and in-line Raman amplification," J. Opt. Soc. Amer. B **22**, 1321-1324 (2005).
4 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**, 405-412 (2000).
5 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**, 2526-2528 (2006).
6 Y. Mizuno, W. Zou, Z. He, and K. Hotate, "Proposal of Brillouin optical correlation-domain reflectometry (BOCDR)," Opt. Express **16**, 12148-12153 (2008).
7 K. Y. Song and K. Hotate, "Brillouin optical correlation domain analysis in linear configuration," IEEE Photon. Technol. Lett. **20**, 2150-2152 (2008).
8 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**, 1248-1255 (2009).