Measurement Range Elongation Based on Temporal Gating in Brillouin Optical Correlation Domain Distributed Simultaneous Sensing of Strain and Temperature

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***Abstract*— We had earlier demonstrated the distributed discrimination of strain and temperature by localizing and scanning both the stimulated Brillouin scattering and the Brillouin dynamic grating along a polarization-maintaining fiber. The localization and scanning were performed by a correlation domain technique, whose measurement range was restricted by the distance between consecutive correlation peaks. To overcome this restriction, in this letter, we apply a temporal gating scheme to the system by enlarging the measurement range from ∼25 to ∼500 m. We report the results confirming the effectiveness of this scheme in a system operated by a single laser source, and demonstrate the strain-temperature discrimination when strain or temperature is applied to segments on the 500-m-long fiber under test.**

***Index Terms*— Brillouin fiber-optic sensor, distributed sensing, strain-temperature discrimination.**

I. INTRODUCTION

OPTICAL fiber sensors based on Brillouin scattering are attractive for their potential to monitor the distribution of strain and temperature in smart structures. Since we first observed Brillouin dynamic gratings (BDG) in a polarization maintaining fiber (PMF) [1], BDGs have been widely researched contributing to the enhancement of Brillouin based sensors. Notably, BDGs have demonstrated efficiency in precise discrimination of strain and temperature [2], which is one of the challenges for Brillouin sensor popularization. However, simultaneous strain and temperature measurements have only been reported for relatively short fibers on both time domain [3]-[4] and correlation domain techniques [5].

For basic Brillouin time domain techniques, 1 m was considered the spatial resolution limit. Though cm order spatial resolution has been reported using BDGs in PMFs [6], it is difficult to realize the strain-temperature discrimination with such high spatial resolution by time domain techniques. For our original technology called Brillouin optical correlation domain analysis (BOCDA) [7], such high spatial resolution is obtained in basic configurations [8], which allow strain-temperature discrimination with high spatial resolution by the BDG principle. In this letter, we overcome the measurement range restriction in BOCDA discriminative measurement by a temporal gating scheme [9]-[11], and present results confirming the effectiveness of the scheme in our single-laser setup [12] by measuring a 500-m PANDA type fiber. This is the longest BDG measurement ever reported. Distributed discriminative measurements are also performed with a nominal spatial resolution of ∼45 cm.

II. MEASUREMENT PRINCIPLE

In PMFs, x-polarized pump and probe writing waves interact through stimulated Brillouin scattering (SBS) and create a BDG that can reflect a readout light launched in the y polarization axis of the fiber [1]. Strong reflection takes place when the readout frequency is higher from that of the pump by f_{xy}, due to the fiber birefringence [1]. Both the Brillouin frequency shift (BFS) and f_{xy} are dependent on strain and temperature. As their variations are different, accurate discrimination of these physical quantities is possible by matricial calculations [2].

The localization of a measurement point along the fiber under test (FUT) is held with the correlation domain technique, by applying sinusoidal frequency modulation (FM) through the injection current of the laser diode (LD). SBS only occurs at points where the pump and probe are strongly correlated on the FUT. The correlation peaks appear with period

$$d_m = c/2nf_m \tag{1}$$

where c is the speed of light in vacuum, n refractive index, and f_m the sinusoidal modulation frequency [7]. To determine a single point on the fiber, i.e. to place a single correlation peak

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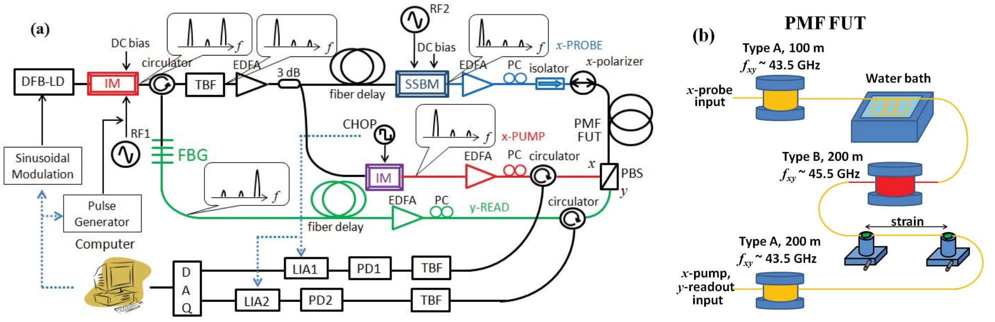

Fig. 1. (a) Setup for Brillouin optical correlation domain distributed simultaneous sensing of strain and temperature with measurement range elongation based on a temporal gating scheme. DFB-LD: distributed feedback laser diode. IM: intensity modulator. RF: radio frequency. TBF: tunable bandpass filter. FBG: fiber Bragg grating. SSBM: single sideband modulator. EDFA: erbium-doped fiber amplifier. PC: polarization controller. FUT: fiber under test. PBS: polarization beam splitter. PD: photodiode. LIA: lock-in amplifier. DAQ: data acquisition. (b) Fiber under test.

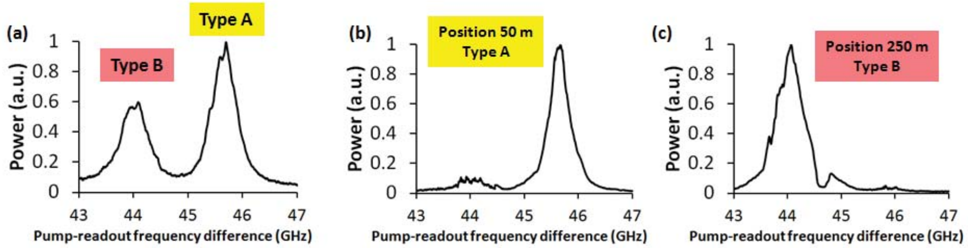

Fig. 2. (a) BDG spectrum without the temporal gating, setting multiple correlation peaks on both types of PMF. (b) BDG spectrum with the temporal gating, selecting only one correlation peak at position 50 m. (c) BDG spectrum with the temporal gating, selecting only one correlation peak at position 250 m.

on it, the total length of the FUT cannot surpass d_m, so it actually represents the measurement range.

To overcome this restriction, some temporal gating schemes were proposed [9]-[11]. In the single-laser setup [12], the writing pump and probe, as well as the readout wave are produced by the same laser source, so the temporal gating presented in [10] is the most convenient. Pulse modulation is applied to the LD output to modulate all the three participating waves. The pulse modulation has $1/N$ duty ratio and $1/N$ repetition frequency compared to that of the LD frequency modulation. The pump-probe interaction occurs only at the positions where the counter propagating probe and pump pulses overlap [10]. Consequently, the measurement range can be elongated by N. Both the correlation peak and the pulse overlapping position are scanned by changing the two repetition frequencies for the LD modulation (f_m) and the pulse modulation (f_m/N) [10].

We developed the setup depicted in Fig. 1, based on the setup presented in [12]. The laser output is intensity modulated with a radio frequency by RF1. The lower 1st order side band is reflected by the fiber Bragg grating (FBG) to be used as x-pump and x-probe lightwaves. The frequency difference between the pump and the probe is generated by the single side band modulator (SSBM) driven by RF2. The Brillouin gain spectrum is measured by sweeping the RF2 frequency, and the BDG spectrum is measured by sweeping the RF1 frequency. Introducing pulse modulation in the radio frequency generator RF1, the temporal gating is implemented. A computer controls both the repetition frequencies for the pulse train and the sinusoidal FM of the LD to localize and scan a single correlation peak on the FUT, while recording the localized BGS and BDG spectrum.

III. Experimental Results

We prepared a 500-m-long fiber composed of two types of PMF, A and B, as shown in Fig. 1(b). The birefringence difference between A and B is significant, leading to an f_{xy} difference of $\sim$2 GHz. The minimum pulse width of the pulse generator is 240 ns. The pulse width has to be as long as one period of the sinusoidal FM for the correlation domain technique [10], thus the FM frequency f_m is chosen around 4 MHz. From the modulation depths, spatial resolution can be calculated to be $\sim$12 cm for BFS measurement, and $\sim$45 cm for f_{xy} measurement [5]. The temperature and strain dependency is also different for both fibers, but their variation coefficients can be calculated by the theory shown in the appendix of [2].

Fig. 2(a) shows the BDG spectrum obtained when only sinusoidal FM is applied to the LD without applying the temporal gating. With f_m $\sim$4 MHz, correlation peak interval is $\sim$25 m, and multiple peaks arise on both types of fiber. The result has two spectral peaks, showing the f_{xy} of both types A and B. When temporal gating is applied to select a single correlation peak on the FUT, we can obtain a single peak spectrum shown in Figs. 2(b) and (c), where the correlation peak is localized at positions 50 m and 250 m, respectively. Fig. 3 shows distributed measurement along the whole 500-m FUT with 5-m step. Distinction between the two types of fiber is clearly observed. There is a slight difference between the BFSs of the two types of fiber, which

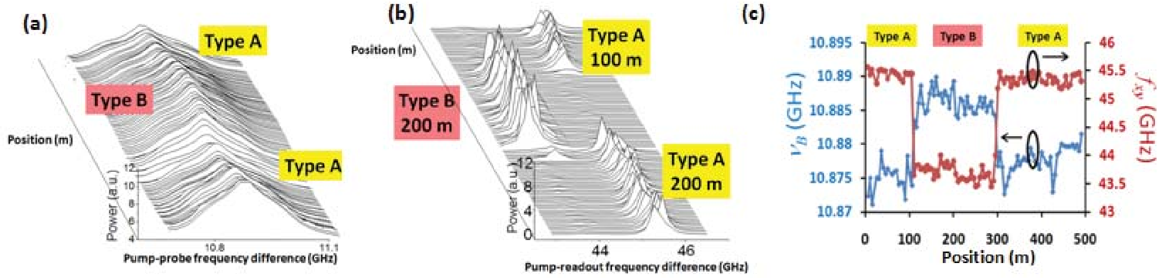

Fig. 3. (a) Brillouin gain spectrum. (b) BDG spectrum. (c) ν_B and f_{xy} distribution measured along the FUT with 5-m steps.

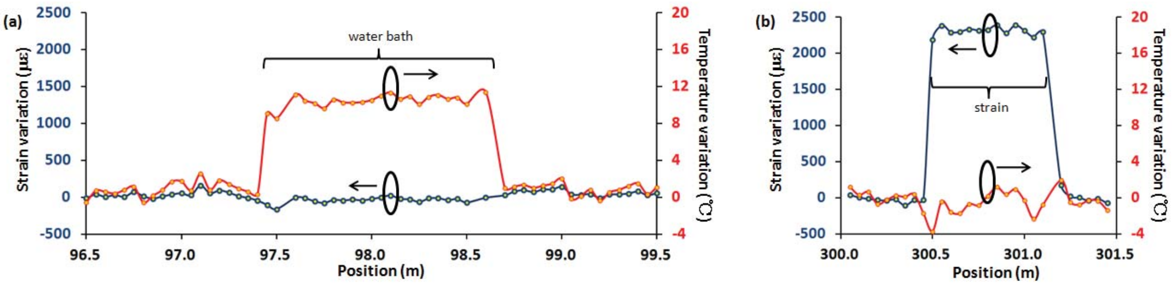

Fig. 4. Discriminative distributed measurements of strain and temperature. (a) Variations when the temperature of the water bath is changed from 35 °C to 45 °C. (b) Variations when the fiber is pulled to load strain.

was detected by our system as shown in Figs. 3(a) and (c). The measurement time was of several minutes for the whole fiber in the experiments. But most of the time is represented by machinery control, which does not represent a theoretical limit. Speed increasing techniques from BOCDA may work on this system.

Discriminative distributed measurements of strain and temperature were held by immersing the fiber in a temperature controlled water bath or loading strain with a movable stage as shown in Fig. 1(b). First, we performed 5-cm step measurements with the water bath set to 35 °C, while the room temperature outside the bath was controlled by air conditioner. We then reset the water bath to 45 °C and measured again. The difference between these results was used in matricial calculations for temperature and strain discrimination [2]. The results are presented in Fig. 4(a), showing the temperature variation of 10 °C, and no strain variation. The same distributed measurement was held at another position by pulling the fiber. The system detected the strain variation without temperature change as shown in Fig. 4(b). The fluctuation in the discrimination results shown in Fig. 4(b) may be caused by the spatial resolution difference between BFS and f_{xy} measurements.

IV. CONCLUSION

To enlarge the measurement range, a temporal gating scheme was successfully introduced in the strain-temperature discriminative BOCDA system with a single laser source. A 500-m-long fiber was measured, and applied temperature or strain was correctly discriminated. The spatial resolution realized in the experiments was 45 cm, which could be improved by applying larger amplitude in the laser frequency modulation [12].

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