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Utilization of a Dispersion-Shifted Fiber for Simultaneous Measurement of Distributed Strain and Temperature Through Brillouin Frequency Shift

C. C. Lee, P. W. Chiang, and S. Chi

Abstract—In this letter, we propose and realize a new method that utilizes a dispersion-shifted fiber having compound compositions with different temperature coefficients in core to simultaneously measure the distributed strain and temperature based on Brillouin frequency shift. In a 3682-m sensing length of large-effective-area nonzero dispersion-shifted fiber, a temperature resolution of 5°C, a strain resolution of 60 $\mu\epsilon$, and a spatial resolution of 2 m are achieved simultaneously.

Index Terms—BOTDR, Brillouin frequency shift, dispersion-shifted fiber.

RECENTLY, the fiber-distributed strain/temperature measurement based on the Brillouin scattering effect has been intensively studied. The Brillouin frequency shift is dependent on the temperature and strain conditions of the optical fiber, which provides the basis for a sensing technique capable of detecting these two parameters. The challenge, then, is to develop a technique to distinguish their individual contributions to the change in the Brillouin frequency of the optical fiber and to avoid the cross-sensitivity problem. Several techniques have been reported to accomplish the simultaneous measurement of fiber strain and temperature. In these methods, the one that uses a half of the fiber isolated from the effects of strain for temperature sensing [1], and another one that utilizes the fiber Bragg gratings combined with optical fiber [2] both require rather complicated sensing structure. Another technique that simultaneously measures the Brillouin power and frequency shift can achieve the fully distributed measurement of strain and temperature [3], but the temperature resolution is limited by the power measurement accuracy (~ 0.013 dB for 1 °C), which is very difficult to reach 0.05 dB over a considerable length of fiber and is very sensitive to environment.

In this letter, we propose a new method that utilizes a dispersion-shifted fiber having compound compositions with different temperature coefficients in core as the sensing fiber to measure the distributed strain and temperature simultaneously. To prove this concept, the large-effective-area nonzero-dispersion-shifted fiber (LEAF), which has been reported to have multiple compositions in the fiber core [4] and now intensively deployed in

dense wavelength-division-multiplexing (DWDM) networks, is chosen as the test fiber. This technique needs only the measurement of Brillouin frequency shifts of the Brillouin spectra and can accomplish the high resolution and accuracy of temperature and strain measurement without modifying the sensing fiber.

If an optical fiber has compound compositions in core, the multipeak structure in Brillouin spectrum of this optical fiber is arisen from the different acoustic velocities, which are due to different compositions or doping concentrations in the core [5]. From a previous experiment [3], the Brillouin frequency shift V_B is dependent on strain and temperature of the standard single-mode fiber (SMF). In the case of an optical fiber with compound compositions in the core, the Brillouin frequency shifts of the main two peaks (peak 1 and peak 2) relating to strain ϵ and temperature, T , are given as:

$$\Delta V_B^{Pk1} = C_\epsilon^{Pk1} \Delta\epsilon + C_T^{Pk1} \Delta T \quad (1)$$

$$\Delta V_B^{Pk2} = C_\epsilon^{Pk2} \Delta\epsilon + C_T^{Pk2} \Delta T. \quad (2)$$

If the strain coefficients for peak 1 C_ϵ^{Pk1} and peak 2 C_ϵ^{Pk2} have the same value and the temperature coefficients for peak 1 C_T^{Pk1} and peak 2 C_T^{Pk2} have different values, then the change in temperature can be given by

$$\Delta T = \frac{\Delta V_B^{Pk1} - \Delta V_B^{Pk2}}{C_T^{Pk1} - C_T^{Pk2}}. \quad (3)$$

In addition, the change in fiber strain can also be obtained by substituting the known ΔT into (1) or (2), and is given by

$$\Delta\epsilon = \frac{\Delta V_B^{Pk1} - C_T^{Pk1} \Delta T}{C_\epsilon^{Pk1}}. \quad (4)$$

Therefore, this method can provide the simultaneously distributed temperature and strain measurement along the length of the fiber link through the frequency analysis of the measured spontaneous Brillouin spectra.

The operation principle of the used Brillouin optical-time-domain reflectometer (BOTDR) is based on spontaneous Brillouin scattering. Pulsed light is launched into one-end of the measured optical fiber and the Brillouin and Rayleigh backscattered light produced in optical fiber are detected by the coherent detection method in a heterodyne receiver, in which a reference light from a continuous-wave (CW) light source is used as an

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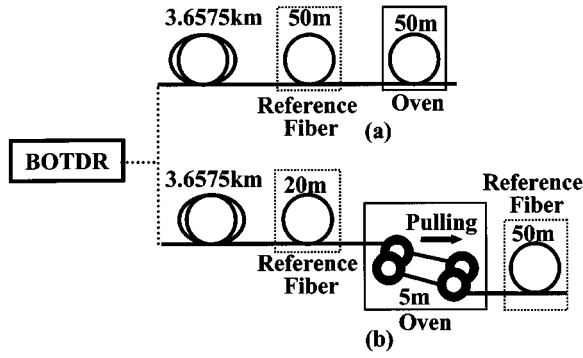


Fig. 1. Experimental setup.

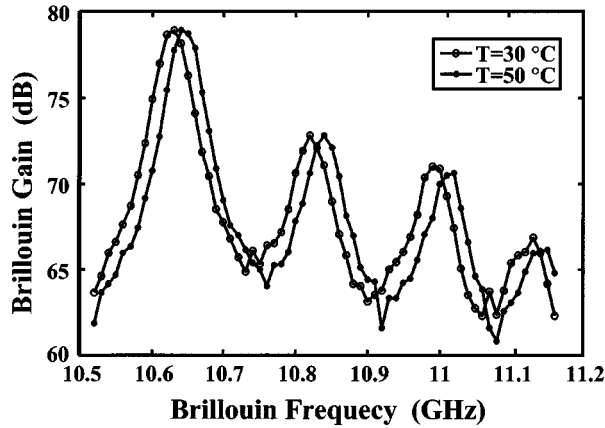


Fig. 2. The measured Brillouin spectra of the final 50-m LEAF at 30 °C and 50 °C.

optical local oscillator. The pulsed light is obtained with a frequency shift from the CW light source after passing through an acoustooptic modulator and an optical frequency shifter. Since the frequency of the Brillouin backscatter is down-shifted for the Brillouin frequency shift V_B from the incident pulsed light, only the Brillouin backscatter light can be detected by adjusting the frequency shift amount of the optical frequency shifter. When measurements are repeatedly performed by changing the frequency shift amount, the Brillouin spectrum at each position of the optical fiber can be measured.

Fig. 1 shows the experimental setup. A BOTDR with an operating wavelength at 1554 nm is used to measure the spontaneous Brillouin spectra along the length of LEAF. The used LEAF has the characteristics with loss coefficient of 0.21 dB/km, effective area of $70 \mu\text{m}^2$, and dispersion of 4 ps/nm km at 1.55 μm . For the temperature measurement, three separate sections of the test LEAF were arranged as shown in Fig. 1(a). The first 3.6575-km LEAF remained on the original spool as supplied by the manufacturer, the subsequent 50-m LEAF was subject to a low-level tension as a reference section, and the final 50-m LEAF was placed in a thermally insulated oven. The operating conditions of BOTDR were as follows: output power of 23 dBm, pulsewidth of 100 ns, average times of 2^{15} , sweep frequency of 5 MHz, and spatial sampling interval of 2 m. The measured Brillouin spectra of the final 50-m LEAF at 30 °C and 50 °C are shown in Fig. 2. The central frequencies of four peaks are

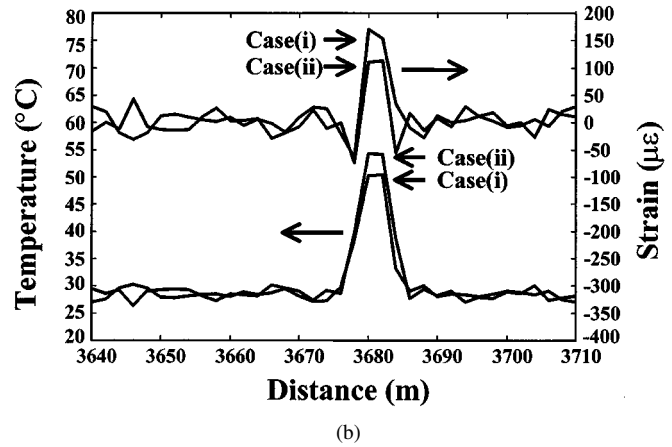
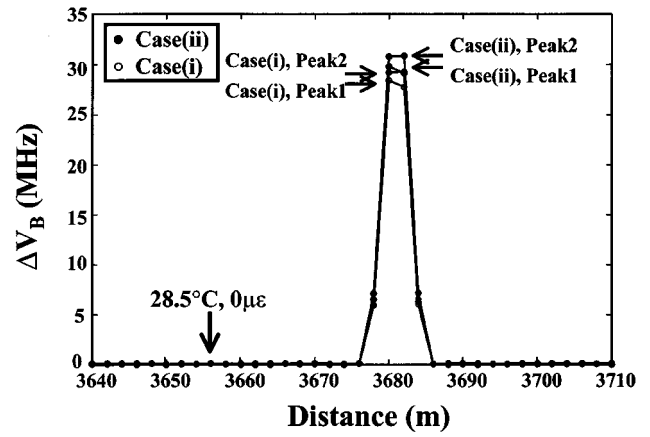


Fig. 3. (a) The measured change in Brillouin frequency shift of peak1 and peak 2 versus distance in the testing cases (i) and (ii). (b) The calculated distributed temperature and strain in the cases (i) and (ii).

10.626, 10.820, 10.99, and 11.12 GHz for peak 1–peak 4, respectively, in the case of 30 °C, and 10.644, 10.840, 11.00 and 11.14 GHz for peak 1 to peak 4, respectively, in the case of 50 °C. When the temperature increment (ΔT) ranging from 19 °C to 28 °C, the averaged ΔV_B for peak 1 and peak 2 in the 50-m temperature-sensing LEAF were measured. From the data, the temperature coefficients of the Brillouin frequency shift C_T^{Pk1} and C_T^{Pk2} are determined to be 0.918 and 0.98 MHz/°C, respectively. In addition, we can observe that the temperature resolution is about 2 °C by using this 50-m sensing LEAF.

For the strain measurement, four separate sections of the test LEAF were arranged as shown in Fig. 1(b). These four LEAF sections were the first 3.6575-km LEAF remained on the original spool, the subsequent 20-m LEAF with low-level tension, the sensing 5-m LEAF, which was wrapped around fiber stretching unit to change the fiber strain only, in the oven, and the final 50-m LEAF with low-level tension. The operating conditions of BOTDR were kept the same except for the pulsewidth of 20 ns. The fiber change in the Brillouin frequency shift were measured in the range of the fiber strain from 107 to 960 $\mu\text{ε}$ for peak 1 and peak 2 in the 5-m sensing LEAF. The strain coefficients C_{ϵ}^{Pk1} and C_{ϵ}^{Pk2} are therefore derived to be the same of 0.05 MHz/ $\mu\text{ε}$ with the measurement

error better than ± 0.03 MHz, which corresponds to the strain accuracy of $6 \mu\epsilon$.

To verify the feasibility of this method for simultaneous strain and temperature measurement of the distributed fiber link, two kinds of conditions for strain and temperature are applied on the 5-m section of the test LEAF in Fig. 1(b). These two cases of temperature and strain are: (i) $50.1^\circ\text{C}/165 \mu\epsilon$ and (ii) $55.1^\circ\text{C}/104 \mu\epsilon$, and the room temperature for reference is 28.5°C . Fig. 3(a) shows the measured change in Brillouin frequency shift of peak 1 and peak 2 versus distance in the testing cases (i) and (ii), respectively. By using (1) and (4), the distributed temperature and strain in the cases (i) and (ii) can be retrieved as shown in Fig. 3(b). For cases (i), the calculated temperature/strain are $50.21^\circ\text{C}/170.3 \mu\epsilon$ at 3680-m length and $50.42^\circ\text{C}/153.2 \mu\epsilon$ at 3682-m length. For cases (ii), the calculated temperature/strain are $54.3^\circ\text{C}/110.7 \mu\epsilon$ at 3680-m length and $54.2^\circ\text{C}/113.1 \mu\epsilon$ at 3682-m length. Since the experimental results of case (i) and (ii) show that the temperature difference of 5°C and the strain difference of $\sim 60 \mu\epsilon$ between case (i) and (ii) were distinguishable in Fig. 3(b), a temperature resolution of 5°C , a strain resolution of $60 \mu\epsilon$ and a spatial resolution of 2 m are achieved over a 3682-m sensing length. From the fluctuation of calculated temperature and strain, a temperature resolution of 2°C , a strain resolution of $20 \mu\epsilon$, and a spatial resolution of 2 m are expected to accomplish over a 3682-m sensing LEAF.

In summary, we have proposed and realized a new method that utilizes LEAF having compound compositions with different temperature coefficients in core to simultaneously measure the distributed strain and temperature based on Brillouin frequency shift. In a 3682-m sensing length of large-effective-area nonzero dispersion-shifted fiber, a temperature resolution of 5°C , a strain resolution of $60 \mu\epsilon$, and a spatial resolution of 2 m are achieved simultaneously.

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