Application of high-precision temperature-controlled FBG filter and light source self-calibration technique in the BOTDR sensor system

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A high-precision temperature-controlled narrow band-stop fiber Bragg grating (FBG) filter and light source self-calibration technique are proposed for application in the Brillouin optical time domain reflectometer (BOTDR) sensor system. With the proposed application, the BOTDR sensor system maintains good long-term stability and temperature precision through the reduction of the center wavelength drift in the FBG filters and corresponding decrease in the changes in light intensity. The experiment result shows that temperature precision of 1 °C and temperature stability of 0.7 °C can be achieved in a temperature sensor over a range of 8 km.

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Optical fiber sensors are widely used for distributed temperature and strain measurement in structural health and fire monitoring. Recently, the Brillouin optical time domain reflectometer (BOTDR) sensor system has garnered extensive attention from researchers because of its excellent advantages, such as high spatial resolution, long-distance monitoring capability, strong resistance to corrosion, and electromagnetic interference (EMI)[1−3].

In the BOTDR system, the temperature and strain information along the sensing fiber can be obtained by detecting the frequency shift of the Brillouin back-scattered light. However, the back-scattered light contains noise, such as Raleigh back-scattered light and Raman back–scattered light, which could interfere with the detection of the Brillouin back-scattered light[4]. In order to reduce the noise, fiber Bragg grating (FBG) filter is introduced to the system. As the center wavelength of the FBG is affected by the temperature and strain[5,6], the filtering effect is decreased when the center wavelength of the FBG drifts away from the wavelength of the Brillouin back-scattered light. In our previous work[3], the FBG filter is controlled by an adjustable cantilever structure, which possesses high sensitivity[7]. However, in our system, this method cannot satisfy the requirement for long-term stability due to the fluctuation of the environmental temperature. In order to maintain long-term stability and noise-filtering capability, the FBG filter must be kept at a fixed temperature as the optimum operating point.

Moreover, fluctuations in the intensity of the light source are influenced by many factors, such as the ambient temperature and the supply voltage. These can lead to the deterioration of the spectrum detection.

In this letter, a narrow band-stop FBG filter with high-precision temperature control is presented for use in the BOTDR system. Simultaneously, a light source self-calibration technique is used. With these applications, the center wavelength drift of the FBG filter is reduced,

and the influence of the intensity fluctuation is decreased. Finally, good stability of the temperature signal along the whole optical fiber is achieved.

The Brillouin scattering is a result of the optical photon scattering brought about by acoustic phonons. When this process occurs in the optical fiber, the scattered light suffers a frequency shift, which contains information about the temperature and strain along the optical fiber. This information can be expressed as[8]

$$v_{\rm B}(T,\varepsilon) = C_{v\varepsilon}(\varepsilon - \varepsilon_0) + C_{vT}(T - T_0), \qquad (1)$$

where $v_{\rm B}$ is the Brillouin frequency shift, $C_{v\varepsilon}$ is the strain coefficient of frequency, and C_{vT} is the temperature coefficient of frequency. In the common single-mode optical fiber, $C_{v\varepsilon} = 0.0483 \pm 0.0004$ MHz/$\mu\varepsilon$ and C_{vT}=1.10±0.02 MHz/K[8].

The frequency shift of the Brillouin back-scattered signal can be used for distributed temperature and strain sensing based on the formula given above[8].

In the BOTDR system, the back-scattered light contains a variety of other frequency components, such as Raleigh back-scattered light and Raman back-scattered light (Fig. 1)[4]. In common single-mode silica fibers, the Brillouin back-scattered light and the Raleigh back-scattered light have a wavelength interval of 0.1 nm (∼11 GHz)[9,10]. Thus, the amplitude of

Fig. 1. Frequency components of the signal and noise in the BOTDR system.

the signal is unstable due to the noise interference from the Raleigh back-scattered light. A feasible method to resolve this is to use a narrow band-stop FBG filter to separate the Brillouin back-scattered signal from the background noise, such as Raleigh back-scattered light and Raman back-scattered light.

The principle of filter demodulation by FBG is demonstrated in Fig. 2. When the center wavelength of the FBG is adjusted to the Brillouin back-scattered light and the 3-dB bandwidth is 0.09 nm, most of the Raleigh back-scattered light can pass through, whereas most of the Brillouin back-scattered light is reflected back. In the opposite direction, most of the reference light can pass through the FBG filter; thus, the Brillouin signal can be separated from the background noise. However, the center wavelength of the FBG drifts when the FBG is affected by the temperature and strain; this can be expressed as[5,6]

$$\Delta\lambda_1 = 6.7 \times 10^{-6}\Delta T \cdot \lambda_1, \tag{2}$$

where $\Delta\lambda_1$ is the center wavelength drift caused by temperature, ΔT is the temperature variation, and λ_1 is the initial wavelength of the FBG.

When the temperature drifts by 1 °C in bare FBG at 1 544.1 nm, the wavelength drift is $\Delta\lambda_1$=0.01 nm, which can be reduced with a high-precision temperature control (0.1 °C) of the FBG.

In this experiment, the FBG filter was fixed in an aluminum groove. Due to the additional deformation of the aluminum groove, the temperature coefficient of the wavelength drift was 0.035 nm/°C, which was bigger than 0.01 nm/°C as mentioned above. As the temperature control accuracy reaches 0.1 °C, the fluctuation of the center wavelength is reduced to 0.0035 nm. Given that the 3-dB bandwidth is 0.09 nm, the fluctuation of the reflectivity does not exceed 0.12 dB.

In the proposed BOTDR system, a light source, self-calibration technique was used to reduce the influence of the power fluctuation of the light source. In the scanning process of the Brillouin spectrum with a step of 2.5 MHz, a photodiode (PD1) was used to record the power of the light source, while the PD2 recorded the intensity of the Brillouin spectrum on each frequency point. Then, the average power of the light source was used as the normalized basis, after which a normalization factor of the light source on each frequency point was obtained. Finally, the spectral intensity was divided by the square of the normalization factor in the corresponding frequency point. The influence of the Brillouin spectral detection by the power fluctuation of the light source was reduced through this process.

Figure 3 shows the configuration of the BOTDR sensor system with the high-precision temperature-controlled FBG filter. Laser beams radiated from the distributed feedback (DFB) laser is divided into two beams by a beam coupler (10:90). Around 90% of the laser is used as a probe light, while the remaining 10% is used as a reference light. The probe light is changed to a 30-ns pulsed light with the modulation of an electro-optic modulator (EOM) and an acousto-optic modulator (AOM),

after which it is amplified by the erbium doped fiber amplifier (EDFA1). When the pulsed probe light is fed into the fiber with a length of 8 km, after passing through

Fig. 2. Principle of filter demodulation by FBG.

Fig. 3. Configuration of the BOTDR sensor system with the high-precision.

the polarization scrambler (PS) and circulator (C1), the back-scattered light comes back through C1 and is then amplified by EDFA2. The second circulator (C2) allows the back-scattered light to come into the reference light path in the opposite direction. On the reference light path, 5% of the reference light detected by the PD1 is used for optical power self-calibration, while the remaining 95% of the reference light passes through the high-precision temperature-controlled narrowband-stop FBG filter with a bandwidth of 0.09 nm. Finally, the Brillouin back-scattered light from C2 is reflected back, through which both the reference light and the Brillouin back-scattered light entering into the PD2 and the beat signal are detected. The signal is amplified and collected by the high-frequency microwave demodulation (HFMD) module and data acquisition card (DA card).

The center wavelength of the DFB laser is about 1 544.2 nm, its power is 10 mW with a bandwidth of less than 100 KHz. The pulse repetition frequency is 2 KHz in this experiment. The FBG filter is set to 1 544.1 nm to fix around the Brillouin spectrum when its operating temperature is controlled at 24 °C.

As the above description shows, the center wavelength of the narrow band-stop FBG filter is adjusted to be the same as that of the Brillouin back-scattered light; afterwards, the Brillouin back-scattered light can be separated from the Raleigh noise and reflected back. Thus, the stability of the Brillouin signal can be improved due to the application of the high-precision temperature controlled FBG filter. Finally, two fiber loops (5 and 8 m) with a space interval of 8 m are placed into the constant

temperature oven (Fig. 3).

Figure 4 shows the Brillouin spectrum for a single point at 6 km along the optical fiber obtained by the data acquisition card and then averaged 2^{12} times in
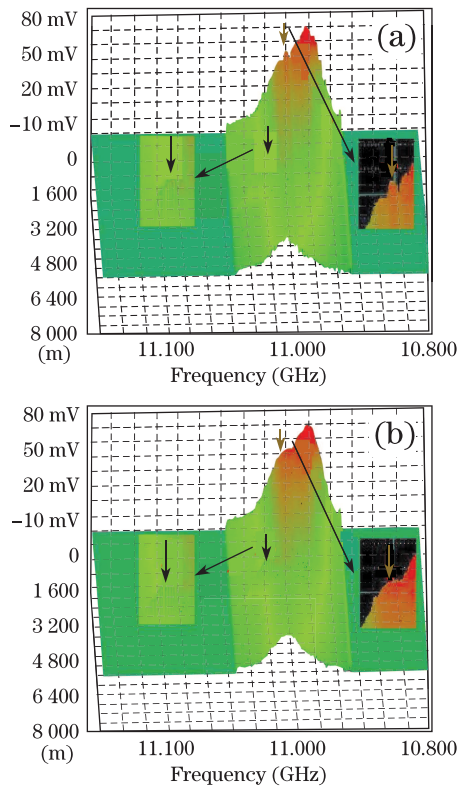

Fig. 4. Measurement results of the 8-km-long optical fiber with the oven heated to 56 °C in different days. Brillouin spectrum (a) without self-calibration and (b) with self-calibration.

different days; the FBG filter works at 24 °C while the 8-km optical fiber is placed at 26 °C room temperature of 26 °C with the oven heated to 56 °C. Figures 4(a) and (b) show the results without and with self-calibration technique, respectively. The intensity of the Brillouin spectral curve has a fluctuation along the frequency axis (Fig. 4(a)), and the Brillouin spectral curve is smooth (Fig. 4(b)). As can be seen, the intensity fluctuation of the Brillouin spectrum has been reduced when the self-calibration technique is used, thus proving the latter's ability to minimize temperature measurement errors.

The Brillouin frequencies of the two fiber loops in the oven at the 5-km point show apparent shifts (Figs. 4(a) and (b), respectively) due to the 30 °C temperature difference between the oven and the room. Figures 5(a), (b), and (c) show the measured Brillouin spectral curves for a single point at 6-km along the optical fiber in different days using the self-calibration technique. As shown in Fig. 5, the peak amplitudes of the Brillouin spectrum at the 6-km point taken in different days are 37.5, 37.7 and 37.2 mV, respectively, and the fluctuation of the amplitudes is less than 1.5%. These indicate good stability of the Brillouin spectral measurement with self-calibration. This spectrum stability is better than that of the tunable FBG filter controlled by an adjustable cantilever structure, whose optimum operating point

must be readjusted when the environment temperature changes.

The bandwidth of the HFMD we used was 300 MHz, and the central frequency was 10.95 GHz. The Brillouin spectrum in our system ranged from 10.95 to 11.07 GHz at a temperature of 26 °C with a full-width at half-maximun (FWHM) of about 60 MHz (Fig. 5). The central frequency of the Brillouin spectrum increases when the temperature increases; thus, the Brillouin spectrum with a high temperature cannot be obtained due to the bandwidth limitation of the HFMD. In order to obtain a larger temperature measuring range, a broader HFMD bandwidth is required; at the same time, the central frequency of HFMD must also be changed.

The result of the temperature signal demodulation is shown in Fig. 6. The measured temperatures of the two fiber loops in the oven heated to 56 °C are about 55.5 and 55.8 °C. The temperature signal obtained from the Brillouin frequency shift of the optical fiber under room temperature shows good temperature resolution. The measured temperature is 26 °C with a root mean square error (RMSE) of 1 °C at the end of the optical fiber with a length of 8 km.

Table 1 shows a good stability of the repeated experiment taken for a week. The RMSE of the temperature is 0.7 °C, with the FBG filter temperature controlled.

In conclusion, high-precision temperature-controlled FBG filter and light source self-calibration technique are proposed for use in the BOTDR system. With these applications, the center wavelength drift of the FBG filter decreases, and the influence of the Brillouin spectral detection by the power fluctuation of the light source is reduced. Thus, a temperature resolution of 1 °C and a temperature stability of 0.7 °C are achieved through our proposed BOTDR system. This improvement can
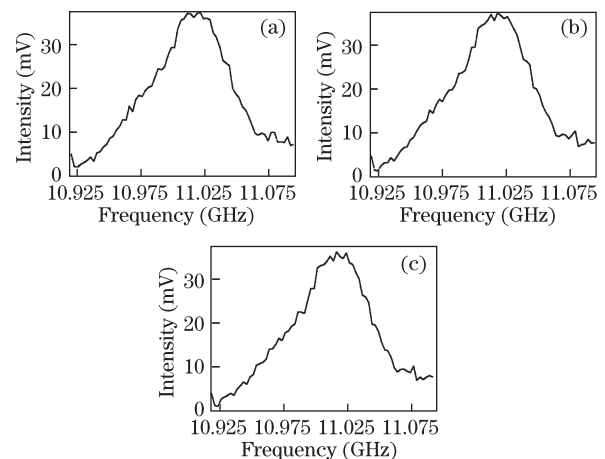

Fig. 5. Brillouin spectrum for a single point at 6-km-along the optical fiber with the oven heated to 56 °C obtained in different days (self-calibration is used in all instances).
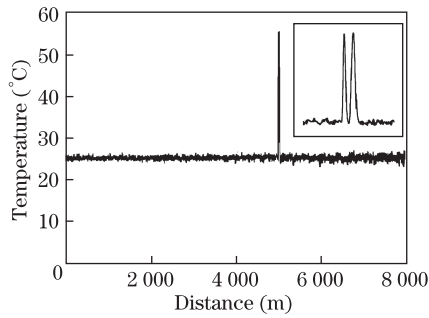
Fig. 6. Results of the temperature signal demodulation with the optical fiber at 26 °C and the oven heated to 56 °C (self-calibration is used in all instances).

Table 1. Results of the Repeated Experiments for Temperature Demodulation [FBG Filter Works at 24 °C with the Oven Heated to 56 °C (Self-Calibration is Used in All Instances)]

Time (Day)	1st	2nd	3rd	4th	5th	6th	7th	Average	RMSE
Loop of 5 m (°C)	55.1	54.3	54.8	55.7	54.0	55.5	55.9	55.0	0.76
Loop of 8 m (°C)	56.1	55.6	55.3	56.6	54.7	55.9	56.7	55.8	0.71

enhance the signal-to-noise ratio and the long-term stability of the system, making it feasible for use in practice under different ambient temperatures.

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