A high sensitive fiber Bragg grating strain sensor with automatic temperature compensation

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A high sensitive fiber Bragg grating (FBG) strain sensor with automatic temperature compensation is demonstrated. FBG is axially linked with a stick and their free ends are fixed to the measured object. When the measured strain changes, the stick does not change in length, but the FBG does. When the temperature changes, the stick changes in length to pull the FBG to realize temperature compensation. In experiments, 1.45 times strain sensitivity of bare FBG with temperature compensation of less than 0.1 nm Bragg wavelength drift over 100 °C shift is achieved.

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It is very appealing to substitute electronic sensors by optical ones for its intrinsic advantages, such as immunity to electromagnetic interference, lightweight, small size, and so on. Among the researches of optical sensors, strain and temperature are two hottest issues and fiber Bragg grating (FBG), as a good sensing element, attracts much more attentions than others[1]. However, the resolution of current FBG strain sensors is too low compared with electronic sensors (1×10^{-4} $\mu\varepsilon$) and their temperature compensation methods are too complicated for practical applications. FBG intrinsic strain resolution is 0.83 $\mu\varepsilon$/pm. Some works have been done to improve the resolution of the demodulation[2−5], but few to improve the sensor head. Moreover, FBG is sensitive to both temperature and strain, and temperature compensation is necessary in strain monitoring. For achieving temperature compensation, most of researchers have used a two-parameter sensing method (sensing strain and temperature at the same time, and then eliminating temperature influence from the results)[6−10]. It is quite complicated and involves special devices.

In this letter, we propose a novel and simple FBG strain sensor with high sensitivity and automatic temperature compensation. Its principle is analyzed and its applications to band filter and temperature sensor are discussed. In experiments, 1.45 times strain sensitivity of a bare FBG is achieved regardless of temperature, and the temperature compensation of less than 0.1 nm Bragg wavelength drift over 100 °C shift is obtained regardless of the measured strain[11]. Therefore, whenever the temperature changes, it is compensated; whenever the measured strain changes, it is enhanced. The strain accuracy, which this sensor can reach, is also discussed.

The resonance Bragg wavelength shift, induced by the temperature and strain change, is

$$\Delta\lambda_{\rm B} = \lambda_{\rm B}(1 - P_{\rm e})\Delta\varepsilon_{\rm FBG} + \lambda_{\rm B}\xi\Delta T, \quad (1)$$

where $P_{\rm e}$ ($\approx$ 0.22) is the photo-elastic constant, ξ ($\approx 6.7 \times 10^{-6}$ /°C) is the thermo-optic coefficient, ΔT is the environment temperature change, and $\Delta\varepsilon_{\rm FBG}$ is the strain change of FBG.

As shown in Fig. 1, a tensioned FBG is fixed between a stick and the object to be measured. The temperature influence on the thermo-optic coefficient of the FBG is compensated by its strain change resulting from the temperature-induced length change of the stick. Therefore, the shift of the resonance wavelength of the FBG only represents the strain change of the measured object. While the measured strain changes, the stick does not change in length but the FBG does. So the measured strain is amplified and transferred to the FBG.

When the FBG is under tension, the strain change of FBG is

$$\begin{aligned}\Delta\varepsilon_{\rm FBG} &= \frac{\Delta d}{d} = \frac{\Delta(d+L) - \Delta L}{d} \\ &= \frac{(d+L)}{d}\frac{\Delta(d+L)}{(d+L)} - \frac{L}{d}\frac{\Delta L}{L} \\ &= \frac{(d+L)}{d}\Delta\varepsilon_{\rm m} - \frac{L}{d}\Delta\varepsilon_l \\ &= \frac{(d+L)}{d}\Delta\varepsilon_{\rm m} - \frac{L}{d}\alpha\Delta T, \end{aligned} \quad (2)$$

where d is the distance between two mounting points, L is the length of the stick, $\Delta\varepsilon_{\rm m}$ is the strain change of the measured object, $\Delta\varepsilon_l$ is the strain change of the stick, and α is the thermal expansion coefficient of the stick.

Substituting Eq. (2) into Eq. (1), we have

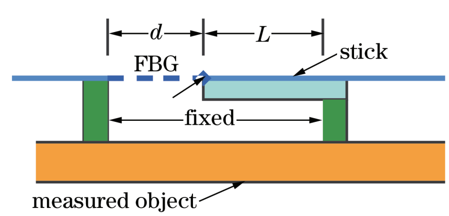

Fig. 1. A high sensitive FBG strain sensor with automatic temperature compensation.

$$\Delta\lambda_B = \lambda_B(1-P_e)\left[\frac{(d+L)}{d}\Delta\varepsilon_m - \frac{L}{d}\alpha\Delta T\right] + \lambda_B\xi\Delta T$$

$$= \lambda_B(1-P_e)\frac{(d+L)}{d}\Delta\varepsilon_m + \lambda_B\left[\xi - (1-P_e)\frac{L}{d}\alpha\right]\Delta T$$

$$= \lambda_B(1-P_e)(1+\frac{L}{d})\Delta\varepsilon_m \quad (3)$$

when $\xi = (1-P_e)\frac{L}{d}\alpha$.

Equation (3) shows that the resonance wavelength shift $\Delta\lambda_B$ is immune to the fluctuation of temperature and $(1+L/d)$ times more sensitive to the change of the measured strain.

When the temperature and/or the measured strain change, both d and L may change a little. But the changing ratio of L/d is so low (around the changing ratio of λ_B) that L/d can be treated as a constant. Its changing ratio is

$$\frac{\left|\frac{L+\Delta L}{d+\Delta d} - \frac{L}{d}\right|}{\frac{L}{d}} = \left|\frac{L+\Delta L}{d+\Delta d}\ \frac{d}{L} - 1\right|$$

$$= \left|\frac{d(L+\Delta L) - L(d+\Delta d)}{L(d+\Delta d)}\right|$$

$$= \left|\frac{d\Delta L - L\Delta d}{L(d+\Delta d)}\right| = \left|\frac{d}{(d+\Delta d)}\frac{\Delta L}{L} - \frac{\Delta d}{(d+\Delta d)}\right|$$

$$= \left|\frac{d}{(d+\Delta d)}\alpha\Delta T - \frac{\Delta d}{(d+\Delta d)}\right|$$

$$< \left|\frac{d}{(d+\Delta d)}\alpha\Delta T\right| + \left|\frac{\Delta d}{(d+\Delta d)}\right| \approx \left|\alpha\ \Delta T\right| + \left|\frac{\Delta d}{d}\right|$$

$$< 1\%, \quad (4)$$

when $\alpha < 50\times10^{-6}$ /°C, $\Delta T \leq 100$ °C, $\frac{\Delta d}{d} < 5000\ \mu\varepsilon$.

That is to say, when the stick is a usual material ($\alpha < 50\times10^{-6}$ /°C), the temperature changes within 100 °C, and when $\Delta\varepsilon_{FBG} < 5000\ \mu\varepsilon$, the changing ratio of L/d is less than 1%.

The temperature compensation of less than 0.1-nm resonance Bragg wavelength drift over 100-°C shift (from −30 to 70 °C) is got, regardless of both the pre-set strain of FBG and the lengths of sensors[11]. To take advantage of these results, we manufactured a sensor with the same ratio of L/d (0.39) and similar FBG (approximately 15 mm long, written with phase masks, Bragg wavelength about 1526 nm). The length of the measured object was tuned by a precise tube (TSM13-2A, Zolix) with a resolution of 0.01 mm. And $L = 39$ mm, $d = 100$ mm. The FBG was fixed by epoxy glue and the stick was fixed by a bolt and a nut[12]. A 40-nm (1525 − 1565 nm) broadband light source was used. The accuracy and resolution of the demodulator (Pi05, Pi-optics) were ±3 pm and 1 pm, respectively. At the room temperature of 16 °C, the strain response of the sensor was tested in steps of 36 $\mu\varepsilon$ (by increasing the length of the measured object by 0.05 mm). It was repeated for 3 times and the results were similar[13]. The average values were compared with the strain response of a bare FBG, as shown in Fig. 2. The reason why the sensitivity is a little larger than expected mainly lies in the measurement errors of the lengths. At 30 and 50 °C (under the sunlight), the experiments were repeated and the strain responses similar. The signal level of resonance Bragg wavelength was not affected in all experiments[11−15].

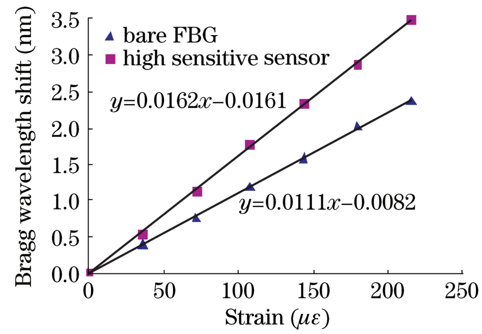

Fig. 2. Variation of resonance Bragg wavelength shift with the change of strain.

This strain sensor also has applications in other fields. When the measured object is made of different material and not subject to any stress, the sensor may become a high sensitive temperature sensor or a waveguide light filtering device. When the measured object has a high coefficient of thermal expansion, its strain sharply changes with temperature. So the resonance Bragg wavelength becomes much more sensitive to temperature, and the strain sensor becomes a high sensitive temperature sensor. When it has a coefficient of thermal expansion around 0, $\Delta\lambda_B$ always stays still and the strain sensor becomes a filter. When a broadband light goes through the filter, a fixed wavelength is eliminated out. Similar temperature sensors[12−15] and filters[11,16] have been studied and demonstrated. In all of them, the strain change of measured objects are amplified by $(1+L/d)$ times and transferred to the FBG; at the same time, the length change of the sticks equally moves to the length change of the FBG in the opposite direction. Particularly, in Ref. [13], 22 $\mu\varepsilon$ variation of the measured object, induced by 1 °C temperature change, results in 699-pm shift of the resonance wavelength (eliminating 10 pm/°C intrinsic temperature response of FBG from its total response 709 pm/°C), and so its strain sensitivity and resolution are 31.77 pm/$\mu\varepsilon$ and 0.03 $\mu\varepsilon$/pm, respectively; its strain accuracy is about ±1.1 $\mu\varepsilon$ ($0.05\ °C\times22\times10^{-6}$ /°C $\times10^6$), corresponding to the temperature accuracy of ±0.05 °C[13].

In conclusion, for improving the FBG strain sensor's sensitivity and overcoming the drawbacks of current temperature compensation methods, a high sensitive strain sensor with automatic temperature compensation is demonstrated. By linking a FBG with a stick that changes in length only in response to temperature, the measured strain is mechanically amplified and transferred to FBG, and the intrinsic temperature dependence of FBG is automatic compensated. This sensor may have various applications in many different fields.

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