OPTOELECTRONICS LETTERS Vol.10 No.1, 1 January 2014

# Union self-compensated packaging of FBG strain sensor*

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(Received 30 September 2013)

To solve the cross-sensitivity to temperature of fiber Bragg grating (FBG) strain sensor, an effective method is firstly proposed for the discrimination of strain and temperature by using a single FBG adopting a special compensated structure, which is based on the thermal stress. The relationship of strain and temperature responses of FBG is analyzed theoretically. The experimental results are in agreement with the obtained theoretical analyses. This sensor structure has excellent characteristics, such as simple structure, easy manufacture and higher strain sensitivity.

**Document code:** A **Article ID:** 1673-1905(2014)01-0030-4
**DOI** 10.1007/s11801-014-3179-7

The wavelength is sensitive to temperature and strain at the same time, which is fatal to fiber Bragg grating (FBG) as a strain sensor. To solve this problem, many methods have been proposed, which include the use of dual wavelength superimposed gratings[1], hybrid Bragg grating/long-period grating[2,3], dual-diameter FBGs[4], FBG combined with a high birefringence fiber loop mirror[5], long-period FBG inscribed Sagnac interferometer[6], integration of miniature Fabry-Perot fiber optic sensor with FBG[7], dual-type FBGs[8], the case of two FBGs, one of which is not bonded to the structure[9], dual-core fiber grating[10], piezoceramic (PZT) driving method[11] and a core-offset polarization maintaining photonic crystal fiber based interferometer[12]. Obviously, most of these methods are to utilize a pair of FBGs or a single FBG with other elements with different sensitivities to strain and temperature, which generally require the calibration for the sensitivity of each element in advance, resulting in complexity for application. It is thus highly desired to utilize a single FBG to achieve the discrimination of strain and temperature. There are also some other methods, such as prestressing packaging[13] and negative expansion material packaging[14]. However, prestressing packaging method can cause FBG to be detached from the structure, and the negative expansion material packaging method can not be used as strain sensor. Moreover, it is possible to obtain different sensitivities of strain and temperature in the FBGs by forming superstructures[15-17]. A novel metallic fiber Bragg grating[18] has the lower temperature sensitivity, but the method can not fully eliminate the temperature response. The mentioned methods are not suitable for low cost sensing applications, because they are very expensive to implement and require complex fabrication technology and/or sophisticated instrumentation.

In this paper, a cost-effective method is firstly proposed for the discrimination of strain and temperature by using a single FBG adopting a special compensated structure. The relationship of strain and temperature response of FBG is analyzed theoretically. The experiment is then carried out, which agrees with the theoretical analyses well.

The compensated structure is composed of part 1 and part 2 as shown in Fig.1. Part 1 is used as the compensated element, and part 2 is used as the strain transferring element. The outer cover denoted as part 3 is used to protect the inner FBG and the other two parts. In this paper, the three parts are made of the same material to solve the problem caused by the junction between the different materials, and the photo of the components is shown in Fig.2. When the temperature is changed, the inner stress between part 1 and part 2 causes the deformation of material to counteract the wavelength drift due to temperature changes, which is our proposed compensation principle.

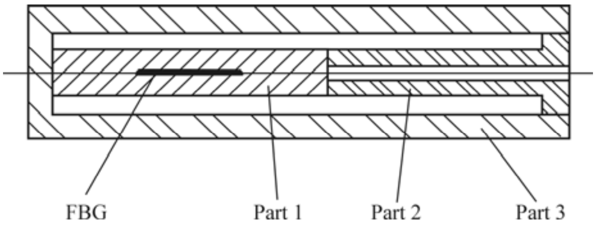

**Fig.1 Schematic diagram of the FBG strain sensor**

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* This work has been supported by the Natural Science Foundation of Hebei Province (No.E2011210058), and the Excellent Young Teachers Program of Shijiazhuang Tiedao University (No.Z90220616).

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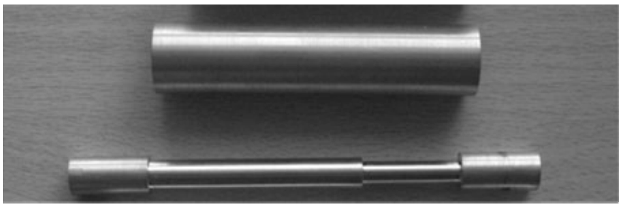


Fig.2 Photo of components of the FBG sensor

The center wavelength $\lambda_B$ of FBG is given by

$$\lambda_B = 2n_{\mathrm{eff}}\Lambda , \tag{1}$$

where $n_{\mathrm{eff}}$ is the effective refractive index of the fiber core, and $\Lambda$ is the periodic spacing of the grating. The Bragg grating resonance, which is the center wavelength of back-reflected light from FBG, depends on the effective refractive index of the core and the periodicity of the grating.

To make FBG achieve complete temperature compensation, this relationship must be satisfied,

$$\Delta\lambda_T = -\Delta\lambda_\varepsilon , \tag{2}$$

where $\Delta\lambda_T$ and $\Delta\lambda_\varepsilon$ are the wavelength shifts due to temperature and strain, respectively.

Without the stress, the following equation must be satisfied,

$$\Delta L_1 = -\Delta L_2 . \tag{3}$$

The strains of part 1 and part 2 are respectively denoted as

$$\varepsilon_1 = \frac{k_T}{k_\varepsilon}\Delta T , \tag{4}$$

$$\varepsilon_2 = \frac{k_T}{k_\varepsilon}\frac{L_1}{L_2}\Delta T . \tag{5}$$

Thus, the following equation is derived,

$$\frac{\alpha_T + \frac{k_T}{k_\varepsilon}}{\alpha_T - \frac{k_T}{k_\varepsilon}\frac{L_1}{L_2}} = \frac{S_2}{S_1} , \tag{6}$$

where $\alpha_T$ is the expansion coefficient of part 1, $k_T$ is the temperature sensitivity, $k_\varepsilon$ is the strain sensitivity, $L_1$ is the length of part 1, $L_2$ is the length of part 2, $S_1$ is the cross-sectional area of part 1, and $S_2$ is the cross-sectional area of part 2.

In this paper, we make three FBG sensors denoted as 1#, 2# and 3# FBG sensors. 1# and 2# FBG sensors are made of duraluminium alloy, and 3# FBG sensor is made of brass. The expansion coefficients of duraluminium alloy and brass are $21.415\times10^{-6}$/°C and $18.259\times10^{-6}$/°C, respectively. The size parameters are shown in Tab.1, where subscripts 1, 2 and 3 represent part 1, part 2 and part 3 of each sensor.

Tab.1 Size parameters of three kinds of sensors

| Sensor number | 1# | 2# | 3# |
|---|---|---|---|
| $L_1$ (mm) | 30 | 30 | 25 |
| $L_2$ (mm) | 40 | 40 | 54 |
| $L_3$ (mm) | 70 | 71 | 80 |
| $\Phi_{1\ \mathrm{inner}}$ (mm) | 4 | 4 | 4 |
| $\Phi_{1\ \mathrm{outer}}$ (mm) | 6 | 6 | 6 |
| $\Phi_{2\ \mathrm{inner}}$ (mm) | 4 | 4 | 4 |
| $\Phi_{2\ \mathrm{outer}}$ (mm) | 8 | 10 | 8 |
| $\Phi_{3\ \mathrm{inner}}$ (mm) | 10 | 10 | 10 |
| $\Phi_{3\ \mathrm{outer}}$ (mm) | 18 | 18 | 18 |
| Strain sensitivity (pm/με) | 1.638 | 1.934 | 1.796 |
| Compensated results (pm/°C) | 0 | –7.6 | –2.4 |

The packaged FBG is placed in the low temperature thermostat to verify the temperature-compensated effect. To test strain sensing characteristics, the sensor is tested by a material testing system (MTS) which applies axial tension at a constant temperature. The temperature range is from –10 °C to 50 °C. With an optical spectrum analyzer (OSA, ANDO AQ6140) and an amplified spontaneous emission (ASE) source (AQ4315A), the temperature dependence and the strain dependence of reflection spectrum at room temperature can be measured. The schematic diagram of the experiment setup is shown in Fig.3.

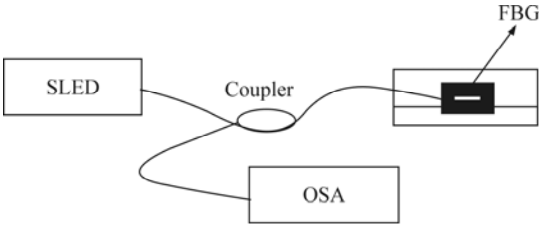
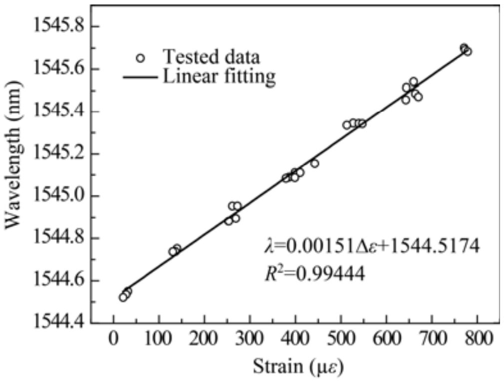
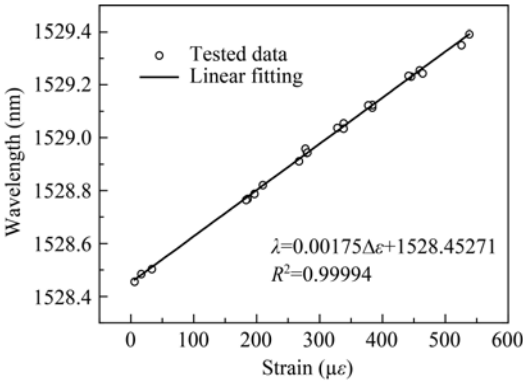


Fig.3 Schematic diagram of the experiment setup

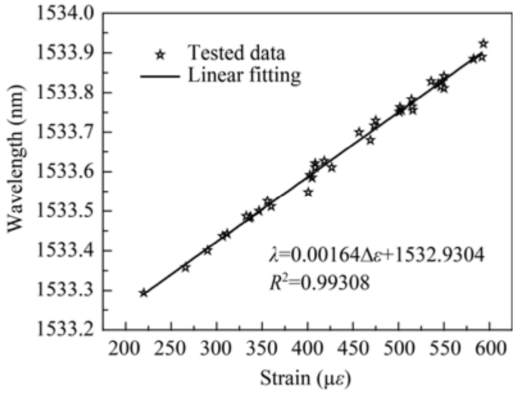
Figs.4 and 5 display the strain and temperature responses of the three sensors. It can be seen from Fig.4 that the linearities of the strain response curves of three sensors are all good. The strain sensitivity of 1# FBG sensor is 1.51 pm/με as shown in Fig.4(a), which is higher than that of the bare FBG. As shown in Fig.4(b) and (c), the strain sensitivities of 2# and 3# FBG sensors are 1.75 pm/με and 1.64 pm/με, respectively, which are both lower than the theoretical values due to the strain transmission is fully effective. Therefore, modifying the structure design equation must be done in the following research. Fig.5(a) shows that the temperature sensitivity is 0.49 pm/°C, which illustrates the FBG wavelength is nearly not affected by the temperature. Fig.5(b) shows that the temperature sensitivity is –8.21 pm/°C, which illustrates the wavelength drift is decreased with the temperature. Fig.5(c) shows that the temperature sensitivity is –3.15 pm/°C, which illustrates the wavelength drift is decreased with the temperature. Therefore, the experimental results in three sensors all agree with the theoretical analyses.



(a) 1# FBG sensor

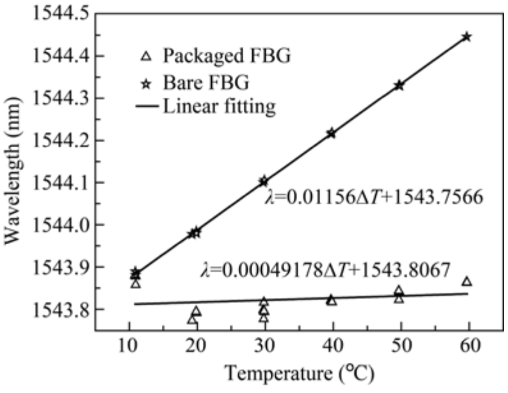


(b) 2# FBG sensor

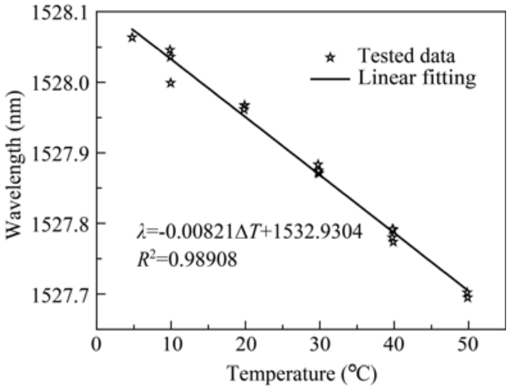


(c) 3# FBG sensor

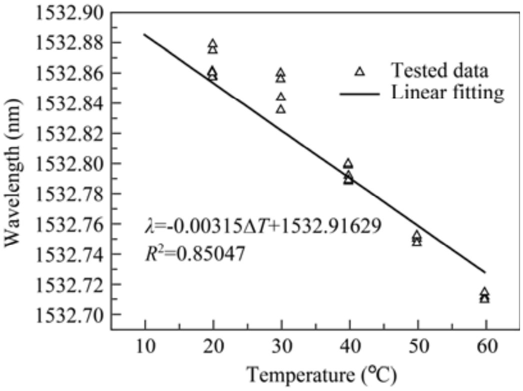
**Fig.4 Strain responses of 1#, 2# and 3# FBG sensors**



(a) 1# FBG sensor



(b) 2# FBG sensor



(c) 3# FBG sensor

**Fig.5 Temperature responses of 1#, 2# and 3# FBG sensors**

In conclusion, an effective method is firstly proposed for the discrimination of strain and temperature by using a single FBG adopting a union compensated structure. Adjusting the structural parameters, the compensation results can be controlled. The temperature self-compensated structure not only counteracts the wavelength changes due to the temperature, but also enhances the strain insensitivity. The relationship of strain and temperature responses of FBG is analyzed theoretically. The experiment is also carried out, and good agreements between experimental results and theoretical analyses are obtained.

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