# Temperature-insensitive fiber Bragg grating strain sensor*

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A fiber Bragg grating strain sensor, whose reflection bandwidth is insensitive to temperature, is presented. The cross-sectional area is designed to change linearly. Under axial stress, there is a linear relationship between stress and average strain. Experimental results show that when temperature increases, reflection center wavelength shifts to longer wavelength, and there is a good linear relationship between center wavelength and temperature. When stress increases, reflection center wavelength shifts to longer wavelength, and reflection bandwidth increases. There are good linear relationships between reflection center wavelength and stress as well as reflection bandwidth and stress.

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Fiber Bragg grating sensors have been widely used in sensor system. They have some obvious features better than fiber optic sensors. As a spectral separation and optical wavelength selection device, its measurement signal is unacted by bending loss, connection loss, light source fluctuations, the aging of measurement instruments, etc. It avoids the problem of phase measurement affected by interferometric optical fiber sensor. However, fiber Bragg grating sensors are sensitive to temperature and stress, and temperature and stress changes also can lead to the shift of reflection center wavelength. Therefore, stress and temperature cross-sensitive problem has been the hot spot with the development of fiber grating sensing technology.

In view of this problem, a number of solutions have been reported, such as reference grating method[1-3], two-period fiber Bragg grating method[4-6], long period fiber grating/fiber Bragg grating fusion method[7-9], different polymer encapsulation method[10], different cladding diameter method[11], etc. The basic idea of these methods is based on the temperature compensation and the simultaneous measurement of temperature and stress. These methods need two or more gratings to overcome the cross-sensitive issues,which increases the difficulty of grating production process and the cost. In addition, some programs also need multiple demodulation light sources, which greatly limits the engineering applications of fiber Bragg grating sensors.

In this paper, a fiber Bragg grating strain sensor, whose reflection bandwidth is insensitive to temperature, is presented. The cross-sectional area of this fiber Bragg grating strain sensor is designed to change linearly.Under axial stress, there is a linear relationship between stress and average strain. For producting this sensor, the annealed fiber Bragg grating is completely vertically imbedded into the 40% hydrofluoric acid, and stepper motor is controlled to have a constant velocity to pull out this fiber Bragg grating from the 40% hydrofluoric acid.

Uniform fiber Bragg grating is shown in Fig.1. It is evenly divided into $N$ units, and each unit is an independent part.

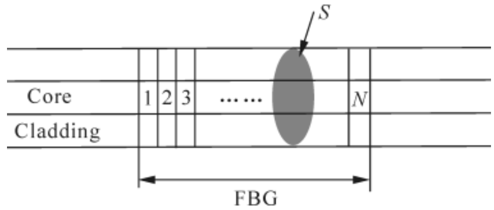


**Fig.1 Schematic diagram of uniform fiber Bragg grating**

For each unit, reflection center wavelengths are the same, and periods are also the same, which can be expressed as

$$\lambda_1 = \lambda_2 = \cdots = \lambda_N \quad , \tag{1}$$

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$$\Lambda_1 = \Lambda_2 = \cdots = \Lambda_N \ . \tag{2}$$

When temperature changes, every small unit has the same thermo-optic coefficient and thermal expansion coefficient, so their refractive indices and grating period changes are the same, which means

$$\Delta\lambda_1 = \Delta\lambda_2 = \cdots = \Delta\lambda_N \ , \tag{3}$$

$$\Delta\Lambda_1 = \Delta\Lambda_2 = \cdots = \Delta\Lambda_N \ . \tag{4}$$

The changes of reflection center wavelength and reflection bandwidth are as follows:

$$\Delta\lambda_{BT} = 2(\xi + a) n_{\rm eff} \Lambda \Delta T \ , \tag{5}$$

$$\Delta W_T = W_T - W_0 = [(\lambda_N + \Delta\lambda_N) - (\lambda_1 + \Delta\lambda_1)] - (\lambda_N - \lambda_1) = 0 \ , \tag{6}$$

where $\xi$ is the thermo-optic coefficient, $\alpha$ is the thermal expansion coefficient, $n_{\rm eff}$ is the effective refractive index of the grating, $\Lambda$ is the period of fiber Bragg grating, and $\Delta T$ is the temperature variation.

Assume axial stress imposed on fiber Bragg grating is $F$, so stress and strain of each small unit are

$$\sigma_n = \frac{F}{S_n} \ , \tag{7}$$

$$\varepsilon_n = \frac{\sigma_n}{E} = \frac{F}{E} \cdot \frac{1}{S_n} \ , \tag{8}$$

where $S_n$ is the cross-sectional area of each unit, $E$ is the Young's modulus, $\sigma_n$ is stress of each small unit, and $\varepsilon_n$ is the strain of each small unit, which can be expressed as

$$\varepsilon_n = \frac{\Delta L}{L} = \frac{\Delta\Lambda_n}{\Lambda_n} \ , \tag{9}$$

so

$$\Delta\Lambda_n = \varepsilon_n \cdot \Lambda_n = \frac{\sigma_n}{E} \cdot \Lambda_n = \frac{\Lambda_n \cdot F}{E} \cdot \frac{1}{S_n} \ . \tag{10}$$

Variations of reflection center wavelength and reflection bandwidth of each unit caused by stress are as follows:

$$\Delta\lambda_n = 2(\Lambda_n \cdot \Delta n_{\rm eff}\varepsilon + n_{\rm eff} \cdot \Delta\Lambda_n) = -2 \cdot \Lambda_n \cdot \frac{1}{2} \cdot n_{\rm eff}^3 [(1-v)P_{12} - vP_{11}] \times \frac{F}{E} \cdot \frac{1}{S_n} + 2n_{\rm eff} \frac{\Lambda_n F}{E} \cdot \frac{1}{S_n} = M\lambda \frac{F}{E} \cdot \frac{1}{S_n} \ , \tag{11}$$

$$\Delta W_\varepsilon = W_\varepsilon - W_0 = [(\lambda_N + \Delta\lambda_N) - (\lambda_1 + \Delta\lambda_1)] - (\lambda_N - \lambda_1) = \Delta\lambda_N - \Delta\lambda_1 = M\lambda \frac{F}{E}\left(\frac{1}{S_N} - \frac{1}{S_1}\right) = KF \ , \tag{12}$$

where

$$M = 1 - \frac{1}{2} n_{\rm eff}^2 [(1-v)P_{12} - vP_{11}], \text{and } K = M\frac{\lambda}{E}\left(\frac{\lambda}{S_N} - \frac{1}{S_1}\right).$$

From Eq.(12), it can be seen that when the cross-sectional areas of the first unit and the $N$th unit are not the same ($S_N \neq S_1$), reflection bandwidth of fiber Bragg grating and bandwidth variation both have a linear relationship with stress.

According to analyses above, in order to ensure the linear relationship between stress and strain, we design cross-sectional area to change linearly. The structure of temperature-insensitive fiber Bragg grating strain sensor is shown in Fig.2.

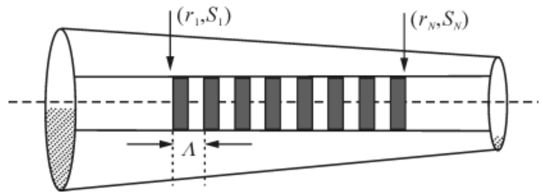


**Fig.2 Structure of temperature-insensitive fiber Bragg grating strain sensor**

Grating length change of each unit caused by axial stress is expressed as:

$$\Delta L_n = \varepsilon_n {\rm d}l \ . \tag{13}$$

Therefore, the average strain of the whole grating region is

$$\varepsilon = \frac{\Delta L}{L} = \frac{\sum \Delta L_n}{L} = \frac{1}{L} \cdot \int \varepsilon_n \cdot {\rm d}l = \frac{1}{L} \cdot \int \frac{F}{E} \cdot \frac{1}{\pi r^2} {\rm d}l \ . \tag{14}$$

The cross-sectional area of fiber Bragg grating is designed to change linearly, so we can assume that $l$ and $r$ have a linear relationship as:

$$l = \frac{r_1 - r}{r_1 - r_N} L \ . \tag{15}$$

So

$$\varepsilon = \int \frac{-F}{(r_1 - r_N)\pi E} \cdot \frac{1}{r^2} {\rm d}r = \frac{F}{(r_1 - r_N)\pi E} \cdot \frac{1}{r}\Big|_{r_1}^{r_N} = \frac{1}{r_1 r_N \pi E} F \ . \tag{16}$$

When temperature-insensitive fiber Bragg grating strain sensor is produced, $r_1$, $r_N$ and $E$ are identified. We can calculate strain region of the fiber Bragg grating by the measured stress information, in order to achieve stress measurement.

For a particular temperature-insensitive fiber Bragg grating strain sensor, calibrate relationships of the temperature-wavelength, stress-wavelength and stress-bandwidth, and determine stress response coefficient $K_\varepsilon$ and temperature response coefficient $K_T$. In actual measurement, measure the variations of center wavelength $\Delta\lambda_B$ and bandwidth $\Delta W$. Determine the stress according to the variation of bandwidth $\Delta W$. Determine the variation of the reflection center wavelength under the stress by

$$\Delta\lambda_\varepsilon=K_\varepsilon \cdot \varepsilon \ . \tag{17}$$

To get rid of the variation caused by the stress, we can get the change of reflection center wavelength only affected by temperature as:

$$\Delta\lambda_T=\Delta\lambda_B-\Delta\lambda_\varepsilon \ . \tag{18}$$

In order to achieve simultaneous measurement of temperature and stress, get the variation of temperature according to temperature-wavelength relationship as

$$\Delta T=(\Delta\lambda_B-K_\varepsilon \cdot \varepsilon)/K_T \ . \tag{19}$$

The experimental setup is shown in Fig.3.

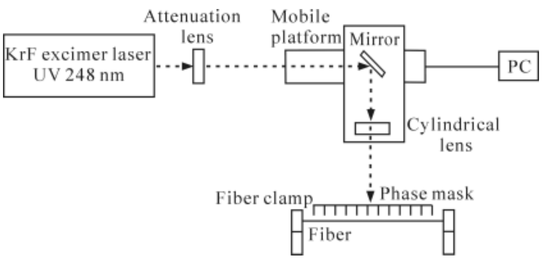


**Fig.3 Schematic diagram of experimental setup**

The broadband light source uses 248 nm excimer laser, and the laser pulse energy is 80 mJ/cm$^2$. The experimental procedures are as follows.

In order to improve photosensitivity of the fiber, the single-mode fiber is placed in the high-purity hydrogen at room temperature for 30 days, and the gas pressure is 10 MPa. After hydrogen loading treatment, use phase mask method to write uniform fiber Bragg grating. Place this fiber grating in incubator from 120 °C to 150 °C annealing for 24 h. After annealing grating, bandwidth or reflectivity can not change with temperature or time. Imbed the annealed fiber Bragg grating completely vertically into the 40% hydrofluoric acid, and control stepper motor with constant velocity to pull out the fiber Bragg grating from 40% hydrofluoric acid. The corrosion rate of fiber diameter is proportional to corrosion time, so cross-sectional area of fiber Bragg grating changes linearly. Pull out the fiber Bragg grating and rinse it with water quickly, and then temperature-insensitive fiber Bragg grating strain sensor is produced.

In this experiment, etching time is 30 min, and the radius of uniform fiber Bragg grating is from 35 μm to 62.5 μm. Fig.4 shows reflection spectrum of temperature-insensitive fiber Bragg grating strain sensor at 20 °C.

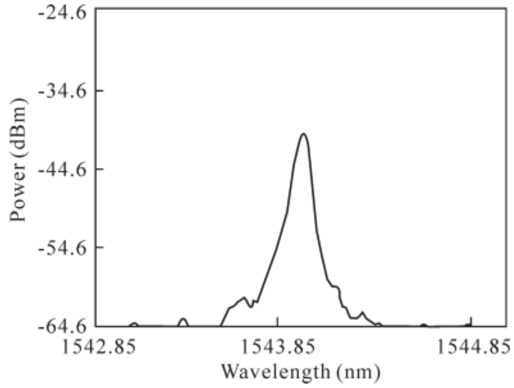


**Fig.4 Reflection spectrum at 20 °C**

In range from -20°C to 170°C, the measured reflection spectra at interval of 10°C are shown in Fig.5.

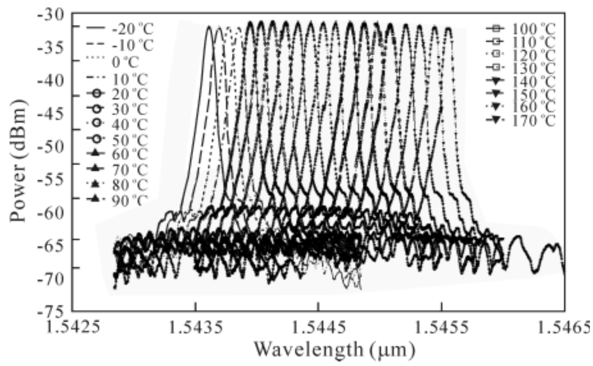


**Fig.5 Reflection spectra under different temperatures**

According to Fig.5, when temperature changes, reflection spectrum shape of this sensor does not change much, and its reflection bandwidth is not subject to temperature changes, but reflection center wavelength shifts to longer wavelength with the increasing temperature. Fig.6 shows the relationship between temperature and center wavelength of this sensor. Fig.7 shows the relationship between temperature

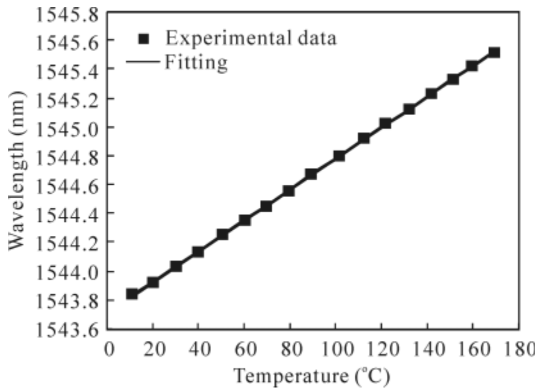


**Fig.6 Relationship between temperature and center wavelength**

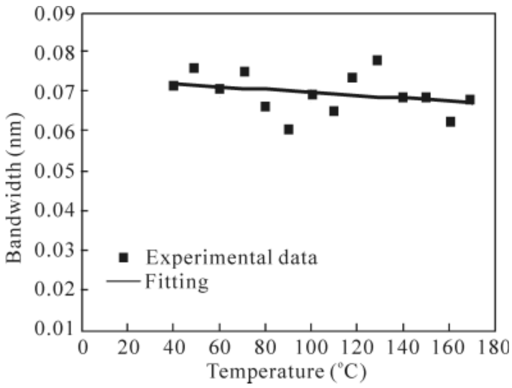


**Fig.7 Relationship between temperature and reflection bandwidth**

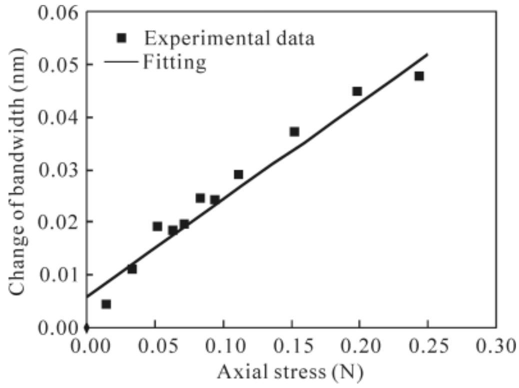


**Fig.9 Relationship between stress and change of reflection bandwidth**

and reflection bandwidth of this sensor.

After temperature experiment, fix one end of the fiber grating, exert different stresses on the other end gradually, and record reflection spectra of temperature-insensitive fiber Bragg grating strain sensor.

Fig.8 shows the relationship between stress and center wavelength of the temperature-insensitive fiber Bragg grating strain sensor. Fig.9 shows the relationship between stress and change of reflection bandwidth of the temperature-insensitive fiber Bragg grating strain sensor. From Figs.8 and 9, we can see that there are good linear relationships between center wavelength and stress as well as reflection bandwidth and stress.

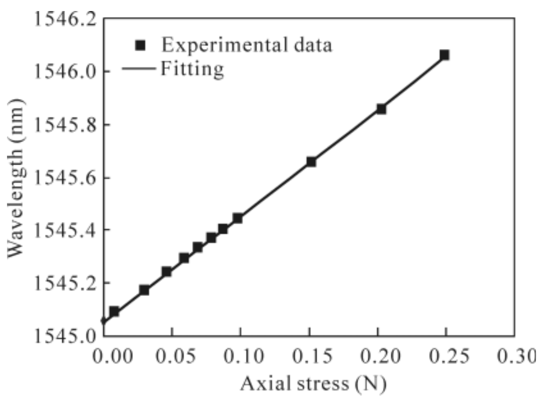


**Fig.8 Relationship between stress and center wavelength**

A fiber Bragg grating strain sensor whose reflection bandwidth is insensitive to temperature is presented in this paper. The cross-sectional area of this sensor changes linearly. Under axial stress, there is a linear relationship between stress and average strain. We can use this sensor to achieve simultaneous measurement of the temperature and stress to solve the problem of sensor cross-sensitivity. Experiment results show that when only temperature changes, reflection spectrum shape of this fiber Bragg grating strain sensor does not change, but reflection center wavelength shifts to longer wavelength with temperature increasing. But when stress changes, reflection center wavelength shifts to longer wavelength, and reflection bandwidth increases with stress increasing.

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