Active temperature compensation design of sensor with fiber gratings

Xingfa Dong (董兴法)[1,2], Yonglin Huang (黄勇林)[2],
Li Jiang (姜 莉)[1], Guiyun Kai (开桂云)[1], and Xiaoyi Dong (董孝义)[1]

[1] *Institue of Modern Optics, Nankai University, Tianjin 300071*
[2] *University of Science and Technology of Suzhou, Suzhou 215011*

Received May 12, 2004

A technique for compensation of temperature effects in fiber grating sensors is reported. For strain sensors and other sensors related to strain such as electromagnetic sensors, a novel structure is designed, which uses two fiber Bragg gratings (FBGs) as strain differential sensor and has temperature effects cancelled. Using this technique, the stress sensitivity has been amplified and gets up to 0.226 nm/N, the total variation in wavelength difference within the range of 3−45 °C is 0.03 nm, 1/14 of the uncompensated FBG. The structure can be used in the temperature-insensitive static strain measurement and minor-vibration measurement.

OCIS codes: 060.2370, 060.2340, 050.2770.

Fiber grating is a new type of photon device with optical wavelength as information, its reflection peak and absorption peak can be easily tuned by strain and temperature. Fiber Bragg grating (FBG) is always a preferable component in sensors, as well as optical transceiver, optical amplifier of communication, which relies mainly on the technique of its wavelength modulation. Generally, in order to measure stress, voltage, and electrical current, FBGs are bonded to the surface of the substance that can accept strain caused by stress, electrical field, and magnetic field[1,2]. But both the strain and temperature can shift the Bragg wavelength of a FBG, the variation of wavelength over 100 °C temperature range for uncompensated grating is up to 1 nm, which is too large for sensing application. Some packaging structures of temperature compensation for FBGs have been proposed. One of the methods is utilizing a combination of two materials having different thermal expansion coefficient[3], the temperature shift rate of the Bragg wavelength for compensating grating over the range of −30−70 °C is only 0.07 nm/100 °C. The other one is sticking two FBGs on the surface of magnetostrictive transducer, but in two perpendicular directions. So, the temperature effects are cancelled out[4]. Used as a sensor, because of the strain and the temperature, the wavelength shift of FBG is the output parameter. In this paper, we propose a method for active temperature compensation in fiber grating sensor. By measuring the wavelength difference of two FBGs that are used as strain differential sensor, it has temperature dependent effects compensated. The design has a wide linear range. It is proved experimentally that the total variation in wavelength difference within the range of 3−45 °C is 0.03 nm, 1/14 of the uncompensated FBG.

Two FBGs with near Bragg wavelengths are epoxied axially onto the surfaces of two employed beams with the same material and shape. When it affected by temperature and axial strain, the relative shift of peak wavelength is

$$\Delta\lambda_{\mathrm{B}}/\lambda_{\mathrm{B}} = (1-p_e)\varepsilon + [\alpha_s + \xi_s + (1-p_e)(\alpha_{sl}-\alpha_s)]\Delta T, \quad (1)$$

where p_e is photoelastic constant of the fiber, ε is axial strain of the FBG, ξ_s is thermo-optic coefficient of fiber, α_{sl} is thermal expansion coefficient of the beam with FBG, which is supposed to be more larger than that of the fiber. Because of the temperature change ΔT, $\Delta\lambda_{\mathrm{B}}/\lambda_{\mathrm{B}}$ can be expressed as

$$\Delta\lambda_{\mathrm{B}}/\lambda_{\mathrm{B}} = (1-p_e)\varepsilon + [\xi_s + (1-p_e)\alpha_{sl}]\Delta T. \quad (2)$$

In order to compensate the temperature effects, four rigid beams are hinged joint to form a flat foursquare. The design is illustrated schematically in Fig. 1. The beam with λ_1 FBG is connected to the one corner of the foursquare, the other with λ_2 FBG is used to join the opposite corners of the foursquare. Then the two FBGs are connected serially. By this structure, the pulling force F can cause equal stretch stress and compression stress on the two beams with FBG. Therefore the wavelength shifts obey

$$\Delta\lambda_1/\lambda_1 = (1-p_e)\varepsilon_l + [\xi_s + (1-p_e)\alpha_{s1}]\Delta T, \quad (3)$$

$$\Delta\lambda_2/\lambda_2 = -(1-p_e)\varepsilon_y + [\xi_s + (1-p_e)\alpha_{s1}]\Delta T, \quad (4)$$

where ε_l and ε_y are stretch strain and compression strain of the two beams, respectively, so $\Delta\lambda_1 > 0$ and $\Delta\lambda_2 < 0$. Because the two beams have the same shape and material, they have the same strain and temperature characteristics. Then the same formula of $(1-p_e)\alpha_{sl}$ is used in Eqs. (3) and (4). The difference of them is

$$\Delta\lambda_1/\lambda_1 - \Delta\lambda_2/\lambda_2 = (1-p_e)\varepsilon_l + (1-p_e)\varepsilon_y. \quad (5)$$

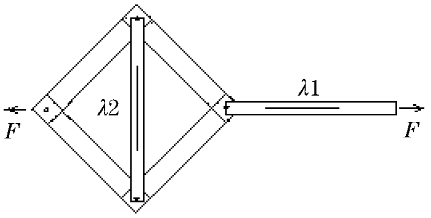

Fig. 1. Diagram of compensation design.

Because λ_1 is near to λ_2, the change of wavelength difference caused by the force F can be expressed as

$$\Delta\lambda_1 - \Delta\lambda_2 = \lambda_1[(1-p_e)\varepsilon_l + (1-p_e)\varepsilon_y]. \quad (6)$$

When beams with FBGs are free, suppose that λ_1 is little more than λ_2, and $\lambda_1 - \lambda_2 = \Delta\lambda_0 > 0$. Because of the pulling F, the wavelength difference is

$$\Delta\lambda = \lambda_{11} - \lambda_{22} = \Delta\lambda_0 + \lambda_1[(1-p_e)\varepsilon_l + (1-p_e)\varepsilon_y], \quad (7)$$

where λ_{11} and λ_{22} are new wavelengths of FBGs affected by the pulling F. Apparently, $\Delta\lambda$ is linear to pulling force and independent of temperature, but the sensitivity to the strain is amplified. The action of F increases the difference between the two reflection peaks of the FBGs.

In order to meet the needs of two–directional strain sensor, a sliding groove for the beam with λ_1 FBG is used, which can maintain the beam as straight as its original status. When F is compression force, the compression strain factor $(1-p_e)\varepsilon_y$ causes $\Delta\lambda_1 < 0$, the stretch strain factor $(1-p_e)\varepsilon_l$ causes $\Delta\lambda_2 > 0$. So the result is that the difference decreases between the two reflection peaks of the FBGs. $\Delta\lambda$ can be expressed as

$$\Delta\lambda = \lambda_{11} - \lambda_{22} = \Delta\lambda_0 - \lambda_1[(1-p_e)\varepsilon_l + (1-p_e)\varepsilon_y]. \quad (8)$$

Because the two beams have the same strain and temperature characteristics, when F changes its direction, the two beams change their strain direction simultaneously. Based on the above analysis, we find that $\Delta\lambda$ is still linear to the action of force F.

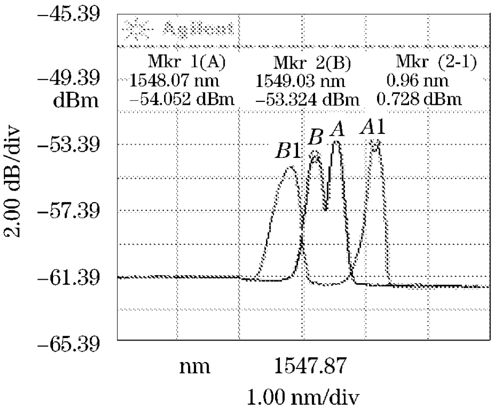

Fig. 2. Reflective spectra at 5-N stretch force.

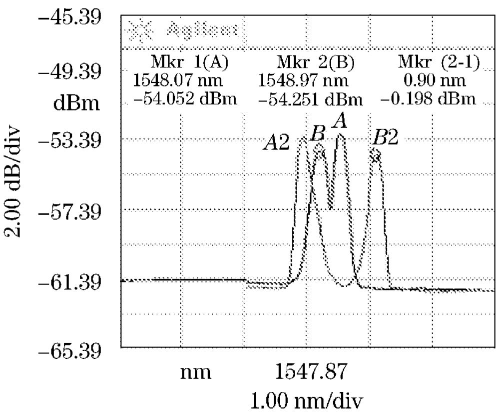

Fig. 3. Reflective spectra at 6-N compression force.

Two beams with the same material and same shape of 3 × 3 × 42 mm^3 are chosen. Two FBGs with near Bragg wavelengths are epoxied axially onto the surfaces of them. Then they are treated by heat. Light from a broadband source (BBS) is coupled via 3-dB coupler into two serial FBGs, the reflectance from a return port of the coupler is monitored by using an optical spectrum analyzer (OSA, Agilent 86140B) with the 0.07-nm minimal resolution. At 18 °C, the peak wavelengths of FBGs are measured to be λ_1 = 1548.37 nm and λ_2 = 1548.07 nm, respectively, which are pointed by A and B in Figs. 2 and 3. By the design shown in Fig. 1, pulling force and compression force of a fine pressure gauge can be loaded. Figure 2 shows the reflective spectra of the structure under applied stretch force of 5 N and that of free status. A_1 and B_1 denote the shifts of peaks A and B, respectively. Figure 3 shows the reflective spectra of the structure under applied compression force of 6 N and that of free status. A_2 and B_2 denote the shifts of peaks A and B, respectively. The difference between the two reflection peaks of the FBG relative to applied pulling force is plotted in Fig. 4. $\Delta\lambda$ is proportional to the force F. From these data we obtain a pulling sensitivity of 0.136 nm/N and press sensitivity of 0.09 nm/N, so the total sensitivity of force is 0.226 nm/N. It is also proved experimentally that compression force can cause the same result, which corresponds to former analysis.

According to theoretic analysis, the measured difference of reflection peaks can give the temperature-insensitive static strain. The relation between the difference of reflection peaks and temperature is also tested, as shown in Fig. 5. In the range of 3–45 °C, the peaks of two FBGs on beams get the temperature sensitivity of 0.029 nm/°C. But the measured difference of reflection peaks is almost changeless. Used as a sensor, the measurands are wavelength encoded, which can offer high accuracy and multiplexing capabilities and make the sensor immune to optical power fluctuations. But it is always decoded by expensive OSA.

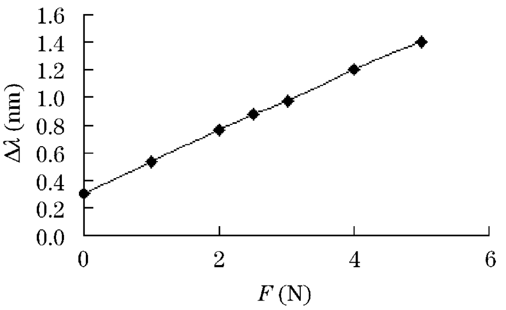

Fig. 4. Relationship between wavelength difference and F.

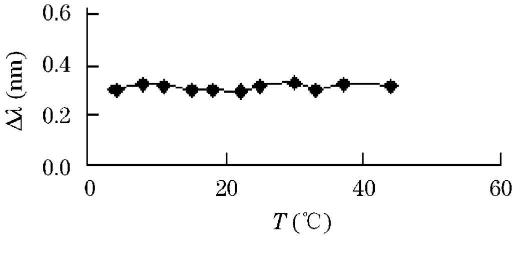

Fig. 5. Temperature response curve of wavelength difference.

In recent years, several techniques have been demonstrated to decode wavelength information. These include methods of unbalance M-Z interferometer and FBG tunable filtering. In accord with the sensor based on wavelength difference, method of long period grating edge filter is preferable. Because of anti-directional shifts of peaks, the ratio of two peak intensities represents wavelength difference $\Delta\lambda$, which maintains the effect of differential amplification and has temperature effects cancelled. When the design is used in temperature-insensitive micro-vibration measurement, the vibration drives two peaks jittering and overlap or not, modulates the output intensity. If the gratings in the structure form the fiber laser cavity, the active fiber grating sensors offer a higher accuracy than passive sensor and maintain temperature-insensitive. In this vibration sensor, the key problem is how to load the vibration signal, which should make the two peaks periodically overlap. Another problem is how to get higher vibration sensitivity by choosing the material of beams.

In our experiments, the Young's modulus of the material is the key factor which affected the sensitivity and the maximum compression force that can be loaded. 10-N compression force makes the beam apparently bent and nonlinear. The bare fiber grating has the most high force sensitivity and the lower temperature sensitivity. However, it needs special protection[6]. If it can be used in our design, the most high force sensitivity gets 2.68 nm/N, the temperature compensation gets the best.

In conclusion, we presented a novel structure of active temperature compensation design of sensor with fiber gratings. Four rigid beams are hinged joint to form a flat foursquare, which converts applied force into two anti-directional strains of FBGs. By the technique, the stress sensitivity has been amplified and the temperature effects have been compensated. The methods how to get the most high force sensitivity are discussed.

This work was supported by the National 863 Project of China (No. 2002AA313110) and the project of National Construction Ministry (01-4-048). X. Dong's e-mail address is dongxfa@eyou.com.

References

1. J. X. Geng, L. Li, L. Zhao, G. Chen, N. Y. Shen, A. L. Li, and Z. J. Fang, Chin. J. Lasers (in Chinese) **30,** 735 (2003).
2. B. Q. Liao, D. J. Feng, Q. D. Zhao, G. Zhou, G. Y. Kai, and X. Y. Dong, Acta Opt. Sin. (in Chinese) **22,** 1092 (2002).
3. G. W. Yoffe, P. A. Krug, F. Ouellette, and D. A. Thorncraft, Appl. Opt. **34,** 6859 (1995).
4. B. S. Yi, R. M. Hu, B. C. B. Chu, and K. S. Chiang, Chin. J. Lasers (in Chinese) **29,** 1085 (2002).
5. Y. L. Yu, S. W. Geng, and H. Y. Tam, Acta Opt. Sin. (in Chinese) **23,** 293 (2003).
6. G. A. Ball and W. W. Morey, Opt. Lett. **19,** 1979 (1994).