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Temperature and strain sensing characteristics of the tilted fiber Bragg grating*

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Theoretical and experimental studies on the tilted fiber Bragg grating (TFBG) temperature and strain sensing characteristics are conducted. The TFBG is stuck to the surface of the beam along the axis direction. When the free end of the beam is forced, both the strain and temperature will induce wavelength shifts. The temperature characteristic of TFBG cladding modes is similar to that of the core mode while the strain characteristics of TFBG core mode and cladding modes are different. A novel method to discriminate the temperature and strain simultaneously is put forward based on TFBG sensing characteristics.

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TFBGs[1-3] not only have properties of fiber Bragg gratings, but also have their unique properties because of the special physical structure[4-6]. TFBGs have been widely used in temperature, strain and other parameters measurements. Both temperature and strain can make the wavelength shift. So the discrimination of temperature and strain responses of FBG becomes very important. The simultaneous measurements of temperature and strain have been studied over the past 10 years[7-9]. Most reported approaches have relied on two sensors with different sensitivities to temperature and strain[10,11]. The methods are usually complicated in experiment. In this paper, theoretical and experimental studies on TFBG temperature and strain sensing characteristics are conducted. A simultaneous measurement method of temperature and strain is also put forward for the first time based on sensing characteristics of TFBG.

The grating plane of TFBG has a tilt angle ξ depicted in Fig.1, and the grid period Λ_g along the fiber core direction is expressed as:

$$\Lambda_g = \frac{\Lambda}{\cos\xi} \quad . \tag{1}$$

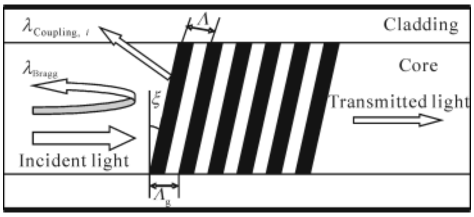

Fig.1 Principle of the tilted fiber Bragg grating

The Bragg wavelength of the TFBG in the core mode is also dependent on the tilt angle

$$\lambda_{\text{core}} = \left(n_{\text{eff, core}} + n_{\text{eff, core}}\right)\frac{\Lambda}{\cos\xi} \quad , \tag{2}$$

where $n_{\text{eff, core}}$ indicates the efficient refractive index of the fiber core. Part of incident light of forward transmission which accords with Bragg conditions is coupled to be back transmission core modes, and the rest of the light is coupled to be cladding modes because of the titled grating plane. The resonance wavelength of cladding modes is expressed as:

$$\lambda_{\text{cladding},\ i} = \left(n_{\text{eff, core}} + n_{\text{eff, cladding},\ i}\right)\frac{\Lambda}{\cos\xi} \quad , \tag{3}$$

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where $n_{\mathrm{eff,cladding},\,i}$ is the efficient refractive index of cladding modes with the order *i*. So the resonance wavelength of tilted fiber Bragg grating cladding modes is the product of the sum of the effective refractive indices of forward transmission core modes and cladding modes and the grid period. For the common single mode FBG, the transmission peak according with Bragg conditions is given by:

$$\lambda_{\mathrm{Bragg}} = 2n_{\mathrm{eff,core}}\Lambda \ . \tag{4}$$

Both the refractive index and grating period of the fiber depend on temperature and strain. The relation between sensing parameters and the wavelength shift can be given by:

$$\frac{\Delta\lambda}{\lambda_0} = (1 - p_{\mathrm{e}})\varepsilon + (\alpha_{\mathrm{s}} + \zeta_{\mathrm{s}})\Delta T \ , \tag{5}$$

where p_{e}, α_{s} and ζ_{s} are photoelastic constant, thermal expansion and thermo-optic coefficients, respectively. For the germanosilicate fiber at room temperature, α_{s} and ζ_{s} are approximately 0.5×10^{-6}/°C and 6.67×10^{-6}/°C, respectively.

Only considering strain effect, when the strain is a few hundred times of $\mu\varepsilon$, each mode's resonance wavelength of TFBG has a different strain shift because the photoelastic constant is different. When the temperature only increases, namely $\Delta T > 0$, each mode's resonance peak will shift to the longer wavelength. Each mode's resonance peak has the same temperature shift approximately, because α_{s} and ζ_{s} are very small. Once the fiber grating is embedded into materials with large thermal expansion coefficient, a change of the grating period will be caused, so the thermal sensitivity of the grating can be enhanced. Let α_{m} ($\alpha_{\mathrm{m}} \gg \alpha_{\mathrm{s}}$) be the thermal expansion coefficient of the material, and then the wavelength shift can be given by:

$$\frac{\Delta\lambda}{\lambda_0} = (1 - p_{\mathrm{e}})\varepsilon + [(1 - p_{\mathrm{e}})\alpha_{\mathrm{m}} + \zeta_{\mathrm{s}}]\Delta T \ . \tag{6}$$

The germanium-drop photosensitive fiber is put under 13 MPa hydrogen condition for 48 h and heated at the photosensitive area to increase the photosensitivity at the same time. The TFBG is fabricated using a Kr-F excimer laser emitting at 248 nm with a phase mark. The phase mark, which can be fine-tuned for an angle θ_{ext}, is fixed on the optical bench. Because of the refraction in the mark, θ_{ext} is not equal to the tilt angle of the TFBG. Fig.2 shows the transmission spectrum of the TFBG.

Fig.3 shows the schematic diagram of TFBG temperature sensing. The light from the broad-band source (BBS) made by ourselves is incident into the TFBG, and the transmitted light is detected by the optical spectral analyzer (OSA). The TFBG is put into a temperature-controlling box. The OSA is fabricated by the Advance Corporation of Japan, and its serial number and precision are Q8383 and 0.1 nm, respectively.

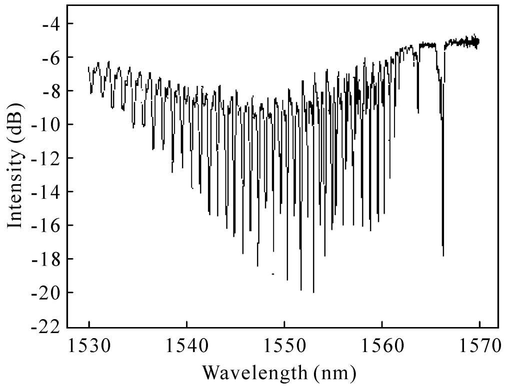

Fig.2 Transmission spectrum of the TFBG

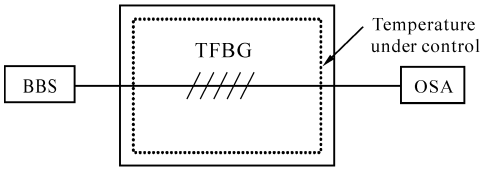

Fig.3 Schematic diagram of TFBG temperature sensing

Fig.4 indicates the temperature characteristics of TFBG in our experiment. When the temperature increases, the difference between the wavelength shifts of core mode and cladding mode for order *i* is very small and the slope efficiency of the fitting line is 0.01. The linear relevancies reach 0.999 and 0.998 respectively. The results show that the temperature characteristic of the cladding modes is similar to that of the core mode.

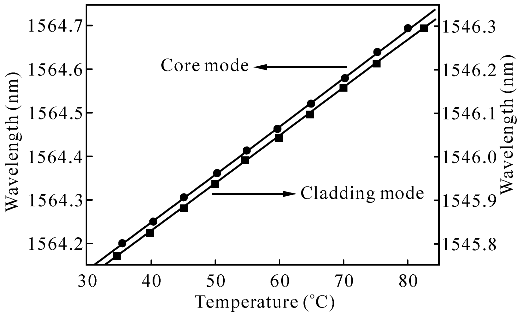

Fig.4 Temperature characteristics of TFBG

By embedding fiber gratings into materials with large thermal expansion coefficient, the thermal sensitivity can be improved. During the embedding, the TFBG must be prestressed properly in order to keep the wavelength without shifting. The relationship between wavelength shift and temperature for the polymer-packaged fiber grating is shown in Fig.5. It can be seen that 2.105 nm wavelength shift of the packed TFBG is achieved by changing the temperature from 30 °C to 65 °C while the wavelength shift of the unpacked TFBG is 0.37 nm. The thermal sensitivity slightly increases with the temperature owing to inherent charaterisitics of the material. The thermal sensitivity of the TFBG is 0.06 nm/°C. 5.5 times of the thermal sensitivity can be achieved.

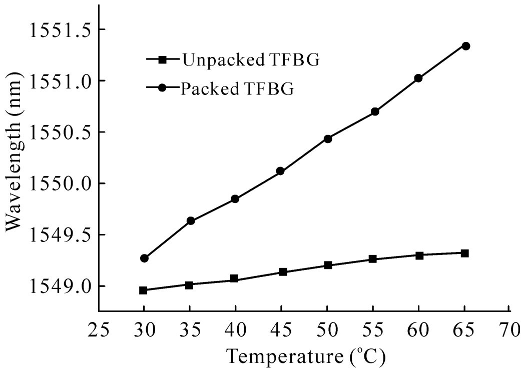

Fig.5 Wavelength shift versus temperature for the polymer-packaged and unpacked tilted fiber Bragg gratings

The schematic diagram of TFBG strain sensing is shown in Fig.6. When the free end of the beam is forced, there is the same strain at any point of the axis on the surface of the beam.

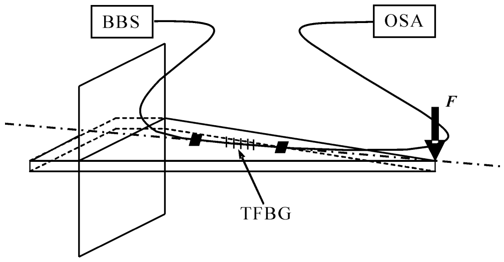

Fig.6 Schematic diagram of TFBG strain sensing

The curves of the stain characteristics of the TFBG are shown in Fig.7 and Fig.8.

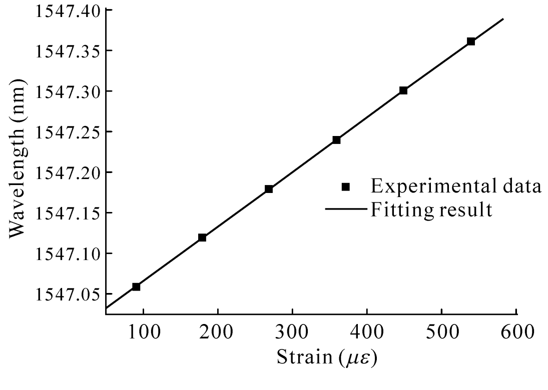

Fig.7 Strain characteristic of the cladding mode LP_{1i}

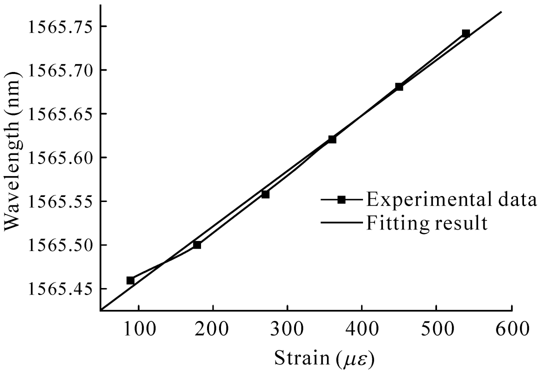

Fig.8 Strain characteristic of the core mode LP_{01}

The linear fitting equations of the cladding mode LP_{1i} and the core mode LP_{01} are given by:

$$\lambda_{\text{cladding},i} = 0.000667\varepsilon_z + 1547 , \tag{7}$$

$$\lambda_{\text{core}} = 0.000636\,\varepsilon_z + 1565.39 . \tag{8}$$

The linear relevancies reach 1 and 0.99834, respectively.

When the strain increases, the wavelength shifts of the cladding mode and the core mode are different and the slope efficiencies of the fitting lines are 0.000667 and 0.000636, respectively. The linear relevancies reach 1 and 0.99834 respectively. The experiments indicate that the characterictics of core mode and cladding modes are different. When the temperature and the strain of the surroundings change simultaneously, the wavelength shift will be induced. A novel system of measuring temperature and strain simultaneously is put forward based on the experiment results above. The relation between temperature and strain can be expressed in terms of a matrix

$$\begin{pmatrix} \Delta\lambda_{\text{core}} \\ \Delta\lambda_{\text{cladding}} \end{pmatrix} = \begin{pmatrix} K_{\text{core},\varepsilon} & K_{\text{core},T} \\ K_{\text{cladding},\varepsilon} & K_{\text{cladding},T} \end{pmatrix} \begin{pmatrix} \varepsilon \\ T \end{pmatrix} , \tag{9}$$

where $\Delta\lambda_{\text{core}}$ and $\Delta\lambda_{\text{cladding}}$ are the wavelength shifts of the core mode and the cladding mode respectively. $K_{\text{core},T}$, $K_{\text{cladding},T}$, $K_{\text{core},\varepsilon}$ and $K_{\text{cladding},\varepsilon}$ are the sensitivity coefficients. When $\Delta\lambda_{\text{core}}$ and $\Delta\lambda_{\text{cladding}}$ are measured by the OSA, the temperature and strain can be calculated from the above equation.

In summary, the theoretical and experimental studies on TFBG temperature and strain sensing characteristics are conducted. The core mode and cladding modes of TFBGs have the same temperature sensing characteristic but different strain sensing characteristics. A new approach to discriminate the temperature and strain responses of TFBG sensors is put forward. This method, compared with the method using two sensors, has the advantages of simple structure and easy measurement. It has potential applications in fields of fiber sensors and communication systems.

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