Principles and realizations of FBG wavelength tuning with elastic beams*

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The general principles and realizations of FBG wavelength tuning with elastic beams are proposed and demonstrated. Theories and experiments show that when displacement at the center point of simple beams, deflection of cantilever beams and torsion strain of torsion beams are relatively small, Bragg wavelength shifts of sensing FBGs have linear relationship with applied external stress, lateral displacement, torque and torsional angles, respectively. The experimental results indicate that the curvature sensitivity of the simple beam is 1.65 nm/m^{-1}, the displacement sensitivity of the equivalent-strain cantilever beam is 4.4 cm/kg and the torque and torsional angle sensitivities of the torsion beam are 6.27 nm/Nm and 0.0867 nm/degree, respectively.

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Fiber Bragg grating (FBG) is a significant technology that is used to design key devices or components in the systems of fiber communication and fiber sensing[1], such as tunable fiber lasers[2], WDW/DM[3], WADM[4], tunable fiber filter[5], fiber dispersion compensation[6], gain flatting of EDFA[7], FBG-type interferometer[8] and fiber grating sensors[9,10]. One of the key research issues on FBG devices is to make the tuning wavelength devices which have good characteristics of wide tunable wavelength range, stable output, good multiplexing capability.

Some works based on the methods of the tuning FBG wavelength (TFW) are proposed, such as those based on mechanical tuning wavelength (MTW)[11-13], electromagnetic tuning wavelength (ETW)[14,15], thermal tuning wavelength (TTW)[16]. Compared with the MTW method, the ETW is more complex and more expensive in its implementation, and the temperature control of the TTW method is also difficult. However, the MTW method is attracted due to its simpicity in fabrication, convenience in implementation and easiness in controlling temperature. Therefore, various FBG devices based on MTW have been proposed in recent years, including these based on the longitudinal stress, the transverse stress and the torsional stress. In this paper, we firstly propose the general principles of FBG wavelength tuning based on elastic beams, then introduce some of the technological realizations of the above principles using simple beams, cantilever beams and torsion beams, and finally point out some important applications of the above technological realizations in the fields of both optical fiber communications and optical fiber sensing.

Many studies show that the strain and the temperature can change the period Λ and the refractive index n of the FBG, resulting in a shift of the reflected (or transmitted) resonant wavelength $\Delta\lambda$ from λ_0. When the temperature is stable, the relationship between the strain ε along the axial direction of FBG and the resonant wavelength shift $\Delta\lambda$ has the following form[1]

$$\frac{\Delta\lambda}{\lambda_0} = (1 - p_e)\varepsilon \tag{1}$$

where p_e is the effective photoelastic coefficient, which is relative to fiber Poisson ratio and the effective refractive index of the fiber core. Equation (1) is a basic principle for the FBG wavelength tuning. If the strain ε is directly applied on the FBG along its axis, the tuning coefficient of the strain is too small ($\sim$1.2 pm/$\mu\varepsilon$) at $\lambda_0 = 1\,550$ nm. Thus, the FBG should be firmly bonded to the surface of a good elastic lining or embedded inside the elastic lining in order to enhance the tuning efficiency in the practical application.

There are three types of elastic beams that can be used for TFW, including the simple beam, the cantilever beam and the torsion beam. In this paper, we assume pure bending for the simple beam and the cantilever beam, and pure turn for the torsion beam.

For the pure bending beam, according to the pure bending theory, the axis strain ε at any position on the

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surface of beam can be expressed as

$$\varepsilon = \frac{z_0 M}{EI} \tag{2}$$

where z_0 is the distance from the measured point to the mid-plane of the beam, M is magnitude of the moment of flexion, E is the Young's modulus of the beam, I is the inertia moment of the beam. If the FBG was bonded to the surface of the beam along the axial direction, from equation (1) and (2) we can obtain

$$\Delta\lambda = \frac{(1-P_e)\lambda_0 z_0 M}{EI} \tag{3}$$

Equation (3) is the basic principle of tuning FBG wavelength using pure bending beams. Here, pure bending beams include the simple beam and cantilever beam.

For the torsion beam, according to the pure torsion theory, the torsional strain γ at any position on the surface of beam can be given by

$$\gamma = \frac{DM_F}{2GI_p} \tag{4}$$

where D is the external diameter of the beam, M_F is the moment of torque, G is the modulus of the transverse elasticity of the beam, I_p is the polar inertia moment of the cross-section of the beam. If the FBG is bonded to the surface of the beam with a determinate angle β along the axial direction of the beam and the torsional angle is not large, the strain ε of FBG can be written as[12]

$$\varepsilon \approx \frac{1}{2}\gamma \sin 2\beta \tag{5}$$

Substituting equations of (1), (4) and (5), we can obtain

$$\Delta\lambda = \frac{(1-P_e)(\sin 2\beta)\lambda_0 DM_F}{4GI_p} \tag{6}$$

Equation (6) is the basic principle of tuning FBG wavelength using the pure torsion beam. From equation (3) and (6), we know that the tuning ranges and the sensitivities of FBG wavelength are relative to the properties of elastic beam (E or G), the shape (I or I_p) and the strain mode (M or M_F). The proper range of tuning wavelength can be obtained through balancing these factors.

In the following, we will introduce some of technological realizations of the above principles using simple beams, cantilever beams and torsion beams. The tuning structure of the simple beam is shown in Fig. 1. The length of the beam is L, external stress F vertically acts on the center to its axis of the beam. Considering the FBG was bonded to the center of beam surface along axis, the FBG length is too short and the radius of curvature in the part is changed so littler, the equal-radius of curvature can be considered. Therefore, the moment of flexion of the center point is $M=FL/4$, the maximal lateral displacement is $\omega=(FL^3)/(48EI)$. Using equation (3) and the above relations, we obtain

$$\Delta\lambda = \frac{(1-P_e)\lambda_0 z_0 L}{4EI}F = \kappa_F F \tag{7}$$

$$\Delta\lambda = \frac{12(1-P_e)\lambda_0 z_0}{L^2}\omega = \kappa_\omega \omega \tag{8}$$

where $\kappa_F = [(1-P_e)\lambda_0 z_0 L]/(4EI)$、$\kappa_\omega = 12(1-P_e)\lambda_0 z_0/L^2$ are the tuning coefficients of the stress and displacement, respectively. They describe the tuning sensitivities of the stress and displacement of the simple beam, respectively. Obviously, in the center of the beam, the tuning sensitivity is maximal. Thus, with the simple beam, the FBG should be bonded to the center of the beam to achieve maximal tuning.

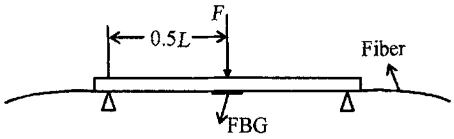

Fig. 1 Structure schematic diagram of tuning FBG wavelength of simple beam

As an applied example, the simple beam can be used to measure the curvature. The relative parameters of the simple beam are as follows: the FBG length 1.1 cm, its center wavelength $\lambda_0 = 1\,550.00$ nm, $p_e=0.22$, $z_0=0.15$ cm, $L=8.0$ cm. Fig. 2 shows the tuning transmission spectrum.

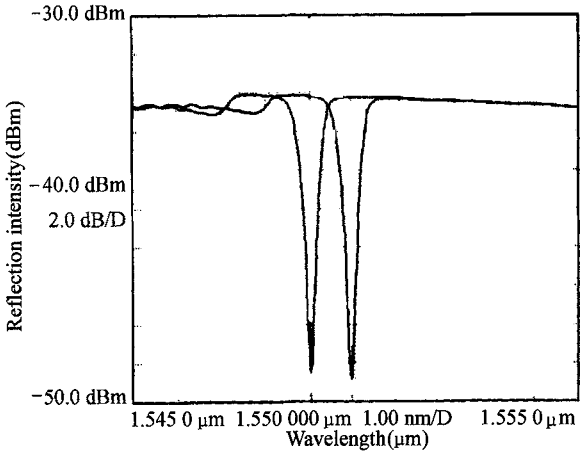

Fig. 2 FBG tuning transmission spectrum

Fig. 3 shows the single Bragg wavelength shift as a function of the curvature for the experimental results. From Fig. 3, we can obtain that the experimental fit-values of tuning sensitivity of the curvature is estimated to be 1.65 nm/m^{-1} at around 1.55 μm for single mode fiber, and the correlation coefficient of the fitting line is up to 0.9987. Moreover, many experiments show that chip effects in the TFW can be reduced using a beam that has uniform strength. The tuning structure of cantilever beam is shown in Fig. 4.

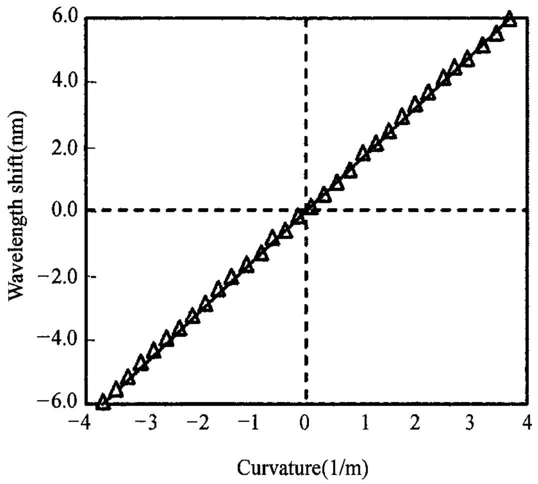

Fig. 3 Single Bragg wavelength shift as a function of the curvature for the experimental results

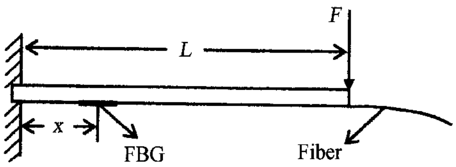

Fig. 4 Structure schematic diagram of tuning FBG wavelength of cantilever beam

The cross section of deformation caused by the moment of flexion M and the weight of the cantilever beam is neglected. External stress F is put on the free end of the beam and is vertical to the axis of the beam. The length of the beam is L, FBG is bonded to the position of surface of the beam along axis, the distance from the bonded position to the fixed end is x and the deflection of the free end is small. So the magnitude of the moment of flexion is $M=P(L-x)$, and the lateral displacement of the free end (deflection) is $\omega=FL^3/3EI$.

Using equation (3) and the above relations, we can obtain:

$$\Delta\lambda = \frac{(1-p_e)(L-x)\lambda_0 z_0}{EI}F = \kappa_F F \qquad (9)$$

$$\Delta\lambda = \frac{3(1-p_e)(L-x)\lambda_0 z_0}{L^3}\omega = \kappa_\omega \omega \qquad (10)$$

where $\kappa_F=(1-p_e)(L-x)\lambda_0 z_0/EI$ and $\kappa_\omega=3(1-p_e)(L-x)\lambda_0 z_0/L^3$ which are the tuning coefficients of stress and displacement, respectively. They represent the tuning sensitivities of stress and displacement of the cantilever beam, respectively. Obviously, in the fixed end ($x=0$), the tuning sensitivity is maximal. Thus, with cantilever beam, the FBG should be bonded to the position nearby the fixed end.

In the practical application, the structure such as a simple beam of uniform strength shown in Fig. 5 is used more often, in which the width of cross-section can be expressed as $b(x)=b_0(1-x/L)$, and the FBG should be bonded to the central line of the beam. The tuning of the FBG wavelength with no chirp or quasi-chirp-free can be realized by using this structure, and wider tuning range of wavelength can be also gained.

As an applied example, the cantilever beam can be used to measure the displacement. The relative parameters of the simple beam are as follows: the FBG length is 1.2 cm, its center wavelength $\lambda_0=1547.1$ nm, $p_e=0.22$, $h=0.55$ cm, $L=60.0$ cm, $b_0=7.2$ cm, Young's

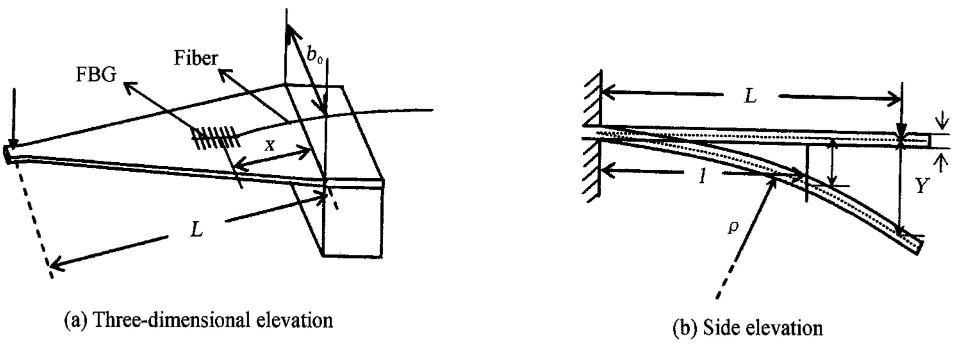

Fig. 5 Structure schematic diagram of tuning fiber grating wavelength of equivalent-strain cantilever beam

modulus of the cantilever beam E is 1.84×10^5 MPa. Fig. 6 shows the tuning reflection spectrum. Fig. 7 shows the displacement as a function of the load for the experimental results. From Fig. 7, we can obtain that the experimental fit-values of tuning sensitivity of the displacement are estimated to be 2.0 cm/kg for $l=52.75$ cm and 4.4 cm/kg for $l=34.75$ cm, respectively, and the correlation coefficients of the fitting lines are up to 0.9997.

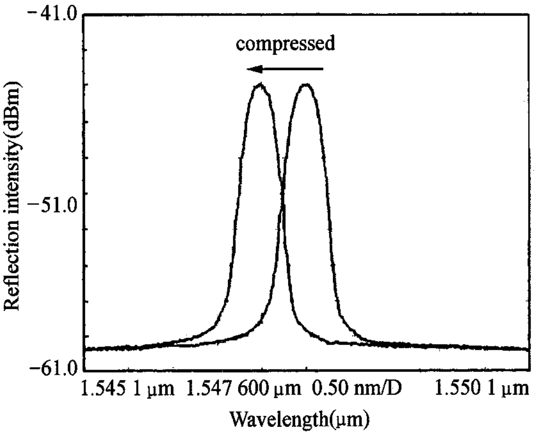

Fig. 6 FBG tuning reflection spectrum

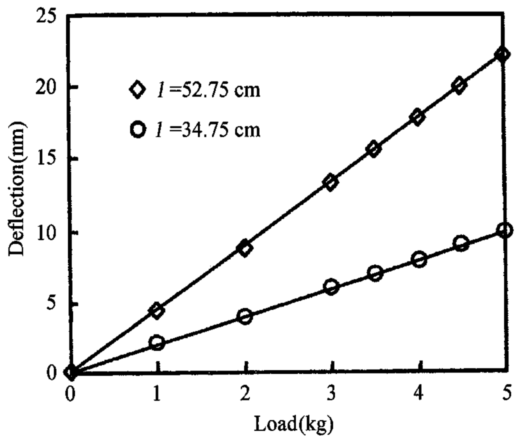

Fig. 7 The Bragg wavelength shift as a function of the load for the experimental results

Fig. 8 shows the structure schematic of torsion beam tuning. Let us use L and D to denote the length and diameter of the torsion beam, respectively. The torque M_t acts at the free end of the torsion beam in the direction along the axial of the torsion beam. Letting r_F be the arm of stress, and the torque is $M_t = r_F \times F$.

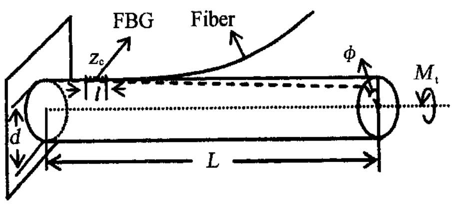

Fig. 8 Structure schematic diagram of tuning fiber grating wavelength of torsion

Assuming FBG is bonded to the surface z_c of the torsion beam with a determinate angle β along the axial direction of the torsion beam. If r_F is normal to F, the magnitude of the torque M_t is $M_t = r_F F$, and the torsional angle of the free end is $\varphi = LM_t/(GI_p)$. Substituting the value of M_t into equation (6), we can obtain

$$\Delta\lambda = \frac{(1-p_e)\lambda_0 sin2\beta}{4GI_p} M_t = \kappa_M M_t \quad D \ll L \quad (11)$$

$$\Delta\lambda = \frac{(1-p_e)\lambda_0 Dsin2\beta}{4L} \varphi = \kappa_\varphi \varphi \quad (12)$$

where κ_M and κ_φ are the torque tuning coefficient and the torsional angle coefficient, respectively. Note that κ_M and κ_φ represent the sensitivities of the torque tuning and the torsional angle tuning of the torsion beam respectively. I_p is the inertia moment of cross section, with $I_p = \pi D^4/32$ for solid torsion beams and $I_p = \pi(D^4 - d^4)/32$ for hollow torsion beams. Proportional factors κ_M and κ_φ can be considered as the sensing sensitivities of the torque and the torsional angle, respectively. Distinctly, the κ_φ value of the air-core column beam is greater than that of the solid column beam when the external diameter D and the length L_0 of both column beams are equivalent, respectively.

As an applied example, the relative parameters of the torsional beam are as follows: the FBG length is 1.2 cm, its center wavelength $\lambda_0 = 1\,562.48$ nm, $z_c = 3.6$ cm, $\beta \approx 20$, $\mu = 0.16$, $p = 0.22$, $L = 25.0$ cm, $D = 0.85$ cm; Young's modulus of the torsional beam E is 2.744×10^9 N/m^2, the modulus of transverse elasticity is $G = E/(2[1+\mu]) = 1.183 \times 10^9$ N/m^2. Fig. 9 shows the tuning reflection spectrum. The experimental indicate that the full width at half maximum (FWHM) almost keeps 0.42 nm when $-45° \leqslant \varphi \leqslant +45°$ (or -0.623 Nm $\leqslant M_t \leqslant 0.623$ Nm).

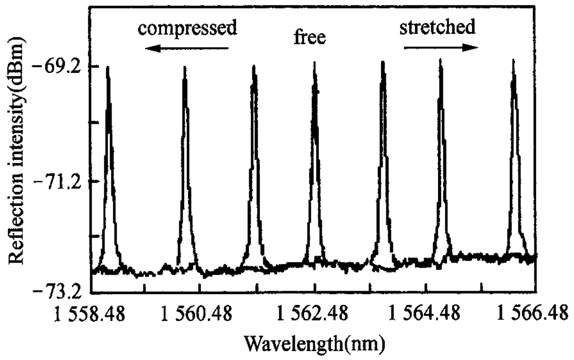

Fig. 9 FBG tuning reflection spectrum

Fig. 10 shows the Bragg wavelength shift as a function of the torsional angle and the torque for both theoretical analyses and experimental results.

From Fig. 10, we can obtain that the experimental fit-

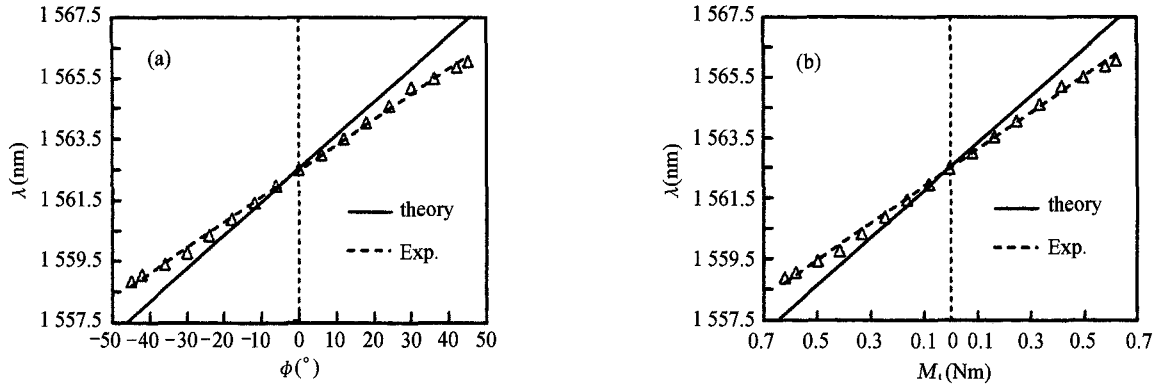

Fig. 10 Bragg wavelength λ of FBG vs the torsional angel φ(a) and the torsion M_t(b)

values of tuning sensitivities κ_M and κ_φ are estimated to be 6.27 nm/Nm and 0.0867 nm/degree at around 1.55 μm for single mode fiber, respectively. This kind of tuning structure can be used to accurately measure the modulus of the transverse elasticity of elastic materials. Moreover, using a kind of combinatorial torsion beam structure that consists of solid and hollow column beams with same cross section, temperature-independent torsion measurement could be realized[13].

In summary, the TFW devices play an important role in the fields of both optical fiber communication and optical fiber sensing. In the field of optical fiber communication, there are tunable fiber lasers and gain flatting device of EDFA using simple beams to tune FBG, fiber dispersion compensations using cantilever beams to tune FBG. In the field of optical fiber sensing, there are many types of FBG sensors based on elastic beams. Both the cantilever beams and the simple beams can be used as packaging substance of strain sensing, stress sensing, pressure sensing, displacement sensing and vibration sensing. Moreover, torsion beams can be used as packaging substance of torsional strain sensing, torsional angle sensing, and torque sensing. If these devices or components of FBG wavelength tuning based on elastic beams are further optimized, the TFW method will has significant prospect for application, such as pulse producing and compressing of fiber laser in the field of optical fiber communication and multi-parameter FBG-type sensors of optical fiber sensing.

The TFW methods and techniques based on elastic beams can make enough use of the various excellent properties of fiber grating, and the TFW devices plays an important role in communication and sensing fields. So far, the TFW methods and techniques using pressure, acoustic wave, chemistry and etc. are still immature and the TFW range is comparative small expecting electromagnetic tuning and thermal tuning. Now, the better technology of tuning wavelength is commercialized and the new tuning methods that have larger tuning range, good stability, quasi-chirp-free and good multiplexing is explored. One available approach is that the tuning range can be enhanced to cover all gain range as soon as possible through coinstantaneous many FBG tuning with various wavelength ranges.

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