High sensitivity fiber Bragg grating pressure difference sensor

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Based on the effect of fiber Bragg grating (FBG) pressure difference sensitivity enhancement by encapsulating the FBG with uniform strength beam and metal bellows, a FBG pressure difference sensor is proposed, and its mechanism is also discussed. The relationship between Bragg wavelength and the pressure difference is derived, and the expression of the pressure difference sensitivity coefficient is also given. It is indicated that there is good linear relation between the Bragg wavelength shift and the pressure difference of the sensor. The theoretical and experimental pressure difference sensitivity coefficients are 38.67 and 37.6 nm/MPa, which are 12890 and 12533 times of that of the bare FBG, respectively. The pressure difference sensitivity and dynamic range can be easily changed by changing the size, Young's modulus, and Poisson's ratio of the beam and the bellows.

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Fiber Bragg gratings (FBGs) used as pressure and temperature sensing elements have attracted extensive attention[1−4], and have been applied to engineering[2,5], such as civil engineering structural monitoring, aerospace applications, etc.. The FBG sensing system is consisted of the sensor, demodulator (interrogation system), broadband light source, and signal transmission system, etc.. The detecting sensitivity is determined mainly by response sensitivity of the sensor and resolution of the demodulator. So, it is an effective way to improve the sensitivity of the sensing system by enhancing sensitivity of the sensor[3].

Encapsulating the FBG with elastic polymer to enhance the pressure sensitivity of FBG is one important way. In Ref. [3], the pressure sensitivity of the FBG coated with polymer is 1770 times of that of the bare FBG. And in Ref. [6], by fixing the coated FBG into a sealed metal bellows, the pressure sensitivity is 2197 times of that of the bare FBG. In this paper, based on uniform strength beam (isosceles trapezoid cantilever) and metal bellows, a novel high sensitivity FBG pressure difference sensor is proposed. The experimental pressure difference sensitivity is 37.6 nm/MPa, which is 12533 times of the pressure sensitivity of the bare FBG. To our knowledge, the pressure sensitivity of the sensor in this paper is the highest one.

According to the coupled-mode theory of electromagnetic field, the Bragg wavelength is given by[7]

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

where n_{eff} is the effective index of the core, Λ is the grating pitch.

When the FBG is stretched or compressed, Λ is changed, n_{eff} of the FBG is also changed for the photo-elastic effect. So a strain change of $\mathrm{d}\varepsilon$ leads to a corresponding wavelength shift of $\mathrm{d}\lambda$,

$$\frac{1}{\lambda}\cdot\frac{\mathrm{d}\lambda}{\mathrm{d}\varepsilon} = \frac{1}{n_{\mathrm{eff}}}\cdot\frac{\mathrm{d}n_{\mathrm{eff}}}{\mathrm{d}\varepsilon} + \frac{1}{\Lambda}\cdot\frac{\mathrm{d}\Lambda}{\mathrm{d}\varepsilon}, \tag{2}$$

where ε is the axial strain.

By using the relations between change of the effective index and photo-elastic coefficient and strain tensor, as well as the relation between the axial strain and the grating pitch, the relative shift of the center wavelength due to axial strain is given by

$$\frac{\Delta\lambda}{\lambda_0} = (1-p_{\mathrm{e}})\varepsilon, \tag{3}$$

where p_{e} is effective photo-elastic coefficient of the fiber. For the fused silica fiber, $p_{\mathrm{e}} = 0.216$.

Figure 1 shows the schematic diagram of the proposed FBG pressure difference sensor. There are two containers named container 1 and container 2, and each container has one entrance (entrance 1 and entrance 2), which lets the liquid/gas flow in or out the container. Between the two containers, there is a sealed container. One end of a uniform strength beam is fixed on the wall of the sealed container, and the other end is connected with two bellows. The FBG is bonded to the uniform strength beam (isosceles trapezoid cantilever). The two bellows are the same. When the liquid/gas pressures P_1 and P_2 in the two containers are different, the effective centralized forces F_1 and F_2 exerted to the two sides of the beam by the two bellows are also different. For the difference of the two forces, there is a net force exerted to the beam, which induces the bend of beam and the shift of the Bragg wavelength. By detecting the shift of the Bragg wavelength, the pressure difference could be measured.

Supposing the effective area of the bellows is A_{eff}, the elastic constant is k, then the effective centralized forces F_1 and F_2 can be expressed as

$$F_1 = P_1 A_{\mathrm{eff}}, \tag{4}$$

$$F_2 = P_2 A_{\mathrm{eff}}, \tag{5}$$

the resultant force is

$$F = F_1 - F_2 = (P_1 - P_2)A_{\mathrm{eff}}. \tag{6}$$

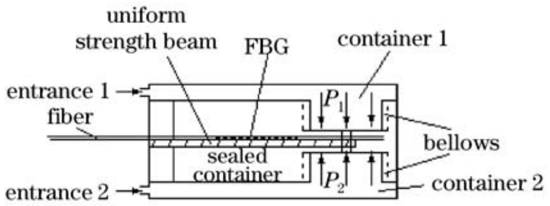

Fig. 1. Schematic diagram of the pressure difference sensor.

The force F_{beam}, which is a component of pressure difference caused force F, exerts to the beam and induces the beam deformation. F_{bellows}, which is the other component of F, exerts to the bellows and induces bellows stretch or compression. When F_{beam} exerts to the beam, the flexivity at the free end of the beam is $V_{\max}$. At this time, F_{bellows} can be expressed as

$$F_{\text{bellows}} = 2kV_{\max}. \tag{7}$$

The axial strain on the beam can be expressed as the function of the flexivity at the free end of the beam,

$$\varepsilon = \frac{hV_{\max}}{L^2}, \tag{8}$$

where

$$V_{\max} = \frac{6}{Eh^3}\frac{L^3}{b_2}F_{\text{beam}}, \tag{9}$$

b_2 is the length of shorter side of the beam's parallel sides, h is the beam thickness, L is the length of the beam, E is the Young's modulus of the beam material, $V_{\max}$ is the flexivity at the free end of the beam. Equations (8) and (9) indicate that the flexivity is linear with the equivalent force and the strain. By simple derivation, the strain as a function of the pressure difference can be expressed as

$$\varepsilon = \frac{6hLA_{\text{eff}}}{(Eh^3b_2 + 12kL^3)}(P_1 - P_2). \tag{10}$$

So, the shift of Bragg wavelength as a function of the pressure difference can be expressed as

$$\Delta\lambda = (1 - p_{\text{e}})\frac{6hLA_{\text{eff}}}{Eh^3b_2 + 12kL^3}\lambda_0(P_1 - P_2) = \eta\Delta P, \tag{11}$$

where

$$\eta = (1 - p_{\text{e}})\frac{6hLA_{\text{eff}}}{Eh^3b_2 + 12kL^3}\lambda_0, \tag{12}$$

λ_0 is the Bragg wavelength when $P_1 = P_2$, η is the pressure difference sensitivity coefficient of the sensor. When $P_1 \neq P_2$, the Bragg wavelength can be expressed as

$$\lambda = \eta\Delta P + \lambda_0. \tag{13}$$

Equations (12) and (13) indicate that the pressure difference is linear with the Bragg wavelength shift, and the sensitivity coefficient of the sensor can be changed by changing the size, Young's modulus, and Poisson's ratio of the beam and the bellows. The sensitivity of the sensor could be very high.

A pressure difference sensor is made according to the structure shown in Fig. 1. In experiments, the effective area of the bellows is $A_{\text{eff}} = 5.73$ cm^2, elastic constant of the bellows is $k = 1635$ N/m. Young's modulus of the beam is $E = 1.28 \times 10^{11}$ N/m^2, thickness of the beam is $h = 1.0$ mm, length of the beam is $L = 45$ mm, length of short side of the beam is $b_2 = 24$ mm. Bragg wavelength at free state is 1549.51 nm. Seal the entrance 2, and let the container 2 keep the normal pressure, that is about an atmospheric pressure. Put the sensor into the acrylonitrile butadiene styrene (ABS) pipeline, a pump is used to change the inner pressure of the pipeline, as well as the pressure difference. An MS9710C optical spectrum analyzer (OSA) is used for measuring the Bragg wavelength. The resolution of OSA is 0.05 nm. A barometer is used for measuring the inner pressure of the pipeline. The resolution of the barometer is 0.02 MPa. Figures 2 and 3 show the spectra at the pressure differences of 0 and 0.05 MPa, respectively. The spectral shapes do not change when the pressure difference changes. But the bandwidths slightly change, and the details spectra change too. Many factors cause the changes, such that the beam is not the ideal uniform strength beam and there are the inhomogeneous stress remained in the FBG.

Figure 4 shows the relation between the pressure difference and Bragg wavelength. In Fig. 4, the discrete dots represent the experimental data, the line represents the least square fit line of the experimental data, the equation of the fit line is $\lambda = -37.6\Delta P + 1549.5$, $R^2 = 0.9963$. The result shows good linearity.

From the aspect of measure precision, the maximum difference between experimental data and fit line is 0.11 nm, the wavelength dynamic range is 1.88 nm, the measurement precision is 5.85%, the wavelength of 0.11 nm corresponds to the pressure of 0.0029 MPa. So the maximum measurement error of pressure difference is

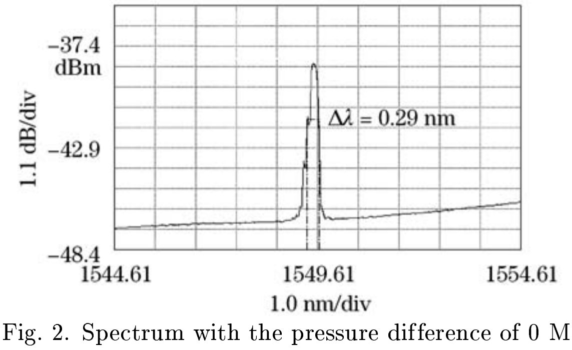

Fig. 2. Spectrum with the pressure difference of 0 MPa.

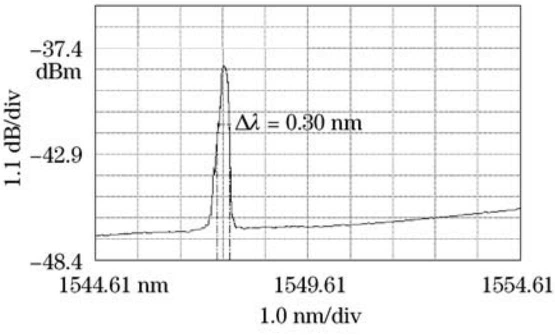

Fig. 3. Spectrum with the pressure difference of 0.05 MPa.

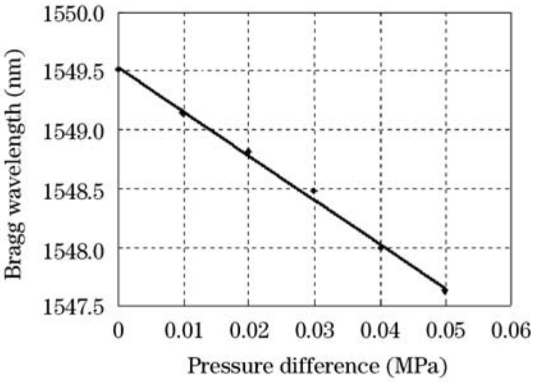

Fig. 4. Relation between the pressure difference and Bragg wavelength.

0.0029 MPa. Because 0.11 nm is much greater than 0.05-nm resolution of the OSA, it is the main element of the measurement error. By improving the inhomogeneous stress remained in the FBG, selecting more suitable bellows and beam, the stability can be improved, the measurement accuracy can also be improved. When the precision of the sensor is high enough, the measurement error is determined by the resolution of OSA. When the resolution of the OSA is 0.05 nm, the measurement error is 0.0013 MPa.

From the aspect of sensitivity enhancement, the experimental sensitivity of the sensor is 37.6 nm/MPa, which is 12533 times of the pressure sensitivity of the bare FBG (0.003 nm/MPa). The theoretical value of the pressure difference sensitivity of the sensor can be calculated by Eq. (12). The theoretical pressure difference sensitivity is 38.67 nm/MPa, which is 12890 times of that of the bare FBG. The experimental value agrees with the theoretical value very well, the relative error is about 2.8%.

Improving the sensor pressure difference sensitivity can improve the pressure difference measurement precision (or measurement resolution), and decrease the signal interrogation difficulty.

In this paper, a model of high sensitivity pressure difference FBG based sensor is proposed. The principle of the sensor is discussed. The relation between Bragg wavelength of FBG and the pressure difference is derived, and the expression of the pressure difference sensitivity coefficient is also given. The pressure difference response of the sensor and the enhancement of pressure difference sensitivity coefficient are also analyzed. It is pointed out that the measurement precision of the sensor can improved by using bellows and beam of good quality, improving the bonding uniformity and bonding tightness. It is also pointed out that the sensitivity of the sensor can be improved by regulating the parameters of the sensor, such as the size, Young's modulus, and Poisson's ratio of the beam and the bellows.

The experimental pressure difference sensitivity is in agreement with the theoretical one very well. The Bragg wavelength shift is linear with the pressure. And the reflection spectrum diagram keeps the profile unchanged under different pressure.

The sensor proposed in this paper can be applied to measure the liquid level, reserves of the oil tank, inner pressure and temperature of the natural gas and coal gas pipeline. It can also be used as an element of differential pressure type flowmeter, etc..

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