Fiber Bragg grating pressure sensor with enhanced sensitivity

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A novel fiber Bragg grating (FBG) pressure sensor with the enhanced sensitivity has been demonstrated. A piston-like diaphragm with a hard core in the center is used to enhance the sensitivity. Both the theoretical analysis and the experimental result show that the radius of the hard core has significant effect on the pressure sensitivity. When the radius of the hard core is 1.5 mm, a pressure sensitivity of 7.23 nm/MPa has been achieved.

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Fiber Bragg gratings (FBGs) have been used in a growing range of sensing applications. Pressure measurement is one of the major areas of interest, and in the past several years a lot of configurations for FBG pressure sensors have been demonstrated, including a glass-bubble housing of FBG[1], polymer coating on bare fiber[2], shielded polymer coating of FBG[3], and the modified shielded polymer coating with half-filled metal cylinder[4]. However, such correction methods are likely to work better if the dimension could be reduced while the sensitivity could be enhanced. In this letter, we report a novel FBG pressure sensor with the enhanced sensitivity by using a piston-like diaphragm and a thin steel cylinder. Owing to the greater deformation of the diaphragm with a hard core in the center, an ultra thin dimension and an ultra high sensitivity are achieved.

The FBG pressure sensor is shown in Fig. 1. The water comes into the sensor from the sensing hole and acts on the surface of the piston-like diaphragms. The diaphragm is pressurized in the axial direction, creating an axial tension strain in the FBG. The diaphragm is made of rubber to induce larger deformation to enhance the sensitivity. But the rubber is rather soft and cannot resist shear stress, which makes it difficult to fix the fiber on the rubber diaphragms. Then a hard core is affixed at the center of each diaphragm to fix the fiber.

The pressure sensitivity, defined as the fractional change in Bragg wavelength, is given by[5]

$$\frac{\Delta\lambda_{\mathrm{B}}}{\lambda_{\mathrm{B}}} = (1-p_{\mathrm{e}})\,\varepsilon_{\mathrm{f}}, \tag{1}$$

where $p_{\mathrm{e}} = 0.22$ is the effective photo-elastic constant of the fiber, ε_{f} is the axial strain in the fiber.

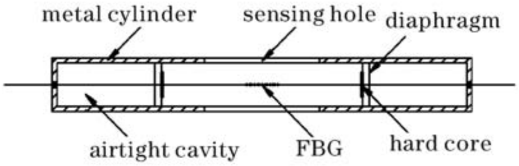

Fig. 1. Schematic diagram of the pressure sensor.

The deflection of the center of the diaphragm under the hydraulic pressure p is given by[6]

$$w_{\mathrm{p}} = \frac{p}{64D}\left(R^4 - r^4 + 4R^2r^2\ln\frac{r}{R}\right), \tag{2}$$

in which the following notation is used

$$D = \frac{Et^3}{12\left(1-\mu^2\right)},$$

where R is the radius of the diaphragm, t is the thickness of the diaphragm, r is the radius of the hard core, E is the Young's modulus of the diaphragm, and μ is the Poisson's ratio. When the diaphragm deforms under the pressure, it induces the tension force T in the fiber

$$T = \varepsilon_{\mathrm{f}} A E_{\mathrm{f}}, \tag{3}$$

where A is the cross section area of the fiber, E_{f} is the Young's modulus of the fiber.

Notice $\varepsilon_{\mathrm{f}} = w/L$, where $2L$ is the fixed length of the FBG and w is the deflection at the center of the diaphragm under pressure p and force T, and we can obtain the strain in the FBG

$$\varepsilon_{\mathrm{f}} = \frac{\frac{p}{64D}\left(R^4 - r^4 + 4R^2r^2\ln\frac{r}{R}\right)}{L + \frac{AE_{\mathrm{f}}R^2}{16\pi D}\left[1-\left(\frac{r}{R}\right)^2\frac{1-\frac{r^2}{R^2}+4\ln^2\left(\frac{r}{R}\right)}{1-\frac{r^2}{R^2}}\right]}. \tag{4}$$

Substituting Eq. (4) for ε_{f} in Eq. (1), the sensitivity of the sensor is

$$\frac{\Delta\lambda_{\mathrm{B}}}{\lambda_{\mathrm{B}}} = \frac{(1-p_{\mathrm{e}})\frac{pR^4}{64D}\left(1-\left(\frac{r}{R}\right)^4 + 4\left(\frac{r}{R}\right)^2\ln\frac{r}{R}\right)}{L + \frac{AE_{\mathrm{f}}R^2}{16\pi D}\left[1-\left(\frac{r}{R}\right)^2\frac{1-\frac{r^2}{R^2}+4\ln^2\left(\frac{r}{R}\right)}{1-\frac{r^2}{R^2}}\right]}. \tag{5}$$

From Eq. (5) we can find that the radius of the hard core has significant effect on the sensitivity of the sensor when the radius of the diaphragm is restricted within 4 mm. To evaluate this effect and predict the likely gain in sensitivity of the FBG pressure sensor, the relationship between the sensitivity and the radius of the hard core is evaluated. The values of the parameters in our configuration are shown in Table 1, and the result is shown in Fig. 2.

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Table 1. Parameters Used in the Configuration

Parameter	Value
L	8 cm
t	1 mm
A	0.0123 mm^2
R	4 mm
μ	0.3
E_f	72 GPa
E	12 MPa
λ_B	1527 nm

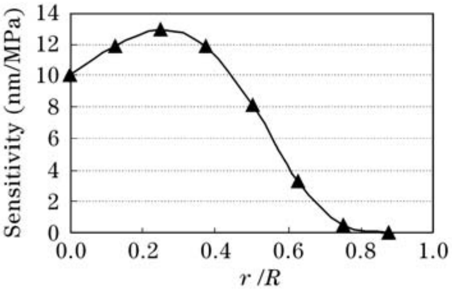

Fig. 2. Predicted sensitivity as a function of the hard core radius.

As Fig. 2 demonstrates, the highest sensitivity appears when the ratio of r/R is about 0.3. If the ratio of r/R is larger than 0.3, the predicted sensitivity decreases when the radius of the hard core increases. So we can enhance the sensitivity by optimizing the radius of the hard core.

Commercially available FBGs were used with a reflective wavelength of 1527 nm. The diaphragm is made of polyurethane rubber and the hard core is made of copper. The outer radius of the metal cylinder is 5 mm. Other parameters are listed in Table 1. The sensor was installed within a high pressure vessel. The pressure was applied using a hydraulic pump and measured by a pressure meter. The pressure induced Bragg wavelength shift was monitored by a high accuracy FBG interrogator (PI Optics, PI03B). Two types of FBG pressure sensors were fabricated and tested. The hard core radii of these two types were 1.5 and 2 mm, respectively.

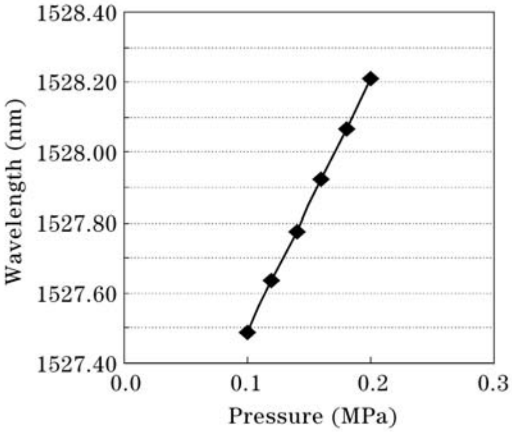

Fig. 3. Tracking of pressure sensor, r = 1.5 mm. Linear fit of the measured data gave the pressure sensitivity of 7.23 nm/MPa.

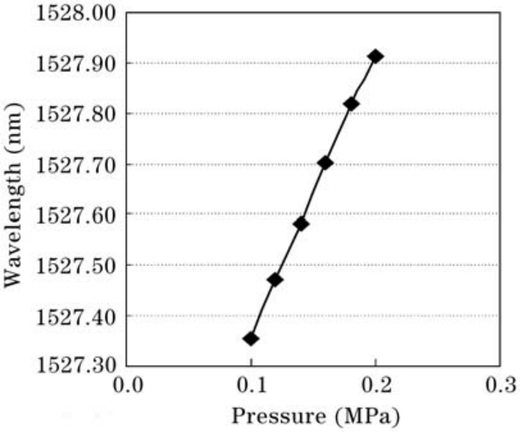

Fig. 4. Tracking of pressure sensor, r = 2 mm. Linear fit of the measured data gave the pressure sensitivity of 5.63 nm/MPa.

Figures 3 and 4 show the measured sensitivity of the two types of the FBG pressure sensors. The measured sensitivities, which are 7.23 and 5.63 nm/MPa respectively, are in the same order of magnitude as the theoretically calculated value. The discrepancy between the experimental result and the estimated one is due to the edge effect when fixing the diaphragm on the steel tube and the dimension error in fabricating the diaphragm and the hard core. However, the pressure sensitivity can be easily changed by changing the radius of the hard core and diaphragm materials.

A new method for enhancing the pressure sensitivity of the FBG pressure sensor by using a piston-like diaphragm with a hard core in the center is proposed in this letter. The theoretical analysis of the sensitivity shows that the radius of the hard core has significant effect on the pressure sensitivity. The measured sensitivity is in close agreement with the theoretical value, which demonstrates that the sensitivity can be changed by changing the radius of the hard core. A pressure sensitivity of 7.23 nm/MPa is achieved when the radius of the hard core is 1.5 mm and the outer radius of the sensor is 5 mm. For the ultrathin dimension, this new sensor is expected to be used in the towed hydrophone arrays.

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