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RESEARCH ARTICLE

A high sensitive FBG pressure sensor using thin metal diaphragm

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Abstract A high sensitive pressure sensor using fiber Bragg grating (FBG), integrated with thin metal diaphragm is designed and investigated both theoretically and experimentally. Under pressure the diaphragm deflection causes an axially stretched-strain along the length of the FBG. The pressure sensitivity of the sensor gained from the test results is 2.05×10^{-2} MPa^{-1}, approximately four orders of magnitude higher than that can be measured with the bare FBG. Experimental results showed good agreement with the proposed theoretical results.

Keywords Fiber Bragg grating · Diaphragm · Pressure sensor · Compressor · Circulator · Optical spectrum analyzer

Introduction

Fiber Bragg gratings (FBGs) have been proved as potential sensing elements in wide range of applications for measurement of strain, temperature, pressure, salinity, liquid level, refractive index and structural health monitoring of civil structures [1–6]. FBG sensors offer many advantages over conventional sensors namely small size, light weight, immune to electromagnetic interference, multiplexing capability, high sensitivity and repeatability [7–9]. In the field of pressure sensing, sensitivity is an important parameter since it determines the resolution and accuracy of the sensing system. Earlier, attempts were made to enhance the pressure sensitivity using various configurations. For example, Xu et al. reported the pressure sensitivity of -1.98×10^{-6} MPa^{-1} with a bare FBG [10]. In their subsequent investigations, the sensitivity was enhanced to -2.12×10^{-5} MPa^{-1} by mounting the FBG in a hollow glass bubble [11]. Liu et al., [12] later improved the pressure sensitivity up to -6.28×10^{-5} MPa^{-1} by using a polymer coated FBG. Ahmad et al. reported pressure sensitivity of 1.07×10^{-3} MPa^{-1} [13], Wen et al. [14] obtained pressure sensitivity of -1.73×10^{-3} MPa^{-1}, Vengal Rao et al. [15] enhanced the pressure sensitivity up to 1.907×10^{-3} MPa^{-1} by embedding the FBG along the diameter of a thin metal diaphragm. Zhang et al. further increased the pressure sensitivity as high as -3.41×10^{-3} MPa^{-1} by embedding an FBG into a polymer filled metal cylinder has an opening on one side and shielded from the other [16]. H.J. Sheng et al. [17] proposed a mechanism for improving the pressure sensitivity of an FBG sensor up to 2.2×10^{-2} MPa^{-1}.

Aiming to attribute enhancement in this direction, in the present study an enhanced pressure sensitivity of FBG pressure sensor integrated with a thin metal diaphragm has been reported. Under the pressure the diaphragm deflects maximum at the centre and minimum at the edges. The transverse deflection of the diaphragm induces an axially stretched-strain along the length of the FBG thereby creating a red shift of Bragg wavelength with increased pressure.

Sensor structure and principle

Sensor design

The schematic structure and photograph of the designed sensor is shown in Fig. 1. Mainly, it consists of four parts, circular metal washer, metal block, FBG and a thin metal diaphragm. The metal washer measures 3 mm in thickness is made of stainless steel has inner and outer diameters of 20 and 40 mm respectively. The metal block also made of stainless steel has the diameter of 40 mm and the thickness of 10 mm. To create

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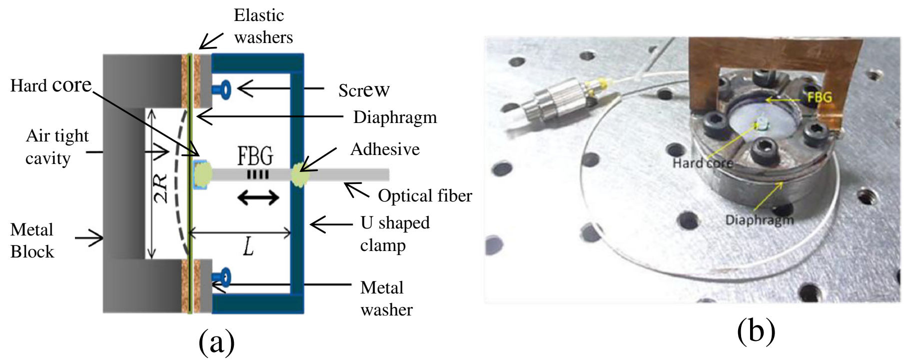

Fig. 1 **a** The schematic structure and **b** photo of the sensor head

an air tight cavity between fixed diaphragm and the metal block, a circular depth of 5 mm measures 20 mm in diameter is machined exactly at the center of the metal block. Thin metal diaphragm made of aluminium (Aluminium 6061) having thickness of 0.32 mm is used as a pressure transducer. The diaphragm is tightly clamped between metal washer and the metal block using elastic washers and screws. An FBG at centre wavelength 1544.96 nm drawn in Boron codoped photosensitive fiber (PS1500, Fibercore, USA) is used as pressure sensing element. A 'U' shaped thin metal clamp is tightly fixed on the metal washer to attach one end of the FBG. Other end of the FBG is firmly attached to the centre of the diaphragm using a thin hard core made of plastic has the diameter of 1.5 mm. The FBG is pre-strained before glued between the diaphragm and the 'U' shaped clamp is illustrated in Fig. 1.

Working principle

Diaphragm deflects when it is subjected to the pressure difference 'P' inside and outside of the diaphragm causes an elongation along the axis of the fiber. The transverse displacement of the diaphragm is directly proportional to 'P', found to be maximum at the centre and minimum at the edges [18, 19]. For the sensor design considered here, the centre deflection of the diaphragm $y(P)$ can be expressed as [20].

$$y(p) = \frac{3(1-\mu^2)PR^4}{16Et^3}\left(R^4 - r^4 + 4R^2r^2\ln\left(\frac{r}{R}\right)\right) \quad (1)$$

Where R is radius of the diaphragm, t is thickness of the diaphragm, r is radius of the hard core, E and μ are Young's modulus and Poisson's ratio of the diaphragm respectively. Under pressure, deflection of the diaphragm induces the tension $F=\varepsilon a E_f$ force in the fiber. Where ε is the strain, a and E_f are the cross sectional area and Young's modulus of the fiber respectively. Therefore transverse displacement at the centre of the diaphragm being caused by force F is expressed as

$$y(F) = \frac{3(1-\mu^2)FR^2}{4\pi Et^3}\left(1-\left(\frac{r}{R}\right)^2 \frac{1-\left(\frac{r}{R}\right)^2 + 4\ln^2\left(\frac{r}{R}\right)}{1-\left(\frac{r}{R}\right)^2}\right) \quad (2)$$

Consequently, the strain induced in the FBG can be expressed as $\varepsilon=[y(P)-y(F)]/L$, where L is the fixed length of the fiber. A well known relation between relative shift in Bragg wavelength of FBG, $\Delta\lambda_B/\lambda_B$ and the axial strain 'ε' applied to the grating at constant temperature is

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-P_e)\varepsilon \quad (3)$$

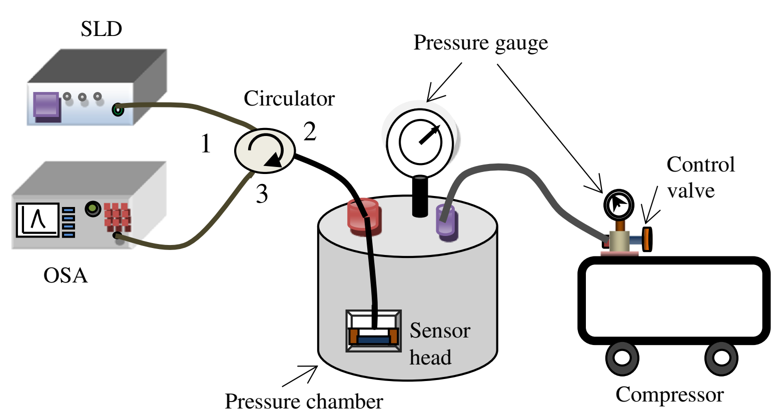

Fig. 2 Schematic of experimental setup

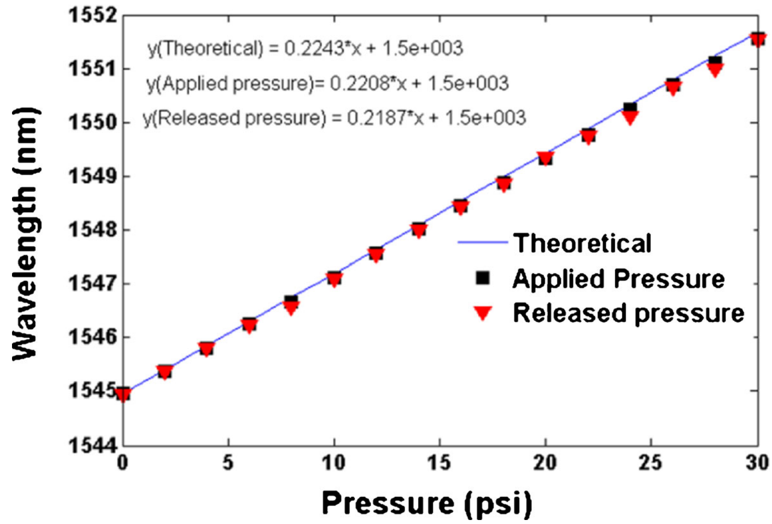

Fig. 3 Corelation of the experimental results with the simulated results

Where P_e is the effective photoelastic coefficient of the optical fiber. For a typical fused silica fiber P_e=0.22 [2]. From the Eqs. (1), (2) and (3), the relative shift of Bragg wavelength can be written as

$$\frac{\Delta\lambda_B}{\lambda_B}=\frac{(1-P_e)\frac{PR^4}{64D}\left(1-\left(\frac{r}{R}\right)^4+4\left(\frac{r}{R}\right)^2\ln\left(\frac{r}{R}\right)\right)}{L+\frac{aE_fR^2}{16\pi D}\left(1-\left(\frac{r}{R}\right)^2\frac{1-\left(\frac{r}{R}\right)^2+4\ln^2\left(\frac{r}{R}\right)}{1-\left(\frac{r}{R}\right)^2}\right)} \tag{4}$$

According to Eq. (4) the Bragg wavelength of FBG shifts linearly with applied pressure. It also evident from Eq. (4) that, the range and sensitivity of pressure measurement can be modulated by varying the parameters; (i) radius of the hard core, (ii) radius, thickness, Young's modulus and poison's ratio of the diaphragm (iii) Young's modulus and cross section area of the optical fiber. The values of the parameters used in our design are E=69 GPa [21], μ=0.35 [21], R=10 mm, r=0.75 mm, E_f=72 GPa [20], a=0.0123 mm^2, and L=19 mm. Making use of these values in Eq. (4) the theoretical pressure sensitivity of the sensor is 2.1×10^{-2} MPa^{-1} (1 MPa =145.0377 psi).

Experimental results and discussions

Schematic of experimental setup is shown in Fig. 2. To test the pressure response, the sensor is placed in a designed well-controllable pressure chamber. Using a compressor the pressure inside the chamber is varied in steps of 2 psi with reference to a precision pressure gauge. Light from a broad band super luminescent diode (SLD, 1525–1570 nm, Thorlabs, USA) is launched into FBG through port 1 to 2 of the optical circulator. The narrow band reflected

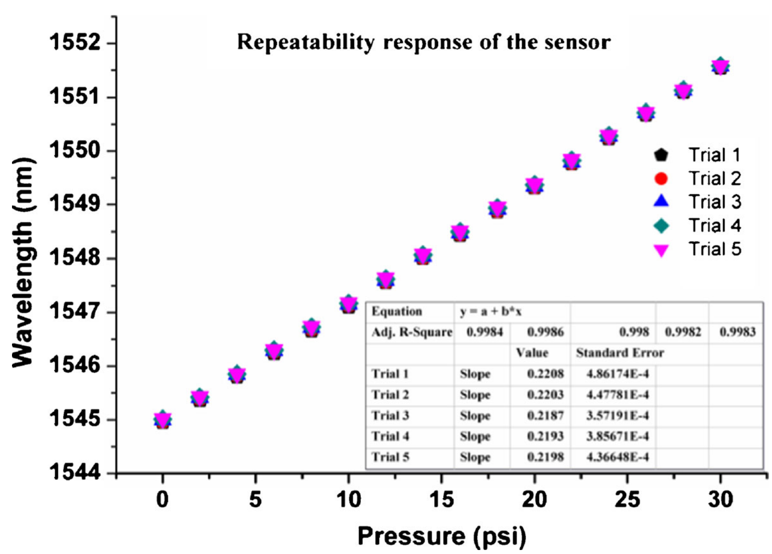

Fig. 4 Repeatability test results of the pressure sensor

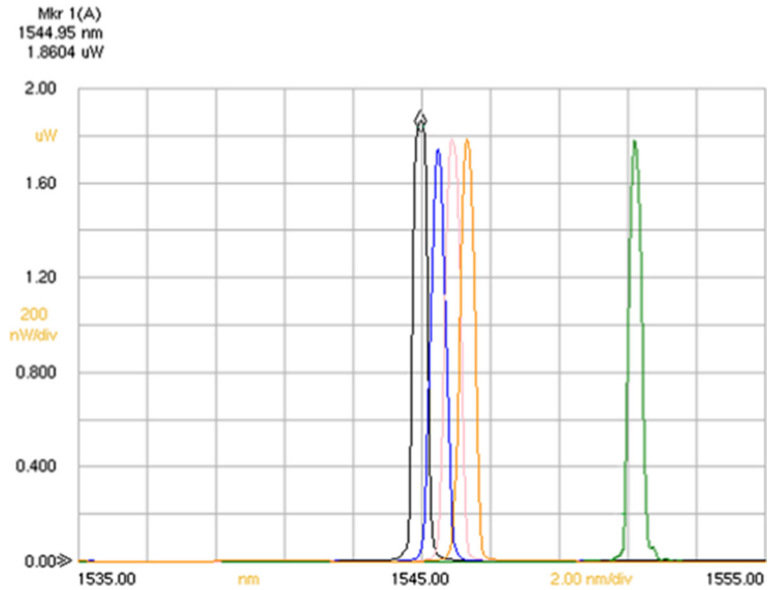

Fig. 5 The spectra of Bragg wavelength shift of the sensing FBG at different applied pressure values 0, 4, 6, 8 and 28 psi, respectively

wavelength of FBG is then routed into optical spectrum analyzer (OSA, Agilent 86142B) through port 2 to 3 of the optical circulator. The entire experiment is carried out at room temperature. As the pressure varies from 0 to 30 psi, the transverse deflection of the diaphragm stretch the fiber in axial direction causes a shift in Bragg wavelength of the FBG.

The corresponding shift of Bragg wavelength due to variation in pressure is monitored using OSA and the results are plotted in Fig. 3. It is evident that the change in Bragg wavelength is linear with respect to applied and released pressure and also coincidence with the theoretical curve plotted by simulating the Eq. (4) using MATLAB software.

To test the repeatability and reliability of the sensor, the experiment is repeated several times and found that the sensor response is consistent. Test results of the pressure sensor for repeated measurements are plotted in Fig. 4. Repeatability error of the sensor for pressure measurement is found to be ±0.087 %. The OSA spectrum of the sensing FBG against applied pressure is shown in Fig. 5. It can be observed from Fig. 5 that the shift in Bragg wavelength varies linearly with applied pressure and exhibit no considerable variation in peak power levels.

The experimentally measured Bragg wavelength shift of the FBG per applied pressure is found to be 0.2208 nm/psi with the linear coefficient of 0.998. This gives a pressure sensitivity of 2.05×10^{-2} MPa^{-1}, which is close order of magnitude with the theoretical value 2.1×10^{-2} MPa^{-1}. The discrepancy between theoretical and experimental results may be attributed to the fact that (i) dimension error in manufacturing of the diaphragm and hard core and (ii) the parameter values of the FBG used in theoretical evaluation may not match exactly with the FBG used for pressure measurement. The measured pressure sensitivity is approximately four orders higher than that can be achieved with the bare FBG [10].

Conclusions

Design and demonstration of a fiber grating pressure sensor with enhanced sensitivity using a thin metal diaphragm is reported. Under pressure, the deflection of the diaphragm induces an axial strain in the FBG, thereby creating a shift in Bragg wavelength of FBG. The experimental pressure sensitivity of the sensor is 2.05×10^{-2} MPa^{-1}, which is well matched with the calculated value from Eq. (4). The reported sensor exhibits good linearity and repeatability in pressure measurements. The designed prototype can be used to measure low and medium range of pressures in industrial applications.

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