Development of high sensitivity pressure sensor using reduced clad FBG

P.Vengal Rao*, K. Srimannarayana, P.Kishore, M. Sai Shankar, D.Sengupta, P. Saidi Reddy
Department of Physics, National Institute of Technology, Warangal, A.P.-506 004, India.
*pachava21@gmail.com

ABSTRACT

This study focused on the development of high sensitivity pressure sensor based on reduced clad FBG encapsulated in a stainless steel cylinder, partially filled with silicon rubber. The sensor works by means of transferring radial or lateral pressure into an axially stretched- strain along the length of the FBG. The experiment is carried out using two different FBG's have core/clad diameters of 9/125µm (FBG1) and 4/80µm (FBG2). FBG2 is chemically etched to reduce the cladding diameter which significantly enhances the pressure sensitivity. The shift of the Bragg wavelength in response to applied pressure is monitored with an optical spectrum analyser (OSA). The measured pressure sensitivity of FBG2 and FBG1 are found to be 5.85 x 10^{-2} MPa^{-1} and 2.07 x 10^{-2} MPa^{-1}, which are approximately 18870 and 6677 times respectively higher than that can be sensed with a bare FBG. A very good linearity is observed between Bragg wavelength shift and pressure. This compact, low cost and robust design of the sensor can find applications in the areas of low and medium pressure measurement.

Key words: Optical fiber, FBG, Pressure sensor, Chemical etching, Strain, Bragg wavelength, OSA, Sensitivity.

1. INTRODUCTION

FBG sensors have been proved a promising technology for wide range of sensing applications like strain, temperature, pressure, salinity, rotation and flow rate. Moreover, they have several inherent advantages over the conventional sensors such as non-conductivity, high sensitivity, fast response, multiplexing capabilities, high stability and repeatability, compact structure, insensitive to electromagnetic fields and wavelength encoded response in measurements [1-2]. In the field of pressure sensing, sensitivity is an important parameter since it determines the resolution and accuracy of the sensing system. To enhance the sensitivity many approaches have been proposed. Xu et al. had reported that the pressure sensitivity of -2.02×10^{-6} MPa^{-1} measured with bare FBG with 70MPa hydraulic pressure [3]. In Xu's subsequent experiment, the sensitivity has been enhanced to -2.12×10^{-5} MPa^{-1} by mounting the FBG in a hollow glass bubble [4]. Liu et al, later improved the pressure sensitivity up to -6.28×10^{-5} MPa^{-1} by coating the FBG with a polymer [5].In other experiments, Wen et al [6] obtained the measured pressure sensitivity of -1.73×10^{-3} MPa^{-1} and 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 which has an opening one side and shielded from the other [7].All the above pressure sensors experienced a compression-strain of an FBG with applied pressure and are responsive to negative pressure sensitivity. H.J. Sheng et al [8] proposed a mechanism for improving the pressure sensitivity of an FBG sensor upto 2.2×10^{-2} MPa^{-1}. In their attempt they obtained positive sensitivity of the sensor based on the applied pressure to be transferred to the axial stretched-strain on the FBG.

The present study addresses a pressure sensor of greatly enhanced sensitivity by encapsulating a reduced clad FBG into a metal cylinder partially filled with polymer. The experiment was done independently using two different FBG's. In the first, we used an unetched FBG (FBG1) packaged in a polymer material for pressure sensing. Later we used reduced clad FBG (FBG2) which enabled the sensor to be highly sensitive to applied pressure. The pressure sensitivity of the sensor is as high as 5.85 x 10^{-2} MPa^{-1} which is four orders higher than that of bare FBG. The obtained experimental results are in good agreement with the theoretical results.

Optical Sensing and Detection II, edited by Francis Berghmans, Anna Grazia Mignani, Piet De Moor,
Proc. of SPIE Vol. 8439, 84392G · © 2012 SPIE · CCC code: 0277-786X/12/$18 · doi: 10.1117/12.922160

2. WORKING PRINCIPLE AND SENSOR DESIGN

It is known that the relation between centre wavelength shift of a FBG , $\Delta\lambda_B/\lambda_B$ and the axial strain 'ε'applied to the grating is [2]

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

Where $P_e = {}^{2}_{\text{eff}}\,[P_{12} - \upsilon(P_{11} + P_{12})]/2$ is the effective photoelastic coefficient of the glass fiber with Poisson ratio υ, photo elastic coefficients P_{11} and P_{12}, and effective refractive index of guided mode, □$_{\text{eff}}$. For a typical fused silica fiber υ=0.16, P_{11} =0.12, P_{12} =0.27, and thus P_e = 0.22.

The sensor head consists of a metal cylinder of inner length 10mm closed at one end with a suitable cap as shown in figure 1. The outer diameter of the cylinder and the cap is 14.5mm and the thickness of their wall is 3mm. 1mm diameter hole is drilled in the centre of the closed end of the cylinder to insert the fiber. For the cylinder two side holes of 7.5mm diameter are drilled inline and these holes are closed with an adhesive tape temporarily. The fiber with FBG written in it is inserted through the 1mm hole of the cylinder and positioned in such a way that the FBG portion is just in line with the two holes of the cylinder, figure 1. The fiber is glued to the cylinder externally at its 1mm hole region. The cylinder is then filled with molten polymer (silicon rubber) mixed with curing agent maintaining the position of the fiber at the central region of the cylinder.

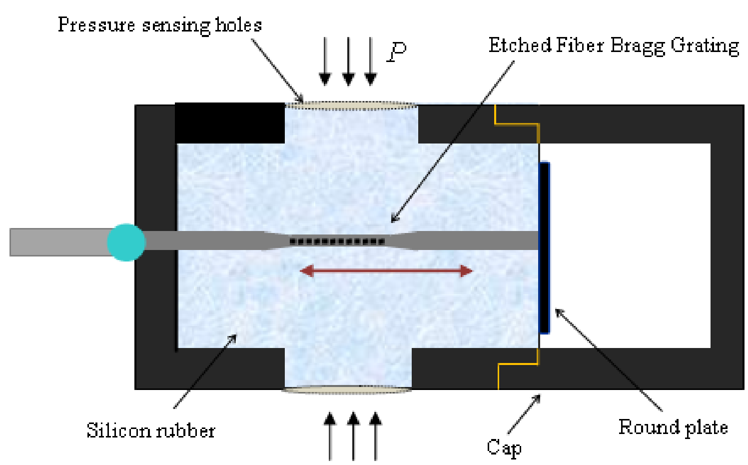


Figure 1.Polymer packaged fiber grating pressure sensor head.

The open end of the fiber is bounded to a thin round plate of 7.5mm diameter. The plate also comes into contact with open end of the filled molten polymer. Then the polymer is allowed to solidify. Now the FBG is completely surrounded by the solidified polymer. The metal cap is fixed to the cylinder from right side and the adhesive tape fixed to the side holes is removed. When pressure is applied on the polymer through the side holes, the resulting compression of the polymer corresponds to an axial force acting on the round plate, causes an axial strain on the FBG. The axial strain 'ε' is [8].

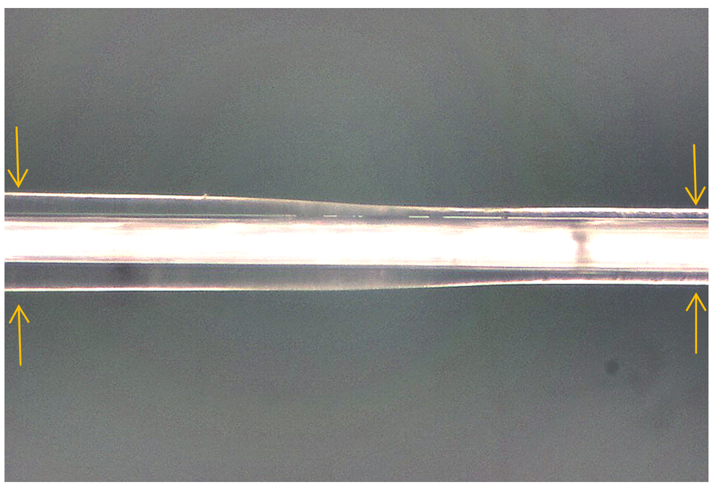
$$\varepsilon = \frac{\upsilon P A}{a E_f + \frac{L_f}{L_P}(A - a)E_p} \tag{2}$$

Where P is the pressure acting on the polymer, A denotes the round plate area, a represents the cross sectional area of the FBG, υ denotes the polymer Poisson's ratio, L_f represents the FBG length, L_P the axial length of the polymer, and E_f and E_p denote the Young's modulus of the FBG and polymer respectively. Hence, the fractional change in Bragg wavelength as a function of applied pressure, from (1)

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\frac{\upsilon P A}{aE_f + \frac{L_f}{L_P}(A - a)E_p} = K_P P \tag{3}$$

Where $K_P = (1\text{-}P_e)\ [\upsilon A/(aE_f + (L_f/L_P)(A\text{-}\ a)E_p)]$ is the pressure sensitivity of the sensor. FBG's fabricated by phase mask technique were used to assemble the sensor head. To study the variation of sensitivity due to variation in the cladding diameter, two sensor heads were made. In one sensor head FBG1 written in a fiber of 9/125 µm was used. In the other sensor head FBG2 with reduced cladding diameter was used. The reduction in the cladding diameter at the grating region is achieved by chemical etching process. For this purpose the fiber was etched using 40% of hydrofluoric acid (HF) for 20 minutes at room temperature. After etching, the fiber was rinsed successively with deionised water and acetone. The etched region being smaller in cross section experiences larger strain and index changes than at unetched region [9].Using an optical microscope with CCD camera attached, image of the etched fiber before and after the etching were taken. From the image shown in figure 2 the diameter of the FBG2 is found using MATLAB.

80 µm



51 µm

Figure 2.Image of the Etched fiber

The major components involved in the sensor head design are silicon rubber with a Poisson's ratio of 0.48, a round plate of an area (A) 44.156 mm^2. The cross sectional area of the unetched and etched FBG's are 0.0122 mm^2 and 0.002mm^2, Young's modulus of both the FBG's (E_f) and polymer (E_p) used are approximately 7.2×10^{10} Nm^{-2} and 1.6×10^{6} Nm^{-2} respectively and length of the FBG and the polymer are 3mm and 10mm. The simulated results of pressure sensitivities for FBG1 and FBG2 from (3) are 1.83×10^{-2} MPa^{-1} and 5.58×10^{-2} MPa^{-1} respectively.

3. EXPERIMENT AND RESULTS

The schematic of experimental set up is shown in figure 3. For the measurement of pressure the polymer packaged FBG sensor head (figure 1) is placed in a well controllable-pressure chamber. All the experiments are carried out at constant room temperature. When pressure was applied, the polymer experiences pressure through side holes of the cylinder resulting in elongation at the right end of the polymer where the thin round plate is present.

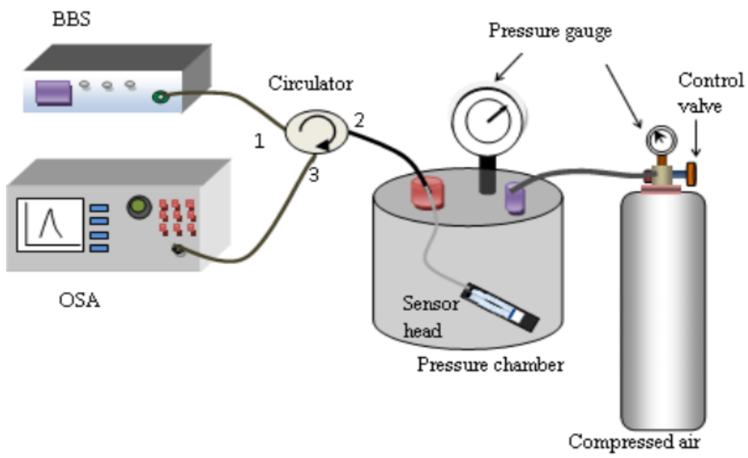


Figure 3.Experimental setup for pressure sensing

Light is launched in to the fiber from a broadband light source (BBS) (1525-1575nm) and an optical spectrum analyser (Agilent 86142B) is used for monitoring the Bragg wave length shift of FBG corresponding to the variation in applied pressure. Figure 4 shows the reflection spectrum of the FBG1.

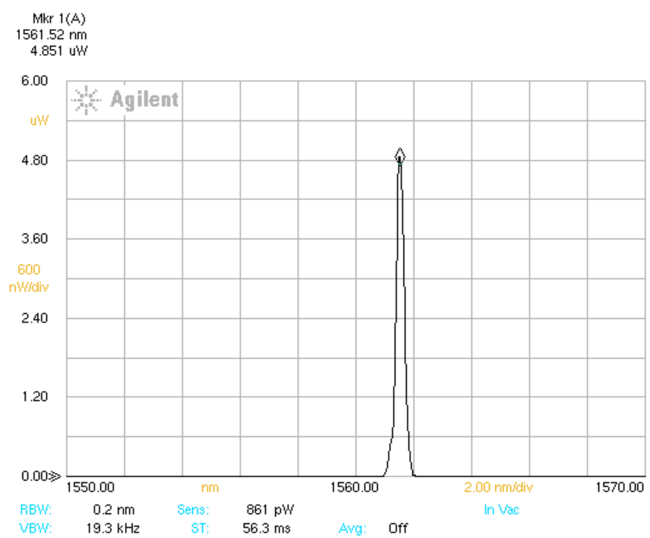


Figure 4.Reflection spectrum of the sensor with FBG1

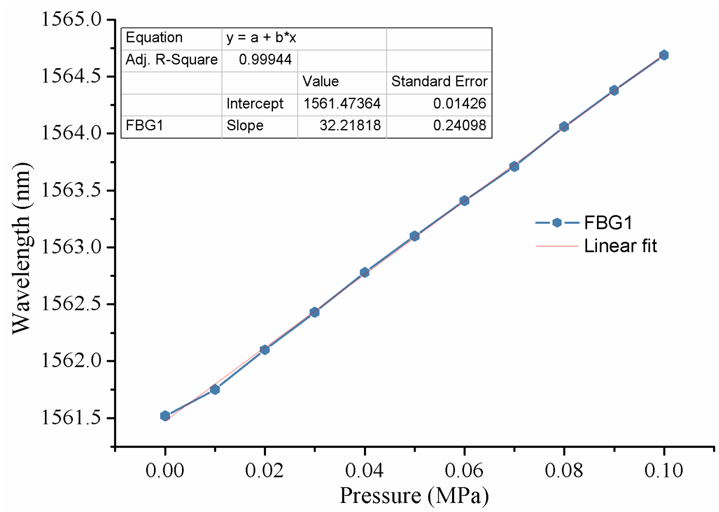


Figure 5.Pressure response of the sensor with FBG1

Figure 5 shows the experimental results of the sensor for which the applied pressure is gradually increased from 0 to 0.1MPa in steps of 0.02MPa.The shift in Bragg wavelength per unit applied pressure for the sensor with FBG1 is $32.2nmMPa^{-1}$. The experiment is repeated with the second sensor head in which FBG2 is the sensing element and the reflection spectrum is shown in figure 6. In this case also the applied pressure is gradually increased from 0 to 0.1MPa in steps of 0.02MPa. For this sensor with FBG2 the shift in Bragg wavelength per unit applied pressure is $90.4nmMPa^{-1,}$ figure 7 which is considerably high compared to that of the sensor with FBG1. From these experimental results the measured pressure sensitivities of sensors with FBG1 and FBG2 are 2.07×10^{-2} MPa^{-1} and 5.85×10^{-2} MPa^{-1} closely approximates with simulated results 1.83×10^{-2} MPa^{-1} and 5.58×10^{-2} MPa^{-1} calculated from (3) respectively. The discrepancy between the experimental and simulated values may be attributed to the applied pressure not acting on the sensor in a single coordinate axial direction and the pressure sensing holes being elliptic and the dimension error during the fabrication of sensor head causing the strain experienced by the silicon on the FBG to exceed the ideal [8].

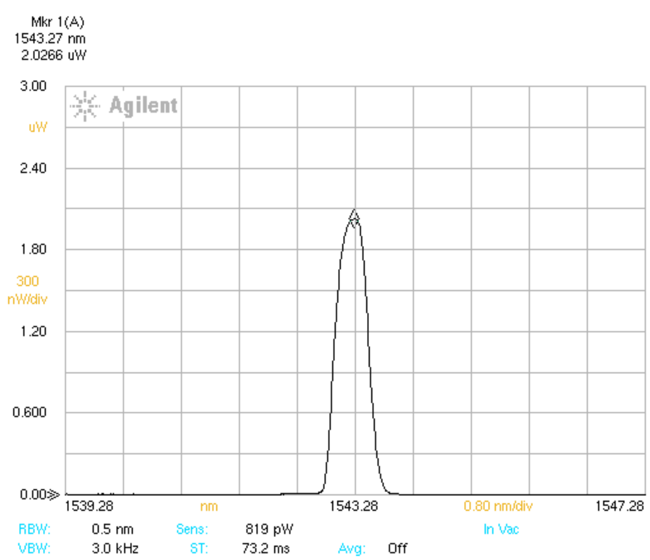


Figure 6.Reflection spectra of the sensor with FBG2

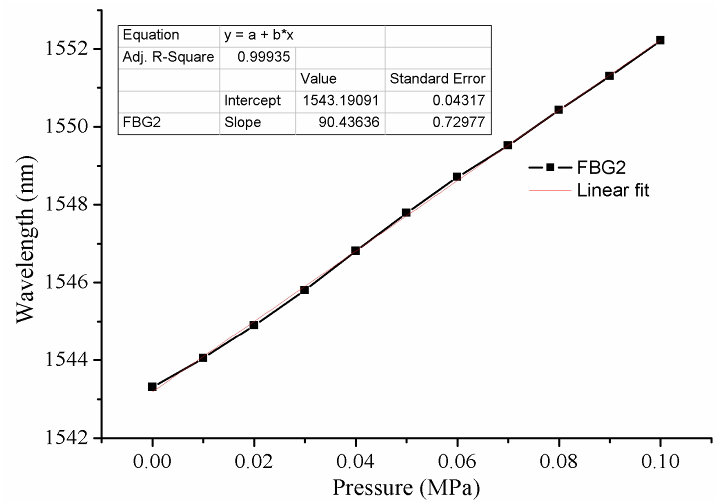


Figure 7.Pressure response of the sensor with FBG2

The pressure sensitivity of the sensor with FBG2 is approximately 18870 times higher than that can be measured with a bare FBG and 2.82 factors greater than that of sensor with FBG1. It is evident that the pressure sensitivity of the sensor can be enhanced by reducing the fiber diameter of the FBG. The performance of the sensor is linear. Within the temperature range 20-70°C the observed shift in Bragg wavelength of sensor with FBG2 is 0.592nm and it accounts the cross sensitivity to temperature is approximately $7.76\text{x } 10^{-6}/°C$. It can be seen that the pressure sensitivity of the packaged FBG sensor is significantly exceeding the temperature sensitivity and thus the thermal-strain cross sensitivity is avoided.

4. CONCLUSIONS

High sensitivity pressure sensor based on an etched FBG embedded in a partially filled polymeric cylindrical package is reported. The sensitivity enhancement obtained is due to reducing the clad diameter and bonding a round plate at the end of the FBG. The measured pressure sensitivity of the FBG2 sensor is $5.85 \text{ x } 10^{-2}\ MPa^{-1}$ which approximately 18870 times higher than that can be measured with bare FBG and 2.82 factors greater than that of FBG1 sensor respectively. This sensor is expected to be an attractive, simple and robust miniature for monitoring underwater depth or axial strain sensing applications.

REFERENCES

[1] A. D. Kersey, M. A. Davis, H. J. Patrick, M. LeBlanc, K. P. Koo, C.G. Askins, M. A. Putnam, and E. J. Friebele, “Fiber grating sensors,” J.Lightwave Technol., vol. 15, pp.1442 –1463, (1997).

[2] W. W. Morey, G. Meltz, and W. H. Glenn, “Fiber optic Bragg grating sensors,” Proc. SPIE, Fiber Optics and Laser Sensors VII” , vol. 1169, pp.98 –107, (1989).

[3] M. G. Xu, L.Reekie, Y.T. Chow, and J.P. Dakin, “Optical in-fiber grating high pressure sensor”, Electron Lett 25, 398 –399, (1993),

[4] M. G. Xu, H. Geiger, and J. P. Dakin, “Fiber grating pressure sensor with enhanced sensitivity using a glass-bubble housing”, Electron. Lett., vol.32, pp. 128–129, (1996).

[5] Yiinqi Liu, Zhumyan Guo, Yiiig Ztiang, Kin Seng Chiang and Xiaoyi Dong, “Simultaneous pressure and temperature measurement with polymer-coated fibre Bragg grating”, Electronics letters, vol.36, No.6, (2000).

[6] Wen Q, Zhu J, Gong S, et al. Design and synthesis of a packaging polymer enhancing the sensitivity of fiber grating pressure sensor”, J. Progress in Natural Science,18(2): 197-200,(2008).

[7] Ying Zhang, Dejun Feng, Zhiguo Liu, Zhuanyun Guo, Xiaoyi Dong, K. S. Chiang, and Beatrice C. B. Chu, "High-sensitivity pressure sensor using a shielded polymer-coated fiber Bragg grating", IEEE Photonics Technology Letters,vol.13,No.6,(2001).
[8] Hao-Jan Sheng, Ming-Yue Fu, Tzu-Chiang Chen, Wen-Fung Liu, and Sheau-Shong Bor, "A Lateral Pressure Sensor Using a Fiber Bragg Grating", IEEE Photonics Technology Letters, Vol. 16, No. 4, (2004).
[9] Masoud Vaziri and Chin-Lin Chen, "Etched fibers as strain gauges", J. Lightwave Technol., vol. 10, No.6 pp. 836- 841, (1992).