High sensitive FBG pressure sensor using metal bellows

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ABSTRACT

A fiber-optic sensor scheme, capable of the simultaneous measurement of pressure and temperature using two in-line Fiber Bragg Gratings (FBGs) is reported. Sensor head is configured by embedding the two FBGs with metal bellows, such that FBG1 is sensitive to both pressure and temperature, whereas FBG2 is only sensitive to temperature. High pressure sensitivity is achieved because of the lower spring rate in longitudinal direction to that of the large elastic modulus in transverse direction of the metal bellows. Pressure and temperature measurement is made by monitoring the shift of Bragg wavelengths of the FBGs corresponds to variation in pressure and temperature. From the test results, the obtained pressure and temperature sensitivities are 86 pm/psi and 9.17 pm/°C, over a dynamic range of 0-40 psi pressure, and 25-110°C temperature measurements respectively. The experimental results well agreed with the theoretical results and show good linearity. This simple design, economical and all fiber optic sensors can be used for liquid and gas pressure measurements, and under-water applications.

Keywords: Fiber Bragg grating, metal bellows, spring rate, pressure, temperature, optical spectrum analyzer and sensitivity.

1. INTRODUCTION

Fiber Bragg gratings have been proved as promising element in variety of applications, particularly in optical communication and optical fiber sensors. Owing to their distinguished advantages such as immune to electromagnetic interference (EMI), high sensitivity, compactness, capable of multiplexing and distributed sensing, corrosion resistance and so on, they have been studied to measure strain, temperature, pressure, vibration, salinity and voltage, etc. Among them, pressure and temperature measurements are two major and direct fields [1, 2]. Since, the Bragg wavelength of an FBG is affected by both pressure and temperature, the cross sensitivity becomes problem in applications where the discrimination between pressure and temperature is required. Many works based on the FBGs have been devoted to the development of the discrimination between the effects of these two parameters. Based on the dual wavelength fiber Bragg grating sensors [3], two fiber Bragg grating sensors with $Al_2 O_3$ thin wall tube substrate [4], Double fiber Bragg grating with polymer package [5], Embedded dual fiber Bragg grating sensors with arc-shaped steel strip [6], fiber Bragg gratings written in standard and grapefruit micro structured fiber [7], Single FBG with broadened reflection spectrum [8], an embedded FBG in a tapered polymer [9], a metal coated FBG [10] and fiber Bragg grating has been written in a novel high birefringence (Hi-Bi) fiber [11]. FBGs combined with other technologies as a long period fiber Bragg gratings [12, 13], a Fabry-Perot interferometer [14, 15], and a thermo-chromic material [16].

In this paper a simple and practicable method to measure pressure and temperature simultaneously is proposed based on dual FBGs written in-line in a photosensitive fiber, which is embedded with metal bellows. Pressure and temperature measurements are made from 0 to 40 psi and 25 to 110 °C respectively. The obtained experimental results were compared with the theoretical results.

2. FIBER BRAGG GRATING TECHNOLOGY AND SENSING PRINCPLE

2.1 FBG Principle

Fiber Bragg grating is characterized by a periodic perturbation of the core refractive index along a given length of an optical fiber. When FBG is illuminated with broad band light, due to the coupling between incident and counter propagating optical modes, the specific narrowband wavelength light will be reflected which is called Bragg wavelength λ_B can be expressed as [1]

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$$\lambda_B = 2\eta_{eff}\Lambda \tag{1}$$

Where η_{eff} the effective refractive index of the fiber core and Λ is the grating period. Any changes in fiber properties, such as strain or temperature which varies the effective refractive index or grating period will change the Bragg resonance wavelength. It can be seen by equation (1) that, except the Bragg wavelength reflected by one FBG, the other wavelengths are transmitted and are incident on to the next FBGs, thus it enables multipoint sensing at one single optical fiber by connecting multiple FBGs in series, and each of them has a different Bragg wavelengths. That means FBG has the multiplexing capability.

2.2 FBG sensing principle

The shift in Bragg wavelength corresponds to applied strain and temperature can be expressed as

$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial\eta_{eff}}{\partial l} + \eta_{eff}\frac{\partial\Lambda}{\partial l}\right)\Delta l + 2\left(\Lambda\frac{\partial\eta_{eff}}{\partial T} + \eta_{eff}\frac{\partial\Lambda}{\partial T}\right)\Delta T \tag{2}$$

The first term in equation (2) denotes the strain effect on an optical fiber. This corresponds to change in grating period and strain-optic induced change in the refractive index. The strain effect term can be expressed as

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

Where P_e is the effective photo-elastic coefficient of the fiber can be approximated as $P_e = 0.22$ [1].The second term in equation (2) represents the temperature effect on an optical fiber. A shift in Bragg wavelength due to thermal expansion, changes the grating pitch and the index of refraction. This Bragg wavelength shift for a temperature change ΔT can be written as

$$\Delta\lambda_B = \lambda_B(\alpha_\Lambda + \xi_n)\Delta T \tag{4}$$

Where $\alpha_\Lambda = \frac{1}{\Lambda}\frac{\partial\Lambda}{\partial T}$ is the thermal expansion coefficient of the fiber. The quantity $\xi_n = \frac{1}{\eta_{eff}}\frac{\partial\eta_{eff}}{\partial T}$ represents the thermo-optic coefficient. Thus from equations (3) and (4) the fractional change in Bragg wavelength associated with the change in strain and temperature can be expressed as

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\varepsilon + (\alpha_\Lambda + \xi_n)\Delta T \tag{5}$$

Accordingly, it is evident from equation (5) that, in sensing applications where only one perturbation is of interest, the discrimination of strain and temperature emerge as significant.

2.3 Simultaneous measurement of pressure and temperature

From the analysis, it indicates that both changes in pressure (strain) and temperature can induce the changes in the Bragg wavelength. In general, the common method to discern them is using another reference FBG (FBG2), being thermal contact with the sensing FBG (FBG1), but is shielded from the applied pressure. When a pressure is applied to the FBG sensor or when there is an ambient temperature change, the effective refractive index and the grating pitch will change, and therefore the resonance wavelengths will shift. The shifts of resonance wavelengths for the FBG1 and the FBG2 can be expressed as

$$\begin{aligned}\Delta\lambda_{B1} &= J_{P1}\Delta P + J_{T1}\Delta T \\ \Delta\lambda_{B2} &= J_{P2}\Delta P + J_{T2}\Delta T\end{aligned} \tag{6}$$

Where J_{P1}, J_{T1}, J_{P2} and J_{T2} are pressure and temperature sensitivity coefficients of FBG1 and FBG2 respectively. From equation (6), when pressure and temperature changes, the pressure can be obtained on the basis of subtracting the Bragg wavelength shift induced by the reference FBG(FBG2) from the total wavelength shift induced by the sensing FBG (FBG1). To realize the simultaneous measurement of pressure and temperature, the Bragg wavelength shift of two resonant peaks of corresponding FBGs need to be measured simultaneously. Thus, the sensitivity matrix can be expressed as

$$\begin{bmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{bmatrix} = \begin{bmatrix} J_{P1} & J_{T1} \\ J_{P2} & J_{T2} \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta T \end{bmatrix} \tag{7}$$

In this way, discrimination between pressure and temperature can be achieved by the following matrix equation which is an inversion matrix of equation (7)

$$\begin{bmatrix} \Delta P \\ \Delta T \end{bmatrix} = \frac{1}{\psi} \begin{bmatrix} J_{T2} & -J_{T1} \\ -J_{P2} & J_{P1} \end{bmatrix} \begin{bmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{bmatrix} \tag{8}$$

Where $\psi = J_{P1}J_{T2} - J_{P2}J_{T1}$. Pressure and temperature sensitivity coefficients can be determined experimentally by measuring separately the shift of Bragg wavelengths of the FBGs.

3. SENSOR DESIGN AND EXPERIMENT

3.1 Sensor structure

The schematic structure of the FBG sensor is shown in figure 1. Metal bellows made up of stainless steel measures 5 cm of total convolution length and thickness of 0.2 mm is used as pressure transducer to enhance pressure sensitivity of the sensor. In the proposed detection scheme, using an epoxy, metal bellow element is air tight sealed between two aluminium metal plate's measure 2.5×2.5×0.3 cm ($l \times b \times h$ cm) and 5×2.5×1.5 cm, respectively. The thick aluminium plate has a 3 mm hole which act as a pressure inlet, machined exactly to coincide with the axis of metal bellows. The base of the sensor head can be fixed to a vibration free table, before subjecting to the applied pressure. Two FBGs have 5 cm apart to each, drawn in-line in a photosensitive single mode fiber are used for simultaneous measurement of pressure and temperature. FBG1 is sealed by using an epoxy (cyanoacrylate adhesive) between the end points of metal bellows, while one end of FBG2 is left freely which is being shielded from the applied pressure as shown in figure 1. Thus FBG1 is sensitive to both pressure and temperature whereas FBG2 is in a state of relaxation; hence, it is only sensitive to temperature.

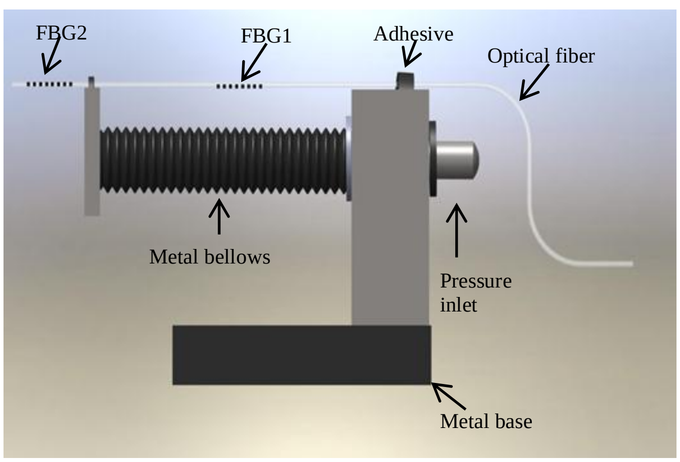

Figure 1. Schematic structure of the FBG sensor.

For metal bellows, along the length it was treated as spring due to the special structure of small spring rate compared with the large circumferential elastic modulus [17] and it obeys the Hook's law. Under pressure the longitudinal strain ε_z is given by

$$\varepsilon_z = \frac{PA}{KL} \tag{9}$$

Where P is the applied pressure, A, K, L are the effective area, spring constant and length of metal bellows respectively. Thus with the longitudinal strain contribution by neglecting the transverse effect, equation (3) becomes

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\frac{PA}{KL} \tag{10}$$

It is evident from equation (10) that the relative shift in Bragg wavelength has a linear relationship with applied pressure. Therefore, when the sensor is subjected to pressure the metal bellows experience an axial expansion along its length, leads to an axially extended-strain in the FBG1, thereby an increase in pressure sensitivity. While the FBG2 is set to be remains unstrained. By using the parameters $K = 197.864$ N/mm, $A = 116.839\,\text{mm}^2$, $L = 50$ mm a theoretical pressure sensitivity of 97 pm/psi was observed. Equation (10) reveals that the sensitivity is dependent on elastic constant. The smaller the spring constant is, better the sensitivity is. For the designed sensor, elastic constant is approximately four times higher than that of Ref [17], but the sensitivity is approximately two folds higher than that. This is attributed to the fact that under pressure the metal bellows was subjected to linear expansion in axial direction causes an axially stretched-strain in the FBG which triggers a great improvement in pressure sensitivity, whereas the metal bellows experienced a compressed strain in Ref [17] when it was subjected to pressure.

3.2 Experimental setup

Figure 2 illustrates a schematic of the experimental setup. It consists of a broadband (BBS) SLD source ranging from 1525 to 1565 nm which illuminates the FBGs through an optical circulator. The Bragg wavelength shift of FBG corresponds to variation in pressure or temperature is read through an optical spectrum analyzer (OSA). Pressure is applied to the sensor system using a well-controlled compressor. The pressure applied to the metal bellows is monitored using a calibrated pressure meter having a resolution of 1 psi. The two Bragg resonance peaks of FBG1 and FBG2 at room temperature are at 1541.15 nm and 1551.16 nm respectively. These FBGs are written in-line in a photosensitive single mode fiber using phase mask technique. We measured the pressure and temperature responses of the FBG sensors by independently applying the pressure and temperature to the sensor system.

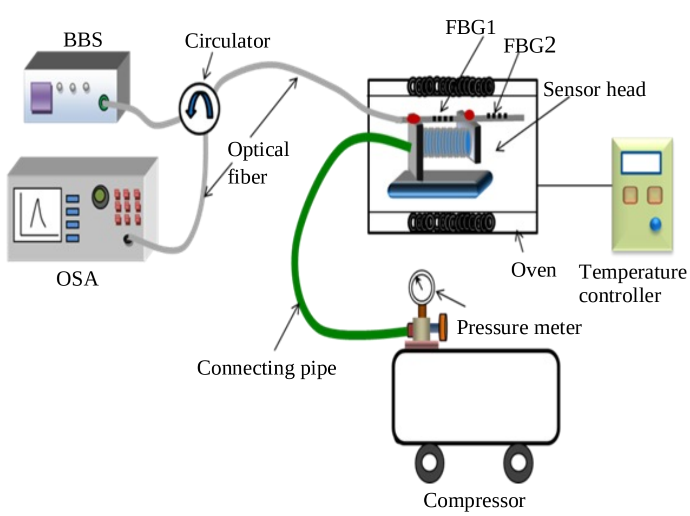

Figure 2. Schematic of experimental setup for simultaneous measurement of pressure and temperature.

4. RESULTS AND DISCUSSIONS

Figure 3 illustrates the result of an experiment in which the temperature is kept constant at 25°C (room temperature), whereas the applied pressure is varied from 0 to 40 psi. The pressure is driven in steps of 5 psi and corresponding Bragg wavelength shift is measured. As shown in figure 3 the center wavelength of FBG1 shifted from 1541.15 to 1544.68 nm, within the range of applied pressure, while there was no shift found in the center wavelength of FBG2. From these experimental data, the measured pressure sensitivities of FBG1 and FBG2 are J_{P1} = 85.97 pm/psi and J_{P2} = 0 pm/psi, respectively. The pressure sensitivity of the proposed sensor is approximately 3910 times higher than that can be achieved with a bare FBG [18].

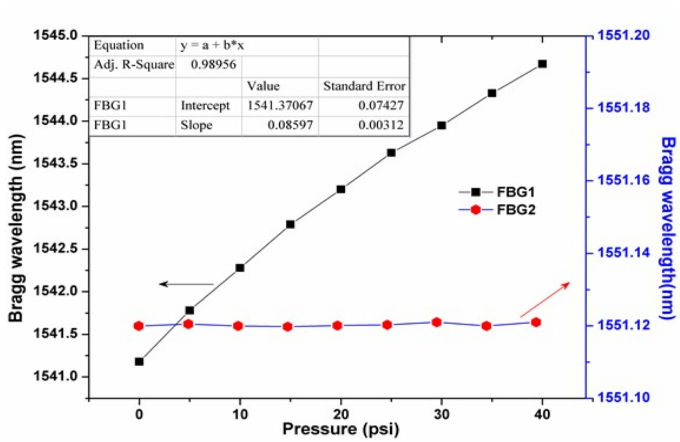

Figure 3.Pressure response of FBG1 and FBG2 at room temperature.

Figure 4 depicts the coincidence of experimental results to that of theoretically calculated results, that is Bragg wavelength shift of FBG1 corresponding to increased and decreased pressure. The experiment is repeated to test the repeatability of the sensor and found to be consistent. The sensor has good linearity with a linear regression coefficient of 98.9 % within the range of pressure. By applying the pressure within the elastic limits of metal bellows and it is made up of stainless steel, the hysteresis is not conceivable. The experimental pressure sensitivity 86 pm/psi is smaller than the theoretical value 97 pm/psi , may be attributed to the fact that change in spring constant of metal bellows under different pressures and bonding performance.

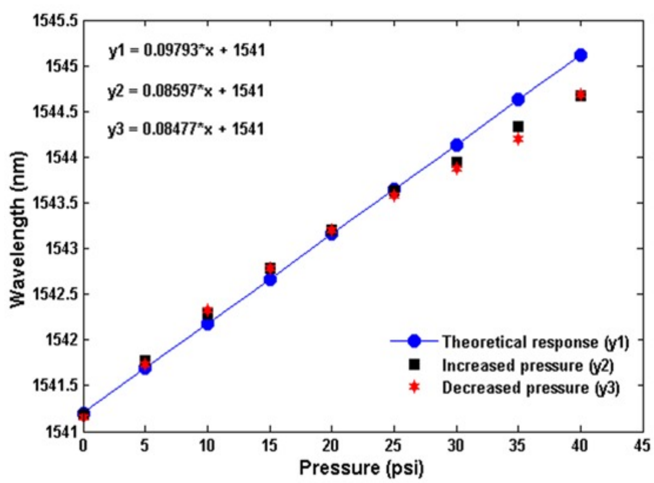

Figure 4. Comparison of the experimental results with the theoretical results.

Figure 5 exhibits OSA recorded spectrum of the Bragg wavelength shift of FBG1 corresponding to the different pressure values of 0, 15, 25, 30, 35, and 40 psi at room temperature.

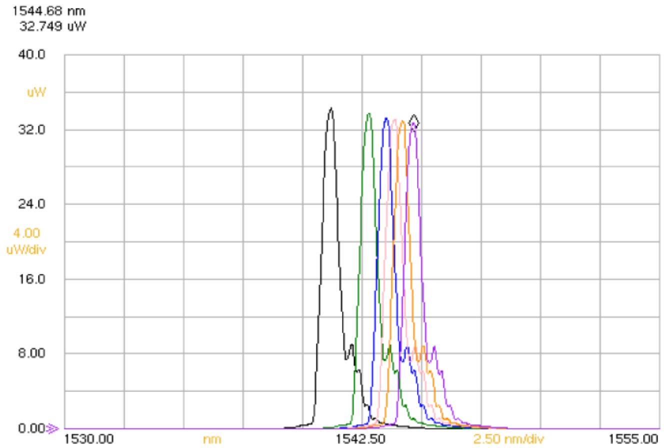

Figure 5. OSA spectrum of the Bragg wavelength shift of FBG1 corresponds to variation in pressure at constant

The experimental results for the determination of temperature sensitivities of FBG1 and FBG2 are plotted in figure 6. In this case, the pressure was fixed at 0 psi, whereas the temperature changes in steps of 5°C from 25 to 110°C using a well controllable oven. The experimental temperature sensitivities of both the FBGs are found to be 9.17 pm/°C and 8.93 pm/°C, respectively.

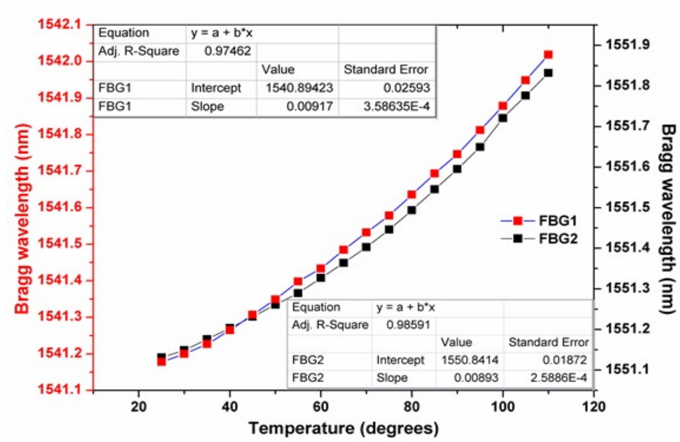

Figure 6. Temperature response of FBG1 and FBG2 at constant pressure.

The sensitivity coefficients of the matrix in equation 8, are replaced with the experimentally measured pressure and temperature sensitivities resulting in

$$\begin{bmatrix} \Delta P \\ \Delta T \end{bmatrix} = \frac{1}{770.56} \begin{bmatrix} 8.93 & -9.17 \\ 0 & 85.97 \end{bmatrix} \begin{bmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{bmatrix} \tag{11}$$

Therefore, with this new matrix equation, the applied pressure and temperature on the FBG sensing head can be calculated by simple wavelength measurement of the two corresponding reflection peaks. Pressure and temperature resolution of the designed sensor are 0.116 psi and 1.09 °C, respectively which are limited by the low resolution of OSA and measurement accuracies of devices such as oven and compressor. At the same time, pressure measurement range and sensitivity of the sensor can be improved by adjusting the physical parameters of metal bellows such as material and dimensions.

5. CONCLUSIONS

In summary, a simple and practical method for simultaneous measurement of pressure and temperature based on FBG sensor, which consists two FBGs in-line embedded with metal bellows is demonstrated. Experimental results show that the sensor can measure pressure and temperature within the range of 0 to 40 psi and 25 to 110°C with sensitivities 86 pm/psi and 9.17 pm/°C, respectively. An especially, high sensitivity of pressure measurement have been achieved which is 3910 times to that of a bare FBG due to appropriate configuration of the FBG sensor. The results from the experiment agree well with that of the theoretically predicted results. In addition, the designed sensor has the advantage of simple structure, low cost and all fiber optic sensors may finds applications in the fields of under water, down-hole oil and gas applications; where one cannot be too close to the test point because it is either difficult to reach or even dangerous.

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