FBG sensor for temperature-independent high sensitive pressure measurement with aid of a Bourdon tube

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ABSTRACT

A temperature independent high sensitive pressure sensing system using fiber Bragg grating (FBG) and 'C' shaped Bourdon tube (CBT) is demonstrated. The sensor is configured by firmly fixing the FBG (FBG1) between free and fixed ends of the CBT. Additional FBG (FBG2) in line to the FBG1 is introduced which is shielded from the external pressure, tend to measure only the ambient temperature fluctuations. The CBT has an elliptical cross section where its free end is sealed and the fixed end is open for subjecting the liquid or gas pressure to be measured. With the application of pressure, the free end of CBT tends to straighten out results in an axial strain in FBG1 causes red shift in Bragg wavelength. The pressure can be determined by measuring the shift of the Bragg wavelength. The experimental pressure sensitivity is found to be 66.9 pm/psi over a range of 0 to 100 psi. The test results show that the Bragg wavelength shift is linear corresponds to change in applied pressure and well agreed with the simulated results. This simple and high sensitive design is capable of measuring static/dynamic pressure and temperature simultaneously which suits for industrial applications.

Keywords: Pressure, Temperature, Fiber Bragg Grating, Bourdon Tube and Sensitivity

1. INTRODUCTION

Since two decades fiber Bragg grating (FBG) sensors have been proved potential sensing elements for the measurement of strain/pressure and temperature [1-4]. These sensors offering distinguished merits over conventional sensors, namely wavelength encoded measurement, immune to electromagnetic interference (EMI), high sensitivity, fast response, large dynamic range, self-referencing, multipoint measurement, multiplexing capability, compact size and compatibility with optical fiber networks [5-8]. One of the notable limitation of these sensing structures is their intrinsic temperature-cross sensitivity which significantly effects the accuracy and resolution of pressure sensing system in under sea water applications like structural health monitoring of ships and submarine structures, liquid level in oil storage tank, down-hole oil and gas explorations. However, a bare FBG has low pressure sensitivity of about 0.022 pm/psi [9]. Many researchers have been dedicated to enhance the pressure sensitivity using different configurations [10-14]. Though these techniques mainly focused on increasing the pressure sensitivity, the problem with temperature induced Bragg wavelength shift has not been fixed. Numerous techniques have been proposed to fix this problem, such as two fiber Bragg gratings embedded in a glass tube[15], fiber Bragg grating combined with a high-birefringence fiber loop mirror[16], Double fiber Bragg gratings with polymer package[17], Bilateral cantilever and fiber grating [18], a fiber Fabry–Perot interferometer and a fiber Bragg grating (FBG) based pressure and temperature multiplexing sensor system[19],super imposed long and short fiber Bragg gratings [20], temperature independent differential pressure sensor using fiber Bragg gratings[21].These methods provide some approaches to discriminate the cross sensitivity effect between pressure and temperature, but most of them implicated specific gratings, complex sensor design and special techniques. Further, some techniques have been reported in the literature, utilize single FBG for discrimination of strain/pressure and temperature require a special care in sensor design [22, 23]. One of the simple and easy technique to discriminate the temperature cross sensitivity is, introducing a reference FBG along with the sensing FBG.

In this paper, design of a simple and high sensitive FBG based pressure sensor with temperature compensation is described. This method uses a separated strain free FBG2 as the temperature sensor to measure the temperature of pressure sensor directly. 'C' shaped Bourdon tube (CBT) is used as pressure transducer which transfers the pressure

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induced strain effectively to the FBG1 thereby increasing the pressure sensitivity. This FBG sensor not only significant to enhance the pressure sensitivity but also provides simple method to immune temperature cross-sensitivity in a certain temperature range. Sensor design is low-cost, easy to install and allows the users to monitor static/dynamic pressure from remote location.

2. SENSOR DESIGN AND PRINCIPLE

2.1 Sensor design

Schematic and photograph of the sensor head designed for temperature compensated pressure sensor is shown in figure 1.

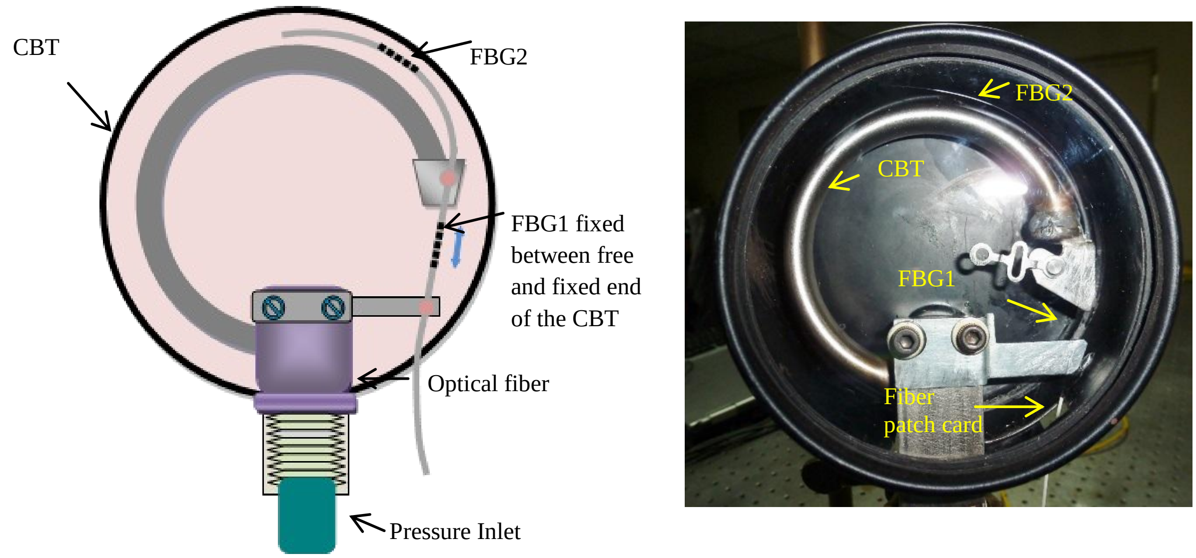

Figure 1. Schematic diagram and Photograph of the sensor head.

It mainly consists of a ‘C’ shaped Bourdon tube (CBT) of a pressure gauge and two inline FBGs are written in an optical fiber. The CBT is made of 316L stainless steel has an elliptical cross section where its free end is sealed and closed end is connected to a pressure test bench. When it is subjected to applied pressure, the tube tends to straighten out and the angular deflection of the free end is taken as a measure of the pressure. Bourdon tubes are fabricated with the material which has stable elastic properties to suit the gas or fluid pressure is to be measured. The empherical formula for the tip displacement of bourdon tube with applied pressure P was written as [24].

$$\Delta L = 0.05\frac{LP}{E}\left(\frac{D}{h}\right)^{0.2}\left(\frac{a}{b}\right)^{0.33}\left(\frac{a}{h}\right)^{3} \quad (1)$$

Where a and b are the cross sectional length and breadth of the bourdon tube h the thickness of the material, D diameter of the ‘C’ shape bourdon tube, L circumferential length, E Young’s modulus and P applied pressure. FBG1 is glued between free and fixed base of the Bourdon tube as shown in figure 1. When CBT is subjected to pressure change the displacement of the free end induces strain in FBG1 causes shift in Bragg wavelength.

2.2 Principle

For an FBG, under axial strain the relative shift in Bragg wavelength at constant temperature can be expressed as

$$\frac{\Delta\lambda_{B1}}{\lambda_{B1}} = (1 - P_e)\varepsilon_{ax} \quad (2)$$

Where ε_{ax} is the axially applied strain, P_e is the effective photo elastic coefficient of the optical fiber. For a fused silica optical fiber $P_e = 0.22$ [5]. The axial strain experienced by the FBG1 is expressed as

$$\varepsilon_{ax} = \frac{\Delta l}{l} \tag{3}$$

Where l the length of the fiber is fixed between free and fixed end of the Bourdon tube and Δl the change in length of the fiber. Due to the deflection of the Bourdon tube corresponding to the change in applied pressure, the strain experienced by the FBG1 is

$$\varepsilon_{ax} = \delta \frac{\Delta L}{l} \tag{4}$$

Where 'δ' is a rational factor that correlates the ΔL and Δl.

Combining equation (1), (2) and (4) the Bragg wavelength shift of FBG1 corresponds to applied pressure is

$$\frac{\Delta\lambda_{B1}}{\lambda_{B1}} = 0.05(1 - P_e)\frac{\delta}{l}\frac{LP}{E}\left(\frac{D}{h}\right)^{0.2}\left(\frac{a}{b}\right)^{0.33}\left(\frac{a}{h}\right)^{3} \tag{5}$$

It can be observed from equation (5) that shift in Bragg wavelength is linear corresponding to the applied pressure.

Table 1. The values of the parameters used to calculate the theoretical pressure sensitivity.

S. No	*Parameter*	*value*
1	*l*	*4 cm*
2	*L*	*16.2 cm*
3	*E*	*193 GPa*
4	*D*	*7.2 cm*
5	*h*	*0.5 cm*
6	*a*	*13.05 cm*
7	*b*	*7.39 cm*

The equation (5) is simulated using MATLAB for the values of the parameters listed in table 1, results in theoretical shift in Bragg wavelength 73.8 pm/psi. Since FBG is inherently sensitive to strain as well as temperature, the effect of temperature change suitably compensated to attain pure pressure measurement. Aiming to this, a reference FBG2 is incorporated to compensate the temperature effect experienced by the FBG1. Since the FBG2 is isolated from applied pressure it is free from strain. As a result no Bragg wavelength shift from FBG2 occurs when there is a change in pressure. The change in temperature effects the shift in Bragg wavelength of FBG1 and FBG2and is given by

$$\frac{\Delta\lambda_{B(i)}}{\lambda_{B(i)}} = (\alpha + \xi)\Delta T \tag{6}$$

Where i=1, 2. Therefore by measuring $\Delta\lambda_{B1}$ and $\Delta\lambda_{B2}$ from FBG1 and FBG2 due to change in pressure and temperature, simultaneous measurement of pressure and temperature can be determined using equation 2 and 6. Since FBG1 and FBG2 having different responses for pressure and temperature, a matrix equation can be written and inverted to yield pressure and temperature from the measurements of the $\Delta\lambda_{B1}$ and $\Delta\lambda_{B2}$.

$$\begin{bmatrix} \Delta P \\ \Delta T \end{bmatrix} = \frac{1}{\psi} \begin{bmatrix} J_{T2} & -J_{T1} \\ -J_{P2} & J_{P1} \end{bmatrix} \begin{bmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{bmatrix} \quad (7)$$

Where $\psi = J_{P1}J_{T2} - J_{P2}J_{T1}$. J_{P1}, J_{T1}, J_{P2} and J_{T2} are the Pressure and temperature sensitivity coefficients FBG1 and FBG2 respectively. In practice, these sensitivity coefficients can be determined experimentally by measuring separately the shift of Bragg wavelengths of the FBGs corresponds to pressure and temperature.

3. EXPERIMENT AND RESULTS

3.1 Experiment

The photograph of the experimental setup to achieve high sensitive pressure measurement is shown in figure 2. 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). The applied pressure to the

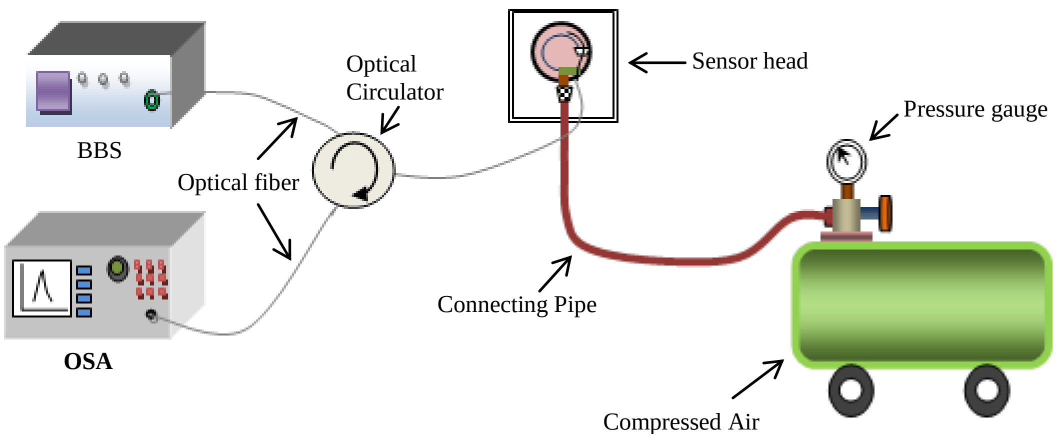

Figure 2. Photo of the experimental setup and OSA spectrum of FBG1 and FBG2 at room temperature.

sensing head is varied from 0 to 100 psi in steps of 5 psi which is precisely controlled using a control valve provided to the compressor. The pressure variation is monitored using a calibrated pressure meter having a resolution of 2 psi. To restore the elastic properties of CBT, the applied pressure is limited to 100 psi which is one half less than its full scale measurement. At room temperature, the Bragg resonance peaks λ_{B1} and λ_{B2} of FBG1 and FBG2 are 1545.4 nm and 1550.28 nm respectively. These FBGs are written in-line in a photosensitive single mode fiber using phase mask technique. The inline FBG2 is free from strain and kept inside the sensor head. The sensor head consists of CBT and two in-line FBGs are enclosed in a sealed box made of Iron to isolate it from surrounding atmosphere. We measured the pressure and temperature responses of the FBG sensors by independently applying the pressure and temperature to the sensor system.

In response to the pressure pumped into the sensor head, the free end of the CBT tend to straighten out causes a red shift in Bragg wavelength of FBG1. The shift in Bragg wavelength is measured using OSA. Since the experiment is done at constant laboratory conditions and the arrangements made such that FBG2 is remains unstrained against applied pressure there is no considerable shift in Bragg wavelength of FBG2 is observed.

3.2 Results and Discussions

Figure 3(a) and 3(b) illustrate the comparison between theoretical and experimental results of the designed pressure sensor, and the shift of λ_{B1} and λ_{B2} corresponds to variation in pressure ranges 0 to 100 psi at room temperature respectively. The λ_{B1} shifts from 1550.24 nm to 1556.88 nm with in the pressure range. The shift in Bragg wavelength of FBG1 per unit applied pressure is found to be 66.9 pm/psi which is approximately 3040 times higher than that can be measured with bare FBG[9]. As expected, there is no shift in Bragg wavelength in FBG2 against change in applied pressure. The OSA recorded spectrum corresponding to the Bragg wavelength shift of FBG1 in response to increase in pressure is shown in figure 4. It is evident from figure 3 that the shift in Bragg wavelength is linear with the correlation coefficient of 99.806 against variation in applied pressure.

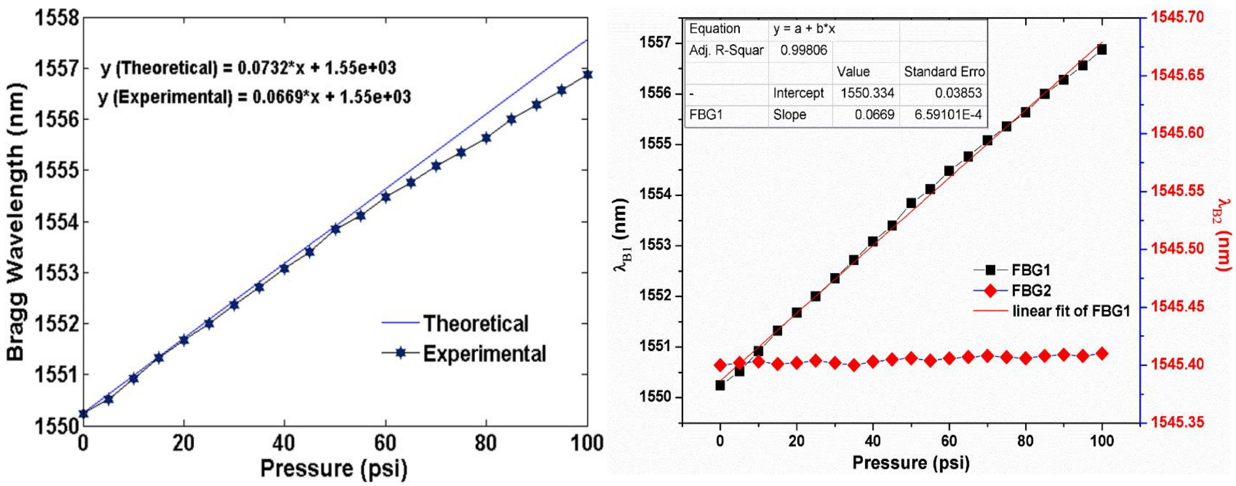

Figure 3. (a) Comparison between theoretical and experimental result, (b) Shift in Bragg wavelength of FBG1 and FBG2 corresponds to change in pressure at room temperature respectively.

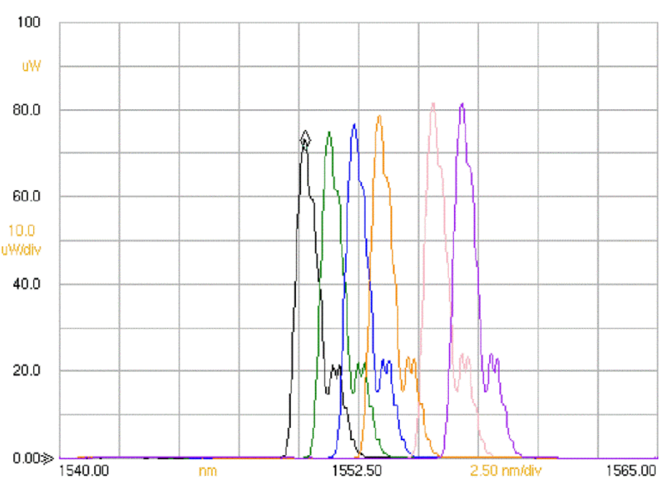

Figure 4. Shift of Bragg wavelength of FBG1 corresponds to increase in applied pressure.

The experimental pressure sensitivity of the sensor is found to be 6.258×10^{-3} MPa^{-1} which is well agreed with the theoretical pressure sensitivity 6.848×10^{-3} MPa^{-1}.The discrepancy between experimental and theoretical pressure sensitivity may be attributed to fact that the inadequate bonding of FBG1 between free and fixed end of CBT and the values of the parameters used for simulation may not be accurate. The rational factor $\delta = 0.63$ is measured from the experimental results. To study the repeatability and reliability response of the designed sensor, experiment is repeated for three times at room temperature with respect to loading and unloading the pressure and corresponding shift in the Bragg wavelength is measured using OSA. The results are plotted in figure 5. While the pressure applied to sensor head is within the elastic limits of CBT, therefore no considerable hysteresis error is observed. Inherently, FBG is sensitive to strain/pressure and temperature it is to discern the effect of temperature to attain pure pressure measurement. In this view, the sensor head is subjected to temperature change from room temperature (24ºC) to 84ºC in steps of 10 ºC. The shift of Bragg wavelength corresponds to variation in temperature is plotted in figure 6.

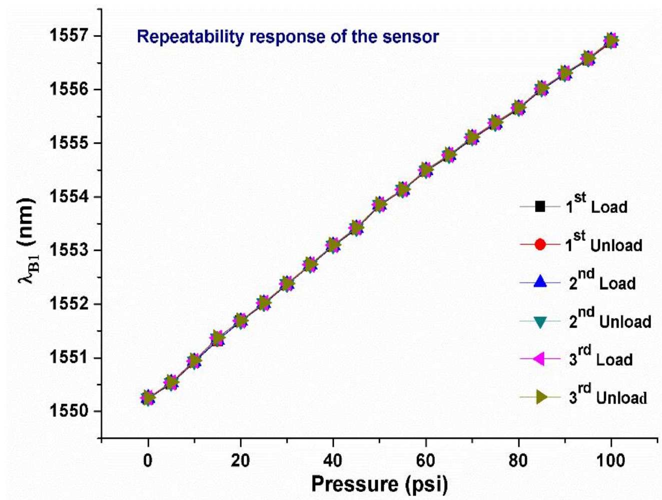

Figure 5. Test results of the proposed sensor for repeated measurements while loading and unloading the pressure.

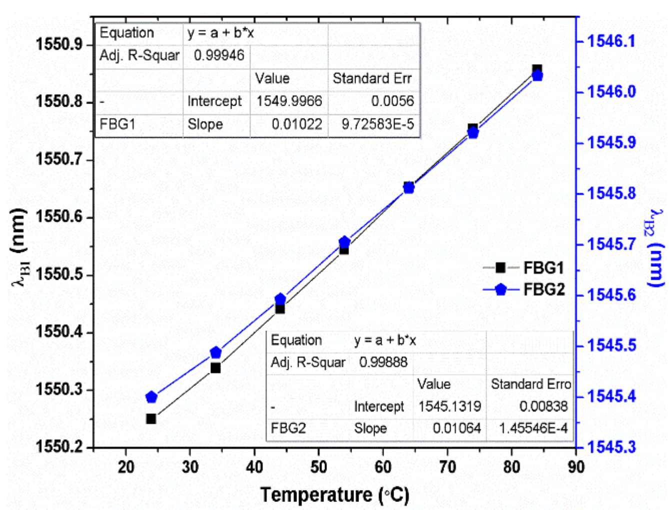

Figure 6. Temperature response of FBG1 and FBG2 at constant pressure.

It can be observed from figure 6, that the wavelength shift of λ_{B1} and λ_{B2} per unit applied temperature are found to be 10.22 pm/ºC and 10.64 pm/ºC respectively. It is evident from the results that being the FBGs close to each other and their response to temperature is approximately similar. Thus, by subtracting wavelength shift of reference FBG2 due to temperature change from the wavelength shift of sensing FBG1 which is combining shift corresponds to pressure as well as temperature, can be accomplish the pure pressure measurement. Therefore pressure and temperature responses of FBG1 and FBG2 measured independently. The pressure and temperature sensitivity coefficients of λ_{B1} and λ_{B2} obtained from experimental results are $J_{P1} = 66.9$ pm/psi, $J_{T1} = 10.22$ pm/ºC, $J_{P2} = 0$ pm/psi and $J_{T2} = 10.64$ pm/ºC respectively. The sensitivity coefficients of pressure and temperature corresponds to λ_{B1} and λ_{B2} can be written in vector form of inverse matrix of equation 7, which enable the simultaneous measurement of pressure and temperature.

$$\begin{bmatrix} \Delta P \\ \Delta T \end{bmatrix} = \frac{1}{711.81} \begin{bmatrix} 10.64 & -10.22 \\ 0 & 66.9 \end{bmatrix} \begin{bmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{bmatrix} \tag{7}$$

where ΔP and ΔT are change in pressure and temperature respectively. The experimental results reveals that the sensing able to perform pressure and temperature simultaneously. The resolution of the sensor obtained from the experimental results are ± 0.15 psi and ± 0.98ºC within the range of pressure (0-100 psi) and temperature (24-84ºC) respectively. The resolution of the sensor mainly limited by the low resolution of the OSA. Better resolution can be achieved by using high sensitive FBG interrogator or OSA.

4. CONCLUSIONS

Design and development of a high sensitive pressure sensor using FBG and CBT with reduced thermal-strain cross sensitivity is demonstrated. Pressure measurement is made in accordance with the shift in Bragg wavelength of FBG. Change in Bragg wavelength of FBG1 corresponds to variation in pressure is linear with a correlation coefficient of 99.806. In order to facilitate the sensor to attribute pure pressure measurement, a reference FBG2 inline to the FBG1 is introduced. The experimental pressure sensitivity obtained from the test results is 6.25×10^{-3} MPa^{-1} which is approximated to that of the theoretical pressure sensitivity 6.848×10^{-3} MPa^{-1}. The sensor show good linearity and repeatability with negligible hysteresis error within the pressure range 0-100 psi. All fiber optic, simple in design, low cost and capable of measuring pressure in contact and remote to the test environment, facilitate the sensor significant in industrial applications.

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