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FBG Based High Sensitive Pressure Sensor and Its Low-Cost Interrogation System With Enhanced Resolution

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Abstract: A fiber Bragg grating (FBG) pressure sensor with high sensitivity and resolution has been designed and demonstrated. The sensor is configured by firmly fixing the FBG with a metal bellows structure. The sensor works by means of measuring the Bragg wavelength shift of the FBG with respect to pressure change. From the experimental results, the pressure sensitivity of the sensor is found to be 90.6 pm/psi, which is approximately 4000 times as that of a bare fiber Bragg grating. A very good linearity of 99.86% is observed between the Bragg wavelength of the FBG and applied pressure. The designed sensor shows good repeatability with a negligible hysteresis error of ± 0.29 psi. A low-cost interrogation system that includes a long period grating (LPG) and a photodiode (PD) accompanied with simple electronic circuitry is demonstrated for the FBG sensor, which enables the sensor to attain high resolution of up to 0.025 psi. Thermal-strain cross sensitivity of the FBG pressure sensor is compensated using a reference FBG temperature sensor. The designed sensor can be used for liquid level, specific gravity, and static/dynamic low pressure measurement applications.

Keywords: Fiber Bragg grating, metal bellows, pressure, long period grating

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1. Introduction

Pressure measurement is a major and direct field of interest in many industries such as petrochemical, hydraulic, sanitary and pneumatic, power and energy, aerospace, biomedical, and down-hole oil and gas explorations [1−4]. For many years, conventional electro-mechanical sensors have been used for pressure measurement, but their full utilizations are limited in harsh environments due to electromagnetic interference (EMI), elevated temperatures, high corrosion, explosive domains, and cannot be used for multiplexing and distributed measurement [5]. In contrast, fiber Bragg grating (FBG)-based fiber optic sensors have significant advantages over conventional sensors such as the small size, lightweight, large dynamic range, immunity to EMI, high sensitivity and accuracy, ease to embed in civil structures, chemical inertness, and remote sensing capability. Moreover, the multiplexing property of FBG sensors makes them potential candidates for spatially distributed measurements [6−11]. However, the pressure sensitivity of a bare FBG (−0.022 pm/psi) is very low,

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which is to be greatly enhanced [12]. To enhance the pressure sensitivity, numerous techniques have been reported [13−17]. Even so, these techniques focused only on enhancement of pressure sensitivity, but did not address the sensor resolution, and the demodulation systems used for sensor interrogation were bulk in size, expensive and time consuming. Moreover, the temperature-cross sensitivity of the FBG sensor was not resolved. Various techniques have been reported for the discrimination of pressure and temperature, but they have relatively complex structure and need specific fiber gratings [18−22]. Hence, it is necessary to develop a pressure sensor with high sensitivity and resolution.

In the present study, an attempt has been made to design and develop a high sensitive FBG pressure sensor using the function of a metal bellows structure with the temperature compensation technique. It also presents a long period grating (LPG) based low-cost interrogation system which greatly enhances the sensor resolution.

2. Sensor design and working principle

2.1 Conceptual sensor design

A schematic design of the proposed FBG pressure sensor is shown in Fig. 1. It mainly consists of a metal bellows structure made of stainless steel (SS, 316L), a fiber Bragg grating, and two aluminium metal plates. The metal bellows structure

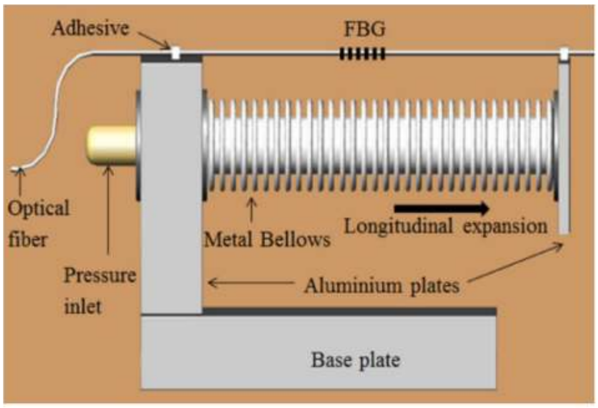


Fig. 1 Schematic structure of the FBG based pressure sensor using metal bellows.

having the length of 5 cm, wall thickness of 0.2 mm and the mean diameter of 11 mm is used as a mechanical transducing element which can effectively transfer the applied pressure to the FBG. The metal bellows is tightly bonded between two aluminium metal plates. A pressure inlet of 3 mm diameter is drilled at the center of one aluminium plate for allowing the pressure to be measured. An FBG written in a photosensitive single mode fiber with the reflectivity of about 99%, 3 dB band width of 0.2 nm, and resonance wavelength at 1541.16 nm is firmly glued between two end positions of the metal bellows structure as shown in Fig. 1. The metal bellows is an elastic element that can be compressed or expanded when the pressure is applied. Subject to pressure, the axial stress induces a longitudinal elongation, whereas the lateral stress results in a longitudinal compression, based on Poisson's principle. In the longitudinal direction, the metal bellows will be treated as a spring due to the special structure of small elastic constant compared with the large circumferential elastic modulus [23]. Therefore, in the longitudinal direction it obeys Hooke's law. In the proposed technique, the longitudinal expansion of the metal bellows caused by the pressure will induce an axial strain on the fiber which can be directly measured using the FBG.

2.2 Principle of operation

FBGs involve a periodic perturbation of refractive index in the core of an optical fiber, fabricated by an intense interference of the ultraviolet (UV) light beam [6]. When the FBG is illuminated with a broad band light, a specific narrowband wavelength called the Bragg wavelength gets reflected, and the other wavelengths get transmitted. The Bragg wavelength, λ_B, can be expressed as

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

where η_{eff} is the effective refractive index of the core guided mode, and Λ is the grating period. Even a minute change in strain or temperature varies the grating period and effective refractive index which results in a shift of the Bragg wavelength. A well-known expression for the shift of the Bragg wavelength that corresponds to a change in strain, ε, and temperature, ΔT, can be expressed as [7]

$$\Delta\lambda_B = \lambda_B\left[(1-P_e)\varepsilon + (\alpha_A + \xi_n)\Delta T\right]. \quad (2)$$

The first term in (2), represents the strain effect on the FBG, where $P_e = 0.5\eta_{\text{eff}}^2\left[P_{12} - \upsilon(P_{11}+P_{12})\right]$ is the effective strain-optic constant, P_{11} and P_{12} are the components of strain-optic constant, and υ is Poisson's ratio. The second term in (2), represents the temperature effect, where α_A and ξ_n are the thermal expansion coefficient and thermo-optic coefficient of the fiber. It is evident from (2) that the Bragg wavelength shift is linearly proportional to the change in strain and temperature. If there is no change in temperature, $\Delta T = 0$, and the wavelength shift of the FBG is considered only due to the change in axial strain, then (2) can be expressed as

$$\Delta\lambda_B = \lambda_B(1-P_e)\varepsilon. \quad (3)$$

Subject to pressure, the longitudinal strain, experienced by the metal bellows is given by [23]

$$\varepsilon = \frac{PA}{KL} \quad (4)$$

where P is the applied pressure, A, K, and L are the effective area, spring constant, and length of the metal bellows, respectively. By neglecting the effect of lateral stress due to the pressure on the metal bellows, the resultant equation using (3) and (4) can be arrived as

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-P_e)\frac{PA}{KL}. \quad (5)$$

It is evident from (5) that the fractional change in the Bragg wavelength has a linear relationship with the external pressure. Using the parameters of K = 197.864 N/mm, A = 116.839 mm^2, and L = 50 mm, (5) is theoretically evaluated using MATLAB software, which gives a pressure sensitivity of 97.9 pm/psi. Equation (5) is clearly explicit that for a fixed length of fiber, the sensitivity is mainly dependent on the elastic constant K of the metal bellows indicating that the smaller the spring constant is, the higher the sensitivity is.

2.3 An LPG-based interrogation scheme for FBG sensors

In general, the FBG based sensor employs an optical spectrum analyzer (OSA) for monitoring the Bragg wavelength, which makes the system bulk in size, expensive and limit scanning speed. Hence, it is essential to develop a compact, low-cost and high resolution demodulation or interrogation scheme for FBG based sensors to make them effective in real-time applications. Aiming to achieve in this direction, various interrogation techniques have been demonstrated [24−29]. One of the simple and easy techniques to interrogate the FBG sensor is based on the LPG which acts as an optical edge filter. The spectral loss of the LPG exhibits linear slope regions on either side of its peak attenuation wavelength, which can be used as optical edge filters for selected wavelengths of FBG sensors. The transmission spectrum of the LPG is shown in Fig. 2.

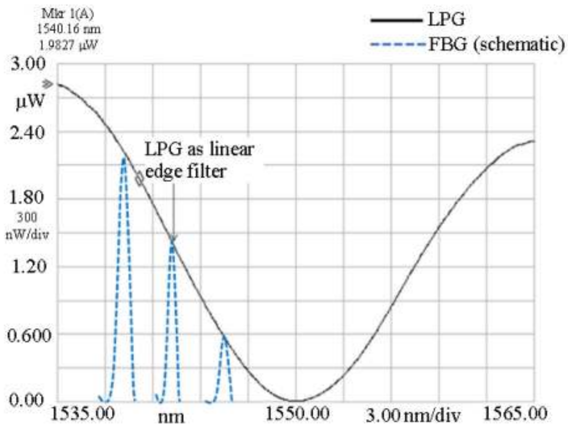


Fig. 2 Transmission spectrum of the LPG used in the interrogation of the FBG sensor.

The LPG interrogation scheme converts the wavelength information of the FBG into its equivalent intensity modulated signals which can easily be detected by a simple photodiode (DPIN-231). In the present study, an LPG having a linear region (falling edge) ranging between

1538 nm and 1547 nm, shown in Fig. 2 is used for the interrogation of the FBG pressure sensor. The reflected peak power of the FBG signal gets modulated according to the LPG transmitted power level at the falling edge filter region as shown in Fig. 2. Thus, the filtering mechanism of the LPG furnishes a linear relationship between the sensor output (intensity modulated signal) and the corresponding pressure.

3. Experiment

3.1 Experimental setup

The schematic of the experimental setup is illustrated in Fig. 3. It consists of a broadband amplified spontaneous emission (ASE) light source (BBS, 1525 nm – 1610 nm) which illuminates the FBG through an optical circulator. The FBG with the Bragg wavelength 1541.16 nm is used as the pressure sensing element. The reflected Bragg wavelength of the FBG is directed to the OSA through the optical circulator. A well-controlled compressor is used to pressurize the sensor head, and the varying pressure is monitored using a calibrated pressure gauge. Under pressure, the metal bellows tends to expand in the longitudinal direction causing an axial strain on the fiber which results in a shift of the Bragg wavelength of the FBG. Under laboratory conditions (20 ℃), the response of the Bragg wavelength as a function of applied pressure is monitored by using the OSA.

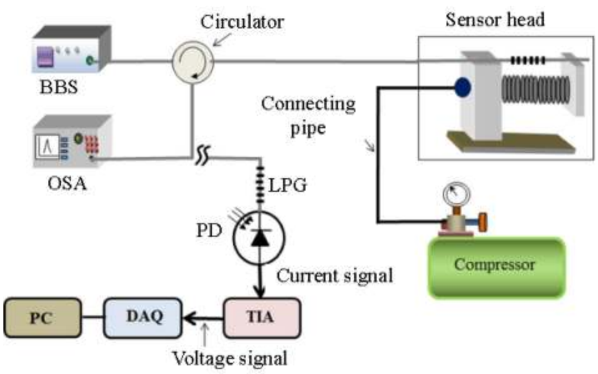


Fig. 3 Schematic of the experimental setup.

Further, the bulk and expensive measurement unit, OSA is replaced by the LPG based low-cost interrogation scheme. Figure 4 shows the photograph of the experimental setup used for the interrogation of the FBG pressure sensor. The output of the interrogation system that is pressure related wavelength-intensity modulated signal of the FBG sensor is captured by the photodiode (PD). Now the intensity modulated signal is converted into the voltage signal by using a transimpedance amplifier (TIA). This voltage signal is further acquired and processed by a data acquisition system (NI-DAQPad-6016) using LabVIEW software and is displayed in a personal computer (PC).

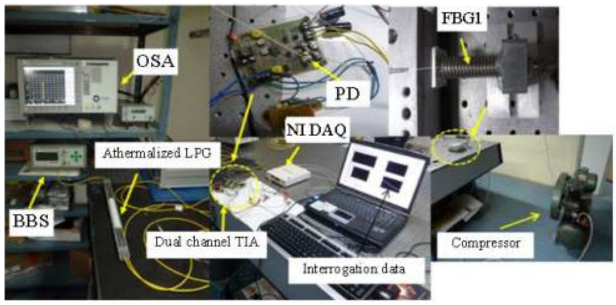


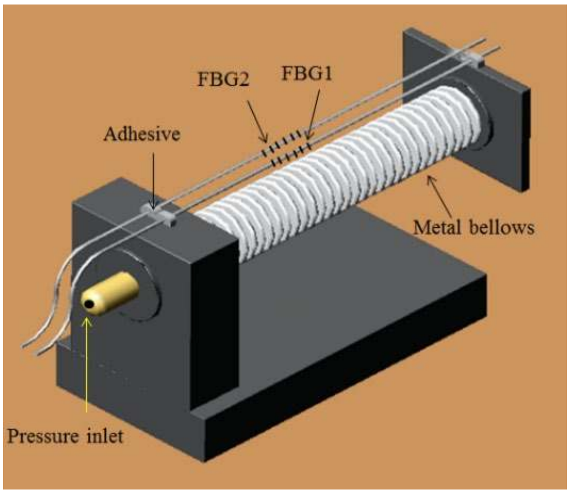
Fig. 4 Photograph of the experimental setup showing the interrogation of the FBG pressure sensor using the LPG.

3.2 Temperature-compensated pressure measurement

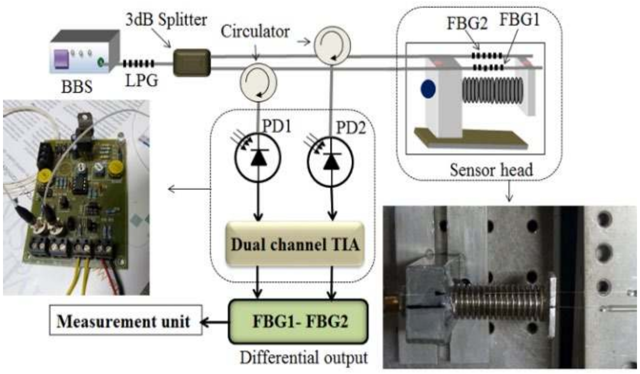
It is well known that inherently an FBG is sensitive to both pressure (strain) and temperature. Hence, the discrimination of pressure and temperature would be significant in practical applications where only one parameter is of interest.

In the present study, to compensate the temperature effect, a similar FBG with the Bragg wavelength 1541.1 nm is introduced as a reference FBG (FBG2) which is closely positioned to the sensing FBG (FBG1) as shown in Fig. 5(a). The FBG2 is glued only at one end of the metal bellows and is left freely at the other end to isolate from the applied pressure and enables to measure only the ambient temperature.

The schematic of the experimental setup for temperature-compensated pressure measurement is shown in Fig. 5(b). The broadband light which is modulated by the LPG is split into two light beams with equal intensity which illuminate both the FBGs through corresponding optical circulators. The temperature related intensity modulated signals corresponding to the Bragg signals of FBG1 and FBG2 are detected by PD1 and PD2, respectively. These intensity modulated signals are further converted into voltage signals by using a dual channel TIA shown in Fig. 5(b). Since the FBG positions are close to each other, it is assumed that the temperature impact is the same on both the FBGs. Therefore, the differential output FBG1-FBG2 of the sensor facilitates temperature compensated pressure measurement.



(a)



(b)

Fig. 5 Temperature-compensated pressure measurement scheme (a) Schematic of dual FBG sensor configuration and (b) schematic of the experimental setup.

4. Results and discussion

4.1 Wavelength response of FBG pressure sensor

To determine the pressure response of the sensor, the applied pressure is varied from 0 to 40 psi, in steps of 5 psi, and the corresponding Bragg wavelength of FBG1 is measured using the OSA. The experimental results are shown in Fig. 6. Within the range of pressure, the resonance wavelength of FBG1 is shifted from 1541.16 nm to 1544.73 nm. It is evident from the Fig. 6 that the Bragg wavelength of FBG1 is linear against the applied pressure with a linear coefficient of 0.9986. From experimental results, the pressure sensitivity of the sensor is found to be 90.6 pm/psi which agrees well with the calculated sensitivity of 97.9 pm/psi. The discrepancy between experimental and calculated results may be attributed from the fact that the change in the spring constant of the metal bellows under different pressures and the values of the parameters used in theoretical evaluation may not be 100% accurate. However, for a fixed length of fiber, the sensitivity and range of pressure can be altered by varying the structural parameters of the metal bellows.

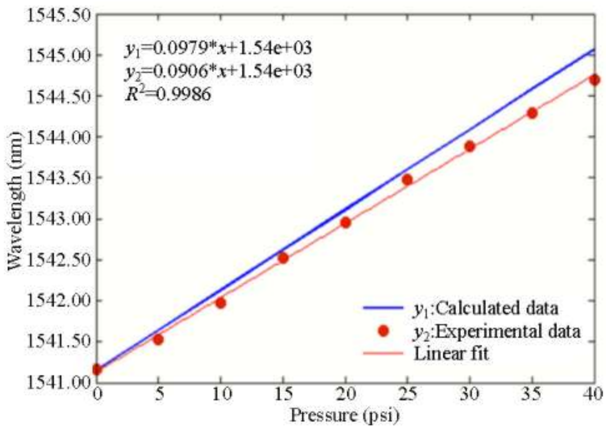
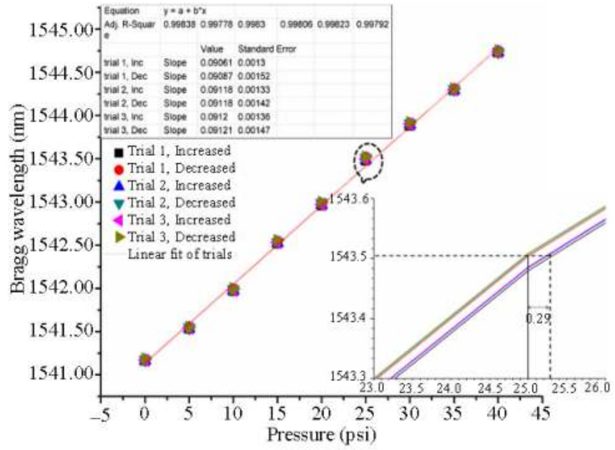


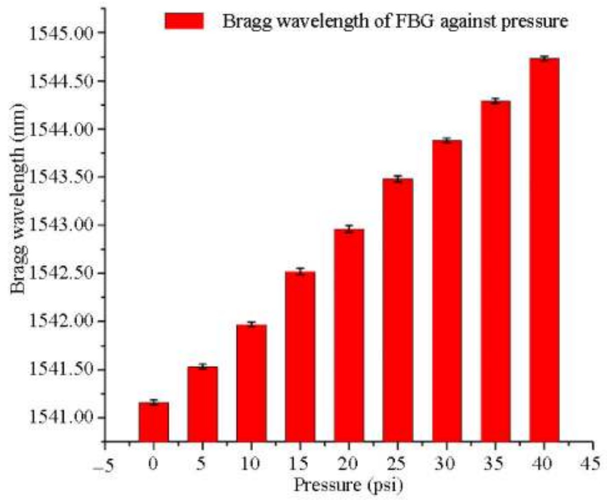
Fig. 6 Bragg wavelength of FBG1 versus applied pressure.

To test the repeatability of the sensor, the experiment is repeated thrice with the increased and decreased pressure. The test results are shown in Fig. 7(a). The sensor response is found to be consistent with a negligible hysteresis error of ±0.018 nm at 25 psi of pressure, which is approximately equal to ± 0.29 psi as shown in the subplot of Fig. 7(a).

Figure 7(b) shows the error bars plotted between the pressure and Bragg wavelength of the FBG sensor. The resolution of pressure measurement for the designed sensor is found to 0.662 psi which is limited by the low resolution of the OSA. Aiming to achieve an enhancement in sensor resolution, the LPG based interrogation system is implemented.



(a)



(b)

Fig. 7 Repeatability response of the FBG pressure sensor: (a) repeatability test results and (b) error bars of bar graph plotted between the FBG Bragg wavelength and pressure.

4.2 Interrogation results of pressure sensor

Figure 8 illustrates how the peak power of the reflected Bragg signal of FBG1 gets modulated by the LPG linear edge filter (shown in Fig. 2) with respect to the change in pressure. From Fig. 8, it is apparent that with an increased pressure the wavelength-intensity of the FBG1 signal is decreased being modulated by the LPG edge filter. Then the pressure related intensity modulated signal of FBG1 sensor is detected by the photodiode and is measured in voltage using the transimpedance amplifier circuit.

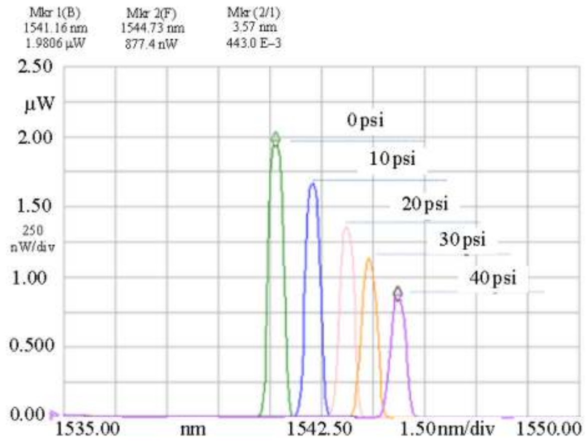


Fig. 8 Modulation in peak power of FBG1 by the LPG edge filter at different pressures values.

Figure 9 illustrates the change in the peak power of FBG1 reflected signal which is measured by the OSA and the corresponding intensity modulated signal that is detected by the PD with respect to the change in pressure. From Fig. 9, it can be observed that the variation in the peak power of FBG1 and its modulated intensity are found to be linear to the pressure change.

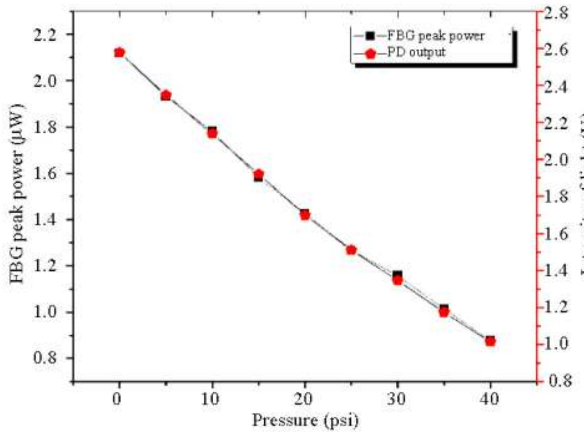


Fig. 9 Peak power of FBG1 Bragg signal and its modulated intensity signal that are measured by the OSA and PD, respectively.

Figure 10 shows the dynamic response of FBG1 sensor with respect to the continuous change in pressure, which is recorded by the data acquisition (NI-DAQPad-6016) system in time domain. Experimental results show that the change in intensity per unit pressure is –39.49 mV/psi, which is equivalent to a resolution of 0.025 psi. The achieved resolution of the sensor by utilizing the LPG based interrogation system is approximately 27 times higher than the resolution obtained by the OSA. The dynamic response of the sensor also confirms that the variation in sensor output (voltage) is 99% linear to the pressure change. Thus, the replacement of the OSA by the LPG-based interrogation system not only enhances the resolution but also enables the system to be compact and low-cost. However, the temperature dependence of the LPG may lead to a significant error in interrogation results of FBG sensors. To avoid this, an athermalization technique [30], reported in our previous study is used, which significantly reduces the temperature effect on the encapsulated LPG in comparison to a bare LPG.

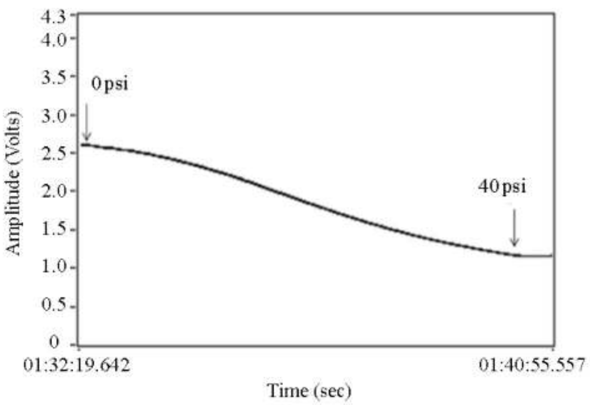


Fig. 10 Dynamic response of FBG (FBG1) pressure sensor.

4.3 Temperature-compensated pressure response of the sensor

At first, the ambient temperature effect on both the FBGs is studied. Further, the effect of temperature on the pressure sensor is investigated. To study the ambient temperature effect on both the FBGs, the sensor head is kept in a heating chamber, and the temperature is varied from room temperature (20 ℃) to 60 ℃ in steps of 5 ℃. Subject to temperature, the output intensity signals of FBG1 and FBG2 are detected by PD1 and PD2, respectively, and the corresponding voltage signals are measured. The temperature responses of FBG1, FBG2, and FBG1-FBG2 are plotted in Fig. 11. It is evident from Fig. 11 that the differential output of FBG1 and FBG2 is negligible to temperature change, indicating the same impact of temperature on both the FBGs.

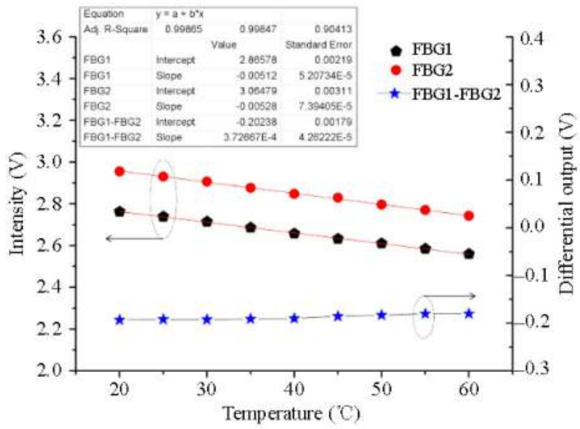


Fig. 11 Effect of ambient temperature on FBG1, FBG2, and FBG1-FBG2.

Figure 12 illustrates the changes in intensities of FBG1 and FBG2 reflected signals which are detected by the corresponding photodiodes, and the differential output of the FBGs against the applied pressure. From Fig. 12, it can be seen that there are two noticeable fluctuations incurred in data curves (pointed with black colored arrows) corresponding to FBG1 and FBG2, as a result of the sensors exposure to suddenly changed temperature (a sudden change in temperature is induced by an air-cooling system at the temperature of 3.6 ℃). But it is evident from Fig. 12 that the differential output of FBGs is independent of temperature fluctuation, indicating the validity of the proposed technique for temperature compensated pressure measurement. Also, the designed sensor can be used for simultaneous measurement of pressure and temperature.

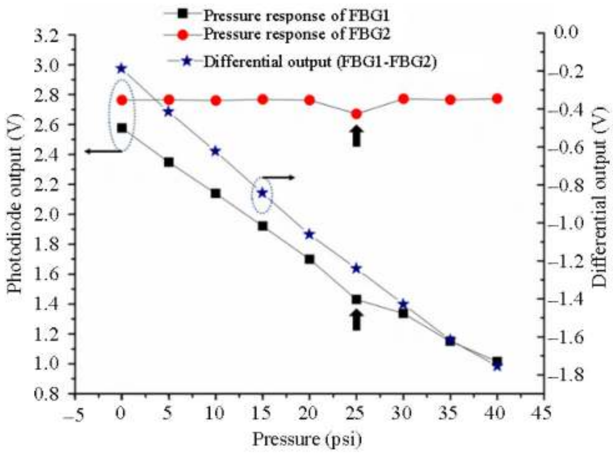


Fig. 12 Intensity variations of FBG1, FBG2 Bragg reflected signals and the differential output (FBG-FBG2) versus the applied pressure.

5. Conclusions

A simple and practicable technique for high sensitive pressure measurement using the FBG and metal bellows is proposed and experimentally demonstrated. The achieved pressure sensitivity of the sensor is about 4000 times as that of a bare FBG. An LPG based interrogation scheme is successfully implemented to the FBG pressure sensor, which enables the system to be compact, inexpensive, and enhances the resolution of up to 0.025 psi. The experimental results agree well with the predicted results and show the good linearity and repeatability. Of having all the merits of fiber optics, the designed sensor has the advantage of simple structure, low cost, and free from ambient temperature within a low temperature range (20 ℃ – 60 ℃).

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