FBG based novel sensor design for low vacuum measurement with high sensitivity

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ABSTRACT

This article demonstrates use of a fiber Bragg grating (FBG) sensor for in situ monitoring of vacuum process with high sensitivity. The sensor head consists of a commercial syringe barrel with plunger, metal spring, pressure chamber, FBG and safeguarding outer tube. The sensor is configured by firmly fixing the FBG between the plunger and the rigid support provided to the safeguarding tube. Under vacuum process the metal spring facilitates the FBG to get strained in axial direction which results in shift of Bragg wavelength of FBG. The Bragg wavelength shift of FBG is found to be linear with respect to vacuum pressure with a linear coefficient of 0.9988. Pressure sensitivity of the sensor is found to be 27 pm/cm Hg. The sensor design is simple, low-cost and has the advantage of all fiber optic sensors.

Keywords: Fiber Bragg grating, Vacuum pressure, sensitivity

1. INTRODUCTION

Measurement of low vacuum has been found potential applications in chemical and metallurgical processes such as distillation, drying, degassing, cleaning, melting, sintering, casting, heat treatment and food processing. The conventional gauges frequently used for vacuum measurement are differentiated as mechanical gauges, liquid filled gauges, thermal conductivity gauges and ionization gauges [1,2]. However, these methods are suffered by the low resolution and sensitivity, and have been limited in harsh environments due to electromagnetic interference (EMI) and corrosion. In contrast to the conventional methods, FBG sensors have distinguished advantages such as small size, lightweight, immune to EMI, high sensitivity, self-referencing, resistivity to high temperatures, chemically inert, insensitive to light source fluctuations and connection losses, capable of multiplexing with various fiber optic networks, flexibility of incorporating number of FBGs in a single fiber which is enable spatially distributed and/or multi-parameter measurements [3,4]. Hence, FBGs have been widely implemented as sensors for monitoring strain, temperature, pressure, liquid level, salinity, voltage, and health monitoring of civil structures and wind turbines [5-10]. As reported in the literature, since 1990's much research has been done on FBG-based high pressure measurement [11-15], but the area of low pressure (vacuum) measurement remains relatively unexplored [16]. And it is currently a topic that has attracted considerable interest from the sensor community because of its applications in important fields such as Pharmaceuticals, chemical and metallurgical, pneumatics and many more.

In this study we describe the design and development of an FBG based sensor acts as low vacuum gauge. The variation in vacuum is measured by means of Bragg wavelength shift of FBG. The structural design and working principle of the sensor head are detailed. Experimental results are compared with the theoretical results.

2. SENSOR DESIGN AND PRINCIPLE

2.1 Principle of FBG sensor

FBG is characterized by a periodic perturbation in refractive index of the core of an optical fiber. When FBG is illuminated with a broad band light, a specific narrowband wavelength called Bragg wavelength which satisfies the Bragg condition gets reflected and the other wavelengths get transmitted. The Bragg wavelength of FBG is given by [4]

$$\lambda_B = 2\eta_{eff}\Lambda \quad (1)$$

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where η_{eff} is effective refractive index of the fiber grating and Λ is grating period. Even a minute change in strain or temperature which vary the grating period and effective index of refraction will cause a shift in Bragg wavelength of FBG. A well-known expression for shift of Bragg wavelength corresponding to the axial strain, ε and temperature change, ΔT is given by [5]

$$\Delta\lambda_B = \lambda_B\left[(1-P_e)\varepsilon + (\alpha_\Lambda + \xi_n)\Delta T\right] \tag{2}$$

The first term in equation (2) represents the strain effect on the FBG. Where $\rho_e = 0.5\eta_{eff}^2\left[\rho_{12} - \upsilon(\rho_{11} + \rho_{12})\right]$ is the effective strain-optic constant, ρ_{11} and ρ_{12} are the components of strain-optic tensor and υ is the poison's ratio. The second term in equation (2) represents temperature effect. Where α_Λ and ξ_n are thermal expansion coefficient and thermo-optic coefficient of the fiber, respectively. In the present study the experiment is conducted under laboratory conditions (air conditioned room at 21ºC), hence the issue of temperature cross sensitivity is neglected. The vacuum process is monitored by measuring the Bragg wavelength shift of FBG caused by the strain induced on the fixed fiber. Therefore, the Bragg wavelength shift of FBG corresponding to the axial strain applied at constant temperature, $\Delta T = 0$ can be expressed as

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

It is apparent from equation (3) that the Bragg wavelength shift of FBG is proportional to the axial strain applied.

2.2 Conceptual sensor design

The schematic structure of the sensor head is shown in figure 1. It mainly consists of a commercial syringe barrel with plunger, a metal spring made of mild steel, a glass jar as evacuation chamber (pressure chamber), a FBG as sensing element and a safeguarding outer tube. The FBG of resonance wavelength at 1551.53 is glued between the plunger and a fixed support (fixture) provided to the safe guarding outer tube using cyanoacrylate adhesive as shown in figure 1. A calibrated vacuum pump that can produce the vacuum ranging from 0 to 76 cm Hg is used to evacuate the pressure chamber. The metal spring is fixed between plunger and orifice of the syringe barrel which is connected to evacuation chamber shown in figure 1. The metal spring prevents the fixed fiber from reaching its maximum strain limit during the evacuation process. The sensor head including FBG and syringe barrel is encapsulated by an outer tube made of acrylic glass enable the FBG to be operated safely from unwanted ambient conditions, easy handling in real time applications and maintains constant reference pressure surrounding to the FBG.

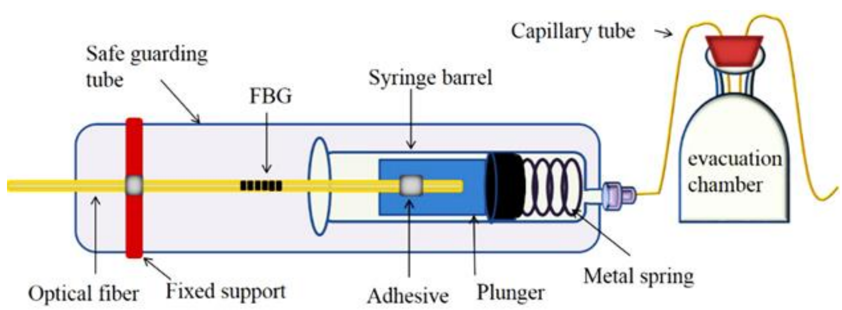

Figure 1. Schematic design of the sensor head

2.3 Sensor working principle

According to Hook's law, the force F exerted on a spring is proportional to the displacement Δx , which is given by [17]

$$F = -K\Delta x \tag{4}$$

where K is the spring constant of the metal spring. Therefore the applied pressure can be expressed as

$$P=\frac{F}{A}=-\frac{K\Delta x}{A} \tag{5}$$

During the evacuation process the compressed metal spring causes the fixed fiber to be elongated in axial direction which results in shift of the Bragg wavelength of FBG. So it can be assumed that the change in length of the fiber $\Delta L=-\Delta x$. Therefore the longitudinal strain, ε corresponding to the applied pressure P can be expressed as

$$\varepsilon=\frac{\Delta L}{L}=-\frac{\Delta x}{L}=\frac{PA}{KL} \tag{6}$$

where A and L are the effective area of the spring and fixed length of the fiber, respectively. Thus, from (3) and (6) fractional change in Bragg wavelength which corresponds to applied pressure can be expressed as

$$\Delta\lambda_B=\lambda_B(1-\rho_e)\frac{PA}{KL} \tag{7}$$

It is evident from equation (7) that the shift in Bragg wavelength of FBG has linear relationship with the applied pressure. Theoretical evaluation of the sensor using equation (7) has given the pressure sensitivity of 29.6 pm/cm Hg.

3. EXPERIMENT

Schematic of experimental setup is shown in figure 2. Light from a broadband source (BBS, 1525-1565 nm) illuminates the FBG through port 2 of the optical circulator. The Bragg wavelength reflected from the FBG is directed to the optical spectrum analyzer (OSA) through port 3 of the optical circulator. To determine the sensor response against applied vacuum the chamber is evacuated from 0 (Zero referenced against atmospheric pressure) to 66 cm Hg in steps of 2 cm Hg, and the corresponding shift in Bragg wavelength of FBG is measured by the OSA.

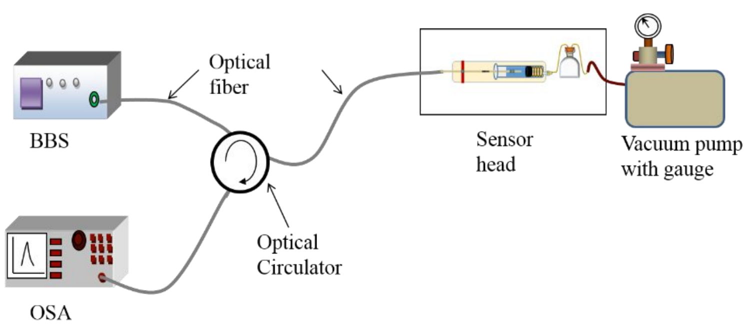

Figure 2. Schematic of experimental setup

4. RESULTS AND DISCUSSIONS

The Bragg wavelength shift of FBG corresponding to the vacuum change is plotted in figure 3. Within the range of applied vacuum (0-66 cm Hg) the resonance wavelength of FBG is shifted from 1551.53 nm to 1553.29 nm. It is apparent from the figure 3 that the shift of Bragg wavelength has a linear relationship with the vacuum change with a linear coefficient of 0.9988. The experimental results show that the vacuum sensitivity of the sensor is found to be 27 pm/cm Hg, which is approximately 6400 times as that of a bare FBG, and is well agreed with the theoretical sensitivity of 29.6 pm/cm Hg. The discrepancy between theoretical and experimental results may be attributed from the fact that the lack of knowledge of the accurate values of spring constant and analytical parameters of the optical fiber used in theoretical evaluation of the sensor.

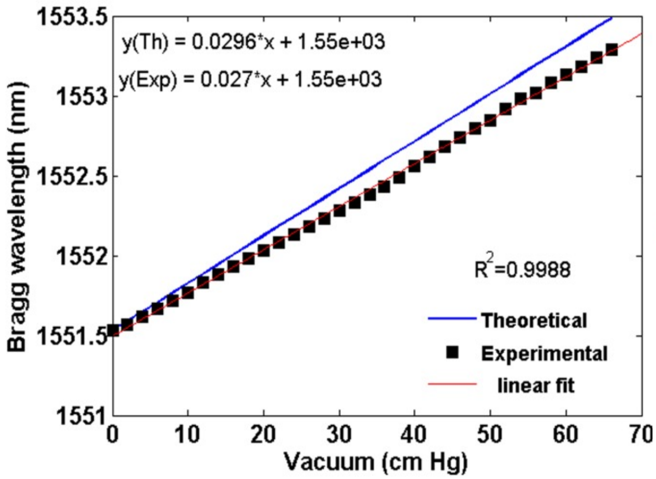

Figure 3.Correlation between experimental and theoretical results.

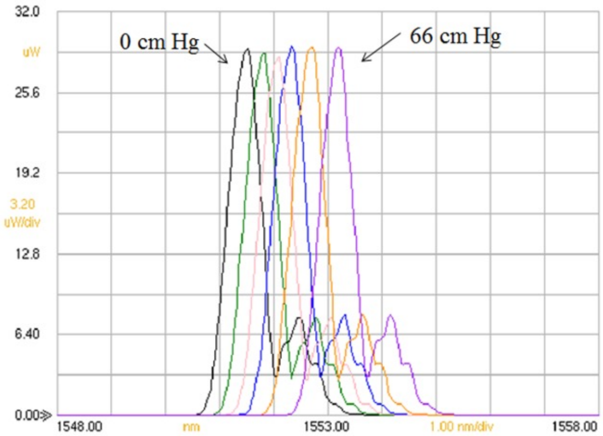

Figure 4.Modulation in FBG spectrum against applied vacuum at 0, 12, 24, 36, 48 and 66 cm Hg, respectively.

Figure 4 shows the modulation in FBG spectrum corresponding to the change in vacuum. The sensitivity and the range of vacuum can be modulated for a fixed length of fiber by changing the structural parameters of metal spring. The resolution of the designed sensor is found to be 0.37 cm Hg, which is limited by the low resolution of OSA. The resolution of the sensor can be enhanced by using a high resolution demodulation or interrogation system [18-20]. The designed FBG based vacuum gauge has the advantage of simple configuration, easy to implement in real time applications and has the advantage of fiber optics. The prominent feature of the sensor is that an extrinsic measurement of the vacuum which avoids the sensor to be incorporated into the region of vacuum to be measured. The proposed sensor has potential to measure the vacuum in chemical and gas plants, pharmaceutical industries.

5. CONCLUSIONS

An FBG based sensor capable of measuring low vacuum pressure ranging from 0 to 66 cm Hg with high sensitivity is designed and demonstrated successfully. This simple and novel technique offers an alternative to conventional method for real time monitoring of evacuation process. The future work is focused to enhance the accuracy, sensitivity and stability of the proposed FBG sensor for high vacuum applications.

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