High-sensitivity pressure sensor based on fiber Bragg grating and metal bellows

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ABSTRACT

An optical fiber pressure sensor based on fiber Bragg grating (FBG) and metal bellows is presented in this paper. Due to the lower spring rate of metal bellows, the sensitivity is improved to 48pm/kPa. The relationship between Bragg wavelength and the applied pressure is derived. Experimental data indicates that there is good linear relation between the Bragg wavelength shift and the applied pressure. This sensor can be utilized in low pressure measurement.

Keyword: Fiber Bragg grating, pressure sensor, metal bellows.

1 INTRODUCTION

Pressure measurement is an essential technology in many industrial applications such as liquid level monitoring in oil storage tank[1], down-hole pressure measurement[2], gas turbine engine[3] and other fields. The available measurement technology is challenged due to the harsh and flammable environment.

Fiber Bragg grating has attracted interest for use as sensor especially under flammable and harsh environment. Compared to the conventional electronic sensors, fiber-optic sensors are known for their immunity to electromagnetic interference, electrical passivity, high resolution, high accuracy and do not pose a spark source hazard for flammable environment application. In this paper, a low pressure sensor is focused. In contrast to the high pressure sensor, the low pressure sensor needs high sensitivity. Due to low sensitivity to pressure of FBG, a wavelength shift of 0.22nm at 70MPa hydraulic pressure [4] which corresponds to a pressure sensitivity of the fractional change in the Bragg wavelength of -1.98×10^{-6} /MPa. Many techniques have been developed to improve the sensitivity of pressure sensor. The sensitivity can be increased to -2.12×10^{-5} /MPa by using a glass-bubble housing for the FBG [5].Liu et al. proposed coating the FBG with a polymer to increase the sensitivity by -6.28×10^{-5} /MPa[6]. Zhang et al. proposed a pressure sensor, which is based on the use of a FBG embedded in a polymer-filled metal cylinder with an opening on one side to enhance the pressure sensitivity -3.41×10^{-3} /MPa. [7]. In this paper, a novel pressure sensor structure based on FBG and metal bellows is proposed. The sensitivity can reach -0.031 /MPa .

2 FIBER BRAGG GRATING TECHNOLOGY FOR SENSING APPLICATION

2.1 FBG principle

The FBG is a permanent periodic modulation of the core refractive index along a given length of optical fiber. Fig.1 shows the schematic structure of the FBG. Owing to the coupling between the forward and backward propagating optical modes, the specific narrowband wavelength light will be reflected if incident with a broadband light. The reflection wavelength is called Bragg wavelength and the Bragg wavelength of this resonance condition in the FBG λ_B can be expressed as [8]

$$\lambda_B = 2n_{eff}\Lambda \qquad (1)$$

Fiber Optic Sensors and Applications VI, edited by Eric Udd, Henry H. Du, Anbo Wang, Proc. of SPIE Vol. 7316, 73160H

Where n_{eff} denotes the effective index of refraction of the optical fiber core and Λ is the period of the refractive index modulation. As can be seen by Eq.(1), except that the definite Bragg wavelength is reflected by one FBG, the other wavelength light are transmitted through the FBG and are incident on to the next FBGs. It is shown in Fig.2. Therefore, it is easier to obtain multipoint sensing at one single optical fiber by connecting multiple FBGs in series, and each of them has a different Bragg wavelength. That means FBG has the multiplexing capability.

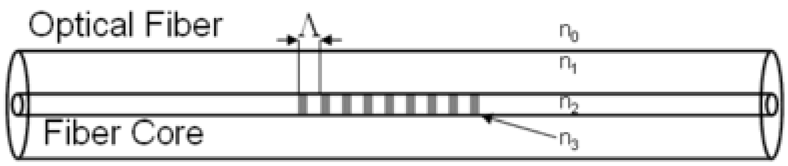

Fig.1 schematic structure of FBG

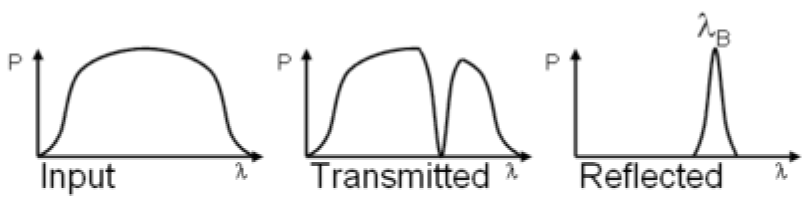

Fig.2 the spectrum response of FBG

2.2 FBG sensing principle

2.2.1 Strain sensitivity of FBG

The sensing function of FBG derives from the sensitivity of both the refractive index and grating period to externally applied mechanical or thermal perturbation [9]. The shift in the Bragg wavelength due to strain is given by

$$\frac{\Delta\lambda_B}{\lambda_B} = \frac{\Delta(n_{eff}\Lambda)}{n_{eff}\Lambda} = \frac{\Delta n_{eff}}{n_{eff}} + \frac{\Delta\Lambda}{\Lambda} \qquad (2)$$

This corresponds to a change in the grating period and the strain-optic induced change in the refractive index. The above stain effect can be simplified to

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

Where P_e is an effective strain-optic constant expressed by

$$P_e = \frac{n_{eff}^2}{2}[p_{12} - \upsilon(p_{11} + p_{12})] \qquad (4)$$

P_{11} and P_{12} are components of the strain-optic tensor, and υ is the Poisson's ratio. For a typical germanosilicate optical fiber P_{11}=0.113, P_{12}=0.252, υ =0.16, and n_{eff} =1.482. Substituting these parameters into the above equations, the expected strain sensitivity at 1.55μm is 1.2pm/micro-stain.

2.2.2 Temperature sensitivity of FBG

The shift in the Bragg wavelength due to temperature changes is given by

$$\frac{\Delta\lambda_B}{\lambda_B}=\frac{\Delta(n_{eff}\Lambda)}{n_{eff}\Lambda}=(\frac{1}{\Lambda}\frac{d\Lambda}{dT}+\frac{1}{n_{eff}}\frac{dn_{eff}}{dT})\Delta T=(\alpha+\beta)\Delta T \qquad (5)$$

Where $\alpha=\frac{1}{\Lambda}\frac{d\Lambda}{dT}$ is the thermal expansion coefficient for the optical fiber, approximately equal to 0.55×10^{-6} for silica optical fiber. the parameter $\beta=\frac{1}{n_{eff}}\frac{dn_{eff}}{dT}$ denotes the thermo-optic constant, which is approximately equal to 8.6×10^{-6} for the Germania-doped silica optical fiber. It can be seen from the above values, the refractive index change is the dominant effect. Substituting the above parameters into the Eq.(5), the anticipated temperature sensitivity of FBG at 1.55μm is 14.2pm/^{0}C.

2.3 Improvement on strain and temperature sensitivity of FBG

From the above discussion, it can be seen the strain and temperature sensitivity of bare FBG is low. To improve temperature sensitivity of FBG, the basic principle is to bond the FBG with the host material which has larger thermal expansion coefficient. To improve strain sensitivity of FBG, the principal principle is to bond the FBG with the host material which has the lower elastic modulus. Therefore, under the same mechanical perturbation, FBG experiences larger strain. Fig. 3 shows a simple bonding method.

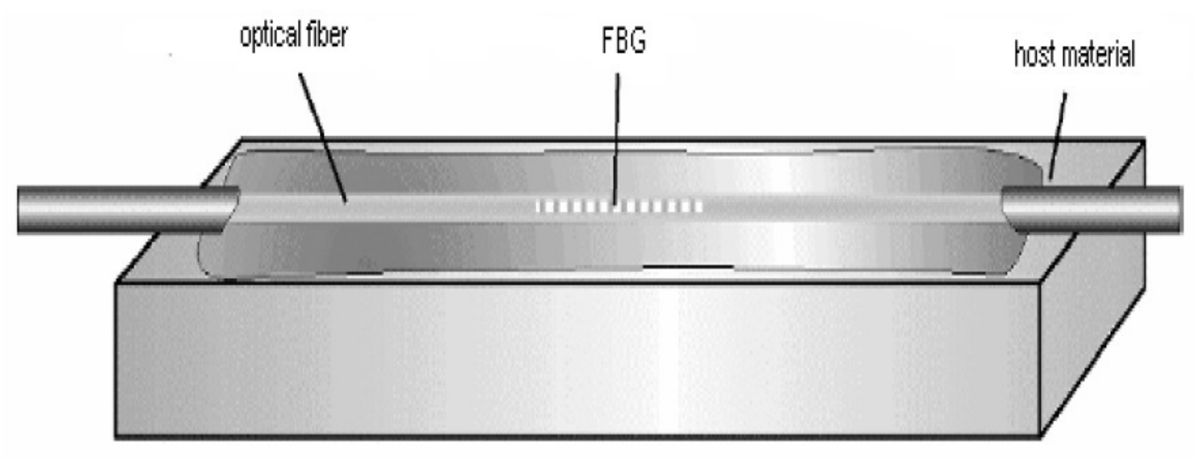

Fig.3 Bonding FBG with host material

2.4 Cross sensitivity of temperature and strain

From the analysis, it indicates that both changes in temperature and strain can induce the changes in the Bragg wavelength. In order to discern them, a lot of methods have been proposed [10-19]. However, the most common approach is to use another reference FBG being in thermal contact with strain FBG, but it is shield from the external strain. This reference FBG is only sensitive to the temperature, and from the Bragg wavelength shift of this FBG, the temperature change can be derived. Subtracting the wavelength shift induced by the temperature change from the total wavelength shift recorded by the strain FBG. The pure Bragg wavelength shift due to the strain can be known.

3 SENSOR STRUCTURE AND PRINCIPLE OF OPERATION

Fig.4 shows the schematic diagram of the proposed metal bellows-based FBG pressure sensor. Fig.5 is the cross section diagram of the FBG pressure sensor. The two aluminum cylinders with a small hole on the center were bonded tightly to the ends of the metal bellows by using epoxy. The neck of metal bellows had an inner diameter of 15.9 mm. The cylinder had inner diameter of 15 mm smaller than that of metal bellows to fit in the metal bellows and the length of the cylinder is to fit the neck length of the metal bellows. The hole had an inner diameter of 1.5 mm to allow the FBG to stay inside. A FBG was placed into the metal bellows from the two holes on the side of the aluminum cylinder. Firstly epoxy was used to bond the one end of FBG to the hole, after this end cured, pretension was applied when the other end of FBG was bonded to the aluminum cylinder. Subject to the external pressure, according to the mechanics principle, the axial stress due to pressure will induce the longitudinal compression, the transverse stress due to pressure will induce the longitudinal elongation based on the Poisson effect. Because of the small spring rate of longitudinal direction compared with the large elastic modulus of transverse direction, the compression effect is greater than that of the elongation. Therefore, the FBG will be compressed under the external pressure. It is necessary to apply the pre-strain on the FBG. The detail analysis is as followed.

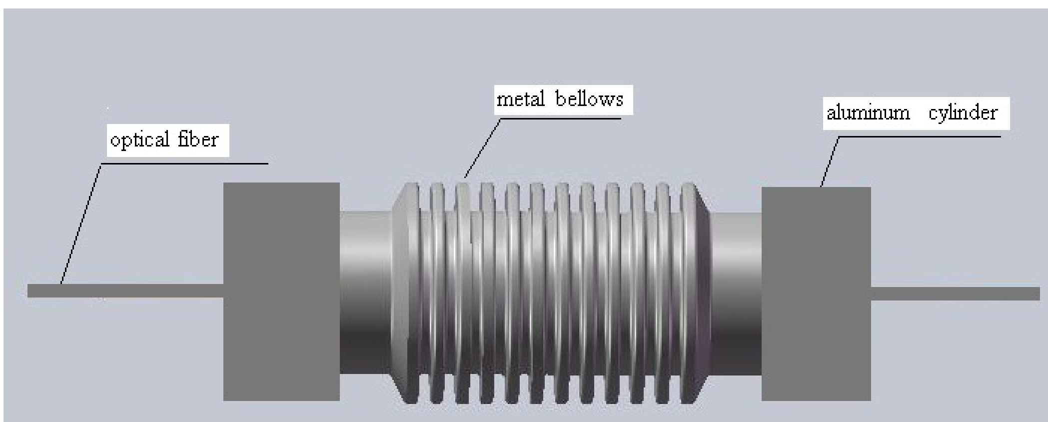

Fig.4 structure of the FBG pressure sensor based on the metal bellows

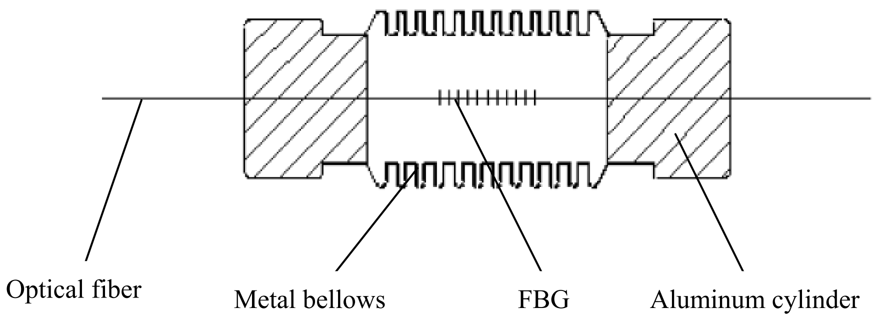

Fig.5 cross section diagram of the FBG pressure sensor based on the metal bellows

It is well known that the relative shift of the Bragg wavelength of FBG $\frac{\Delta\lambda_B}{\lambda_B}$ in response to axial strain ε_z applied to the grating is given by[20]

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\varepsilon_z \tag{6}$$

For metal bellows in the longitudinal direction, it was treated as spring due to the special structure of small spring rate compared with the large circumferential elastic modulus [21]. Accordingly in the longitudinal direction it obeys the Hooke's law. Under pressure the longitudinal strain ε_{z1} is given by

$$\varepsilon_{z1} = -\frac{PA}{KL} \tag{7}$$

Where P is the applied pressure, A , K , L is the effective area, elastic constant and length of metal bellows , respectively. With the longitudinal strain contribution of transverse effect neglected, Eq.(6) becomes,

$$\frac{\Delta\lambda_B}{\lambda_B} = -(1 - P_e)\frac{PA}{KL} \tag{8}$$

From the Eq. (8), it indicates that the relative Bragg wavelength shift of the FBG has a linear relationship with the applied pressure. Based on the parameters of K =47.75N/mm, A = 201mm^2, L = 42mm, a theoretical pressure sensitivity of 78.1pm/kPa was expected. Eq.(8) shows that the sensitivity is dependent on the value of elastic constant. The smaller elastic constant is, the better sensitivity is. In this paper, the elastic constant is 29 times bigger than that of Ref.[22], but the sensitivity is better than that. That is due to the novel structure in this paper which means the pressure is directly applied on the sensing element of the metal bellows, unlike the structure in Ref.[22] consisting of the metal bellows and uniform strength beam which limits the sensor's sensitivity to the pressure due to the large Young's modulus of the uniform strength beam.

4 EXPERIMENT AND DISCUSSION

4.1Experiment on FBG pressure sensor

The setup used to test the characteristic of FBG pressure sensor is shown in Fig.6 FBG pressure sensor was put in a chamber. The pressure in chamber is applied by pumping air into chamber by a pressure pump. A pressure calibrator shows how much the pressure in chamber is, the accuracy of calibrator is 0.1% of reading and the resolution is 70pa. The Bragg wavelength of the FBG was monitored with an optical spectrum analyzer. The experimental result is shown in Fig. 7. From this figure, it can be seen that the Bragg wavelength shift of FBG sensor is a linear function with the applied pressure. The pressure sensitivity is found to be 48pm/kpa, which corresponds to the fractional sensitivity of 0.031/MPa because of the center wavelength of FBG λ_B equal to 1549.736nm. The measured pressure sensitivity is smaller than the theoretical value mainly due to the change in spring rate of metal bellows under different load, cylinder boundary and bonding performance.

Due to the good performance of the metal bellows made from Titanium, the hysteresis is not apparent. From our repeated experiment, the sensor can not exactly go back to the original point, but the gradient is pretty same which means the change of the Bragg wavelength corresponding to the change of the pressure is approximately same. As regards the long-term reliability of the sensor, it depends on the performance of the metal bellows. It will degrade due to multiple uses. Furthermore it is well known that the change of temperature will also induce the Bragg wavelength shift of the FBG, to compensate for this effect, the other reference FBG temperature sensor being in thermal contact with the pressure sensor can be employed, but shielded from strain changes. In Ref.[23], the shielded methods were proposed.

4.2 Broadband light source design

In this experiment, we designed the ASE source as broadband light source. The design shown in Fig.8 utilizes the backward traveling amplified spontaneously emission light which is also called the counter-propagating which means the pump and signal light have opposite propagating direction. Optical oscillator is utilized at the end of the signal output to allow the light traveling in one direction and prevent the multiple reflection and laser oscillation. Based on the same reason, the end of the erbium fiber needs to be terminated by cutting the angle. Through the experiment result, the optimum erbium-doped fiber length of 15m is chosen. The spectrum of the ASE is shown in Fig.9.

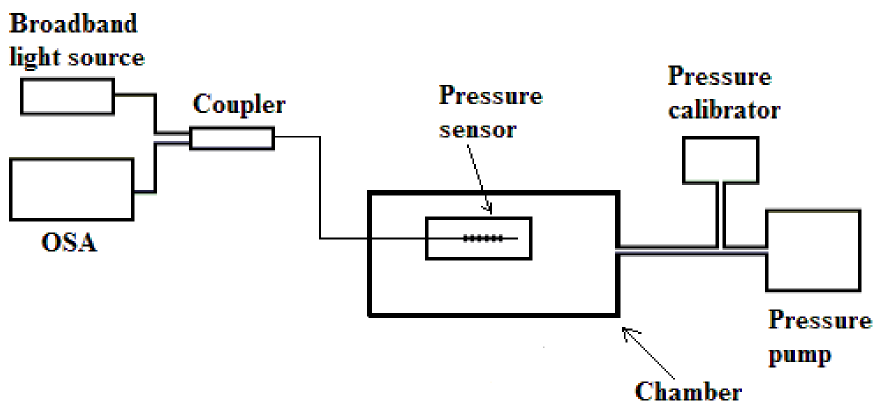

Fig.6 setup for FBG pressure sensor test

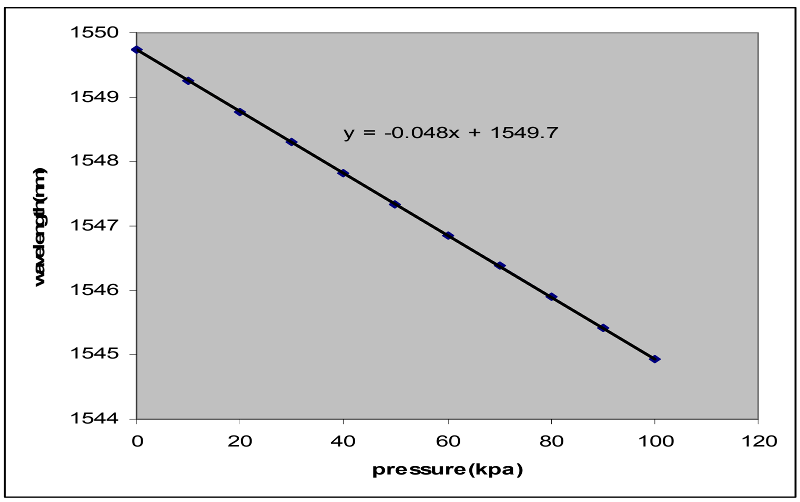

Fig. 7. Measured Bragg wavelength in response to the applied pressure

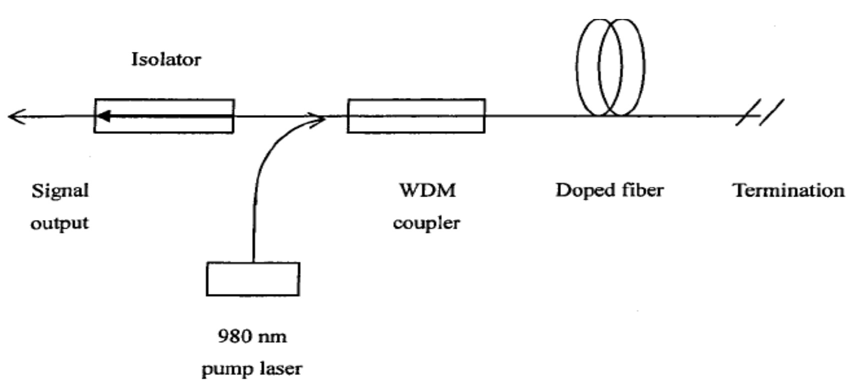

Fig.8 Schematic of ASE

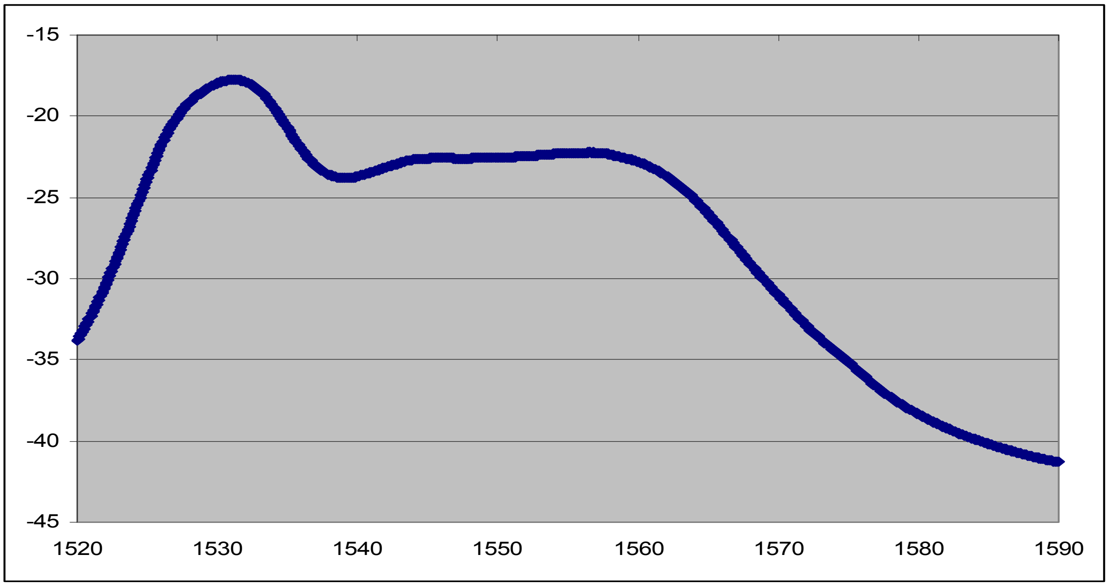

Fig.9 spectrum of ASE

5 CONCLUSION

A metal bellows based FBG pressure sensor with high sensitivity is proposed. The sensitivity enhancement is achieved due to the lower spring rate of the metal bellows. The pressure sensor can be utilized in the low pressure measurement of hydraulic pressure, oil tank liquid level, air pressure and other applications.

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