High sensitivity fiber-optic pressure sensor based on equilibrium structure

Wenhua Wang (王文华)[1,2*] and Xinsheng Jiang (姜心声)[3]
[1] *School of Science, Guangdong Ocean University, Zhanjiang* 524088, *China*
[2] *School of Physics and Optoelectronic Engineering, Dalian University of Technology, Dalian* 116024, *China*
[3] *Fujian Castech Crystals Inc., Fuzhou* 350002, *China*
* *Corresponding author: mrwangwh@yahoo.com.cn*

Abstract A novel high sensitivity diaphragm-based extrinsic Fabry-Pérot (FP) interferometric fiber-optic pressure sensor with back-pressure equilibrium structure is present. The sensor possesses backpressure-independence and small temperature-dependence. The ultra-thin fused silica is bonded to the end surface of the double holes fused silica ferrule by use of CO_2 laser, and the double holes structure enhances the sensor performance. The operating point does not drift. The sensor with sensitivity of 9.51 nm/kPa (65.57 nm/psi) has been achieved.

OCIS codes 060.2370, 120.2230, 280.4788
doi: 10.3788/CJL201239.s105005

1 Instroduction

Pressure measurement is very important in the variety of fields such as health care, aerospace industries, water level, down-hole monitoring, and fuel storage tank, etc. A number of pressure sensors based on semiconductor, electrical and optical techniques have been developed. The semiconductor and electrical sensors have been widely used, but they have a few primal drawbacks such as conductivity, lower maximum operating temperature, sensitivity to temperature changes, corrosion, electromagnetic disturbance, and so on. The interferometric fiber-optic pressure sensors have drawn great attention due to the advantages of intrinsic electrical passivity, high temperature survivability, corrosion resistance, immune to electromagnetic interference, high sensitivity, high resolution, allowing remote and distributed measurement, and compact size[1,2]. Over the past decades, a variety of fiber-optic pressure sensors have been investigated. These include elasto-optical effect sensors[3], fiber grating sensors[4-6], and Fabry-Pérot (FP) fiber-optic sensors[6-9], etc. Here in to, the precision of the interference-based fiber-optic sensors is the highest, and their potential applications are considerable extensive. The diaphragm-based extrinsic Fabry-Pérot interferometric (DEFPI) fiber-optic sensor is the typical case of the interference-based fiber-optic sensors, and becomes the research focus in the pressure measurement. The diaphragm-based configurations are more suitable for pressure measurements requiring high sensitivity[10,11]. However, either DEFPI fiber-optic sensor head usually covers several materials or the sensor head involves several elements for obtaining higher sensitivity or reducing temperature dependence. Therefore, the mismatch in coefficient of thermal expansion (CTE) among materials will induce undesirable stress, resulting in pressing each other. The stress will degrade the performance of fiber-optic sensors, and even cause failure of sensors. Also, even if the fiber-optic sensor configuration is made up of a kind of material, the current common bonding adhesive of epoxy will influence on the performance of sensors, and decompose at high temperature, and cause a large temperature dependence due to the bonding adhesive having a different CTE from the sensor materials. In addition, the thermal expansion of air trapped by FP cavity will induce the undesirable pressure applied on the inner diaphragm surface when environment temperature up, increasing the sensor temperature dependence. And, the background pressure with slow fluctuations will cause the operating point of DEFPI sensor to shift. As to such small size sensor, laser heating fusion bonding is inconvenient. To meet different application requirements, the CO_2 laser heating fusion bonding technology for fabricating DEFPI sensor had been developed in the past few years, and the fabrication technology improved sensor′s performance. But, they included usually several elements/steps for obtaining better performance, or were fabricated in vacuum-sealed system, so the process of fabrication is relatively complicated[12].

In this letter, a novel high sensitivity DEFPI fiber-optic pressure sensor based on a double through holes fused silica ferrule with horn-shape cup is present. The double holes configuration will provide small temperature dependence as a result of eliminating the pressure induced by the trapped air thermal expansion, and maintain the operating point not to vary with background pressure change. The sensor head is fabricated by means of heating fusion bonding technique. The ultra-thin fused silica diaphragm is directly welded onto the horn end face of the ferrule by CO_2 laser, which avoids the problem of thermal expansion mismatch among different materials. These sensors have high sensitivity and low temperature dependence, and the sensors with different sensitivity can be obtained by varying the thickness of diaphragm or the inner diameter of horn-shape cup, making them suitable for pressure measurement in different application fields. Moreover, compared with the fabrication technology previously researched, this fabrication process in laser heating fusion bonding is simple, clean, environment-friendly, and cost-effective.

2　Essential principle of operation

The structure of the DEFPI fiber-optic pressure sensor is shown in Fig. 1. The optical fiber tip surface and the inner surface of the diaphragm form the FP cavity (air gap), and its length will reduce because of the applied pressure resulting in the diaphragm to deflect. Light is injected into the lead-in optical fiber and partially (about 4%) reflected by the fiber-optic tip surface and the inside surface of the diaphragm respectively. The beam reflected by the diaphragm couples into the lead-in optical fiber, then propagates back along the lead-in fiber and generates interference fringes with the beam reflected by the fiber tip surface, which will be for the demodulation of the FP cavity length.

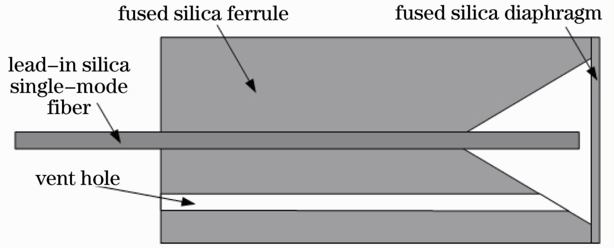

Fig. 1. Configuration of DEFPI pressure sensor

Since light is partially, about 4%, reflected by the fiber-optic tip surface and the inside surface of the diaphragm, the FP cavity is a low finesse FP interferometer. The interference optical intensity can be expressed by

$$I = 2RI_0\left(1 - \cos\frac{4\pi L}{\lambda}\right), \tag{1}$$

where I_0 is the incident optical intensity, and R is the reflectivity of the fiber tip and the diaphragm inner surfaces, and λ is the light wavelength, and L is the FP cavity length. The diaphragm will deflect under the applied pressure P, causing the FP cavity length to change. The interference intensity will sinusoidally vary with the FP cavity length change. Also, the sensor should operate in a linear scope of interference fringe, which avoids fringe direction ambiguity.

3　Sensor design and fabrication

For a clamped rigidly round diaphragm of the sensor, it will deform under the applied pressure P, as shown in Fig. 2. The out-of-plane deformation Y is a function of the pressure difference, the ferrule inner radius r, and the diaphragm thickness h etc. Y is given by[13]

$$Y = \frac{3(1-\mu^2)P}{16Eh^3}(a^2 - r^2)^2, \tag{2}$$

where μ and E are the Poisson's ratio and Young's modulus of diaphragm material respectively, a is the effective radius of the diaphragm (inner radius of the fused silica ferrule horn-shape cup), r is the radial distance to the diaphragm center, and h is the diaphragm thickness.

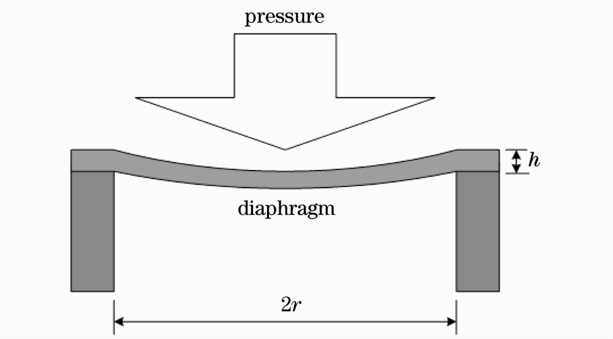

Fig. 2. Deflection of a diaphragm under applied pressure

For a round DEFPI sensor, we define the ratio between the deflection and the pressure difference as the pressure sensitivity S. Assume the optical fiber is fixed to the center hole of silica ferrule, S at normal temperature is given by

$$S = 2.4943 \times 10^{-6} \cdot \frac{r^4}{h^3}, \tag{3}$$

where the r and h are in microns.

In our case, the sensor parameter is designed such that a is 0.5-mm-wide, and h is 25-μm-thickness. According to the Eq. (3), the diaphragm sensitivity is 9.98 nm/kPa (1.45 nm/psi) in pressure measurement.

For conventional hermetic sensors, the undesirable pressure generated by the trapped air thermal expansion is a serious issue in practical applications, especially in high temperature surroundings. In this letter, we used a fused silica ferrule with double through holes (both 127-μm-diameter) and with a horn-shape cup. One of them (side hole) is vent hole for providing the sensor temperature stability because it eliminates the trapped air thermal expansion when environmental temperature varies, and balances the pressure inside and outside the FP cavity. As a result, the sensor with background pressure equilibrium structure can eliminate backpressure shift issue, which is the major problem encountered by most of DEFPI sensor. In addition, because the two through holes is parallel with each other, and the vent hole connects to the environment via the packaged stainless steel tube, the environmental pressure energy applied on diaphragm does not diffract into the FP cavity via the vent hole. So the sensitivity to the environmental pressure does not entirely decrease due to the vent hole. In the Ref.[14], the very small acoustic energy diffracts into the FP cavity through the vent hole, even through its influence on sensor is negligible.

A 25-μm-thickness ultra-thin fused silica diaphragm was directly welded onto the horn end face of the double through holes ferrule with 1.8-mm outside diameter and 7-mm length, whose material is also fused silica, by CO_2 laser heating fusion bonding technique as shown in Fig. 3. The 1.5-mm-deep horn-shape cup with 1-mm inside-diameter is formed in the process of the silica ferrule preparation. If the diaphragm thickness is 25 μm and the ferrule horn-shape cup inside diameter changes from 1.0 to 1.5 mm, the sensor can be designed for a wide range of pressure measurements with 50.51 nm/kPa (348.01 nm/psi) of sensitivity. The diaphragm was locally and quickly heated at the edge with laser heating fusion bonding technique, so its surface nearby the center was not influenced, even when coated with a gold or other metal film (central region 1-mm in diameter). A lead-in silica single-mode fiber (SMF) was cleaved and inserted in the central hole of the double holes ferrule, forming an FP cavity between optical fiber tip surface and the inside surface of the diaphragm. Since the ferrule wall is too much thick (about 0.9 mm), the lead-in fiber is bonded with the ferrule by epoxy. Such above steps, the sensor head with 7-mm length and 1.8-mm outside-diameter is achieved. The FP cavity in horn-shape cup makes the circular diaphragm to deflect with environment pressure variation. Figure 4 shows the interference spectrum of FP cavity in the fabrication process; the micrograph of laser bonding diaphragm with ferrule, the bare sensor and the packaged one are shown in Fig. 5. For the packaged structure, we used the 316 stainless steel to protect the bare sensor, and meanwhile the tail fiber of sensor was protected with 316 stainless steel tube.

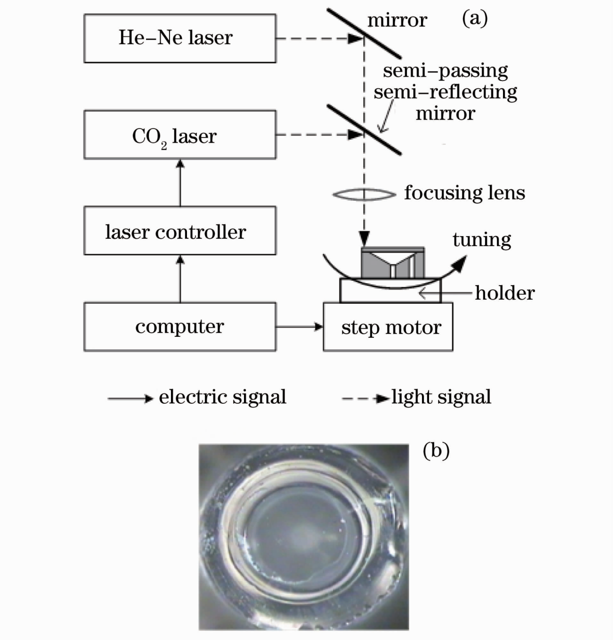

Fig.3. (a) Illustration of CO_2 laser heating fusion bonding system and (b) top view of bonding diaphragm with ferrule

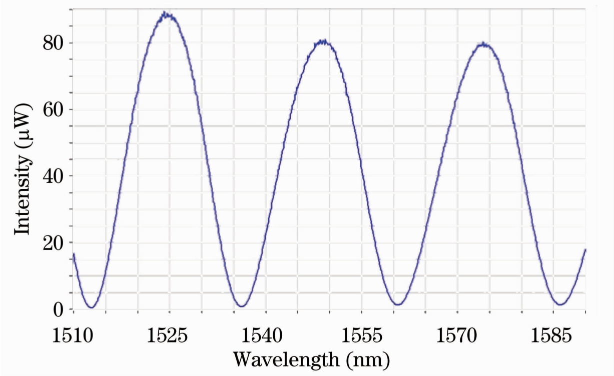

Fig.4. Interference spectrum of DEFPI sensor

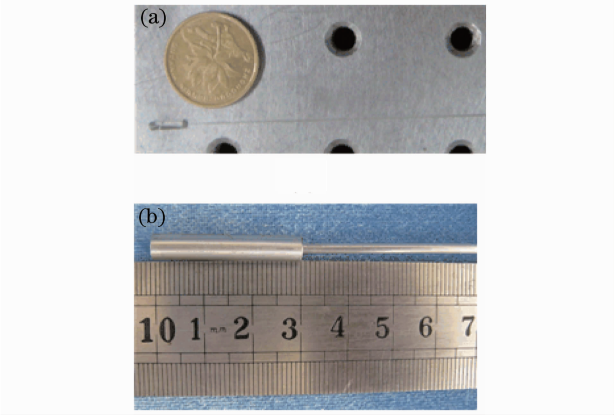

Fig.5. (a) Bare pressure sensor; (b) packaged pressure sensor

4 Experimental results and discussion

Experimental setup of static pressure test is shown in Fig. 6. The optical light from Optical Sensing Analyzer Si720 (Micron Optics) propagated to the FP cavity through a 3-dB SMF coupler, and its interference signal was routed back through the same coupler to the detector built in the Si720. The sensor head was submerged in the water and the applied pressure on diaphragm is proportional to water level, which can be calculated by measuring the depth of the sensor head submerged in the water. The FP cavity length varied with water level.

A cross-correlation signal processing method with 0.2-nm resolution was used to process the interference signal for demodulating the FP cavity length. The pressure response of the DEFPI sensor present in our case is shown in Fig.7. The FP cavity length change versus the applied pressure from 0 to 3 kPa (0.44 psi) is 29.04 nm. The sensor pressure sensitivity is 9.51 nm/kPa (65.57 nm/psi), and the pressure resolution of our system based on the cross-correlation signal processing

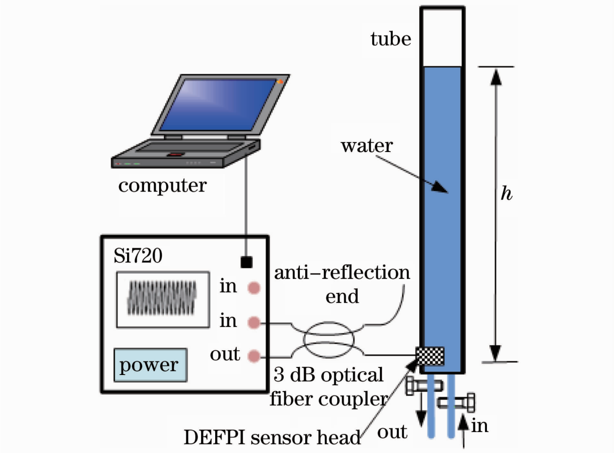

Fig. 6. Experimental setup of static pressure test

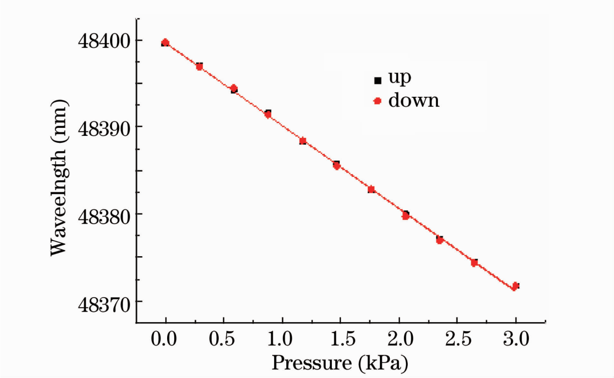

Fig. 7. Pressure response characteristics of sensor from 0 to 3 kPa

method is about 21 Pa (0.003 psi). In order to investigate the temperature dependence of the sensor, a temperature test should be performed. The temperature was increased from room temperature to 80 ℃ and decreased to room temperature. The dependence between the temperature and FP cavity length is shown in Fig. 8, which indicates the temperature dependence is about 0.92 nm/℃. The thermal induced pressure measurement error is about 0.096 kPa/℃ (0.014 psi/℃), and the temperature dependence is about one over fifty-five times than that of the epoxy bonding methods, 50 nm/℃ [15]. Obviously, the designed optical fiber sensor in our scheme reduces significantly the temperature dependence and the pressure measurement error, but the residual temperature dependence and pressure measurement error are still relatively large. It makes the fiber-optic FP sensor to be employed in the condition of the relative small temperature change range. We may carry out two approaches to decrease/eliminate the influence of the temperature dependence, guaranteeing the sensor to be applied in the large-range temperature change fields. First, improving the laser heating fusion bonding technique reduces further the temperature dependence. Second, we may also employ temperature self-compensation of sensor head structure to eliminate pressure measurement error caused by temperature dependence. In addition, because the ferrule have the side vent hole eliminating the influence of the background pressure and the trapped air thermal expansion, the sensor can excellently run with no need to adjust the operating point in our case.

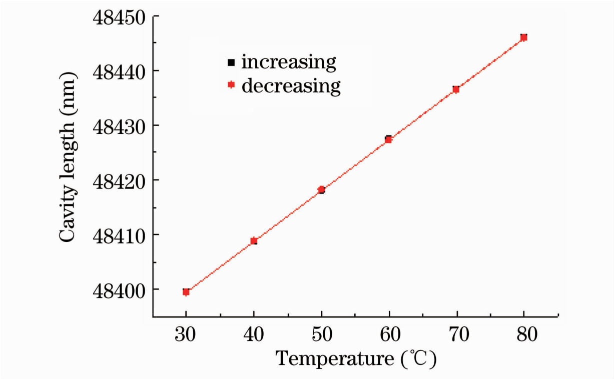

Fig. 8. Temperature-dependence of sensor from room temperature to 80 ℃ at atmospheric pressure

5 Conclusions

In conclusion, a novel high sensitivity DEFPI fiber-optic pressure sensor with small temperature dependence and with backpressure-independence has been developed. We realize the welding between the ultra-thin fused silica diaphragm and the horn end face of the ferrule by use of CO_2 laser, and the fabrication process is simple, clean, environment-friendly, and thus reducing the system cost; the proposed double holes fused silica DEFPI configuration enhances the sensor performance. The operating point of sensor does not drift without Q-point control, and the sensor with sensitivity of 9.51 nm/kPa (65.57 nm/psi), resolution of 21 Pa (0.003 psi), and pressure measurement error of 0.096 kPa/℃ (0.014 psi/℃) induced by the temperature dependence is achieved. Further work will study the dynamic pressure measurement and much low temperature dependence of the sensor. To reduce/eliminate the temperature dependence and the pressure measurement error, the improvement of the laser heating fusion bonding technique and temperature self-compensation scheme are under the way.

6 Acknowledgements

This work was support by the Project for Industrial Research Program in Science and Technology of Zhanjiang, Guangdong Province, China under Grant NO. 2011C3108005.

References

1 J. Sirkis, T. A. Berkoff, R. T. Jones, H. Singh, A. D. Kersey, E. J. Friebele, and M. A. Putnam, J. Lightwave Technol. **13**, 1256 (1995).
2 K. A. Murphy, M. F. Gunther, A. Wang, and R. O. Claus, Proc. SPIE **2192**, 282 (1994).

3 N. Hiroyuki, W. Yu, O. Masashi, and S. Takashi, Opt. Engng. **47**, 044402 (2008).

4 J. Dai, M. Yang, X. Li, H. Liu, and X. Tong, Opt. Fiber Technol. **17**, 210 (2010).

5 X. Shu, L. Zhang, and I. Bennion, J. Lightwave Technol. **20**, 255 (2002).

6 A. D. Kersey, Opt. Fiber Technol. **2**, 291 (1996).

7 B. Yu, A. Wang, G. Pickrell, and J. Xu, Opt. Lett. **30**, 1452 (2005).

8 W. Wang, Q. Yu, Q. Wang, and X. Zhou, Proc. SPIE **7544**, 75446U (2010).

9 J. Yi, E. Lally, A. Wang, and Y. Xu, IEEE Photon. Technol. Lett. **23**, 9 (2011).

10 J. S. Sirkis, Top. Appl. Phys. **77**, 233 (2000).

11 M. I. Belovlov, M. M. Bubnov, and S. L. Semjonov, in *Proceedings of Lasers Electro-Optics Europe* 192 (1996).

12 J. Xu, G. R. Pickrell, X. Wang, B. Yu, K. L. Cooper, and A. Wang, Proc. SPIE **5998**, 599809 (2005).

13 M. D. Giovanni, *Flat and Corrugated Diaphragm Design Handbook* (New York: Mercel Dekker, 1982).

14 M. Han, X. Wang, J. Xu, K. L. Cooper, and A. Wang, Opt. Engineer. **44**, 060506 (2005).

15 J. Deng, Development of Novel Optical Fiber Interferometric Sensors with High Sensitivity for Acoustic Emission Detection, Ph D. Thesis (Virginia Tech, 2004).