©Freund Publishing House Ltd., International Journal of Nonlinear Sciences & Numerical Simulation 11(3): 225-229, 2010

An MEMS Optical Fiber Pressure Sensor Based on a Square Silicon Diaphragm: Numerical Simulation and Experimental Verification

Xue-jin Li[a,b], Cheng-jun Qiu[c], Yuan-long Deng[b], Wei Qu[c], Jun-nan He[a]

[a] *College of Physics Science and Technology, Shenzhen University, Shenzhen 518060, China*
[b] *Shenzhen Key Lab of Sensors Technology, Shenzhen 518060, China*
[c] *College of Electronic Engineering, Heilongjiang University, Harbin 150080, China*
Email: lixuejin@szu.edu.cn

Abstract

A simple MEMS optical fiber pressure sensor with the Fabry–Perot interferometer configuration is constructed that is based on a square silicon diaphragm and the intensity demodulation technology. A large area ratio of the moving mirror to the stationary one is employed to minimize the non-planarity of the deflection, and a reference light generated by a 2×2 optical fiber coupler is used to reduce the errors that are produced by the intensity variations of the light source. The theoretical analysis, simulation and experimental results all show that the pressure sensor has reasonable sensitivity, stability and measurement range. With a low cost and simple fabrication process, this sensor has great potentials for mass production and commercialization.

Keywords: Optical fiber sensor, MEMS, Fabry–Perot interferometry, intensity demodulation, square diaphragm.

1. Introduction

Optical fiber pressure sensors are better than their conventional electrical counterparts in many ways, especially when they are combined with the MEMS technology. Pressure sensors are, for example, more adaptable to harsh environments, more resistant to electromagnetic interference, smaller in size, and more capable of multiplexing and potential applications to distributed measurements. Many kinds of optical fiber pressure sensors have been reported recently that are based on the Fabry–Perot interferometry [1-6]. In general, an F-P micro-cavity is formed between an optical fiber end and the inside surface of a silicon diaphragm, the two being separated by an air gap. This kind of sensors was first demodulated by detecting the changes in the reflected interference light intensity [4] and the Fourier-transform based phase demodulation method [1,6] and dual-wavelength interrogation method [3] are usually employed to reduce the effects of the fluctuations of the light source on the experiments and to obtain a wider measurement range and better linearity and sensitivity. The application of these two methods, however, requires the purchase of some expensive devices as well as the use some complicated technologies. Wang et al has experimented with mesa-diaphragms for this kind of sensor systems [1] to reduce the non-planarity of the deflection and the signal averaging effect, but the silicon diaphragms are extremely difficult to fabricate and hence cannot be massed produced and commercialized.

In this paper, we design and fabricate an MEMS optical fiber pressure sensor by using a simple intensity demodulation technology that uses a monochromatic light source and two ordinary photodetectors. To achieve better consistency, a square silicon diaphragm is used instead of the more common circular diaphragm. A large area ratio of the moving an enhanced linearity, sensitivity and stability for this sensor. The measurement range is expected to reach several Mega Pascal by suitably adjusting the size of the silicon diaphragm.

2. Theoretical analysis

The configuration of the sensor is shown in Figure 1. A commercial communication multi-mode optical fiber of diameter 62.5μm is used and the F–P cavity is formed between the inside surface of the silicon diaphragm and the fiber end face. The diaphragm serves as a moving mirror for the F-P interferometer and the fiber end face serves as the stationary reflecting mirror. Both mirrors are uncoated and light is incident into the sensor through the optical fiber where one part will be directly reflected by the fiber end face and the other part will enter the F-P cavity to be reflected by the air-silicon interface. Loaded pressure will introduce a deflection of the silicon diaphragm thus producing an optical path difference between the two backward-travelling lights which will then interfere with each other, producing a pressure variation that is dependent on the intensity of the reflected lights.

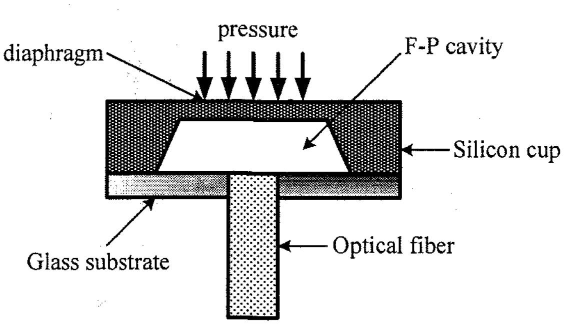


Fig. 1: Configuration of the sensor

The diaphragm surface is modeled as a square thin membrane with four clamped edges (see Figure 2) whose deflection, when the loaded pressure is assumed to be uniform and the maximum deflection small compared to the membrane's thickness, is approximately described by

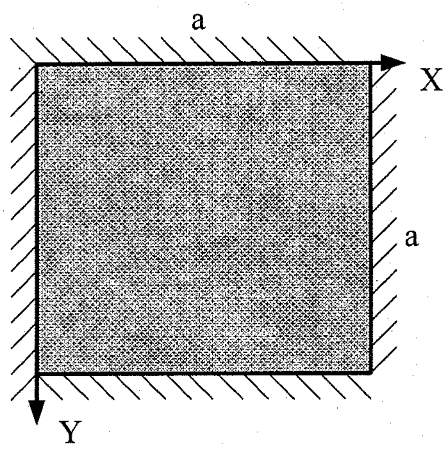


Fig. 2: Mechanical model of square diaphragm

$$\omega_{x,y} = \frac{16q}{\pi^6 D} \sum_{m=1,3,5,\ldots}^{\infty} \sum_{n=1,3,5,\ldots}^{\infty} \frac{\sin\frac{m\pi x}{a} \sin\frac{n\pi y}{a}}{mn\left(\frac{m^2}{a^2}+\frac{n^2}{a^2}\right)^2}, \tag{1}$$

where a is the side-length of the square diaphragm, h is the thickness, q is the loaded pressure, D is the flexural rigidity given by

$$D = \frac{Eh^3}{12(1-\mu^2)}, \tag{2}$$

where E is Young's modulus and μ is Poisson's ratio [7]. The deflection of the diaphragm is then calculated by considering the first 25 terms of equation (1), (i.e. m = 1,3,5,7,9; n = 1,3,5,7,9) and the results are shown in Figure 3.

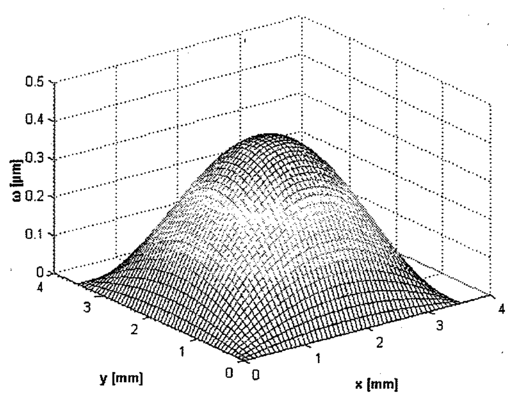


Fig. 3: Deflection of the square diaphragm

(a = 3.5mm, h = 162μm, q = 40KPa, E = 160GPa, μ = 0.22, ωmax = 0.409μm)

The maximum deflection

$$\omega_{\max} = 0.00406 \frac{qa^4}{D}, \quad (3)$$

occurs at the center of the diaphragm (as predicted by [7]) and is proportional to the uniform pressure when $\omega_{\max}$ is small compared to the thickness h. It follows from equations (2) and (3) that the sensitivity is

$$S = \frac{0.04872a^4(1-\mu^2)}{Eh^3}, \quad (4)$$

which is directly proportional to a^4 and inversely proportional to h^3. The sensitivity can therefore be increased by increasing the side-length and decreasing the thickness of the diaphragm. The measurement range, however, will be reduced.

The deflection at intermediate positions along the X-axis is shown in Figure 4 and for a 62.5μm diameter multimode optical fiber, it suffices to consider the deflection in the range of x from x = 1.72μm to 1.78μm. The experimental results yield a deflection range from 409.2nm to 409.4nm which corresponds to a variation of $\Delta\omega_{\max} \approx 0.2nm$ and the parallelism error of the F-P mirrors, which is given by

$$\delta = \frac{\Delta\omega_{\max}}{\omega_{mean}} \approx 0.05\%, \quad (5)$$

is relatively small.

Figure 5 illustrates the F-P cavity manufacturing process using MEMS technology and Figure 6 shows a computer simulation model and picture of the silicon cups.

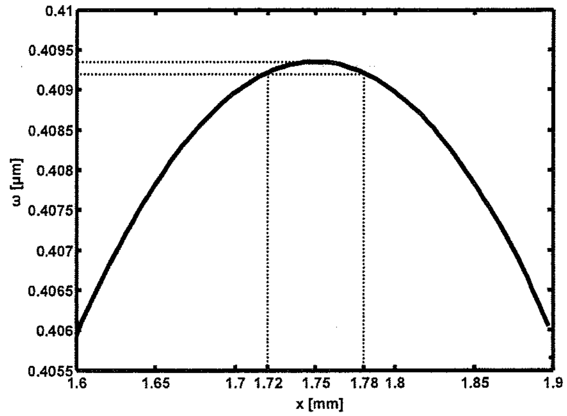


Fig. 4: Non-planarity of the deflection at intermediate positions

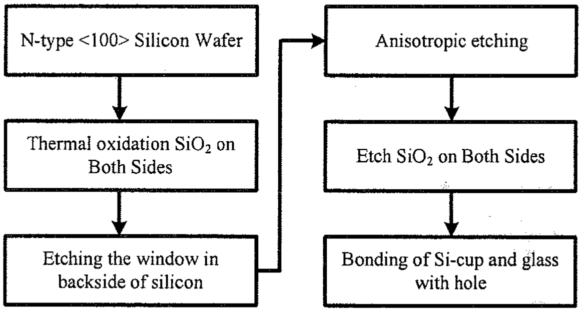
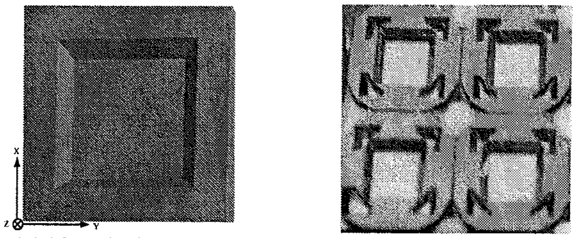


Fig. 5: The F-P cavity manufacturing process



(a)Simulation model (b) Silicon cups

Fig.6: Simulation and photograph of silicon cups

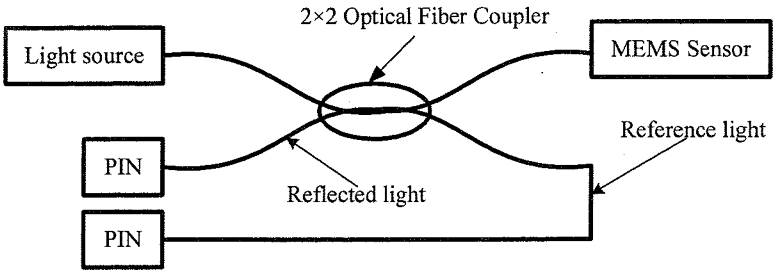


Fig. 7: Experimental set-up of the pressure sensor measurement range as a result of decreased sensitivity.

3. Experimental results and discussion

Figure 7 illustrates the sensing system, where the configuration of the MEMS sensor is as shown in Figure 1. The side-length of the square diaphragm is 3.5mm and its thickness h is 162μm. The light source used is an ordinary commercial light with wavelength 1550nm and the incident light is divided into two parts by a 2×2 optical fiber coupler. One part of the incident light enters the MEMS sensor to produce a measurement signal and the other part is directed into a PIN photodetector to produce a reference signal that is used to eliminate the errors arising from the intensity variations of the light source. The relationship between the normalized reflectivity and loaded pressure can therefore be computed by comparing the measured and reference signals, as shown Figure 8 which shows a sinusoidal relation between the two with period 76KPa.

Even though the measurement range is limited to 38KPa by equation (3), the maximum deflection of the diaphragm is required not to exceed λ/4, i.e. $\omega_{\max} \leq 387.5nm$ for a single-value measurement to be obtained. There is thus a mismatch between the reflectivity of the fiber end and the inside surface of the silicon cup when they are not coated which leads to unsatisfactory interference modulation. This mismatch is obvious from Figure 8, which shows a less than 10% variation in the normalized reflectivity over the whole measurement range as a result of decreased sensitivity.

The maximum reflectance can be made to occur at zero-loaded pressure by suitably adjusting the original depth of the F-P cavity and Figure 9 shows some original experimental results where the normalized reflectivity is plotted as a function of pressure. A fitting line for this set of data is $R = -0.0027 \times q + 1.0062$, with a nonlinearity of about 3.6% and a sensitivity (i.e. change in normalized reflectivity/loaded pressure) of 0.27%/KPa. The stability of the sensor has clearly been greatly enhanced in Figure 9.

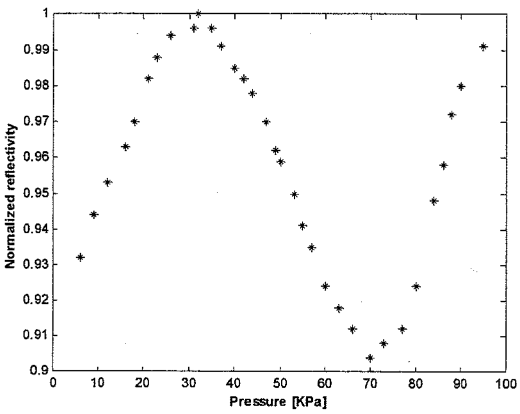


Fig. 8: Measured data for normalized reflectivity

It is also clear from Figure 4 and Equation (5) that the measurement range could be improved by suitably choosing the length and thickness of the silicon diaphragm. If the length of the square diaphragm is reduced to 1mm and the loaded pressure increased to 4MPa, for instance, the deflection at intermediate positions will be as shown in Figure 10. As the mirrors have a non-planarity of only about 0.5%, the requirements of F-P interferometry are still satisfied and single-value measurements are obtained because the maximum deflection is far less than λ/4.

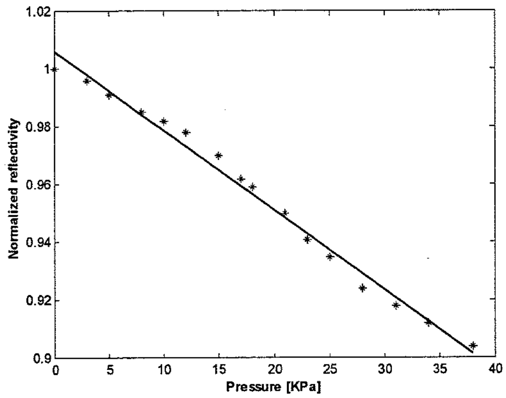


Fig. 9: Experimental results and fitting line

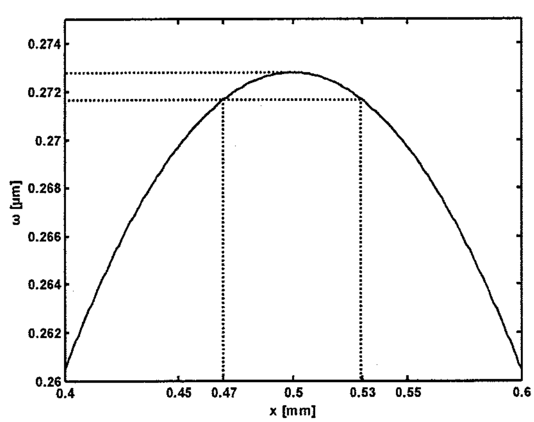


Fig. 10: The deflection at intermediate positions. (a = 1mm, q = 4MPa)

4. Conclusions

A simple MEMS optical fiber pressure sensor with the Fabry-Perot interferometer configuration has been designed, constructed and characterized. A square silicon diaphragm is used as a sensitive element to enhance consistency and commercial optical communication components are fitted for intensity demodulation. A large area ratio of the moving mirror to the stationary one is employed to reduce the non-planarity of the deflecting mirror and both the theoretical analysis and the simulation and measurement results show that the constructed pressure sensor has all the desired properties of reasonable sensitivity, stability and measurement range. With a low fabrication cost and a simple production process, this sensor system has great potentials for mass production and comm.ercialization.

Acknowledgements

This research project is funded by the NSFC (60777036) and the Shenzhen Fundamental Research Project Grant (JC200 903130271A).

References

[1] Ge YX., Wang M., Yan H.T. Optical MEMS pressure sensor based on a mesa-diaphragm structure. *Optics Express* **16**(2008) 21746-21752.

[2] Watson Stuart, Gander Matthew J, Jones Julian D.C, Klotzbuecher Thomas, Braune Torsten, *et al.* Laser-machined fibes as Fabry-Perot pressure sensors. *Applied Optics* **45**(2006) 5590-5596.

[3] Ni X.Q., Wang M., Chen X.X., Ge Y.X., Rong H., An optical fibre MEMS pressure sensor using dual-wavelength interrogation. *Meas. Sci. Technol.* **17**(2006) 2401-2404.

[4] Abeysinghe D. C., Dasgupta S., Boyd J. T., Jackson H.E., A novel MEMS pressure sensor fabricated on an optical fiber. *IEEE Photonics Technol. Lett.* **13**(2001) 993-995.

[5] Xu J.C., Pickrell G., Wang X.W., A novel temperature-insensitive optical fiber pressure sensor for harsh environments. *IEEE Photonics Technol. Lett.* **17**(2005) 870-872.

[6] Ge Y.X., Wang M. Chen X.X. Rong H., An optical MEMS pressure sensor based on a phase demodulation method. *Sensors and Actuators A* 2008, **143(2),** 224–229.

[7] Yang, B.Y., Zhang Y.T. ,*Engineering Elastic-plastic Mechanics,* China Machine Press, Beijing 2003, p. 154.