Optical MEMS pressure sensor based on a mesa-diaphragm structure

Yixian Ge, Ming Wang*, and Haitao Yan

Jiangsu Key Lab on Opto-Electronic Technology, School of Physical Science and Technology, Nanjing Normal University, Nanjing 210097, P. R. China

*Corresponding author: wangming@njnu.edu.cn

Abstract: An optical MEMS pressure sensor based on a mesa-diaphragm is presented. The operating principle of the sensor is expatiated by Fabry-Perot (F-P) interference. Both the mechanical model and the signal averaging effect of the mesa diaphragm is validated by simulation, which declares that the mesa diaphragm is superior to the planar one on the parallelism and can reduce the signal averaging effect. Experimental results demonstrate that the mesa structure sensor has a reasonable linearity and sensitivity.

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OCIS codes: (060.2370) Fiber optics sensors; (050.2230) Fabry-Perot; (230.4685) Optical microelectromechanical devices

References and links


1. Introduction

By employing the MEMS technology, a variety of optical MEMS pressure sensors based on Fabry-Perot interference have recently been proposed and fabricated [1-3]. The major advantages of the optical fiber sensors over the conventional electrical sensors include the immunity to electromagnetic interference, resistance to harsh environment and capability of multiplexing. At present, planar membrane is usually adopted to form F-P cavity, such as, a silicon diaphragm was bonded to a glass substrate with a previously etched cavity [4]. One of the major obstacles to these F-P cavity pressure sensors is the degradation of device performance arising from non-planar deflection of an edge-clamped diaphragm when subjected to an external pressure load. Two alternative techniques have been proposed to date to address the issue [5-6]. One technique towards minimizing the non-planarity of the deflecting mirror is to maximize the area ratio of the moving mirror to the stationary one, therefore maximize the size of the sensing element. The other alternative flatness-enhancing technique is to form corrugations in the deflecting diaphragm.

In this paper, we design and fabricate an optical fibre sensor with a mesa diaphragm to enhance the flatness of the diaphragm. Both analysis and finite element model (FEM)
simulation have shown that the flatness-enhancing effect can be achieved with the mesa structure, and therefore the signal averaging effect can substantially be reduced for the mesa structure pressure sensor. Phase demodulation based on Fourier Transformation is interrogated to the sensor [7]. Experimental results show the sensor has a better linearity and good performance.

2. Theoretical analysis

2.1 Mechanical analysis

The proposed F-P microcavity pressure sensing element, as shown in Fig. 1, consists of two major components: a mesa-diaphragm that serves as the moving mirror; an optical fiber that serves as the stationary mirror; and an air gap between the moving and stationary mirrors of the F-P microcavity. Light is introduced into the sensor from an optical fibre. One part of the incident light will be directly reflected by the fibre end face, and the other will come into the sensor and be reflected by the air-silicon interface. The reflected light will interfere with each other. When pressure is loaded onto the silicon diaphragm, the F-P cavity depth will change because of the deflection of the silicon diaphragm. The optical path difference in the F-P cavity will change, resulting in a change of phase of the sensor. By measuring the shift of the reflection spectrum, it is expected that one can easily know the loaded pressure.

The section configuration of the mesa membrane is shown in Fig. 2. Considering the radius of the circular membrane is \( a \) and the thickness is \( h_1 \), the radius of the mesa is \( b \) and the thickness is \( h_2 \). \( E \) is Young’s modulus, \( \nu \) is Poisson’s ratio, and \( P \) is the loaded pressure. Due to the structural discontinuation of the circular membrane, the thickness of the membrane has the mutation. The differential equations are as follows [8]:

\[
\begin{align*}
\frac{d^4w_i}{dr^4} + \frac{2}{r} \frac{d^3w_i}{dr^3} - \frac{1}{r^2} \frac{d^2w_i}{dr^2} + \frac{1}{r^3} \frac{dw_i}{dr} &= \frac{P}{D_1} \quad (0 \leq r \leq b) \\
\frac{d^4w_2}{dr^4} + \frac{2}{r} \frac{d^3w_2}{dr^3} - \frac{1}{r^2} \frac{d^2w_2}{dr^2} + \frac{1}{r^3} \frac{dw_2}{dr} &= \frac{P}{D_2} \quad (b \leq r \leq a)
\end{align*}
\]

\[
D_1 = \frac{E(h_1 + h_2)^3}{12(1-\nu^2)} \quad D_2 = \frac{Eh_1^3}{12(1-\nu^2)}
\]

From the equations above, we could get...
\[ w_1 = P \left( \frac{r^4}{64D_1} - \frac{b^2}{32D_1}r^2 + \frac{a^4 - b^4}{64D_1} + \frac{b^3}{16D_1} \log \frac{b}{a} \right) \] (4)

\[ w_2 = q \left( \frac{r^4}{64D_2} - \frac{a^2 + b^2}{32D_2}r^2 + \frac{a^2b^2}{16D_2} \log r + \frac{(a^2 + b^2)a^2}{32D_2} \cdot \frac{a^2b^2}{16D_2} \log a - \frac{a^4}{64D_2} \right) \] (5)

Where \( \omega_1 \) is the deflection from 0 to b, \( \omega_2 \) is the deflection from b to a, \( r \) is the distance from random point to the center of circle.

The maximum deflection of the membrane is as follows:

\[ w_m = P \left( \frac{a^4 - b^4}{64D_2} + \frac{b^4}{64D_1} + \frac{a^2b^2}{16D_2} \log \frac{b}{a} \right) \] (6)

We choose the \( a = 1650 \mu m, b = 500 \mu m, h_2 = 120 \mu m \). The Young’s modulus \( E = 160 \) GPa, Poisson’s ratio \( \nu = 0.22 \). The pressure measurement ranges from 0 to 2MPa. The deformation of the mesa diaphragm is simulated by the ANSYS and shown in Fig. 3.

Figure 4 presents the deformation of the two membranes by ANSYS simulation. Horizontal axis denotes diametric orientation, longitudinal axis denotes the deflection. Compared with the two figures, we can find the deflections of the mesa structure in central positions are flatter than the planar one. Therefore, more effective deflection can be produced and can highly satisfy the request about the parallelism.

Fig. 3. The deformation of the mesa-diaphragm
2.2 Signal Averaging Effect

Due to the deflection of membrane in the radius direction is not entirely the same, the reflectivity in the corresponding position is not the same. We employ the averaging reflectance through the summation method to obtain the actual reflectance of the F-P cavity of a given gap. The specific method is to partition radius \( r \) to \( \text{step} \) units, the reflectance in the same radius cirque is same, and then reflectance of each cirque is sum to get the actual reflectance. The weighted average response was [9]:

\[
R_{\text{avg}} = \frac{\sum R(g)A(g)}{\sum A(g)}
\]  

Where \( R(g) \) is the reflectance of the F-P cavity, \( A(g) \) is the area, \( g = r / \text{step} \). The actual reflectivity of the F-P cavity is: \( R = R_{\text{avg}} \times R_{\text{avg}}^* \).

![Fig. 4](image_url)

**Fig. 4.** The comparison between the mesa membrane and the planar one. (a) the deformation of the mesa membrane. (b) the deformation of the planar membrane.

![Fig. 5](image_url)

**Fig. 5.** Evaluation of SAE of the F-P cavity with a conventional planar diaphragm and the mesa structure.

Figure 5 shows the reflectivity as a function of loaded pressure at the center of the diaphragm with the conventional flat diaphragm and the proposed mesa structure. It is evident that the reflectivity of the F-P cavity with the flat diaphragm does not have a completely regular sinusoidal change and have the trend of attenuation, demonstrating the signal averaging effect caused by the non-uniform deflection of the deflected diaphragm. However, it can clearly be seen that using the mesa structure can substantially reduce the signal averaging effect.
3. Fabrication process

In our work, surface and bulk MEMS techniques are used to fabricate the sensing elements. Figure 6 shows the processing steps of fabrication.

1) A silicon-dioxide layer is grown on the silicon wafer both sides and then a silicon nitride is deposited by using low pressure chemical vapor deposition (LPCVD) (Fig. 6(a)).

2) The reactive ion etching (RIE) and lithography technology are employed to remove the SiO₂ and Si₃N₄, and selectively open a window in the upper side which is protected by thick photoresist (Fig. 6(b)).

3) As forming the mesa, the chemical anisotropic etching is used to etch the silicon (Fig. 6(c)).

4) The SiO₂ and Si₃N₄ on both upperside and underside are removed by the RIE etching (Fig. 6(d)).

5) The mesa diaphragm is anodically bonded onto the glass ring (Fig. 6(e)).

Figure 7 shows the SEM photograph of the mesa fabricated by RIE and anisotropic etching silicon.

Finally, the fabricated structure is adhered to the optical fiber plate flange with an epoxy method. The epoxy glue is used to stick in the four screws of plate flange to prevent oil leakage, for the screw of flange can not bear the pressure of 2MPa. Then, an optical fiber plug is inserted to the plate flange to form the F-P cavity. The inner diameter of the glass ring is 3.3 mm, the outer diameter of the glass ring is 5.3 mm, and the diaphragm thickness is about 180 μm. The plate flange is half of the whole one, and the diameter is 6 mm. The sample of the sensor is shown in Fig. 8.

4. Measurement of the sensor

Figure 9 shows the measurement system of the sensor. An optical sensing analyzer (MIO-720) is used for real-time demodulation of the sensor. The scan laser, which is used to illuminate the sensor, provides output wavelengths in the range from 1510 to 1590 nm. The spectrums of
both the incident and the reflected light are simultaneously swept and the data are transmitted to the computer through the network.

Pressure versus reflectivity plot of a planar and a mesa diaphragm is shown in Fig. 10. For the case of planar diaphragm (Fig. 10(a)), the signal average effect of optical response prevails as the applied pressure increases, which is caused by the non-uniform deflection of the deflected diaphragm. Therefore it will reduce the precision of the demodulation.

Figure 11 shows the experimental results, where the cavity of the sensor is plotted as a function of pressure. The fitting line is $L=217.3024-1.7112\times P$, the linearity is 0.9% and the sensitivity (i.e. change in cavity/loaded pressure) is $1.707\,\mu m/MPa$. Figure 12 shows the repeatability of the sensor where 1, 2, 3, 4 denote the results of the morning and afternoon between two days, respectively. The figure indicates that the sensor has good repeatability and performance.

5. Conclusions
A novel pressure sensor with a mesa structure diaphragm has been designed, fabricated and characterized. The operating principle of the sensor has been introduced. The device performances were evaluated by both theoretical analysis and measurements. Results show
that the signal averaging effect was substantially reduced for the mesa pressure sensor by the flatness-enhancing diaphragm structure. Since the proposed F-P cavity is used MEMS technology, which can be mass production and can be used in petrochemical, and other flammable and explosive conditions.

Acknowledgments

This work was supported by the Jiangsu province Scientific and Technical Supporting project (BE2008138).