A novel optical fibers MEMS pressure sensor

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Abstract. A novel pressure sensor based on the Fabry-Perot interferometry and micro-electromechanical system (MEMS) technology is proposed and demonstrated. Light is coupled into the sensor through a fiber. Dual-wavelength demodulation method is used to analyze the reflected optical signals and compensate the errors independent of optical wavelength. Theoretical analysis and simulation results are presented. Experimental results for pressure measurements ranging from 0 Mpa to 3 Mpa demonstrate reasonable linearity and sensitivity.

1. Introduction
Optical MEMS pressure sensors based on Fabry-Perot interferometry have recently been proposed and fabricated. This kind of sensors is used to measure pressure by detecting changes of the optical path length or reflectance. MEMS technology is effective for many kinds of sensors, e.g., pressure sensing and temperature sensing. Optical MEMS sensors have additional advantages over other electrical sensors, including high adaptability in harsh environments and the possibility of measurement for distributed physical quantities such as pressure, temperature and stress.

Here, we designed and fabricated a kind of optical MEMS pressure sensor which provides wide measurement range, good detection linearity and sensitivity. MEMS and optical fiber techniques were loaded to fabricate and connect the pressure sensor. The optical MEMS sensor can be easily incorporated into sensor arrays by using multiplexing methods and are expected to be more suitable than electrically MEMS sensor for liquid and gas pressure measurement in harsh environments. The proposed sensors are effective for practical application with small and definite size. The pressure-sensitive diaphragm with the designed thickness is fabricated by etching the single crystal silicon. The Fabry-Perot cavity is formed by etching shallow cavity in single crystal silicon and by anodizing the glass. Aluminum is plated on the etched silicon diaphragm in order to increase the reflectivity. Light is coupled into the sensor and interfered between each medium. The reflected optical power changes with the diaphragm deflection due to external pressure. Dual-wavelength demodulation method is used to analyze the reflected optical signals and compensate the errors independent with optical wavelength. Theoretical analysis, simulation and the experimental results are presented.

2. Fabrication process and packaging configuration
Figure1 is the sketch of optical MEMS pressure sensor based on Fabry-Perot interferometry. The incident light comes into the cavity through a single-mode fiber and is reflected by the
Figure 1 Sketch of optical fiber MEMS pressure sensor. A silicon diaphragm, which has been plated with aluminum, deflects when pressure is applied. This deflection changes the Fabry-Perot cavity length. The tight connection between the sensor's absolute reflectance and diaphragm deflection allows for dual-wavelength signal demodulation to analyze reflectance and eliminate wavelength-independent errors.

Figure 2 Fabrication process:

(a) Oxidation and deposit Si$_3$N$_4$

(b) Lithograph and selectively remove SiO$_2$ and Si$_3$N$_4$

(c) Etching silicon using RIE fabrication

(d) Silicon-glass anodic bonding

(e) Selectively etching to form silicon diaphragm with thin layers of Al, Si$_3$N$_4$, SiO$_2$, and glass.

Figure 2 Fabrication process.
Figure 2 shows the fabrication process. Processing is initiated with a silicon wafer oxidized and deposited on both sides that are lithographed. Bulk etching techniques are used to thin the silicon wafer down to the desired diaphragm thickness, and to form the silicon diaphragm for the sensors. RIE fabrication is used for etching a series of Fabry-Perot cavities in the silicon wafer polished on both sides. Then aluminum is plated on the etched side of the silicon in order to enhance the reflectivity. At last the silicon wafer is anodically bonded to the glass wafer. The glass wafer and the fiber were assembled in a package by epoxy.

3. Optical demodulation scheme

Dual-wavelength method is presented for demodulating the optical MEMS sensor. It is proved that the method can eliminate errors resulting from wavelength-independent variations in the fiber interconnect to the sensor. The sensor reflectance is given as

\[ R(\lambda) = \frac{I_R}{I_0} = \frac{r_0 + r_{23} \exp(j\Omega)}{1 + r_{23} \exp(j\Omega)} \]

(1)

Where \( r_{23} \) is the reflection coefficient of the composite structure that consists of a layer of air sandwiched between glass and aluminum and is given by

\[ r_{23} = \frac{r_2 + r_3 \exp(j\Omega_2)}{1 + r_2 r_3 \exp(j\Omega_2)} \]

(2)

and

\[ \Omega_1 = \frac{4\pi}{\lambda} n_{\text{glass}} t_{\text{glass}} \]

\[ \Omega_2 = \frac{4\pi}{\lambda} n_{\text{air}} t \]

(3)

Where \( r_1, r_2, \) and \( r_3 \) are the reflection coefficients for normal incidence at the fiber-glass, glass-air and air-aluminum interface, respectively and

\[ r_1 = \frac{n_{\text{fiber}} - n_{\text{glass}}}{n_{\text{fiber}} + n_{\text{glass}}} \]  
\[ r_2 = \frac{n_{\text{glass}} - n_{\text{air}}}{n_{\text{air}} + n_{\text{glass}}} \]  
\[ r_3 = \frac{n_{\text{air}} - n_{\text{Al}}}{n_{\text{air}} + n_{\text{Al}}} \]

(4)

\( \lambda \) is the operating wavelength, \( t_{\text{glass}} \) is the thickness of glass layer, and \( t \) is the air cavity depth.

The reflectance ratio is obtained as

\[ I(p, \lambda_1, \lambda_2) = \frac{R(\lambda_1)}{R(\lambda_1) + R(\lambda_2)} \]

(5)
Where \( R(\lambda_1) \) and \( R(\lambda_2) \) are two reflectance at two wavelengths \( \lambda_1 \) and \( \lambda_2 \). Choosing the two wavelengths \( \lambda_1=1525 \text{ nm} \) and \( \lambda_2=1530 \text{ nm} \), we get the simulation result as shown in figure 3.

The figure shows that the ratio of reflectivity at two wavelengths has a linear function with respect to cavity depth when the depth varies in a certain range. So the pressure loaded on the sensor, what leads to the variety of cavity depth, can be deduced by calculating the ratio. In practical application, we usually get the pressure from the equation that forms through least square fitting of different ratios at different pressure. In order to keep the linearity, the max deflection of the silicon diaphragm must be smaller than \( \lambda/4 \), and the initial depth of the air cavity \( t_0 \) must be deeper than \( \lambda/4 \). We choose \( t_0=4.1 \text{ um} \) and the deflection of the silicon diaphragm is 0.38 um at the max pressure of 3 Mpa, so the min cavity depth is 3.72 um. From the figure, we can see that in the depth range from 3.72um to 4.1um, the ratio appears linear as a function of the pressure.

We initially designed the pressure sensors to respond over the pressure range from 0 to 3 Mpa and cavity radius 300 \( \mu \text{m} \). The depth of the etched cavity is chosen 4.1\( \mu \text{m} \) and the diaphragm thickness 46\( \mu \text{m} \).

4. Experimental results and Discussions

The sensor system is shown in Figure 4. An optical sensing analyzer is used for demodulating the optical MEMS sensor, which consists of a tunable laser and an optical spectrum analyzer. The tunable laser used to illuminate the sensor provides output wavelengths in the range from 1510 to 1590 nm. Throughout this wavelength region, the glass is transparent and aluminum diaphragm has high reflectivity. There are two detecting channels, one for incident light and the other for the reflected light from the sensor. Ratio of the intensity of the reflected light and the incident light is calculated as the sensor reflectance. The spectrums of both the incident and the reflected light are simultaneously swept and the data are transmitted to the computer through the network. The software Labview is used to deal with the data. A manometer is used to load pressure on the sensor from 0 Mpa to 3 Mpa, stepped by 0.1 Mpa. Both the incident and the reflected spectrums are acquired at every step, and the spectrum of sensor reflectance can be calculated according to the equation (1). Choose the reflectance at 1525 nm and 1530 nm, calculate the reflectance ratio using the equation (5) and at last fit the calculated data using least square fitting. We get the results as below:

For distinction, the reflected spectrum at wavelength regions from 1520 nm to 1530 nm, when the pressure is 0.0, 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0Mpa, are shown in figure 5. The spectrum ascends
when the pressure loaded increases. Figure 6 shows the experimental results where reflectance ratio from the sensor is plotted as a function of pressure. The fitting line is \( I = 0.52771 - 0.00866 \times P \), the related linear regression coefficient of the experimental result is 99.8\%, and the sensitivity is 0.00866/Mpa. The standard deviation is \( 4.3 \times 10^{-4} \). The experimental results identified the correctness of theoretical investigation.

![Figure 5: Reflected signals of optical MEMS pressure sensor measured by optical sensing analyzer](image)

![Figure 6: Relation between pressure and reflectance ratio of dual-wavelength](image)

5. Conclusion

A kind of optical MEMS pressure sensor based on the principle of Fabry–Perot interferometry has been demonstrated. Basic and simplified micromachining techniques have been used to fabricate the pressure sensor. With Fabry–Perot cavity, the sensor reflectance is theoretically analyzed and presented. An optical sensing analyzer is used to provide the light source and get the reflected
spectrum. A Dual-wavelength demodulation method is used to analyze the reflected optical signals and compensate the errors independent with optical wavelength. Experimental results show that the pressure sensor has wide measurement range, good detection linearity and sensitivity. The results given show a good agreement between the experimental and the theoretical results.

References

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