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Wavelength-demodulation MEMS Fabry Perot temperature sensor based on bimetallic diaphragm

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ABSTRACT

A novel wavelength-demodulation MEMS optical fiber temperature sensor based on a bimetallic diaphragm is presented. The sensor is designed by following the basic principle of optical Fabry – Perot interference and the bimetallic diaphragm effect. The mechanical model of the bimetallic diaphragm with the mesa structure is validated by simulation and the ANSYS software is used to optimize the sensor structure. By tracing a peak point in the interference spectrum, the gap length of the sensor can be demodulated. Experimental results demonstrate a temperature-induced cavity length change of 0.407 nm/°C with a good linearity and reasonable accuracy in the range of 20 – 70 °C. The proposed sensor could be fabricated as sensor arrays for micro level applications, thus reducing production costs considerably.

1. Introduction

In recent years, optical MEMS sensors with advantages, such as immunity to electromagnetic interference, small size, resistance to harsh environments, have been developed. Such MEMS sensors can be applied to oil fields, coal mines, and other harsh working environments. Further, owing to the development of MEMS processing techniques suitable for large-scale mass production, the cost of producing a single device has been considerably reduced [1–5]. Over the past few decades, several optical fiber temperature sensing techniques have been reported in the literature, such as optical fiber sensors for temperature measurement based on silicon thermo-optics effect [6], intrinsic fiber optic temperature sensor [7], and a Fabry – Perot (FP) temperature sensor with sensitivity of 0.95 pm/°C developed by etching a multimode graded index fiber [8]. However, these temperature sensors have inherent drawbacks, such as design complexity, high temperature variation, and low resolution. Moreover, planar membranes have been used as the sensitive diaphragms of the most of these sensors, which have the signal averaging effect and cannot guarantee parallelism of the FP cavity [9].

In this paper, a new optical fiber temperature sensor is presented, along with a detailed theoretical analysis. The proposed sensor could be fabricated as sensor arrays for micro-level applications, thus considerably reducing production costs. The main advantages of the proposed sensor are that the MEMS-based fabrication process will be done on a commercial optical fiber end face, and that the bimetallic diaphragm has a mesa structure, which is superior to the planar one in terms of parallelism and can reduce the signal averaging effect [9], thus making it suitable for measuring small temperature variations with high sensitivity. The wavelength-demodulation method with combined single and double peak is used to analyze the reflected spectrum in such a sensor. The results of this study would be useful for the design and fabrication of silicon-based sensors for measuring pressure or other physical quantities.

2. Theoretical analysis

Fig. 1 shows a schematic of the proposed MEMS optical fiber FP temperature sensor, which consists of two primary components: a bimetallic diaphragm and a multimode fiber (MMF). A single mode fiber (SMF) is used to guide the light and to illuminate the MMF and bimetallic diaphragm. The thermal bimetallic diaphragm acts as a sensing unit when a temperature is applied. It will generate heat deflection due to different thermal expansion for the two metals, and the length of the FP cavity will change correspondingly, which will cause a shift in the reflectivity spectrum of Fabry-Perot interferometer. The diaphragm also has a mesa structure that is superior

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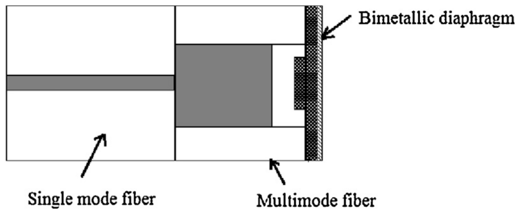

Fig. 1. Sketch of optical fiber temperature sensor.

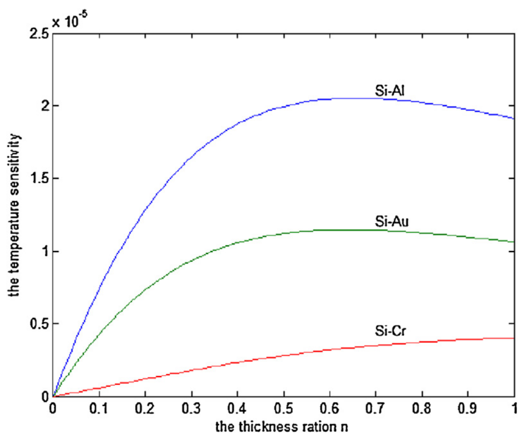

Fig. 2. The relationship between the temperature sensitivity and the thickness ratio.

to the planar one in terms of parallelism, and it can reduce the signal averaging effect.

2.1. Mechanical analysis

The bimetallic diaphragm with the mesa structure is shown in Fig. 1. The upper layer is an active layer with a larger thermal expansion coefficient. The thickness of this layer is h_1, the thermal expansion coefficient is α_1, Young's modulus is E_1, and Poisson's ratio is μ_1. The lower layer is a passive layer, and its thickness is h_2, thermal expansion coefficient is α_2, Young's modulus is E_2, and Poisson's ratio is μ_2. Because the mesa height has little effect on the deflection of the diaphragm, when the temperature increases by ΔT, heat deflection occurs in the bimetallic diaphragm. The maximum deflection at the membrane center is given as follows [10]:

$$\delta_{\max} = \frac{3K_B \pi r^2(\alpha_1 - \alpha_2)\Delta T}{4h_2 K_D} \quad (1)$$

where, r is the radius of the circular membrane, and K_B is a constant related to the boundary conditions.

$$K_D = \frac{1}{n+1}(4 + 6n + 4n^2 + \phi\omega n^3 + \frac{1}{\phi\omega n}) \quad (2)$$

where, $n = \frac{h_1}{h_2}$, $\phi = \frac{E_1}{E_2}$, $\omega = \frac{1-\mu_2}{1-\mu_1}$.

We set the parameter $M = (\alpha_1 - \alpha_2)/K_D$. Under the same conditions, the larger difference of the thermal expansion coefficient between the bimetallic diaphragms, the greater deflection produced. A silicon material is used for the lower layer in the fabrication of the proposed temperature sensor by a conventional MEMS fabrication process. Al, Au, and Cr are separately deposited on the silicon wafer to form different samples. According to Eq. (1), the relationship between the temperature sensitivity and the thickness ratio is simulated as shown in Fig. 2. It can be seen from Fig. 2 that the temperature sensitivity of the Al deposition layer is the highest. When Al is used as the coating material, which has exhibited large temperature sensitivity, the optimum coating thickness ratio is 0.6, as seen from Fig. 2.

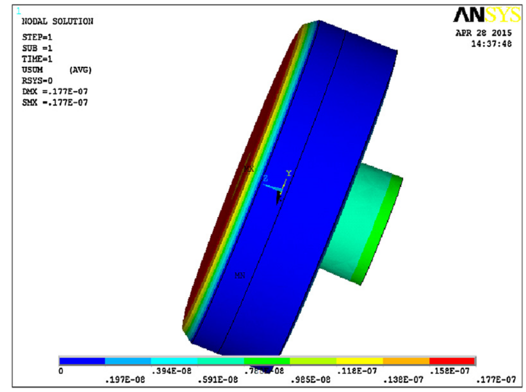

Fig. 3. View of the deflected diaphragm at an applied temperature of 80 °C.

2.2. ANSYS simulation

Numerical simulation of the proposed sensor was carried out using ANSYS software to understand the deflection response of the sensor diaphragm for a small temperature range. The geometric model has a core diameter of 62.5 μm. To realize higher sensitivity of the sensor, the selected silicon wafer should be as thin as possible. In line with our level of fabrication technology, the silicon wafer thickness for this simulation was selected as 10 μm. Because the mesa height had little effect on the deflection of the diaphragm, the thickness of the diaphragm was selected as 8 μm. The thickness of the deposited Al layer was selected as 6 μm. Fig. 3 shows a view of the deflected diaphragm at an applied temperature of 80 °C in order to give the reader a better view of diaphragm deflection due to change in surrounding temperature.

From Fig. 3, it can be noted that the maximum vertical deflection of the diaphragm occurs at the center of the diaphragm, and it increases significantly in upward surface as temperature increases. When using the mesa structure, the movement of the bimetallic diaphragm is considered to be translation.

2.3. Optical properties of the sensor

As discussed in the previous section, the bimetallic diaphragm can serve as a temperature sensing element. The length of the FP cavity will change due to the difference in thermal expansion of the two metals resulting from the outer temperature change. The low finesse FP device can thus be modeled using the two-beam optical interference equation, as follows [11]:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\frac{4\pi L}{\lambda} + \phi) \quad (3)$$

Another key design parameter is the initial depth L of the FP cavity, which is obtained by etching 62.5-μm borosilicate glass fiber. However, if the etching time is too long, the wall supporting the diaphragm will be very thin, resulting in lower mechanical strength of the spacer. Furthermore, the bottom reflectivity of the cavity will become low, resulting in weaker reflected signal and demodulation. Therefore, the cavity cannot be too long. We selected the initial cavity depth to be around 50 μm. Fig. 4 shows results for the simulated normalized reflected light intensity under different cavity lengths. In Fig. 4, d_1 = 50 μm refers to the initial cavity depth, d_2 = 50.018 μm refers to the change in cavity length under the temperature of 80 °C.

By tracing the peak point in the interference spectrum, the cavity length of the sensor can be demodulated [12]. For the adjacent fringe order m and $m+1$ in the spectrum, the wavelengths of the