Simultaneous Measurement of Pressure and Temperature Based on Graphene

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Abstract: This paper presents an ultrahigh sensitive pressure and temperature sensor based on a Fabry-Perot interferometer (FPI) using a graphene diaphragm. The cavity of the FPI is the gap between the end-face of fiber Bragg gratings (FBG) and the graphene diaphragm. To prevent the serious cross-impact of pressure and temperature, a FBG is used to replace the single mode fiber. The sensitivities of pressure are 17.4698 nm/kPa and 0.0267 pm/kPa for FPI and FBG, respectively. The sensitivities of temperature are 5.075 nm/°C and 10.9 pm/°C, for FPI and FBG, respectively. The resolutions for pressure and temperature measurement are ±0.0267 kPa and ±0.459 °C with the wavelength resolution of 5 pm. The experimental results show that the sensor is able to measure pressure and temperature simultaneously and accurately by a matrix on sensitivity. The proposed sensor can be applied on wide applications such as ocean exploration, biomedical science, and microfluidic, etc.

1. Introduction

Optical fiber sensors have been attracting increasing research attention because of their ultra-compact size [1], high sensitivity [2, 3] and wide applications such as biomedical, environmental and embankment applications [4, 5]. Many methods have been used in fabrication such as electrical arc discharge [6], femtosecond laser [7], and the use of an FPI tip with an elastic diaphragm. Simultaneous measurement of double parameters have been researched in recent years. The sensitivity matrix has been used in simultaneous measurement of strain and temperature [8]. Owing to the superior mechanical properties and ultrathin thickness of graphene sheets, FPI sensors based on graphene diaphragms are widely studied [9]. The similar structure has become a promising candidate on different measured parameters such as vibration [10], adhesion energy [11], thermal expansion [12], and biomolecules [13]. The FPI based on graphene is demonstrated to have a pressure sensitivity of more than 39.4 nm/kPa for a diaphragm diameter of 25 μm [14]. The same sensor structure with a graphene film is experimentally demonstrated for temperature measurement [15], and dip wavelengths are employed to demonstrate a change in the temperature. The proposed sensor exhibits an ultrahigh sensitivity of 1.56 and 1.87 nm/°C in wavelength change at temperatures of 500–510 °C and 1000–1008 °C, respectively. From the above, the FPI based on graphene has both ultrahigh sensitivities between pressure and temperature. But the serious intersect effect is passed. The paper proposed here mentions the cross impact of pressure and temperature firstly. And the larger diameter used in this sensor realizes the greater pressure sensitivity with a diameter of 125 μm. The shifts of wavelength are recorded to express the pressure and temperature sensitivities. The pressure sensitivity of the sensor are 17.4698 nm/kPa and 0.0267 pm/kPa for FPI and FBG, respectively. The temperature sensitivity are 5.075 nm/°C and 10.9 pm/°C for FPI and FBG, respectively. The cross impact between
pressure and temperature is 290.5 Pa/°C. To prevent the cross-impact between pressure and temperature, the FBG replaces the SMF and carries the temperature-compensation effectively.

2. Sensor Fabrication and Principle

2.1. Sensor Fabrication

The fabrication of the pressure and temperature fiber sensor is schematically shown in Figure 1. The compact fiber sensor consists of a zirconia ferrule, a FBG and a 6~8-layer commercial Trivial Transfer Graphene (TTG) sample covered with polymethyl methacrylate (PMMA) using chemical vapor deposition on a polymer substrate (ACS Material®, http://www.xfnano.com). The process for preparing the graphene membrane and transferring it onto the fiber tip to form an FP cavity is similar to that in Ref. [7]. Firstly, because cleanliness and flatness are important to adhesiveness, the zirconia ferrule is successively each 30 minutes cleaned with acetone and alcohol in an ultrasonic cleaner. Then, the ferrule is cleaned with deionized (DI) water for 30 minutes. Secondly, the FBG inserts the ferrule carefully and forms the cavity between the end-face of FBG and the end-face of the ferrule by using a 1-μm resolution translation stage with epoxy glue. Thirdly, the graphene film is easily separated from the substrate by immersing the TTG in DI water. After suspension in DI water for 2 h to ensure sample smoothness, a filter paper is used to transfer and cut the graphene sample. Before cutting, the additional water is removed by using a straw until there were no drops of water. Then, the sample is cut down to a suitable size in a moist state. After natural drying, the sample is released into the water again for 2 h. Finally, the ferrule fiber tip is moved down slowly toward the floating graphene until it touched the graphene sample. Under the effect of Van der Waals force, the graphene together with the PMMA layer is then adsorbed on the surface of the ferrule tip. After putting in a drying cabinet for hours, the membrane is firmly attached to the surface. After natural drying, the end face with the graphene membrane is completely dipped into acetone solution for 30 min to etch away the PMMA layer. The ferrule with graphene is dried in a cabinet at room temperature for 2 h. After water evaporation, the graphene was firmly stuck to the surface of the ferrule and formed a reflecting surface of a sealed FP microcavity.

2.2 Principle

The measuring system is shown in Figure 2. The system consists of a tunable laser (Agilent 81980A), and an optical power meter (Agilent 8163B), a computer and the fabricated fiber sensor. The sensor connects the tunable laser and the optical power meter by a 3dB coupler. The pressure measurement is realized by placing the sensor in a closed chamber connecting the pressure gauge. The temperature measurement is realized by placing the sensor in a furnace.
According to two-beam interference theory, the output light intensity can be stated as

\[ I = I_1 + I_2 + \sqrt{I_1 I_2} \cos \phi \]  

(1)

Where \( I_1 \) and \( I_2 \) are the intensities of the two reflective beams, \( \phi = 4\pi n_{eff} L_{eff} / \lambda \) is the relative phase difference in the FP cavity, \( n_{eff} \) is the effective reflective index of the guided mode transmitting in the FPI.

The interference pattern shown in Figure 3 is analyzed, and the cavity length, \( L \), is calculated to be 23.059 µm by using the expression:

\[ L = \frac{N \lambda_1 \lambda_{N+1}}{2(\lambda_{N+1} - \lambda_1)} \]  

(2)

Where \( \lambda_1 \) and \( \lambda_{N+1} \) are the wavelengths of two resonant dips in the spectrum sampling. The phase difference between \( \lambda_1 \) and \( \lambda_{N+1} \) is \( \phi_{N+1} - \phi_1 = 2N\pi \).

The graphene diaphragm deflection changes with the pressure increasing obviously. Therefore, the fringe contrast changes with the wavelength shifts. The pressure sensitivity increases as the diaphragm thickness decreases, as shown in [16]

\[ \frac{\Delta \lambda_{FPP}}{\Delta P} = \frac{(1-u)\lambda R^2}{2Edt} \]  

(3)

Where \( \Delta \lambda_{FPP} \) is the wavelength change of FPI caused by pressure, \( u \) is the Poisson’s ratio, \( R \) is the radius of diaphragm, \( E \) is the Young’s modulus of graphene, \( d \) is the deflection, \( t \) is the diaphragm thickness.

Where \( K_{FPP} \) is the pressure coefficient of the FPI. The wavelength shifts with the pressure change. When the temperature changes, the thermal expansion of graphene film and the thermo-optic coefficient of graphene film change.

The center reflection wavelength shift of the FBG can be given as

\[ \Delta \lambda_{FBG} = 2\delta n_{core} \Lambda \]  

(4)
Where $\Lambda$ is the grating period of the FBG and $\delta n_{\text{core}}$ is the difference in the effective refractive index of the core with changing temperature.

Since the FPI and the FBG have different spectral responses to the changes of pressure and temperature, it is easy to distinguish the measured signals without cross impact, so pressure and temperature measurement can be realized by using the fiber sensor.

Simultaneous measurement can be realized by measuring the resonance wavelength shifts of the FPI and the FBG. When the peak wavelength shifts of the FP ($\Delta \lambda_{FP}$) and the peak wavelength shifts of the FBG ($\Delta \lambda_{FBG}$) are determined, a sensitivity matrix can be constructed as

$$
\begin{bmatrix}
\Delta \lambda_{FP} \\
\Delta \lambda_{FBG}
\end{bmatrix} =
\begin{bmatrix}
K_{FP,P} & K_{FP,T} \\
K_{FBG,P} & K_{FBG,T}
\end{bmatrix}
\begin{bmatrix}
\Delta P \\
\Delta T
\end{bmatrix} \tag{5}
$$

Where $K_{FP,P}$ and $K_{FP,T}$ are the pressure and temperature coefficients of the FPI, respectively; $K_{FBG,P}$ and $K_{FBG,T}$ are the corresponding pressure and temperature coefficients of the FBG. By using matrix inversion, the relative values of pressure and temperature can be obtained through the following matrix:

$$
\begin{bmatrix}
\Delta P \\
\Delta T
\end{bmatrix} =
\frac{1}{M}
\begin{bmatrix}
K_{FBG,T} & -K_{FP,T} \\
-K_{FBG,P} & K_{FP,P}
\end{bmatrix}
\begin{bmatrix}
\Delta \lambda_{FP} \\
\Delta \lambda_{FBG}
\end{bmatrix} \tag{6}
$$

Where $M = K_{FP,P}K_{FBG,T} - K_{FP,T}K_{FBG,P}$, which is the determinant of the coefficient matrix. The matrix coefficients can be determined by individual measurements of the pressure and temperature response with a change in the cavity length of the FP and the peak wavelength of the FBG, respectively. Therefore, the loaded pressure and temperature variation can be obtained by simultaneously measuring the change in resonant wavelength of the FP and the wavelength shifts of the FBG.

3. Pressure and Temperature Measurement

3.1 Measurement of Pressure

For the measurement of pressure, the sensor is placed in a pressure chamber (E-P25). The resolution of the digital pressure gauge was 0.01 kPa. To control variable, the experiment is conducted in room temperature. The cause of leakage in the sensor is mainly the non-ideal adhesion of the graphene layer to the silica capillary end-face. Due to this problem, continuous tests of the sensor under static pressure would cause measurement errors. Hence, to avoid the measurement errors, the measurement of the pressure response was conducted by applying a target pressure, recording the spectrum, and releasing the pressure, with all these steps done within the duration of only several seconds. The measured pressure was in the range of 0–0.84 kPa. During the pressure tests, after the pressure was reset, the spectrum coincided with the initial time spectrum. The scatter plot and linear fit of the experimental data are shown in Figure 4.

![Figure 4](image-url)
Based on the experimental results, the pressure sensitivity of the FPI ($K_{FP,P}$) and the FBG($K_{FBG,P}$) are 17.469 nm/kPa and 0.0267 pm/kPa, respectively.

3.2 Measurement of Temperature
For the measurement of temperature, the sensor is placed in furnace and the temperature is measured between 20 and 100°C. The resolution of the furnace was 1°C. To ensure equality of the temperature test, data were recorded after the temperature had been maintained at a constant value for 30 minutes. During the temperature tests, both the FPI and the FBG have redshift such as Figure 5.

![Figure 5 Wavelength Shift of the Interference Dip with Temperature Applied (a) for the FP (b) for the FBG](image)

Figure 5 Wavelength Shift of the Interference Dip with Temperature Applied (a) for the FP (b) for the FBG

Because of the limitation of FSR, in order to examine the sensitivities under different temperature ranges, we measure the temperature with a step of 1°C under different dip wavelength. The thermo expansion coefficient of graphene film will increase and lead to increased sensitivities in different temperature ranges with the temperature rising. Figure 5(a) is the temperature sensitivity of FP between 96 and 100°C. Based on the experimental results, the temperature sensitivity of the FPI ($K_{FP,T}$) and the FBG ($K_{FBG,T}$) are 5.075 nm/°C and 10.9 pm/°C, respectively. However, the temperature sensitivity of the FPI ($K_{FP,T}$) is lower than 5.075 nm/°C in lower temperature, such as shown in Figure 6, the temperature sensitivity of FP between 35 and 39°C is 3.13 nm/°C. Which agrees with theory prediction.

![Figure 6 Wavelength Shift of the Interference Dip with Temperature Applied for the FP between 35 and 39 Degree](image)

Figure 6 Wavelength Shift of the Interference Dip with Temperature Applied for the FP between 35 and 39 Degree

3.3 Cross-impact
The pressure and temperature sensitivities of FP and FBG have been analyzed based on the tests. The obvious cross impact can’t be neglected. When the ambient pressure increases, the spectrum has a blueshift. When the ambient temperature increases, the spectrum has a redshift. The variation trends of the wavelength shifts are opposite between pressure and temperature. The cross impact was computed to be 290.5 Pa/°C.

From the aforementioned results, Eq. (6) can be updated with the known pressure and temperature sensitivities as

\[
\begin{bmatrix}
\Delta P \\
\Delta T
\end{bmatrix} = \left[ \begin{array}{cc}
10.9 \times 10^{-3} & 5.075 \\
0.0267 \times 10^{-3} & 17.4698
\end{array} \right]
\begin{bmatrix}
\Delta \lambda_{FP} \\
\Delta \lambda_{FBG}
\end{bmatrix}
\]

(7)

By using Eq. (7), we can demodulate the pressure and temperature easily from the measured wavelength shifts of the FPI and the FBG. Based on the wavelength resolution, 5pm, of the used tunable laser, the resolutions for pressure and temperature measurement are ±0.0267kPa and ±0.459°C.

4. Conclusion
In conclusion, a pressure and temperature optical fiber sensor has been proposed based on a graphene diaphragm. Based on the measured results, the pressure sensitivity and temperature sensitivity of FPI are 17.4698nm/kPa and 5.075nm/°C. The introduction of an FBG can effectively prevent cross-impact errors and achieve precise temperature compensation. The resolutions for pressure and temperature measurement are ±0.0267kPa and ±0.459°C, respectively. The proposed sensor has great potential in biomedical, environmental, and embankment applications.

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