Research on highly sensitive Fabry-Pérot cavity sensing technology in frozen soil*

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A high-sensitivity low-temperature sensor based on Fabry-Pérot interferometer (FPI) is fabricated and experimentally demonstrated in this letter. The FPI air cavity is fabricated by splicing a single-mode optical fiber (SMF) with a glass capillary tube partially filled with ultraviolet (UV) glue. Due to the high coefficient of thermal expansion of UV-glue, the sensor can obtain high sensitivity. Experimental results show that the sensor has a temperature sensitivity of −3.753 4 nm/°C in the temperature range of −4—4 °C, and the linearity is 0.999. The engineering performance of the sensor is tested by simulating the frozen soil environment. The proposed sensor has high sensitivity and good temperature response. The sensor structure is compact and simple, low cost and has potential application in the cryogenic detection environment.

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Compared with traditional electrical sensors, optical fiber sensors have been widely concerned and studied in biomedical, food safety, structural health and other sensing fields, owing to the advantages of small size, high temperature resistance, anti-electromagnetic interference and compact structure[1-5]. Temperature is an essential physical quantity in industrial production and engineering detection. The state of frozen soil plays an important role in the stability assessment of engineering buildings in its region, temperature around zero can reflect the state of frozen soil, and the low temperature sensing has potential application value to the condition monitoring of frozen soil. Compared with electrical type sensor, optical fiber temperature sensor has many advantages. There are also many kinds, such as temperature sensors based on fiber grating, Michelson interferometer, Mach-Zehnder interferometer, and Fabry-Pérot interferometer (FPI) and so on[6-10].

The temperature sensor based on fiber FPI has the characteristics of compact structure and excellent performance, so it has been deeply studied by researchers for the past few years. The Fabry-Pérot (F-P) cavity sensor is filled with high thermal expansion coefficient, so its sensitivity is higher than that of all-fiber air F-P cavity sensor. Therefore, researchers have filled various materials with high thermal expansion coefficients to increase sensitivity in recent years. ZHANG et al[11] proposed a single-mode optical fiber (SMF) into a polymer-filled glass capillary to form an F-P air microcavity. Due to the high thermal expansion coefficient of the polymer, the sensor had a temperature sensitivity of 5.20 nm/°C in the temperature range of 15—22 °C. GAO et al[12] filled the hollow core fiber with polydimethyl-siloxane as a temperature sensitive material, and then fused SMFs at both ends of the hollow fiber. The sensitivity of the sensor is −0.384 nm/°C in the temperature range of 25—80 °C. The thermal expansion coefficients of various materials are different, which leads to the sensitivity of the sensor is different. GAO et al[13] fused SMF and hollow fiber filled with UV-glue to form an F-P cavity, which has a temperature sensitivity of 1.227 nm/°C in the range of 39—54 °C. In addition, they also utilized the Vernier effect to improve the temperature sensitivity by parallel connecting an all-fiber F-P air cavity, which increased the sensitivity up to −15.617 nm/°C. LIANG et al[14] fused SMF with a hollow cylindrical waveguide filled with polydimethyl-siloxane, and fused a semi-elliptical shape at the other end of hollow cylindrical waveguide to form Vernier effect to increase sensitivity. The temperature sensitivity of the sensor is 3.150 nm/°C in the temperature range of 25—95 °C. The sensitivity of the sensor increased obviously after using the Vernier effect, but

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the sensor structure was not compact enough at the same time. Changes in temperature can affect the state of the frozen soil, which in turn affects the stability of buildings and structures in the frozen soil. Low temperature sensing has important reference value in the frozen soil detection field. This letter will make a low temperature sensor with low cost and high sensitivity.

In this letter, a high sensitivity F-P sensor with low temperature detection is fabricated and experimentally demonstrated. Ultraviolet (UV) glue has a greater thermal expansion coefficient than optical fiber, which could be used as F-P cavity to increase sensitivity while maintaining a small volume. The cavity is formed by inserting an SMF into a capillary glass tube partially filled with UV glue. The sensing principle of the sensor is analyzed theoretically and the preparation process is described in detail. The optical fiber F-P cavity temperature sensor system is constructed and sensor temperature response is studied experimentally. This letter simulates frozen soil environment to detect its temperature response. The experimental results show that the sensor has high sensitivity, and has potential applications in low temperature detection and other fields.

The working principle of optical fiber FPI is as follows. When the light is incident into SMF, reflection occurs on the end face of SMF and air cavity, and the rest of the light continues to transmit into the air cavity until it is reflected on the surface of UV-glue. Reflection and refraction are repeated on the two reflective surfaces. The two ends of the FPI air cavity are composed of SMF M_1 and UV-glue M_2, respectively. Thus, multi-beam interference is generated at the interface of M_1. The reflection R_1 and R_2 of these two surfaces are respectively expressed as[15]

$$R_1=\left(\frac{n_{\mathrm{SMF}}-n_{\mathrm{AIR}}}{n_{\mathrm{SMF}}+n_{\mathrm{AIR}}}\right)^2,\quad R_2=\left(\frac{n_{\mathrm{AIR}}-n_{\mathrm{UV}}}{n_{\mathrm{AIR}}+n_{\mathrm{UV}}}\right)^2, \tag{1}$$

where n_{SMF}, n_{AIR} and n_{UV} are the refractive indexes (RI) of SMF, air and UV-glue, respectively. Owing to the core RI of the fiber (1.450) is close to that of the solidified UV-glue (1.470), for simplicity, we consider that the reflectance of the two surfaces is approximately equal to R, and the interference intensity can be expressed as

$$I_R=\frac{4R\sin^2\left(\Delta\varphi/2\right)}{\left(1+R\right)^2+4R\sin^2\left(\Delta\varphi/2\right)}I_0, \tag{2}$$

where $\Delta\varphi$ is the phase difference of any two adjacent beams. Without considering the half-wave loss, $\Delta\varphi$ can be expressed as

$$\Delta\varphi=\frac{4\pi n_{\mathrm{AIR}}L}{\lambda}, \tag{3}$$

where λ is the wavelength of input light. According to the theoretical knowledge of fiber F-P cavity sensing, the free spectral range (*FSR*) can be expressed as the wavelength distance between two adjacent wave peaks or wave valleys of the reflected spectrum, so the *FSR* is expressed as[14]

$$FSR=\lambda_{m+1}-\lambda_m=\frac{\lambda_{m+1}\lambda_m}{2n_{\mathrm{AIR}}L}, \tag{4}$$

where λ_m and λ_{m+1} are two adjacent wave valleys of the reflection spectrum respectively. The sensor sensitivity formula can be expressed as[14]

$$S_{\mathrm{FP}}=\Delta\lambda/\Delta T=\lambda\left(\beta+\alpha\right), \tag{5}$$

where β and α are the thermal expansion coefficient and thermal-optical coefficient of UV-glue, respectively. It is observed that owing to the high coefficient of thermal expansion of UV-glue, the sensor can obtain higher sensitivity.

The temperature reflection spectra of the all fiber FPI and partially filled UV glue FPI were simulated, as shown in Fig.1. It can be seen that when the temperature changes, namely from the initial temperature to T_1 and then to T_2, under the same temperature variable, the wavelength of the sensor filled with UV-glue as the reflection surface changes more.

The sensor fabrication process is as follows. The structure of FPI sensor is shown in Fig.2. First, the capillary glass tube end was filled with UV glue partially, and illuminated with an UV lamp for 5—10 min to fix it. Secondly, a cutter was used to cut the end face of the SMF (SMF128) with the coating removed flat and wiped SMF clean with alcohol. After that, a standard SMF was inserted through the other end of the glass tube and fixed with UV glue to form an air cavity. The SMF has 8.5 μm core diameter and 125 μm cladding diameter.

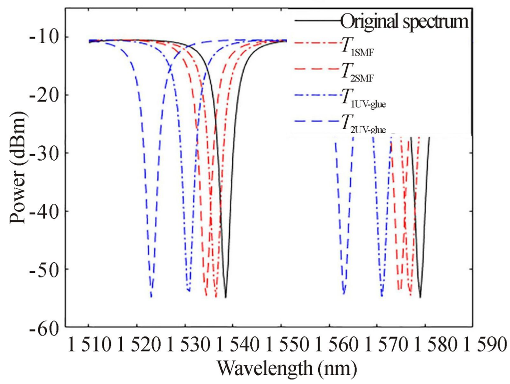

Fig.1 Simulated reflectance spectra of all fiber FPI and partially filled UV glue FPI

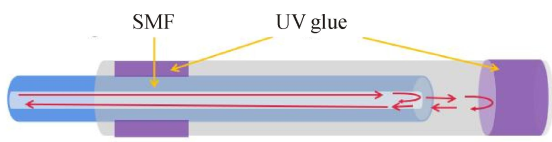

Fig.2 Schematic of the temperature sensor

As shown in Fig.3, an experimental equipment of temperature sensing was constructed to study the performance of the temperature sensor. The wavelength resolution of the optical sensing interrogator (TV125) is 1 pm, the demodulator contains a laser device, and the wavelength range is from 1 500 nm to 1 600 nm. The temperature controller (YM-CDC-R80) resolution is 0.01 °C.

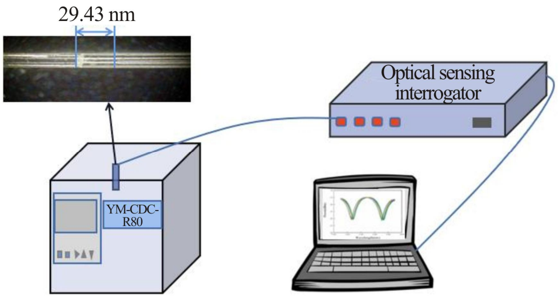

Fig.3 Temperature sensor system diagram

Put the sensor into the temperature controller to control its operating ambient temperature of the sensor. The light emitted in the demodulator entered the sensor through the SMF, and generated a reflected light signal in the sensor, then the interference light signal reflected back was detected by the demodulator, and the reflected spectrum was transmitted to the computer. Computer software SM125_V1.03 was used to demodulate and record interference spectrum.

In order to verify the performance of the fabricated FPI sensor, the low temperature response of FPI was studied experimentally. In the experiment, the sensor was put into the temperature controller, and the temperature changed from 4 °C to −4 °C. Meanwhile, the interference spectrum was recorded at 1 °C interval for each change. As can be seen from Fig.4(a), the wavelength blue shifts to 29.87 nm and the *FSR* is 41.24 nm. According to the linear fitting diagram of the measuring points of the two groups of data in Fig.4(b), the sensor has good repeatability.

Frozen soil is a significant part of the earth's ecological environment. The stability of frozen soil with temperature change has great influence, and further affects the construction of road foundation and engineering project buildings. As the water in the soil freezes into ice, the soil expands and the surface rises unevenly, which makes the engineering buildings on the soil displacement and damage the buildings. Frozen soil properties are largely influenced by internal ice, which is extremely sensitive to temperature changes around the temperature range of ice water phase transition. The change of temperature near zero degree will have a significant effect on the content of ice and unfrozen water, thus affecting the physical and mechanical properties of frozen soil.

In order to test the application performance of sensor, we simulated the frozen soil environment and tested the temperature response of the sensor. As shown in Fig.5, the sensor was placed in the container, and the soil was filled into the container. The whole container was placed in the temperature controller to simulate the temperature sensing of the sensor in the frozen soil environment.

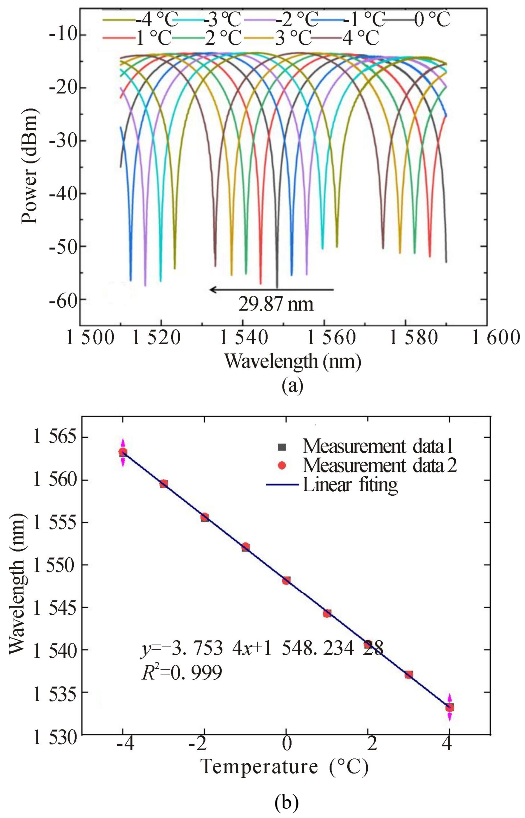

Fig.4 (a) Temperature reflection spectrum of sensor; (b) Linear fitting diagram

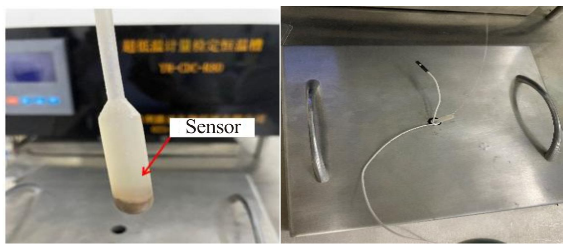

Fig.5 Sensor temperature detection in frozen soil environment

The temperature sensing spectra of frozen soil are shown in Fig.6(a). When the temperature changed from 4 °C to −3 °C, we observed that the wavelength of reflection spectrum showed a blue shift to 31.12 nm with the decrease of temperature. A particular wave-valley wavelength in the reflectance spectrum was tracked as the wavelength changed with temperature, and the fitting linear figure of temperature and wavelength change was fabricated according to the measurement points of two sets of data, as shown in Fig.6(b). The sensor sensitivity was −4.467 4 nm/°C, and the linearity was 0.999. It can be proved that the sensor has good linear response.

The working mechanism of the sensor is that the temperature affects the change of the cavity length to measure the temperature. When the sensor was shaken, the whole sensor vibrated, and the change of the cavity length was not independently affected. Therefore, the vibration didn't affect the temperature measurement performance of the sensor theoretically. As the decrease of temperature, the water in the soil condensed into solid ice, caused the soil volume to grow in size, so soil produced extrusion stress on the sensor cavity. It can be seen that if the sensor is applied in practical engineering, it needs to be packaged against pressure.

Since the ice inside the frozen soil has a great influence on its physical properties and the temperature near zero degree has a great influence on the phase transition of water ice, the detection range of this experiment was near zero degree. In fact, the sensor application can detect other low temperature ranges in conjunction with the actual environment.

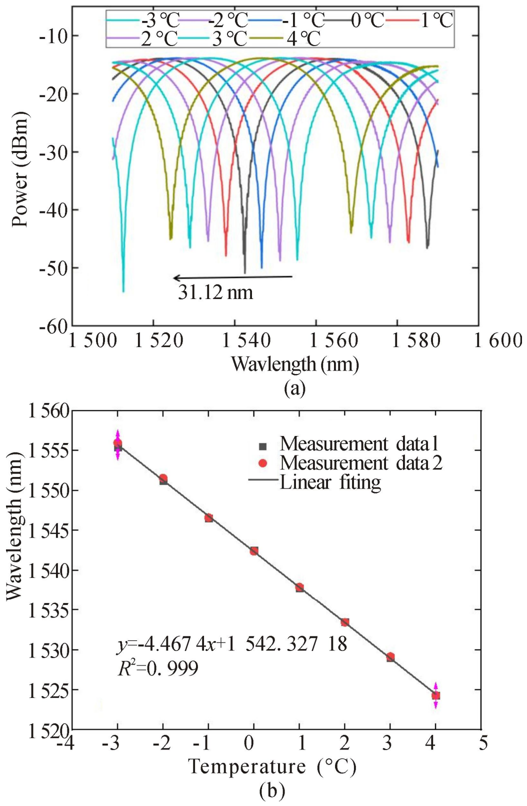

Fig.6 (a) Temperature reflection spectrum of sensor in frozen soil; (b) Sensor linear fitting diagram in frozen soil

Compared with the Vernier effect type sensor, fiber optic temperature sensor based on single cavity FPI has the advantages of compact structure and simple manufacturing process. As can be seen from Tab.1, the single cavity sensor made in this letter has the advantages of simple structure, high sensitivity, and can work in harsh environment, which has potential engineering application value.

Tab.1 Sensitivity comparison based on single cavity FPI temperature sensor

Sensitivity (nm/ºC)	References
<3.5	[12—14], [16—20]
>3.5	[11], [15]
This sensor: −3.753 4	This study

In conclusion, a highly-sensitive low-temperature sensor based on UV-glue filled has been fabricated in this letter, and its performance was tested by experiments. The sensitivity of the sensor is −3.753 4 nm/°C in the temperature range of −4—4 °C, and the linearity is 0.999. Also for the sensor temperature sensing in frozen soil experimentally, the sensitivity of the sensor is −4.467 4 nm/°C in the range of −3—4°C, and the linearity is 0.999. It is indicated that the sensor has good sensitivity in engineering applications. The sensor has the advantages of small size, low cost and compact structure, and has a potential wide application prospect in the field of frozen soil. To extend the detection range while maintaining sensitivity, the sensor can be connected with other devices.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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