High sensitivity diaphragm-based extrinsic Fabry-Pérot interferometric optical fiber underwater ultrasonic sensor

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Optical fiber sensors for ultrasonic signals detection have become a research focus in the past years. In this paper, a novel structure of the diaphragm-based extrinsic Fabry-Pérot interferometric (DEFPI) optical fiber ultrasonic sensor with a through vent hole of the fused silica ferrule was present. In this sensor system, the amplified spontaneous emission (ASE) optical source and the Fabry-Pérot filter are used to adjust the wavelength of the operation point of the sensor. We performed the ultrasonic distance detection experiment from 1 cm to 31 cm and the sensor sensitivity experiment, and the pressure sensitivity of the sensor is 9.68 nm/kPa (66.69 nm/psi). The sensitivity of the fusion silica structure DEFPI optical fiber is much higher than that of the HCPCF-ILFP (hollow-core photonic crystal fiber in-line fiber-optic Fabry-Pérot) and the fiber Bragg grating (FBG).

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1. Introduction

Ultrasonic wave in the frequency range from 20 to 200 kHz is applied in various ways in technology, medicine and so no. Currently, a number of acoustic wave sensors based on semiconductor and electrical technique have been widely used, but they have a few primary drawbacks such as conductivity, lower maximum operating temperature, sensitivity to temperature changes, corrosion, electromagnetic disturbance, and so on. As a result, the optical fiber sensors have been extensively developed for acoustic wave detection as an alternative to semiconductor or electrical technology for decades because of the advantages of intrinsic electrical passivity, high temperature capability, corrosion resistance, immune to electromagnetic interference, high sensitivity, high resolution, high frequency response, compact size, and allowing remote and distributed measurement [1-4]. Among the optical fiber sensors, the sensitivities of the acoustic sensor based on fiber Bragg grating FBG (3.48×10^{-3}nm/MPa) [5, 6] and on hollow-core photonic crystal fiber in-line fiber-optic Fabry-Pérot cavity (HCPCF-ILFP, 7.29×10^{-3}nm/MPa) [7] are relatively much lower, while the diaphragm-based extrinsic Fabry-Pérot interferometric (DEFPI) optical fiber sensors are suitable for measuring the acoustic signal (dynamic pressure) due to their high sensitivity and high bandwidth, so they become the research focus in the acoustic signal detection field. However, because the background pressure induces the pressure difference inside and outside the Fabry-Pérot (FP) cavity due to the air trapped by FP cavity, it will made the operating point of the sensor to shift in an uncertain way; the thermal expansion of the trapped air will induce a undesirable pressure applied on the inner surface of diaphragm when environment temperature up, increasing the sensor temperature dependence. That is, the air trapped will induce the problems of the operation point and the increasing temperature dependence. In addition, the mismatch in coefficient of thermal expansion (MCTE) among materials will induce undesirable stress which degrades the performance of the sensor and even causes sensor failure. Especially, the current common bonding adhesive of epoxy will decompose at high temperature, and cause large temperature dependence due to the bonding adhesive having a different CTE from the sensor materials. Therefore, Q-point control has been used to resolve the problem of operating point shift [8, 9], but there are a considerable increase in system complexity and cost. Refs [10, 11] resolve the problems of trapped air, but the fabrication processes are relatively complicated. Ref [12] employing the same materials to resolve the problem of MCTE, but they don't entirely resolve the problem of trapped air. Ref [13] present sapphire FP cavity sensor at extreme high temperature, but the fabrication is very complicated and the cost is very high.

In this paper, in order to resolve the problems of the trapped air inducing the operation point shift, we present a novel structure of the DEFPI optical fiber ultrasonic sensor with a through vent hole of the fused silica ferrule. The sensor head is fabricated in heating fusion bonding technique by use of a CO_2 laser, and the ultra-thin fused silica diaphragm is directly welded onto the top surface of the fused silica ferrule, which avoids the problem of the MCTE among different materials. Compared with the fabrication technology previously researched, this fabrication process in laser heating fusion bonding is simple, clean, environment-friendly, and inexpensive.

2. Principle of operation

Fig. 1 shows the basic structure of sensor. The air gap between the optical fiber end surface and the inner surface of the diaphragm is FP cavity of the DEFPI optical fiber sensor, and the FP cavity length will reduce with deflection of the diaphragm as a result of the applied pressure. Light is injected into the lead-in optical fiber and propagates along the fiber, which reaches the DEFPI senor head, and partially (about 4%) reflected by the fiber end surface and the inside surface of the diaphragm because of Fressnel reflection at the glass-air interface, respectively. The beam reflected by the diaphragm couples into the lead-in optical fiber, then propagates back along the lead-in fiber and produces interference fringes of cosine intensity variations with the beam reflected by the fiber end surface. When the ultrasonic signal is applied to the DEFPI sensor, the FP cavity length will change according to the deflection of the diaphragm. These interference fringes are modulated by the ultrasonic signal pressure, which will be for the demodulation of the FP cavity length. In this way, we realize the ultrasonic signal detection.

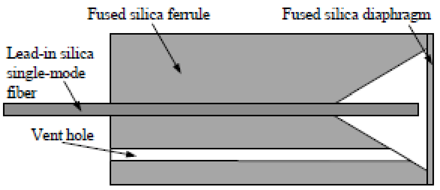

Fig. 1. The DEFPI optical fiber sensor basic structure.

The interference optical intensity for a FP interferometer is given by [14]

$$I = \frac{2R(1-\cos\varphi)}{1+R^2-2R\cos\varphi}\cdot I_0 \tag{1}$$

where I_0 is the incident optical intensity, R is the reflectivity of the fiber end and the diaphragm inner surfaces, and φ is the round trip phase shift inside the FP cavity, and is given by

$$\varphi = \frac{4\pi L}{\lambda} \tag{2}$$

where λ is the free space light wavelength, and L is the FP cavity length. Since light is partially, about 4%, reflected by the optical fiber end surface and the inside surface of the diaphragm, the FP cavity is a low finesse FP interferometer. The interference optical intensity can be approximately expressed by

$$I = 2RI_0\left(1-\cos\frac{4\pi L}{\lambda}\right) \tag{3}$$

When the ultrasonic signal is applied, the diaphragm will deflect under the applied ultrasonic signal pressure P, causing the FP cavity length to change. So the φ will vary with diaphragm deflection, inducing the shift of the interference spectrum. The sensor system should operate in a linear scope of interference fringe, which avoids fringe direction ambiguity.

3. Sensor design and fabrication

3.1 Design of the sensor

For a clamped rigidly round diaphragm of the sensor, it will deform under the ultrasonic pressure P. The out-of-plane deformation Y is a function of the acoustic pressure, the ferrule inner radius r, and the diaphragm thickness h etc. Y is given by [15]

$$Y = \frac{3(1-\mu^2)P}{16Eh^3}\left(a^2-r^2\right)^2 \tag{4}$$

where μ and E are the Poisson's ratio and Young's modulus of diaphragm material respectively, a is the effective radius of the diaphragm (inner radius of the fused silica ferrule horn-shape cup), r is the radial distance to the diaphragm center, and h is the diaphragm thickness.

As depicted in Fig. 1, the sensor head is formed by three parts, covering optical fiber, fused silica diaphragm, and fused silica ferrule with a through vent hole and with a horn-shape cup. For a round DEFPI sensor, we define the ratio between the deflection and the acoustic pressure as the pressure sensitivity, S. Assume the optical fiber is fixed to the center hole of silica ferrule, the S at normal temperature is given by

$$S = 2.4943\times10^{-6}\cdot\frac{r^4}{h^3}\left(nm/KPa\right) \tag{5}$$

where the r and h are in microns.

In our case, the relative parameter of the sensor is designed such that a is 0.5-mm-wide, and h is

25-μm-thickness. According to the equation (3), the diaphragm sensitivity is 9.98 nm/kPa (68.76 nm/psi) in ultrasonic pressure measurement. The fused ferrule has two through holes, one of which (side hole) is vent hole for balancing the pressure difference inside and outside the FP cavity due to the thermal expansion of the trapped air, and for maintaining operating point not to shift because it balances the pressure difference inside and outside the FP cavity due to the trapped air at different environmental backpressure. Therefore, the sensor system has no need to employ operating point or Q-point control procedures for detecting the acoustic pressure. For the conventional hermetic EFPI sensors, the undesirable pressure generated by the trapped air thermal expansion is a serious issue in practical applications, especially in high temperature surroundings, because the undesirable pressure induces larger temperature sensitivity [16]. In addition, Q-point control or other approaches have to be used to compensate the shift of the operating point, but the price is a comparative increase in system complexity and cost.

3.2 Fabrication of sensor

A 25-μm-thickness ultra-thin fused silica diaphragm was directly welded onto the horn end face of the ferrule with 1.8-mm outside diameter and 7-mm length by CO_2 laser heating fusion bonding technique as illustrated in Fig. 2(a), and the micrograph of bonding diaphragm with ferrule is shown in Fig. 2(b). The 1-mm in inside diameter and 1.5-mm-deep horn-shape cup is formed in the process of the silica ferrule preparation. The diaphragm was locally and quickly heated at the edge by CO_2 laser, so its surface nearby the center was not influenced, even when coated with a gold or other metal film (central region ~1-mm in diameter). A lead-in silica single-mode fiber (SMF) was cleaved and inserted in the central hole of the double holes ferrule, and then the fiber was positioned to the ferrule inner wall, forming an FP cavity between optical fiber end surface and the inside surface of the diaphragm. Fig. 3 shows the interference spectrum of FP cavity with 50μm-length. Such above steps, the sensor head with 7mm length and 1.8 mm outside diameter is achieved. The bare sensor head and the packaged one are shown in Fig. 4. For the packaged structure, we used the 316 stainless steel to protect the bare sensor, and meanwhile the tail fiber of sensor was protected with 316 stainless steel tube. After packaging, the air in the FP cavity connects to the constant pressure and temperature environment via the through vent hole of the ferrule and the 316 stainless steel tube.

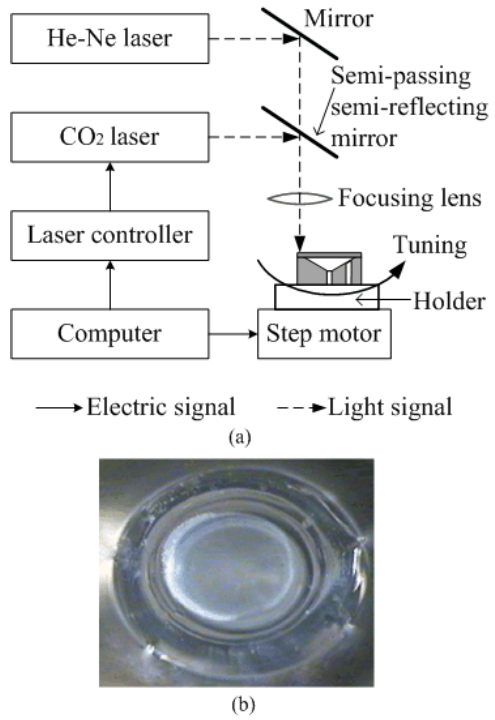

Fig. 2. (a) Block diagram of the heating fusion bonding system and (b) top view of bonding diaphragm with ferrule.

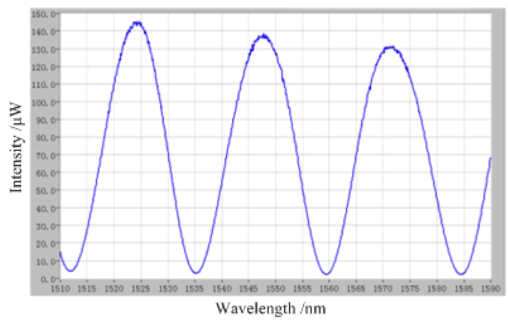

Fig. 3. Interference spectrum of the sensor with 50μmcavity length.

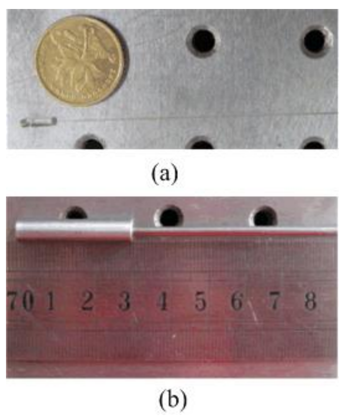

Fig. 4. (a) Image of the bare ultrasound sensor; (b) Image of the packaged ultrasound sensor.

4. Experiments and results

4.1 Distance detection for ultrasonic signal

Fig. 5 illustrates the scheme of the experimental system for distance detection of the ultrasonic signal in a water tank. Optical signals from the amplified spontaneous emission (ASE) light source based on Erbium doped fiber are emitted and propagate along the fiber, which reaches the fiber DEFPI acoustic head through the isolator, the FP filter (micro optics Inc.) and the 3dB optical fiber coupler. Optical signals reflected by the DEFPI sensor head is modulated by the incident ultrasonic wave. The modulated optical signals are detected by a photodiode through the same 3dB coupler, and the induced photocurrent is transformed by a transimpedance amplifier into a signal voltage U. After amplification, the U is digitized by the digital oscilloscope and displayed on it. The DEFPI sensor head and the ultrasonic transducer head are submerged in the water, and the sensor head is mounted on the setting where the ultrasonic transducer head can be vertically moved up or down under the sensor head. The diaphragm of the fiber sensor is exactly submerged in the water. The sine wave ultrasonic signal is generated by the ultrasonic transducer head driven by an ultrasonic signal source with the frequency of 40 kHz. The optical phase variation of the interference fringe induced by the ultrasonic signal is transformed to the optical intensity change by means of tuning the wavelength to the operation point of the linear part of interference signal. The wavelength is adjusted to the operation point, λ=1541 nm, of the sensor system by tuning of the FP filter, and the output spectrum of the FP filter through the 3dB optical fiber coupler is displayed on the optical spectrum analyzer (OSA, ANDO AQ6317C), and is shown in Fig. 6.

The principle of the ultrasonic distance measurement is shown in Fig. 7. The ultrasonic signal pressure decreases with the increasing of the distance between the fiber sensor head and the ultrasonic transducer head, so the signal voltage U displayed on the oscilloscope will reduce. As illustrated in Fig. 5, the ultrasonic transducer head under the DEFPI sensor head generates the ultrasonic signal, and the incident ultrasonic wave pressure applied to the diaphragm of the sensor causes the deformation of the diaphragm, so the cavity length of the FP cavity (corresponding to the optical phase) varies with ultrasonic signal pressure, inducing the optical intensity acquired by the photo detector to change, and the output waveform of the DEFPI sensors is illustrated in Fig. 8 when the pressure of the ultrasonic signal with a frequency of 40 kHz is applied to the diaphragm of the fiber sensor. As depicted in Fig. 9, with the distance between the sensor head and the transducer head increasing from 1 cm to 31 cm, the acoustic wave pressure applied to the diaphragm will decrease gradually. The sensitivity of the sensor system is 11.2 mV/cm. It can be seen from Fig. 9 that the experimental results when the distance increasing accord basically with those when the distance decreasing.

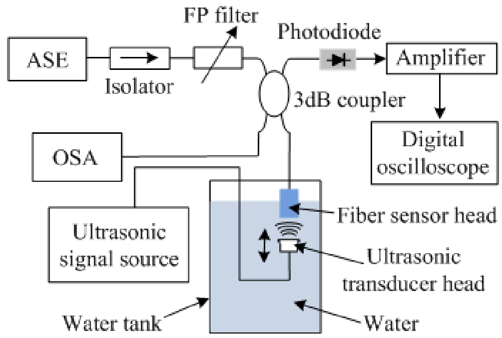

Fig. 5. Schematic diagram of the experimental system for detecting ultrasonic distance.

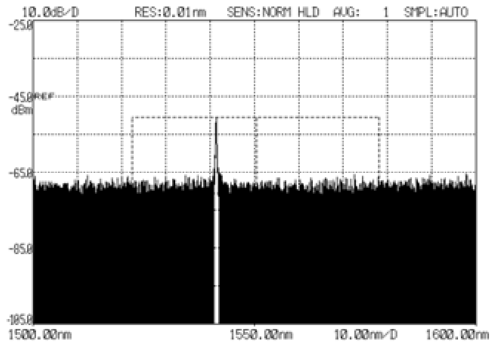

Fig. 6. Output spectrum of the operation point of the test system via FP filter.

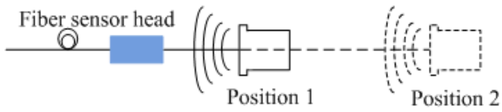

Fig. 7. Schematic diagram for measuring ultrasonic distance. Position 1 and position 2 are both ultrasonic transducer head, and the pressures induced by them on the diaphragm are respectively the P1 and P2, (P1>P2).

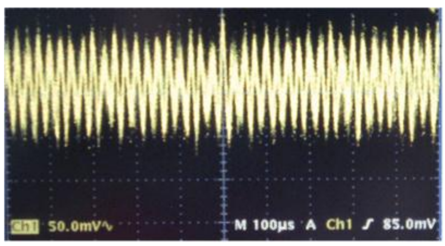

Fig. 8. Output waveform of the DEFPI sensor corresponding to the ultrasonic signal with a frequency of 40 kHz.

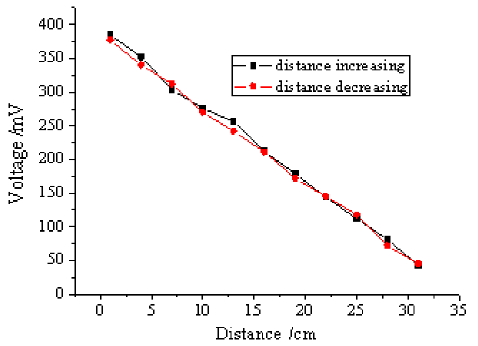

Fig. 9. Signal voltage change against distance when the transducer head vertically moves up or down.

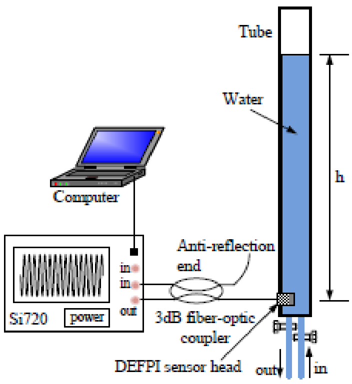

Fig. 10. Experimental setup for testing pressure sensitivity.

4.2 Pressure sensitivity test

Experimental setup of pressure sensitivity test is shown in Fig. 10. The optical light from Optical Sensing Analyzer Si720 (Micron Optics) propagates to the FP cavity through a 3-dB SMF coupler, and its interference signal is routed back through the same coupler to the detector built in the Si720. The sensor head is submerged in the water and the FP cavity length varied with water level. A cross-correlation signal processing method with 0.2nm resolution is used to process the interference signal for demodulating the FP cavity length [17]. The pressure response of the DEFPI sensor present in our case is shown in Fig. 11. The sensor pressure sensitivity is 9.68 nm/kPa (66.69 nm/psi), and the pressure resolution of our system based on the cross-correlation signal processing method is about 21Pa (0.003psi). These results are consistent with the theoretical values.

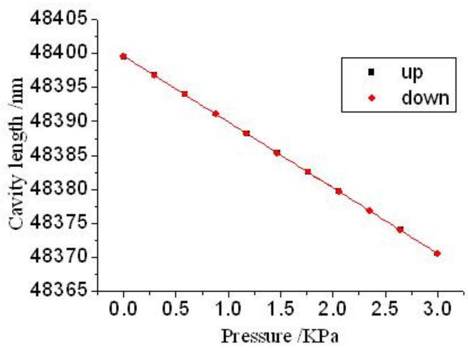

Fig. 11. Sensor pressure response from 0 to 3kPa.

5. Conclusions

In summary, we propose a new method to fabricate a DEFPI optical fiber ultrasonic sensor, and a novel structure of the DEFPI sensor based on the fusion silica structure with a through hole is achieved. In this sensor system, we designed the ASE optical source and the FP filter to easily adjust the wavelength of the initial operation point of the sensor. The system exhibits excellent performance of ultrasonic signals detection, with a sensitivity of 11.2 mV/cm. In addition, the DEFPI sensor head based on the novel structure possesses high pressure sensitivity, 9.68 nm/kPa (66.69 nm/psi), and high pressure resolution, 21Pa (0.003psi). Also, the vent hole balances the pressure difference inside and outside the FP cavity, and maintains operating point not to shift. The sensitivity of the fusion silica structure DEFPI optical fiber is several thousand times than that of the HCPCF-ILFP and the FBG. The DEFPI sensor has the potential to be used as a high performance and low-cost optical microphone.

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