Polymer diaphragm based sensitive fiber optic Fabry-Perot acoustic sensor

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Received May 20, 2009

A sensitive polymer diaphragm based fiber Fabry-Perot (F-P) sensor for aeroacoustic wave measurement is presented. A novel polymer material poly (phthalazinone ether sulfone ketone) (PPESK) diaphragm is used as the acoustic sensing element. The effective dimensions of the diaphragm are 4 mm in diameter and 6 μm in thickness. Owing to the good mechanical and optical features of the diaphragm and application of the interferometric/intensity demodulation, a system sensitivity of 31 mV/Pa is achieved in the frequency range of 0.1–12.7 kHz, and a signal-to-noise ratio (SNR) of 29 dB at 1 kHz is obtained. The linear response of the sensor is from 0.35 to 2.82 Pa, corresponding to 85 – 103 dB sound pressure level (SPL) (re: 20 μPa). The sensor has the potential to be used as a universal and low-cost optical microphone.

OCIS codes: 060.2370, 120.2230, 050.2230.

doi: 10.3788/COL20100803.0266.

Fiber optic acoustic sensors have been researched for decades because of the advantages over conventional acoustic sensors, such as electrically passive, immunity from electromagnetic interference, resistance to corrosion, remote sensing operation[1], light weight, and small size. Diaphragm-based extrinsic Fabry-Perot interferometric (EFPI) fiber optic sensor, as a branch of fiber optic acoustic sensors, has become a hot topic in the acoustic signal detection due to its high sensitivity and wide frequency response. Various kinds of diaphragm-based EFPI fiber optic sensors, such as a silica diaphragm spliced with a silica capillary[2−5], a glass or a silicon diaphragm bonded to a silicon base[6−8], and a dipped polymer membrane on a hollow fiber tip[9,10] have been developed, and some of these sensors are applied in the detection of hydroacoustic waves and partial discharge in power transformer[8]. But most of these sensors do not suit aeroacoustic detection due to the mismatch of the acoustic impedance with the sensors diaphragm.

In this letter, an ultra-sensitive diaphragm-based fiber optic EFPI aeroacoustic sensor is proposed. A new polymer diaphragm of poly (phthalazinone ether sulfone ketone) (PPESK) is used as the sensing element. Theoretical analysis of the diaphragm structure and fabrication of the sensor are presented. The configuration of the diaphragm-based fiber optic EFPI acoustic sensor is shown in Fig. 1. A low-finesse Fabry-Perot (F-P) interferometer is formed between the end surface of optical fiber and the inner surface of PPESK diaphragm. Light propagates along the lead-in fiber, and then the partial light is reflected by the fiber end face and the inner surface of diaphragm. The reflection light which contains the F-P interferometric signal travels back along the same fiber. For a low-finesse F-P interferometer, the reflected optical intensity can be expressed by[11,12]

$$I_{\mathrm{r}} = 2RI_0 \left[1 - \cos(\frac{4\pi L}{\lambda})\right], \quad (1)$$

where I_0 is the incident optical intensity, R is the reflectivity of the fiber end face and the inner surface of diaphragm whose refractive index is nearly the same as that of the fiber core, λ is the wavelength of the light source, and L is the length of F-P cavity. When the length of F-P cavity changes one half of the light wavelength, the reflected intensity will change a period. The relationship between I_{r}/I_0 and L with different wavelengths is shown in Fig. 2. For an interferometric/intensity modulated sensor, the initial static operating point of sensor should be set at the quadrature point (shown in Fig. 2 as Q points) of the sinusoidal curve.

When a pressure is applied to the diaphragm, the deformation of diaphragm will cause the changes of the F-P cavity length and the reflected optical intensity. In our experiment, only the diaphragm center deflection is of interest. For a rigidly clamped round diaphragm, the

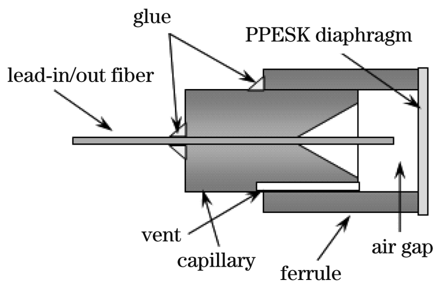

Fig. 1. Configuration of fiber acoustic sensor.

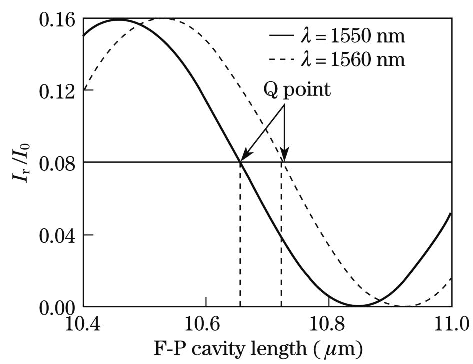

Fig. 2. Relationship between the cavity length and intensity with different wavelengths.

center deformation is given by[13]

$$\Delta L = \frac{3(1-\mu^2)P}{16Eh^3}\ a^4, \quad (2)$$

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 defined by the inner radius of the quartz capillary, P is the applied pressure, and h is the diaphragm thickness. Equation (2) is valid only when the deformation is no more than 30% of the thickness of the diaphragm. From Eq. (2), we know that there is a linear relationship between the diaphragm center deflection and the applied pressure. The deflection of the diaphragm is proportional to the fourth power of the diaphragm radius and inversely proportional to the cube of the diaphragm thickness for a certain material. Large deformation can be got by choosing materials with low E and μ, or by increasing the effective radius and decreasing the thickness of diaphragm. When the diaphragm deforms, the length of the F-P cavity changes as

$$L = L_0 - \Delta L, \quad (3)$$

where L_0 is the initial or static length of F-P cavity. From Eqs. (1)–(3), one can get the conclusion that there is a sinusoidal relationship between the reflected intensity and the input acoustic pressure. When the sensor static working point is set at quadrature point and the acoustic-wave-caused diaphragm deformation is not too large, a linear response of the intensity to acoustic pressure is obtained.

For achieving a sensitive response of the acoustic sensor, a new polymer material PPESK is used to fabricate the sensing diaphragm. PPESK is a kind of thermoplastic which has good mechanical properties, thermal and chemical stabilities, and adjustable optical refractive index. The mass density is 1.3 g/cm^3 and the Young's modulus and Poisson's ratio of PPESK are about 8 GPa and 0.3, respectively. As the sensing element, the PPESK diaphragm with a thickness of 6 μm and a diameter of 4 mm is selected. The PPESK diaphragm fabrication process includes spin coating, baking, and separation from the substrate. A few drops of PPESK solution are dipped onto the surface of a silicon substrate and the PPESK diaphragm is formed on the silicon substrate by spin-coating process. After spin coating, the diaphragm is baked in a vacuum oven to evacuate the solvent. The diaphragm thickness can be controlled by varying the spin velocity[14]. As shown in Fig. 1, a 1.8-mm-outer-diameter quartz capillary with cone-shaped cup is used to collimate and hold optical fiber, and a quartz ferrule with 4-mm-outer diameter and 1.8-mm-inner diameter is bonded to the capillary with epoxy to support the PPESK diaphragm. For eliminating the effect of air pressure difference between two sides of the diaphragm, a vent is formed by grinding the capillary into D shape in cross section. The outer surface of diaphragm is roughened with acetone to eliminate the light reflection from outer surface, and the F-P cavity is formed between the end face of the fiber and inner surface of PPESK diaphragm. Once the F-P cavity length is adjusted to the initial operating point, the fiber can be bonded to the capillary with epoxy.

The configuration of the experimental system is shown in Fig. 3. A tunable fiber laser is used as the light source. Light emitted from the laser is propagated into the sensor through a circulator and partially reflected back from the sensor. The reflected light which contains the F-P interferometric signal is detected by a photodiode and recorded by a data acquisition (DAQ) device in a computer. A reference condenser microphone (ME 102, Sennheiser) is placed next to the fiber acoustic sensor, and assumed to sense the same acoustic field with fiber acoustic sensor. A loudspeaker excited by a function generator is used as an acoustic source. In order to detect the changes of reflected intensity, an interferometric/intensity demodulation mechanism is used. The initial operating point is set at Q point (as shown in Fig. 2) for sensitive and linear detection. During the operation, the Q point of sensor will drift slowly due to the change of environmental temperature. In the experiments, the drifts can be compensated by adjusting the wavelength of the light source as shown in Fig. 2. An automatic compensation of the initial F-P cavity length drift is realized by calculating the direct current (DC) component of the interferential signal and tuning the tunable fiber laser with a computer.

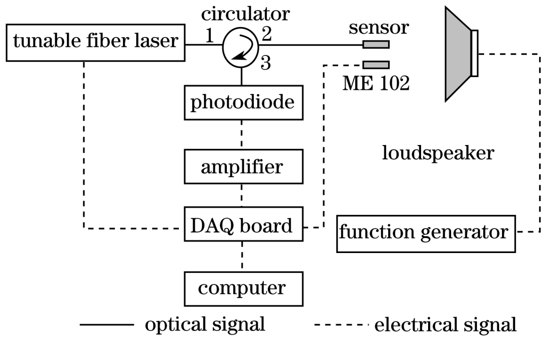

Fig. 3. Structure of fiber acoustic sensor system.

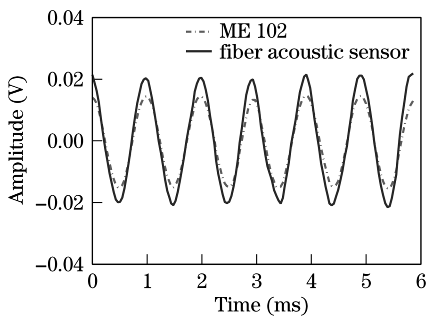

Fig. 4. Comparison between fiber acoustic sensor and ME 102 at 1 kHz.

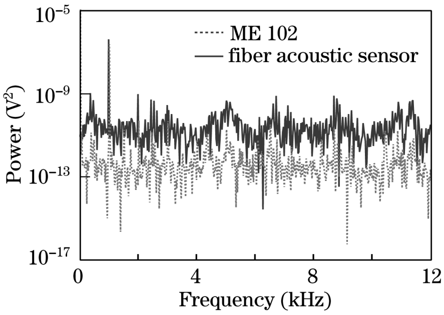

Fig. 5. Power spectra of fiber acoustic sensor and ME 102 at 1 kHz.

The fiber acoustic sensor is studied in the frequency range from 0.1 to 12.7 kHz. The performances of fiber acoustic sensor and ME 102 at 1 kHz are shown in Fig. 4. It can be seen that the fiber acoustic sensor compares well with the condenser microphone ME 102. The power spectra of fiber acoustic sensor and ME 102 in frequency domain are given in Fig. 5. The fiber acoustic sensor shows a bit higher noise floor than ME 102, which is mainly attributed to the laser source noise and electrical noise of the system. From the experimental results, the signal-to-noise ratio (SNR) of fiber acoustic sensor at 1 kHz is 29 dB, which is smaller than that of ME 102 (38 dB). The lower SNR of fiber acoustic sensor is mainly caused by the intensity noise of light source and inherent noise of electrical components. The intensity noise of light source can be suppressed by using a light source with stable intensity and high optical power output. The noise of electrical components can be reduced by choosing proper photodiode and amplifier circuit.

The sensitivity of the fiber acoustic sensor at 1 kHz is tested. As a reference, the condenser microphone ME 102

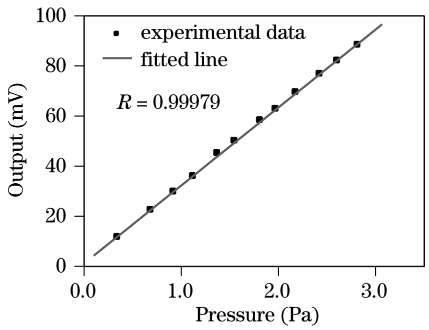

Fig. 6. Linearity of fiber acoustic sensor with sound pressure.

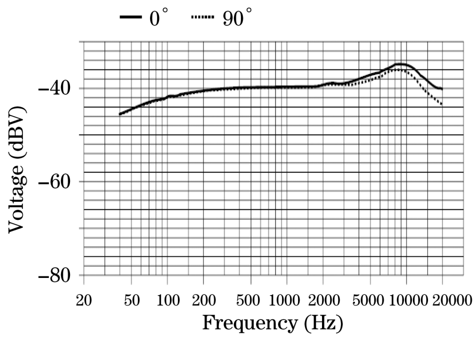

Fig. 7. Frequency response of ME 102.

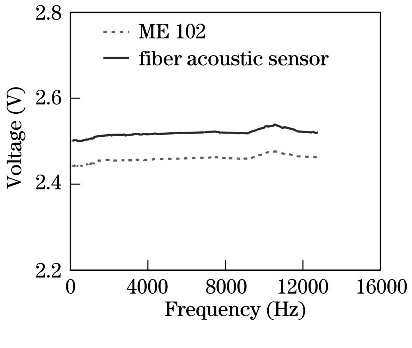

Fig. 8. Frequency response of fiber acoustic sensor compared with ME 102.

has a linear response to the sound pressure with a sensitivity of 10 mV/Pa provided by the manufacturer[15]. The output of fiber acoustic sensor is shown in Fig. 6. The acoustic pressure is increased from 0.35 to 2.82 Pa, corresponding to 85–103 dB sound pressure level (SPL) (re: 20 μPa), and the fiber acoustic sensor shows an excellent linear response. The sensitivity of fiber acoustic sensor is 31 mV/Pa and the linear correlation coefficient (R) is 0.99979. The experimental results agree with the theoretical analysis very well.

The frequency response of ME 102 provided by the manufacturer is shown in Fig. 7[12]. The frequency response of the fiber acoustic sensor compared with ME 102 is shown in Fig. 8. It can be seen clearly that the frequency response of the fiber acoustic sensor is nearly the same as that of ME 102 in the frequency range from 0.1 to 12.7 kHz. The fluctuation of the response curves are mainly caused by the performance of the loudspeaker.

In conclusion, we present a polymer diaphragm-based EFPI fiber acoustic sensor system. In this system, the new polymer material PPESK is used as the sensing element, and the interferometric/intensity demodulation scheme is used to measure sound pressure. For readily controlling the static working point, a tunable fiber laser is used as light source. The sensitivity of fiber acoustic sensor is 31 mV/Pa. This optical acoustic system has a flat response in the range of 0.1–12.7 kHz and the SNR at 1 kHz is 29 dB. The experimental results demonstrate that the sensor is able to detect a low frequency acoustic pressure in the air and has the potential to be used as a high performance and low-cost optical microphone.

This work was supported by the National Natural Science Foundation of China under Grant No. 60677010. The authors would like to thank Professor Xigao Jian from Department of Polymer Science and Materials and Professor Mingshan Zhao from School of Physics and Optoelectronic Technology in Dalian University of Technology for their help in making PPESK diaphragm.

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