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High-sensitivity fiber-optic acoustic sensor for photoacoustic spectroscopy based traces gas detection

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We demonstrate a high sensitive fiber-optic Fabry-Perot acoustic sensor with a wide measuring range based on a thin silver diaphragm. The silver diaphragm is fabricated by vacuum magnetron sputter deposition, therefore it has strong adhesion and good compactness. Based on these characteristics, the silver diaphragm is fabricated with few millimeters lever of diameter for a high pressure sensitivity of 5.97 μm/kPa and a low temperature sensitivity of 0.139 nm/°C. Acoustic testing demonstrates a noise equivalent acoustic signal level of ∼40 μPa/Hz$^{1/2}$ at the frequency of 1.6 kHz. The acoustic sensor is applied in an all-optical trace gas detection system based on photoacoustic spectroscopy. With the wavelength modulation and harmonic detection method, the detection limit of acetylene is achieved to be 0.87 parts-per-billion volume (signal-to-noise ratio = 1) at the wavelength of 1531.59 nm.

1. Introduction

Trace gas detection plays an important role in many areas, such as environmental atmospheric monitoring, plant and insect respiration studies, and combustion studies [1–4]. Photoacoustic (PA) spectroscopy (PAS), which is characterized by fast response, overall high selectivity and sensitivity, is the most versatile method for trace gas analysis [5–7]. The sensitivity of the microphone will ultimately determine the capability of the PAS based sensing system. Most of the PAS systems reported so far use electric capacitive microphones [8–10], which transform the acoustically induced membrane vibration into an electric signal. A representative alternative is to use a piezoelectric transducer such as a quartz tuning fork [11–13]. However, the electric nature of these microphones limits their applications in circumstances with electromagnetic interference. Therefore fiber-optic microphones for PA detection have been investigated in recent years. The first attempt to use optical fiber to detect PA pressure wave was reported by Leslie et al. in 1981 [14]. Fiber-tip Fabry-Perot (FP) interferometer (FPI) is a typical type of microphone used for PA detection [15,16]. Because of its compact size, this type of fiber probe is particularly useful for space-limited applications. Cao et al. demonstrated a miniature all-optical PAS gas sensor [15]. The sensor head comprised of a fiber-tip FPI with a thin polymer diaphragm, which acted as a PA cell for light-gas interaction, as well as an acoustic probe. With this setup, a minimum detection concentration level of 4.3 parts-per-million (ppm) for acetylene (C_2H_2) was achieved. Wang et al. developed a diaphragm-based acoustic sensor which was integrated into a PA cell for gas detection [16]. With a polymer diaphragm of ∼4 mm in diameter and an excitation laser power of 500 mW, they demonstrated the detection of C_2H_2 gas with a minimum detection concentration of 1.56 parts-per-billion (ppb). Recently, in order to improve pressure sensitivity of the FPI, fiber-tip FP pressure sensors with silver diaphragms were reported [17–19]. Guo et al. made silver diaphragms with inner diameters of 75 μm by vacuum thermal evaporation deposition, leading to a static pressure sensitivity of 1.6 nm/kPa [17]. A nanothick silver diaphragm was fabricated by the electroless plating method, with a high pressure sensitivity of 70.5 nm/kPa [18]. However, attributed to lacking of adhesion and compactness, the diameters of these nanothick silver diaphragms could not be fabricated to be few millimeters level, which result in poor sensitivities. A Fabry-Perot acoustic sensor based on a large-area silver diaphragm with a high sensitivity was proposed [19]. But the measuring range of acoustic pressure is narrow, and temperature influence is a hidden trouble. Some fiber-optic FP sensors with graphene diaphragms have been reported [20,21], and the sensitivities were further improved. However, the grapheme diaphragms are too thin, which limit the measuring range of pressure, because the pressure response of the diaphragm is a linear response only when the diaphragm deformation is less than 30 percent of the diaphragm thickness [22].

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Meanwhile, the fabrication process of graphene diaphragm is especially complicated.

In this paper, we present a FPI-based acoustic sensor based on a thin silver diaphragm with a high sensitivity and a wide measuring range. The silver diaphragm is fabricated by vacuum magnetron sputter deposition and it has strong adhesion and good compactness. The FPI-based acoustic sensor, together with a tunable erbium-doped fiber laser (TEDFL), constitutes an all-optical PAS system for trace gas analysis. The system is successfully used for C_2H_2 gas detection and achieves a low concentration detection limit.

2. Sensor fabrication and response to acoustic pressure

Fig. 1(b) and Fig. 1(d) are the schematic and photograph of the sensor head that comprises of a special structured ferrule and a nanothick silver diaphragm. There is an air hole on the sensor head in order to keep the balance of internal and external pressure. The sensor head is easy disassembled and matched with the standard physical contact (PC) type of fiber optic connectors shown in Fig. 1(a). A PC type of fiber optic connector is screwed into the sensor head till the dashed line in Fig. 1(b) and then the acoustic sensor is fabricated. The picture of the final FPI-based sensor is shown in Fig. 1(c).

The fabrication process of the sensor head is schematically shown in Fig. 2. Firstly, a half-inch sodium chloride (NaCl) crystal is used as a substrate. The silver diaphragm is fabricated by the magnetron sputtering system (K575XD, E.M. Technologies Ltd.). A 500 nm intermediate layer of silver film is first deposited onto the NaCl substrate followed by a layer of 50 nm thin gold film shown in Fig. 2(a). The thin gold film is used to improve the reflectivity of the diaphragm. Some epoxy adhesive is then applied to the edge of the tube shown in Fig. 2(b). To improve the elasticity of the diaphragm, the adhesive film must be made very thin. Secondly, the diaphragm together with the NaCl substrate is glued to the sensor head. Finally, the NaCl substrate is applied into a drop of water. Because the substrate is a pure sodium chloride crystal, it is easy to be dissolved in the water with a few minutes. Meanwhile, the sensor head is lifted from the substrate to complete the sensor fabrication. In order to ensure that the water do not spread into the air hole to break the diaphragm, the silver diaphragm is positioned at substantially the same level or above the lever of water. The silver diaphragms have three different inner diameters, which are 4 mm, 5 mm and 6 mm, respectively. When we fabricate a diaphragm with the diameter of 6 mm, we find it is easy to be ruptured. In order to enhance adhesion of the diaphragm, we cover the gold film some extremely thin epoxy adhesive before glued on the sensor head.

Fig. 3 shows the reflection spectrum of a fabricated sensor with inner diameter of 6 mm measured by a swept laser interrogator (si720, Micron Optics Inc.). The FP cavity length is 1200 μm in order to stabilize the working point when the system suffers various environmental perturbations [23]. The response to static gas pressures of the FPI-based sensor is measured using a nitrogen cylinder tank and a gas regulator. In order to ensure leakproofness of the sensor, some epoxy adhesive is applied to the zirconia ceramic ferrule of the standard PC type of fiber optic connectors, as well as the air hole on the sensor head. A tunable distributed feedback laser with center wavelength of 1550 nm and maximum wavelength tuning range of 0.6 nm is employed as the light source. The laser beam is launched into a circulator, and then propagates into the probe of sensor. The differential extra gas pressures deform the diaphragm, leading to decrease of the FP cavity length. Then the signal can be demodulated from the changes of the reflected intensity detected by the interferometric intensity demodulation mechanism [24]. An InGaAs PIN photo detector (PD) is used to convert light signal into electrical signal. Amplified electrical signals are acquired by the data acquisition (DAQ), and then be transmitted to the computer. As shown in Fig. 4(a), the static pressure response of the FPI-based sensor with inner diameter of 6 mm shows that the pressure sensitivity is as high as 5.97 μm/kPa. The temperature dependence of the proposed sensor is tested in a temperature controlled chamber. Fig. 4(b) shows that the temperature sensitivity is 0.139 nm/°C

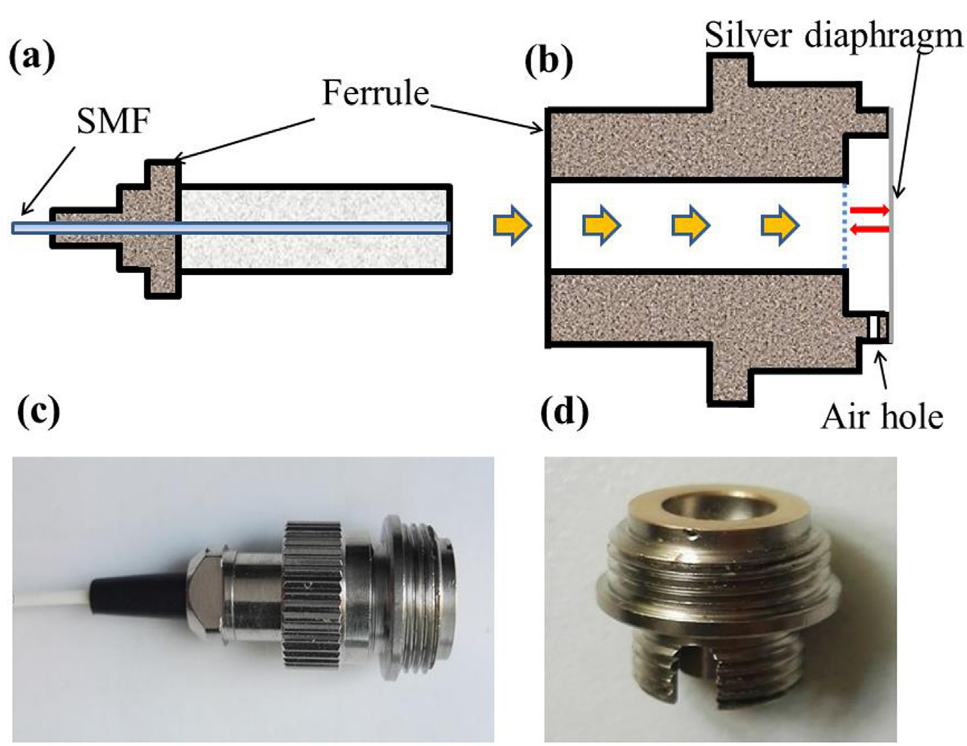

Fig. 1. (a) Schematic of a standard PC type of fiber optic connector; Schematic (b) and photograph (d) of the proposed FPI-based sensor head; (c) The picture of the final FPI-based sensor.