High-sensitivity, high-frequency extrinsic Fabry–Perot interferometric fiber-tip sensor based on a thin silver diaphragm

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We propose and demonstrate a fiber-tip sensor based on an ultra-thin silver diaphragm for highly sensitive and high frequency ultrasonic detection. The diaphragm is prepared by the vacuum thermal deposition method and then transferred to the fiber tip. The sensor demonstrated in this letter has a 300 nm thick diaphragm with an inner diameter of 75 μm, leading to a static pressure sensitivity of 1.6 nm/kPa and a resonant frequency of 1.44 MHz. This sensor has potential applications in many fields such as structural health monitoring and medical ultrasonography. © 2012 Optical Society of America

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Fiber-optic sensors possess many advantages over their electronic counterparts, including small size, light weight, immunity to electromagnetic interference, and capability for remote sensing. Among the smallest fiber-optic sensors are those fabricated on a fiber tip. The so-called fiber-tip sensors have attracted a great deal of attention in past years for pressure, temperature, and acoustic sensing. Such sensors typically consist of a Fabry–Perot (FP) cavity formed by a diaphragm attached to the fiber end. Several fabrication techniques for fiber-tip sensors using various diaphragm materials have been demonstrated. Most of them are based on a silica diaphragm which is obtained by splicing another piece of optical fiber to the fiber end face followed by cleaving [1–3]. These sensors have high temperature capacity. However, due to the limited precision of the cleaving process, the diaphragm is typically tens of micrometers thick, which reduces the sensor sensitivity. Although hydrofluoric acid etching can reduce the diaphragm thickness and improve the sensitivity [3–4], it is still a challenge to achieve submicrometer thickness for a silica diaphragm. Polymer diaphragms fabricated onto the fiber tip from solutions have also been demonstrated [5–6]. They are typically a few micrometers thick. The thermal and chemical instability of polymer diaphragms have limited their applications. Recently, a FP fiber sensor based on an ultra-thin silver diaphragm with a thickness of ~130 nm was developed for high-sensitivity pressure measurement [7]. The diaphragm was prepared by solution-based silver mirror reaction and was absorbed onto the end face of a fiber ferrule. The diaphragm preparation method is limited to the silver material. In addition, the sensor size is much larger than the fiber diameter due to the use of a fiber ferrule, and cannot be considered as a fiber-tip sensor.

For a fiber-tip sensor based on an edge-clamped circular diaphragm, the static pressure sensitivity, defined as the diaphragm deformation at the center due to pressure, is proportional to r^4/h^3, where r and h are the radius and thickness of the diaphragm, respectively; whereas the lowest resonant frequency is proportional to h/r^2 [8]. It is seen that the small thickness and the small diameter of the diaphragm of a fiber-tip sensor allow the sensor to achieve high sensitivity and high frequency response simultaneously. These qualities are attractive in many applications such as structural health monitoring and medical ultrasonography. However, most of the study on fiber-tip sensors has been focused on the sensor fabrication and sensor tests under static pressure.

In this letter, we present a fiber-tip sensor based on an ultra-thin silver diaphragm for high sensitivity and high frequency ultrasonic measurement. The diaphragm is prepared by vacuum thermal evaporation deposition which is subsequently transferred to a tube spliced to the end face of a single-mode fiber. The diaphragm preparation method is versatile and many materials can be used. The sensor reported in this letter has a 300 nm thick diaphragm on a tube with an inner diameter of 75 μm. The static pressure sensitivity is measured to be 1.6 nm/kPa, and the lowest order resonant frequency is measured to be 1.44 MHz.

The sensor fabrication process is schematically shown in Fig. 1. First, a single-mode fiber was spliced with a fused silica microtube using a fiber splicer in manual mode. The outside diameter of the tube is 125 μm, same as the fiber diameter; the inner diameter of the tube is 75 μm. Then we cut the microtube to a specified length using a fiber cleaver facilitated by an optical microscope and a linear translational stage. The resulting structure is shown in Fig. 1(a) We then applied a UV-curable, low-viscosity epoxy to the edge of the tube. In order to ensure that the epoxy did not spread into the tube or the diaphragm, we first spin coated a uniform thin layer (~3 μm) of the epoxy onto a glass substrate and then transferred the epoxy to the tube end by pushing the tube onto the epoxy film and lifting it up [Fig. 1(b)].

The silver diaphragm was prepared by vacuum thermal evaporation deposition. A shutter mask with arrays of round holes of 125 μm diameter, same as the diameter of a bare optical fiber, was placed on top of the glass substrate before deposition. A 100 nm intermediate layer of lithium fluoride (LiF) was first deposited onto the glass substrate followed by a layer of 300 nm silver thin film

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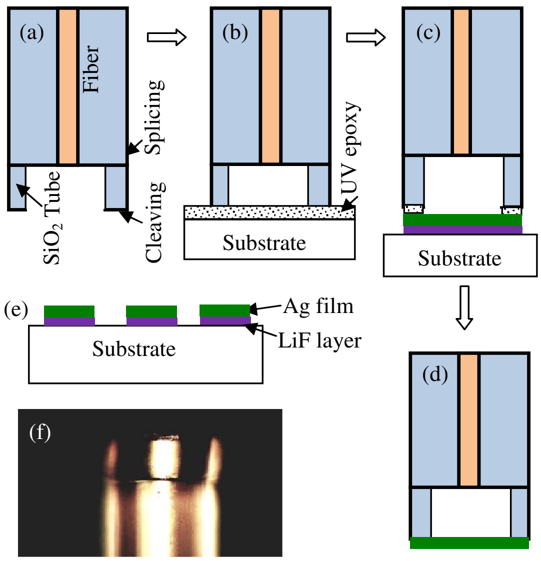

Fig. 1. (Color online) Sensor fabrication process (a)–(d), silver thin film deposited on a glass substrate (e), and an optical microscope picture (f) of a typical sensor fabricated.

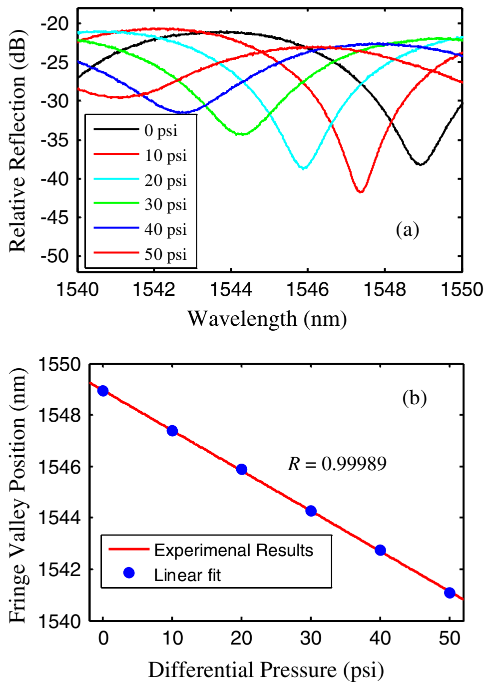

Fig. 3. (Color online) Static pressure test of the fiber-tip sensor: (a) Reflection spectrum at different pressure levels; (b) spectral position of the fringe valley versus differential pressure.

[Fig. 1(e)]. Thinner or thicker thin films can also be produced by controlling the deposition time. The intermediate LiF layer is water soluble and facilitates the transfer of the silver thin film to the end of the fused silica microtube on the fiber tip, to form the diaphragm of the fiber-tip sensor. Each deposition process produces arrays of 125 μm diameter thin films that can be used for fabrication of a number of sensors. The thin film transfer was achieved by pushing the microtube with preattached UV epoxy onto a silver film. The alignment of the microtube and thin film was facilitated by an optical microscope. Then the epoxy was cured by a UV lamp. After UV curing, a drop of water was applied to the substrate to dissolve the LiF layer, and the sensor was lifted from the substrate [(Fig. 1(d)] to complete the sensor fabrication. Figure 1(f) is a microscope picture of a typical fiber-tip sensor fabricated by this method.

Figure 2 shows the reflection spectrum of a fabricated sensor measured by a sensor interrogator (Si125, Micron Optics). The sinusoidal interference fringes indicate that the FP cavity length is ~110 μm. We tested the sensor for response to static gas pressures using a nitrogen (N_2) cylinder tank and a gas regulator. The differential gas pressure was changed from 0 psi to 50 psi in steps of 10 psi. Figure 3(a) shows the reflection spectrum of the fiber-tip sensor at different differential pressure levels as measured by the Si125 sensor interrogator. As expected, the fringes shifted toward the lower wavelength as the gas pressure increase deformed the diaphragm and reduced FP cavity length. We notice that the fringe visibility varied with the pressure. The mechanisms responsible for the variations are still under investigation. Figure 3(b) shows the wavelength position of the spectral valley in the range of 1540–1550 nm, and its linear fitting curve as a function differential pressure. The linear fitting curve indicates that the fiber-tip sensor has very good linear response to differential pressure, with a correlation coefficient (R) of 0.99989. From the FP cavity length and the linear fitting curve, we calculate that the pressure sensitivity of the sensor is approximately 1.6 nm/kPa.

In addition to the static pressure test, we characterized the impulse response of the same sensor to an ultrasonic pressure field generated by an ultrasonic piezoelectric transducer (PZT) in water and then obtained the frequency response of the sensor by carrying out the Fourier transform of its impulse response. The experimental setup is schematically shown in Fig. 4. A wavelength tunable

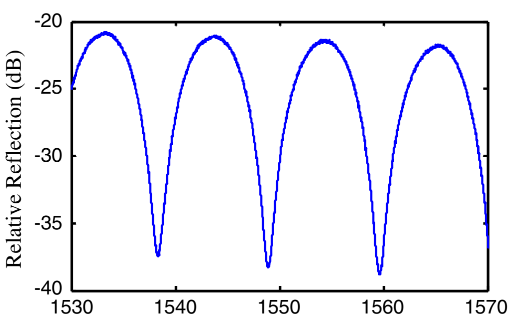

Fig. 2. (Color online) Reflection spectrum of a fiber-tip sensor.

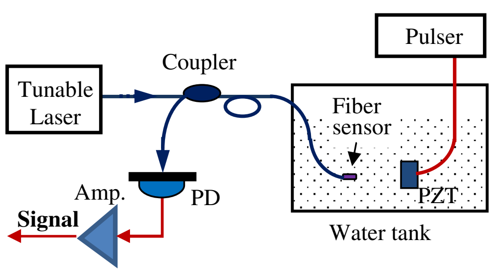

Fig. 4. (Color online) Setup for frequency response test of the fiber-tip sensor. PD, photodetector; Amp., amplifier.

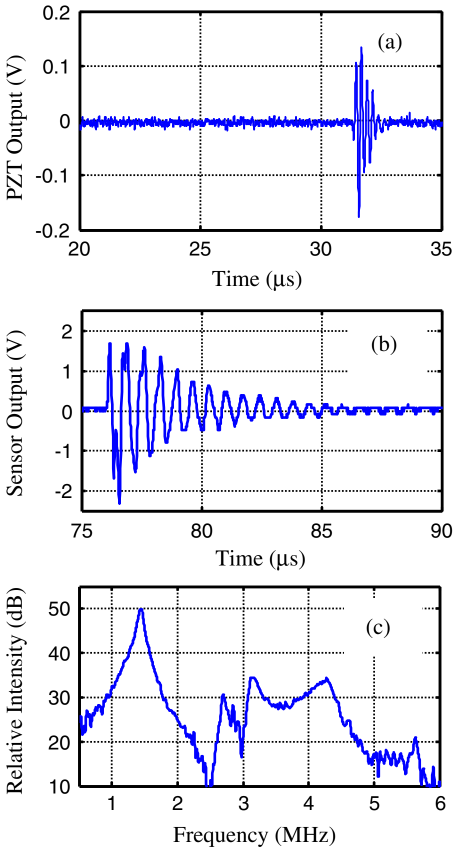

Fig. 5. (Color online) Frequency response test of the sensor: (a) ultrasonic impulse signal measured by a 5-MHz PZT; (b) response of the fiber-tip sensor to the ultrasonic impulse in (a); (c) Fourier transform of the impulse response shown in (b).

laser was used as the light source, whose wavelength was tuned to a quadrature point of the reflection fringes of the sensor. The reflected light from the sensor was detected by a photodetector followed by a bandpass amplifier. The bandwidth of the photodetector is from DC to approximately 6 MHz and the amplification bandwidth of the amplifier is 50 kHz–20 MHz, resulting in an overall detection bandwidth from 50 kHz to 6 MHz. The PZT has a resonant frequency of 5 MHz and is powered by a pulser to generate an ultrasonic impulse. Figure 5(a) shows the ultrasonic impulse, which was measured by the same PZT using the pulse echo mode through a point reflector inserted in place of the fiber-tip sensor. It is seen that the ultrasonic pulse consists of a few cycles of a 5 MHz signal. The pulse width, defined by the full width at half maximum of the ultrasonic envelope, is approximately 600 ns. Figure 5(b) shows the response of the fiber-tip sensor to the ultrasonic impulse. The exponentially decreasing ringing signal typical to the impulse response of a resonator is evident in the figure. The frequency response of the sensor, given by the Fourier transform of the impulse response, is shown in Fig. 5(c). The resonant frequency of the fiber-tip sensor is 1.44 MHz and the 3-dB bandwidth of the frequency response is 0.10 MHz, from which we calculate that the Q-factor of the diaphragm resonance in water is 14.4. The spectral response also shows a few peaks at higher frequencies between 2.5 and 5 MHz. However, these peaks are much weaker than the resonant peak at 1.44 MHz, and their origins need to be further investigated.

In summary, we have proposed and experimentally demonstrated a novel fabrication method for fiber-tip sensors based on an ultra-thin diaphragm. The diaphragm is prepared by a vacuum thin film deposition technique and then transferred to a microtube that has been spliced to the fiber tip and cleaved to a desired length. The fabrication method leads to ultra-thin and precisely controlled diaphragm thickness, and many materials can be used for the diaphragm. The ultra-thin and ultra-small diaphragm renders a fiber-tip sensor with high sensitivity and high frequency response. The fiber-tip sensor demonstrated here has a 300 nm thick silver diaphragm on a 75 μm inner diameter microtube, which achieves a sensitivity of 1.6 nm/kPa and a resonant frequency of 1.44 MHz. The sensitivity and frequency response can be further improved by using thinner diaphragms and microtubes with smaller inner diameters. Such sensors are expected to find applications in many areas, such as structural health monitoring and medical ultrasonography, where sensitive and high-frequency ultrasonic sensors are desired.

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