High-Sensitivity Gas-Pressure Sensor Based on Fiber-Tip PVC Diaphragm Fabry–Pérot Interferometer

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***Abstract*—We demonstrate a novel polyvinyl chloride (PVC) diaphragm-based fiber-tip Fabry–Perot interferometer for gas-pressure measurements with ultrahigh sensitivity. The PVC diaphragm has been coated to the end facet of a well-cut standard single-mode fiber by use of a plastic welder. An ultrahigh-pressure sensitivity of ∼65.5 nm/MPa at 1565 nm and a low-temperature cross sensitivity of ∼–5.5 kPa/°C have been experimentally demonstrated. The proposed sensor has advantages of high pressure sensitivity, miniature size, low cost, and easy fabrication.**

***Index Terms*—Optical fiber devices, optical fiber measurements, thin-film devices.**

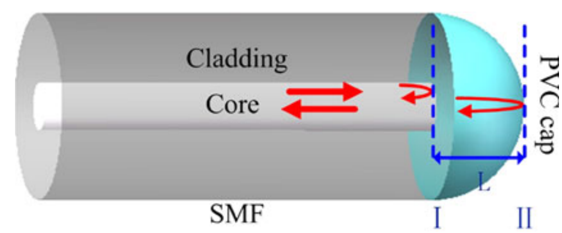

Fig. 1. Schematic of the proposed fiber-tip FPI.

I. Introduction

FIBER-OPTIC Fabry-Perot interferometers (FPIs) have advantages such as immunity to electromagnetic interference, miniature size, and the capability of taking probe-type measurements, making it a good candidate for many applications in biomedicine, artificial intelligence, and environmental monitoring. Various FPI sensors have been proposed and applied for measurements of strain [1], refractive index [2], [3], vibration [4], temperature [3], [5]–[8], pressure [9]–[15], and acoustic signal [16]–[18]. Among them, FPI-tip pressure sensors employing an elastic diaphragm at the fiber tip as one of the reflecting mirrors have attracted tremendous research interest. The elastic diaphragm may be composed of polymer [9], [19], silica [10], [20], silver [12], graphene [15], or even water film [13]. Polymer materials with the advantages of versatility, easy fabrication, and low-cost processing have been considered an excellent choice for optical sensor structures. A low elastic modulus can provide adequate sensitivity for polymer-based FPI pressure sensors. Usually, the polymer tip of the FPI is fabricated using conventional semi-conduction processes such as photolithography, chemical vapor deposition (CVD), and/or reactive-ion etching (RIE) on wafer scale [21], [22], or by use of dip coating [16], [23] or ultraviolet (UV) curing adhesive [9], [18], [24] methods. However, all of the aforementioned fabrication methods are complicated and the pressure sensitivities achieved are not high enough.

In this Letter, a novel method of fabricating ultrasensitive FPI pressure sensors is experimentally demonstrated. The proposed probe-type sensing structure is miniaturized and based on a **polyvinyl chloride** (PVC) cap created on the end facet of a standard single-mode fiber (SMF). The pressure sensitivity of the proposed sensor at 1565 nm is ∼65.5 nm/MPa, which is ∼60 times higher than reported in our previous work [24], and the temperature cross-sensitivity is ∼5.5 kPa/°C, which is ∼40 times lower than that reported in [24]. Moreover, the proposed fabrication method is highly efficient, low cost, and repeatable, and employs only a fiber cleaver and a plastic welder.

II. Sensor Fabrication

Fig. 1 is a schematic of the proposed fiber-tip FPI. A few layers of commercial PVC diaphragm are folded together (multilayer PVC diagram) and welded to the end facet of a well-cut SMF by use of a plastic welder. In this process, the PVC diaphragms fused and solidified, forming a PVC cap on the end facet of the SMF. Two reflected waves are collected and transmitted back to the SMF: one is from the interface between the fiber end

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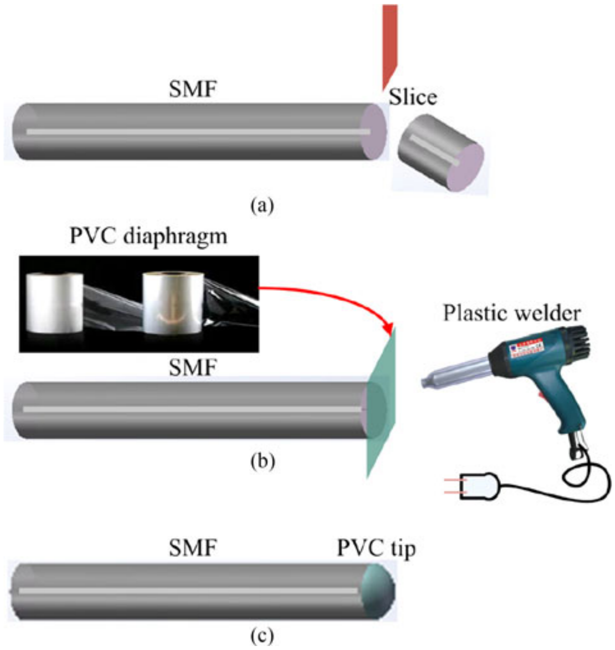

Fig. 2. Schematic of the fabrication process of PVC-diaphragm-based fiber-tip FPI pressure sensor.

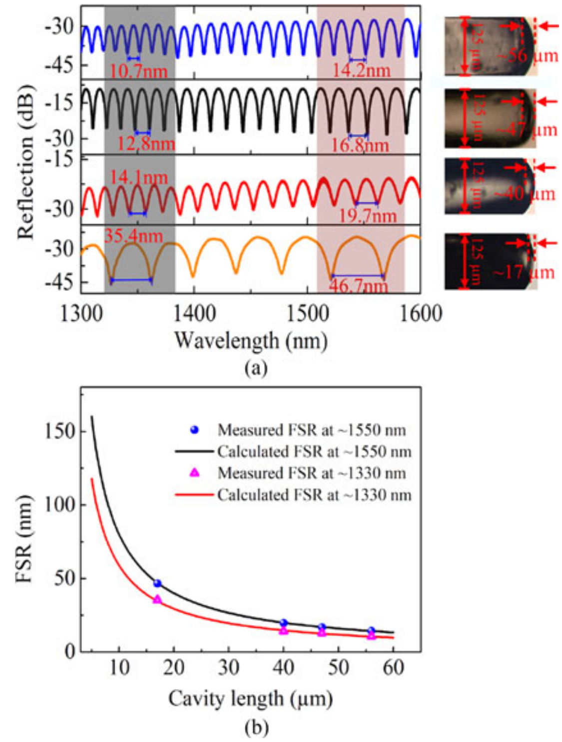

Fig. 3. (a) Reflection spectra and the corresponding microscope images of the four FPIs with different cavity lengths in air at room temperature. (b) Measured and calculated FSRs of the four FPIs at ~1330 and ~1550 nm, respectively.

and the PVC cap, i.e., surface I, and the other is from the outer surface of the PVC cap, i.e., surface Π. The working principle was introduced in Ref. [20].

Fig. 2 schematically illustrates the fabrication process of the PVC-diaphragm-capped FPI, which involves two steps. In step 1, as shown in Fig. 2(a), a section of standard SMF is well cut by a fiber cleaver. In step 2, the multilayer PVC diaphragm is welded to the well-cut end of the SMF by a commercial plastic welder, as illustrated in Fig. 2(b). Using this method, we successfully fabricated a series of solid PVC caps on the end facets of SMFs. Furthermore, the thickness of the PVC cap can be changed by adjusting the layer numbers of the PVC diaphragm.

The reflection spectra and corresponding optical microscope images of the PVC-capped FPI sensors with different cavity lengths of ~56, ~47, ~40, and ~17 μm are shown in Fig. 3(a), where it is seen that the free spectral range (FSR) in the reflection spectrum increases with decreasing cavity length. The FSR is given by the Fresnel reflection equation, $FSR = \lambda^2/(2nL)$, where L is the cavity length, n the refractive index of the cavity, and λ the wavelength. The experimental measured and calculated FSRs are compared at ~1330 and ~1550 nm, respectively, and the measured FSRs agree well with the calculated values, as shown in Fig. 3(b).

III. Pressure Response and Temperature Influence

An experimental setup, schematically illustrated in Fig. 4, was employed to test the proposed pressure sensor. The setup features a broadband light source (BBS) and an optical spectrum analyzer (OSA) (Model AQ6370C, Yokogawa Electric Corp., Tokyo, Japan) with a resolution of 0.5 nm connected to the other end of the SMF via a 3-dB coupler for the reflection spectrum measurements. A PVC-capped FPI with a cavity length of

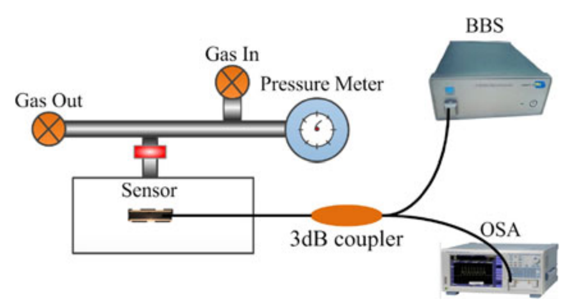

Fig. 4. Experimental setup for pressure measurement.

~40 μm was placed into a gas chamber; the chamber employed is the same as that described in [20]. The reflection spectrum of the tested FPI at room temperature (~25 °C) and standard atmospheric pressure is shown in Fig. 5(a), where the fringe contrast is ~15 dB, and the fringe spacing is ~21 nm at ~1565 nm. The fringe contrast γ can be expressed as [31]

$$\gamma = \frac{2\alpha\sqrt{R_1 R_2 \eta}}{R_1 + R_2\eta}, \quad (1)$$

which depends on the source coherence α, the intensity ratio of the two reflected light beams, and the transmission coefficient η. The intensity ratio of the two reflected light beams, R_1/R_2, is determined by the reflectivity of the two interfaces. For the diaphragm-based FPI shown in Fig. 1, the reflectivity of the fiber end/diaphragm interface, R_1, and that of the diaphragm/air

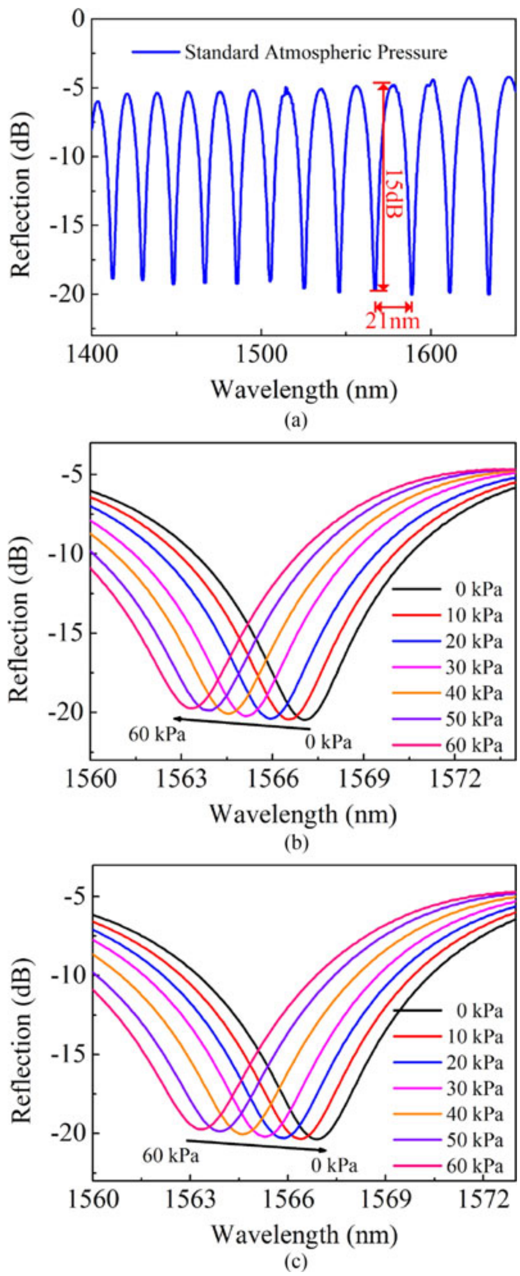

Fig. 5. (a) Reflection spectrum of the FPI with $L = 40\ \mu$m at standard atmospheric pressure and room temperature. Reflection spectrum evolution of the FPI sensor with (b) an increased gas pressure from 0 to 60 kPa and (c) a decreased pressure from 60 to 0 kPa.

interface, R_2, is given by

$$R_1 = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2}, \quad R_2 = \frac{(n_2 - n_3)^2}{(n_2 + n_3)^2}, \tag{2}$$

where n_1, n_2, and n_3 are the refractive indices of the fiber, of the diaphragm, and of the air, respectively. The maximum fringe visibility γ can be achieved for the condition $R_1 = \eta R_2$. For the FPI with long cavity length, high reflectivity R_2 is necessary to compensate the loss caused by the decreased transmission coefficient. In our configuration ($n_1 = 1.446$, $n_2 \approx 1.53$, $n_3 = 0$), R_2 is higher than R_1 according to (2), which results in a high fringe

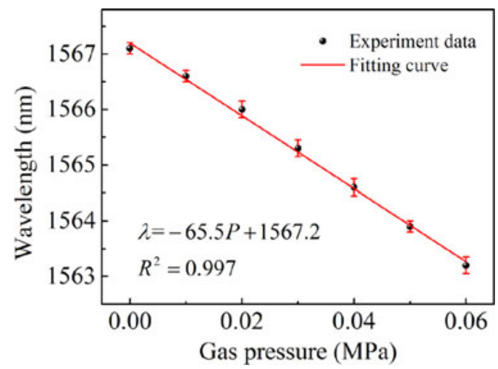

Fig. 6. Wavelength of the tracked dip vs gas pressure.

TABLE I
GAS-PRESSURE SENSITIVITY OF SEVERAL FIBER-OPTIC FPI STRUCTURES

FPI structure	Wavelength sensitivity
FPI embedded in pressure fittings [25]	0.24 nm/MPa
Fiber-tip air-bubble FPI [20]	1.06 nm/MPa
Pendant polymer droplet-based FPI [24]	1.13 nm/MPa
FPI based on concave well on fiber end [26]	1.53 nm/MPa
FPI with open cavity [27]	2.46 nm/MPa
FPI based on dual capillaries [28]	4.15 nm/MPa
Hollow-core photonic bandgap fiber with a side opened channel FPI [29]	4.24 nm/MPa
PVC diaphragm-based FPI (present work)	**65.5nm/MPa**

contrast. Moreover, owing to the low reflectivity R_1, the average reflection level seems to be larger than -10 dB.

The chamber pressure is increased from 0 to 60 kPa in increments of 10 kPa, remaining at each step for 5 min. Resonant dips at approximately 1565 nm are tracked, as shown in Fig. 5(b), where the fringe dip shifts toward shorter wavelength with pressure increasing. Then, the applied pressure is decreased from 60 to 0 kPa, and the tracked dip shifts back to longer wavelength, as shown in Fig. 5(c). The gas pressure is increased and decreased five times and the error-bar charts is provided to illustrate the measurement repeatability. The wavelength of fringe dip versus the applied pressure is illustrated in Fig. 6, where a linear fitting yields an ultrahigh-pressure sensitivity of -65.5 nm/MPa. It is worth noting that the linear response of the sensor can be only achieved in a small pressure range. Due to the mechanical property of the PVC diaphragm, the sensor will present a nonlinear response to gas pressure in a large measurement range. A variety of reported fiber-optic FPI gas-pressure sensors that employed different cavity structures are presented in Table I, where the proposed PVC diaphragm-based fiber-tip pressure sensor exhibits the highest sensitivity. The pressure response of the sensor is expressed as

$$\frac{d\lambda}{dP} = \lambda \left(\frac{1}{L}\frac{dL}{dP} + \frac{1}{n}\frac{dn}{dP} \right), \tag{3}$$

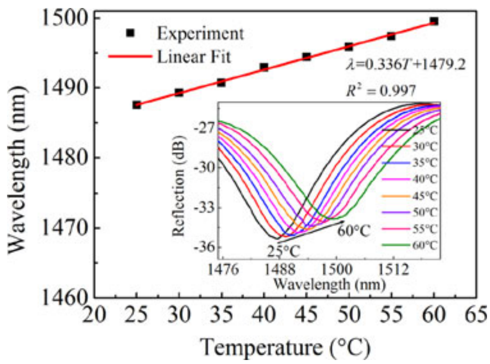

Fig. 7. Wavelength of the fringe dip at ~1500 nm vs applied temperature. Inset: reflection spectral evolution from 25 to 60 °C.

where n is the refractive index of the PVC cavity, L the cavity length, P the applied pressure, and λ the wavelength of the interference dips. Since the low elastic modulus of PVC material, dL/dP, can be large, a high pressure sensitivity results. The "blue shift" of the tracked dip with increasing pressure can be explained by both cavity deformation and the refractive-index change of the cavity medium. In the pressure test, it is known that dL/dP is negative and dn/dP is positive, and therefore we believe that the cavity deformation plays a major role in the pressure response of the sensor. The diaphragm we employed is a compound comprised of PVC and some unknown plasticizers, and its elasto-optic coefficient and elastic modulus cannot be assigned, so the quantitative analysis is not given here.

The temperature-induced measurement error was investigated by placing the device in an electrical oven with a temperature stability of ±0.2 °C. The measurement method has been described in [6] and [30]. The reflection spectral evolution from 25 to 60 °C is illustrated in the inset of Fig. 7, where a red shift is clearly observed with increasing temperature. The shift of the dip wavelength at ~1490 nm with increasing temperature is also shown in Fig. 7, where a linear fitting yields a temperature sensitivity of ~366 pm/°C. We believe that the temperature drift of the fiber sensor is a result of thermal expansion and thermo-optic effects of the PVC cap according to

$$\frac{d\lambda}{dT} = \lambda\left(\frac{1}{L}\frac{dL}{dT} + \frac{1}{n}\frac{dn}{dT}\right). \quad (4)$$

When no temperature compensation is employed, the error resulting from temperature cross-sensitivity is ~ -5.5 kPa/°C, which is ~40 × lower than that in our previous work [24].

IV. Conclusion

We have experimentally demonstrated a novel method of fabricating a PVC diaphragm-based fiber-tip FPI for gas-pressure measurements. The proposed sensor exhibits an ultrahigh gas-pressure sensitivity of −65.5 nm/MPa at ~1565 nm and a small temperature cross-sensitivity of ~ -5.5 kPa/°C. The fabrication method is highly efficient, low cost, and repeatable, and employs only a plastic welder and a piece of PVC diaphragm. Owing to advantages of high sensitivity, simple structure, and good repeatability, the micron PVC diaphragm-based fiber-tip FPI sensor is attractive for pressure monitoring in practical applications.

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