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Simultaneous measurement of gas pressure and temperature with integrated optical fiber FPI sensor based on in-fiber micro-cavity and fiber-tip

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ABSTRACT

In paper, an integrated optical fiber Fabry-Pérot interferometer (FPI) sensor is proposed and fabricated. The all-fiber sensor is composed of an in-fiber micro-cavity machined by 193 nm excimer laser and a tiny segment of single-mode fiber (SMF). Due to the production of reflection mirrors, the composite FPI structure with different interference cavity is formed between every two surfaces of micro-cavity and fiber-tip. Resulting from the influences of thermal expansion effect of fiber and the thermo-optic effect of in-cavity gas, the interference spectrum of FPI sensor can shift with the temperature and pressure change with different rules. Experimental researches indicate, the low-frequency interference fringe of air cavity is sensitive to pressure change and insensitive to temperature change, but the high-frequency interference fringe of micro-fiber cavity is sensitive to temperature change and insensitive to pressure change. Through analyzing with fast Fourier transform (FFT) and Fourier band-pass filtering (FBPF) methods, we obtain the temperature and pressure sensitivities of the two different cavities. Owning to the different responses to gas pressure and temperature change, the fiber sensor can be used in simultaneous measurement of them, and has excellent merits of miniature size, strong tip structure, simple manufacturing and low cost.

1. Introduction

Optical fiber Fabry–Pérot interferometer (FPI) sensor as one kind of promising fiber sensor to realize smart measurement has attracted much more investigations. Especially for the precision measurement, optical fiber FPI sensor is applied widely owning to its intrinsic features of compact size, immunity to electromagnetic interference, and better sensitivity [1,2]. As the sensing principle of FPI is based on changing the optical path difference (OPD) or the reflectance of interference cavity surfaces [3,4], the variations of the factors associated with micro-cavity such as cavity length, refractive index (RI) and reflectance will result in the spectral wavelength shift or intensity variation of interference fringes. These characteristics made the FPI sensor with different cavity can be used in air pressure, ambient RI, temperature, strain and even the simultaneous measurement of them [5–9], and some relevant types FPI sensor structures based on cavity or fiber-tip are proposed. In literature [5], Wu. C et al. demonstrated an open-cavity optical fiber FPI sensor by splicing a thin piece of C-shaped fiber between two standard single-mode fibers. In range of RI (1.33–1.36), the RI sensitivity was measured to be 1368 nm/RIU, and the effect of material dispersion of analyte on the sensitivity of open-cavity FPIs was identified for the first time. Liao et al. [10] made use of improved discharge technology to produce a sub-micron silica diaphragm-based fiber-tip FPI sensor for pressure measurement, where the silica diaphragm of micro-bubble at the fiber end has a thickness of only 320 nm. The pressure sensitivity of spectral wavelength shift is 1.036 nm/MPa. In order to realize the simultaneous measurement of pressure and temperature, Sun et al. [11] utilized the method of forming polymer end cap on fiber end face to obtain a fiber FP sensor. Consequently, the temperature sensitivity of 0.249 nm/°C and pressure sensitivity of 1.13 nm/MPa are obtained, respectively. Tian J. et al. [12] proposed a cascaded-cavity FPI sensor. The two cascaded FP cavities comprise a micro-air-cavity in a hollow-core tube fiber and a micro-silica-cavity in a standard single-mode fiber. Due to the different responses of two FP cavities for temperature and strain, by solving a sensitivity-coefficient matrix equation, the simultaneous measurement was realized.

It is easily concluded that different medium FP cavity will lead to different response to ambient change. For the pressure measurement, the proposed methods in literatures [4,8–11] are obviously sensitive to pressure change, and the temperature cross-insensitivity also can be compensated. Nevertheless, the mechanical strength of sensor is weakened because of thinner sub-micron silica diaphragm, and the temperature measurement range is limited since polymer is not suitable for working in high temperature environment. For the needs of achieving

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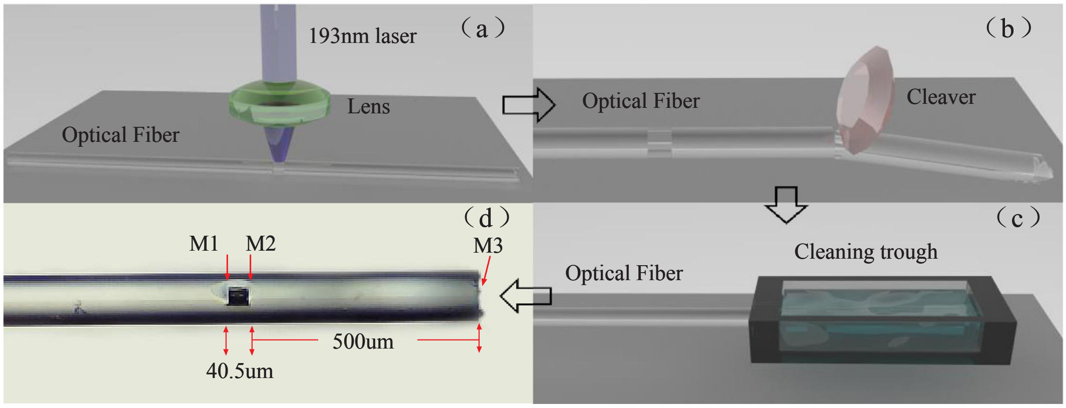

Fig. 1. Schematic diagrams of sensor fabrication: (a) Machining micro-hole in SMF. (b) Cleaving fiber near the micro-hole position. (c) Cleaning fiber micro-hole with 5% HF solution. (d) Micrograph of composited FPI fiber sensor.

higher pressure sensitivity, wide employing temperature range, and much more compact size, as well as simplified production method, based on the method of constructing composite sensing structure with micro-silica-cavity and micro-air-cavity [12], we make an all-fiber FPI-composite-based sensing structure for the measurement of gas pressure and temperature. For our proposed sensor, it is composed of an open in-fiber micro-cavity and a tiny section of fiber. Due to the three beams interference resulting from surface reflections of micro-cavity and fiber-tip, and the air FP cavity and fiber FP cavity have different responses to pressure and temperature change. Hence, the sensor not only can be used in temperature and pressure measurements, but also has higher pressure sensitivity compared with the other proposed structure [10,11]. Because of having the properties of simple structure, small size, and all-fiber structure, the sensor is very suitable for measuring high temperature and high pressure in extreme environments.

2. Fabrication and principle

2.1. Sensor fabrication

The schematic diagrams of sensor fabrication process are shown in Fig. 1. The main instruments include the 193 nm AF excimer laser (Atlex-500, ATL, Germany) and high precision cleaver (CT-30A, Fujikura, Japan). Their setting parameters are shown in Table 1. At first, we put a section of SMF without plastic coating on the tunable 3D micro-displacement platform (10 µm, China) and fixed fiber on it, and then let the shaped transmission light that comes from the excimer laser pass through a rectangular slot and focus on fiber surface. At the same time of irradiating the fiber for about ten seconds, the laser pulse and the height of micro-displacement platform are simultaneously increased gradually. Consequently, a rectangular micro-hole can be fabricated, and the depth of micro-hole is approximate to the whole diameter of fiber. Secondly, the machined fiber with micro-cavity is moved to a fiber cleaver. The fiber at one side of micro-cavity will be cut off, and a fiber length of about 500 µm is remained. Thereupon, three reflection mirrors are produced, the two of them are the surfaces of micro-cavity, and the other is the end surface of fiber-tip. Correspondingly, three FP cavities are formed. One is the open micro-hole, and the other two are micro-fiber cavity and the micro-hole-fiber combined cavity, respectively. And then, in order to clean the material powder in the micro-hole, the fiber structure is etched by the hydrofluoric (HF) acid solution of 5% [13,14] for a moment. After finishing the etching, the fiber structure is washed by distilled water. Lastly, a composited optical fiber FPI sensor is fabricated successfully, and the micrograph and dimension parameters are shown in Fig. 1(d).

Table 1
193 nm Excimer Laser Processing Parameters.

No.	Name	Parameters
1	GAS	ArF
2	Warelength	193 nm
3	Energy	20 mJ
4	Rep Rate	50 hz
5	Power	0.5–2.0 w
6	Pulse-width	5–8 ns
7	Spot-size	4 * 6 mm
8	BDA (V*H)	1 * 2 mrad

Gas medium units are the same as GAS; BDA = beam-divergence angle, nm = nanometer; mJ = millijoule, hz = hertz, w = watt, ns = nanosecond, mm = millimetre, mrad = milliradian.

2.2. Sensing principle and spectrum analysis

For the proposed sensing structure that is shown in Fig. 1(d), because of having three reflection surfaces M1, M2 and M3, there will be three FP cavities which are formed between the every two surfaces. The two basic cavities are the open micro-hole between M1 and M2 and the fiber between M2 and M3. Therefore, the third one is the composite cavity consisting of micro-hole and the section fiber between M1 and M3. Once coming into being interference in fiber, the spectral intensity of reflection light can be given by [15]:

$$I(\lambda) = |A_1 - A_2\cos(\varphi_1) + A_3\cos(\varphi_1 + \varphi_2)|^2 = A_1^2 + A_2^2 + A_3^2 - 2A_1A_2\cos\varphi_1 - 2A_2A_3\cos\varphi_2 + 2A_1A_3\cos(\varphi_1 + \varphi_2) \tag{1}$$

where A_1, andA_2 are the reflective amplitudes of incident light through M1, M2 and M3. The symbols φ_1 and φ_2 represent the phase differences of reflected light coming from M1 and M2, M2 and M3, respectively.

$$\varphi_1 = \frac{4\pi n_0 l_0}{\lambda}, \quad \varphi_2 = \frac{4\pi n_1 l_1}{\lambda} \tag{2}$$

In Eq. (2), λ is the light wavelength, l_0 and n_0 are the length and medium refractive index (RI) of the micro-hole cavity, and l_1 and n_1 are the length and RI of the micro-fiber cavity, respectively.

From Eq. (1), we can conclude that the final spectrum results from the spectral superposition of three FPIs with different cavity length. The optical path difference (OPD) of each FP cavity can be expressed as $2n_0l_0$, $2n_1l_1$, and $2n_0l_0 + 2n_1l_1$ through contrasting Eq. (1) with (2), which means there are three kinds of different free spectral ranges (FSR) in the superposition spectrum. But due to the different amplitudes of incident light at M2, M2 and M3, the different FP cavities have uncoordinated contributions for the spectral intensity. These facts can be demonstrated by fast Fourier transform (FFT) from the experimental spectrum and simulated spectrum of sensor in Fig. 1(d).

As shown in Fig. 2(a), it is the experimental interference spectrum of