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Optical fiber tip interferometer gas pressure sensor based on anti-resonant reflecting guidance mechanism

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ABSTRACT

We propose and demonstrate a gas pressure sensor based on an anti-resonant reflecting guidance (ARRG) mechanism in quartz capillary tube with an open cavity. The device is simple in fabrication by only fusion splicing a segment of capillary tube with single mode fiber. It has compact size, robust structure, convenient mode of operation, and high sensitivity of 4.278 nm/MPa. Moreover, as two Faby-Perot cavities exist in the device, which create the interference spectrum with several distinct resonance dips, a simultaneous gas pressure and temperature detection can be readily achieved by tracing two dip wavelengths. The error in the measurement due to the choice of different resonant dips can be effectively reduced by using the Fourier band pass filtering method.

1. Introduction

Optical fiber gas pressure sensor has received increased research attention due to its features such as immunity to electromagnetic interference, compact size, remote detection and multiplexing capability. Among many configurations of optical fiber gas pressure sensors, fiber tip Fabry-Perot interferometer (FPI) cavity is particularly attractive owing to its high sensitivity, ultra-compact size and convenient reflection mode of operation [1–13]. Such a sensor mainly operates on two mechanisms: cavity length change [1–8] or cavity medium refractive index (RI) variation [9–13]. The FPI gas pressure sensors based on cavity length change usually have relatively low sensitivity, except those using ultra-thin diaphragm on the fiber tip [4–6]. Although a high sensitivity of up to tens of nm/MPa can be achieved, the sensor has only limited measurement range of a few tens of kPa and more importantly, the sensor head with thin diaphragm on the fiber tip has poor robustness, and is difficult to sustain hazardous environment. For the FPI gas pressure sensors relying on cavity RI change, a large measurement range and better robustness can be achieved however, a relatively low sensitivity, typically in a few tens of pm/MPa, is obtained. Moreover, temperature cross-sensitivity is still an issue needs to be carefully addressed in many of above-mentioned sensors.

Anti-resonant reflecting fiber is a kind of waveguide whose spectral characteristics are governed by the thickness of the first high refractive index layer rather than the lattice constant, in the near-infrared and terahertz optical signal transmission and other related fields has received widespread attention and recognition [14]. Many structures of anti-resonant reflective fibers have been used for sensing measurements on a variety of occasions, including humidity-insensitive temperature sensor in quartz capillary [15], hollow-core fiber (HCF) coated with functional material films for humidity sensing and magnetic field sensing [16,17]. Moreover, HCF drilled through femtosecond lasers are used for air pressure sensing [18].

In this paper, we propose and demonstrate a gas pressure sensor based on an anti-resonant reflecting guidance mechanism in capillary tube. The cladding of the capillary tube waveguide can be considered as a Fabry-Perot (FP) etalon. The device is ultra-compact, robust and easy in fabrication and has high pressure sensitivity of 4.278 nm/MPa. Moreover, as two FP cavities exist in the device, which create the interference spectrum with several distinct resonance dips, a simultaneous gas pressure and temperature detection can be readily achieved by using multiple-dip tracing technique and the Fourier band pass filtering (FBPF) method.

2. Device fabrication and operating principle

The fabrication process of the proposed fiber FP Interferometer (FPI) sensor head is illustrated in Fig. 1. It includes a number of steps:

(a) A segment of capillary tube (Polymicro Technologies, TSP050150) with outer diameter of ∼150 μm and inner diameter of ∼50 μm, respectively, is fusion spliced to a standard SMF (Corning, SMF-28e +) by using a fusion splicer (Fujikura, FSM-60S) as shown in Fig. 1(a). The length of the capillary tube used is ∼0.8 mm.
(b) The other end of capillary tube is then fusion spliced with another section of SMF as shown in Fig. 1(b). During the fusion process, the

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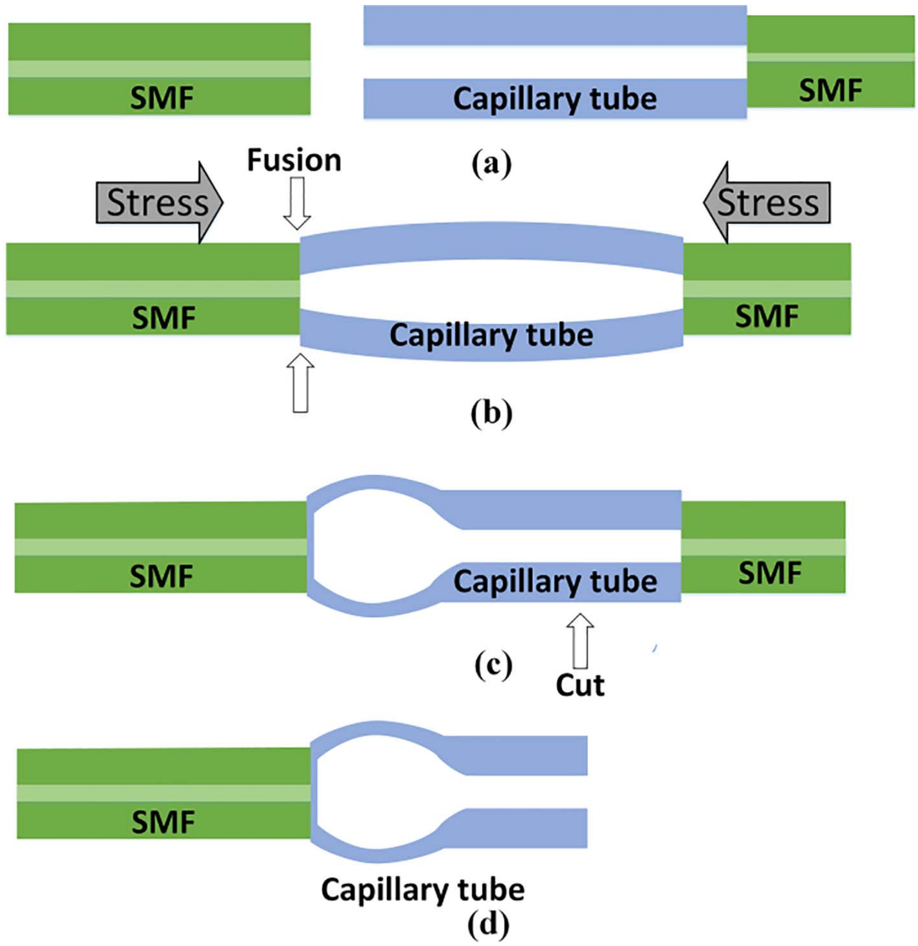

Fig. 1. The fabrication process diagram of the sensor head (a) One end of the capillary tube is fusion spliced with a SMF; (b) The other end of the capillary tube is fusion spliced with another SMF; (c) Hollow sphere cavity is formed by continuously discharging the SMF-capillary tube junction; (d) The capillary tube is cut at a position distant from the hollow sphere cavity.

SMF-capillary tube junction is continuously discharged to allow collapse of the capillary tube until part of the capillary tube is expanded into a hollow sphere cavity and a thin layer is formed in the SMF-capillary tube junction as shown in Fig. 1(c).

(c) Finally, the capillary tube is cut at a position distant from the hollow sphere cavity.

The schematic diagram and the microscope image of the sensor head fabricated are demonstrated in Fig. 2(a) and (b) respectively. The material of the capillary tube is pure silica with a RI value of 1.444.

As shown in Fig. 2(a), the sensor has two different modes of interference, one is a standard FPI, in which three different reflecting surfaces are formed, S_1, S_2 and S3. The thin layer at the SMF-capillary tube junction has a front surface S_1 and a back surface $S_{2,}$ and the tail end of the capillary tube is S_3. A multi-beam interference occurs when light is incident from the side of SMF. The first reflection happens at S_1 due to the change in RI from the core of the SMF to the layer of capillary tube material, and the second reflection occurs at S_2 because of the change in RI from the layer of capillary tube and air. Part of the transmitted light enters into the hollow sphere air-cavity and transmit in the air while the rest propagates along the thin wall of capillary tube before being reflected by the end surface of the capillary tube S_4. As shown in Fig. 2(d), The interface between the hollow sphere cavity and the capillary tube is not generated reflected surface. The other optical guidance mechanism that occurs in the quartz capillary tube can be explained according to the Anti-Resonance Reflective Optical Waveguide (ARROW) model, in which a hollow quartz capillary is equivalent to a FP etalon. When the light wavelength is close to the resonant wavelength λ_m (anti-resonant wavelength region), the light traveling along the wall of the capillary tube will be reflected by its inner wall and outer wall, and then reflected back to form a periodic lossy dip. If the propagation wavelength is far away from the resonant wavelength, the light is internally reflected and confined in the quartz capillary tube as the guiding mode. The resonance wavelength λ_m can be expressed as [19]:

$$\lambda_m = \frac{2d}{m}\sqrt{n_2^2 - n_1^2} \tag{1}$$

where m is an integer beginning with 1, d is the equivalent F-P cavity length and $n_2 = 1.444$ (around 1550 nm) and $n_1 = 1$ (under normal pressure).

From Eq. (1), it can be calculated that the FSR (Free Spectral Range) of this sensor under the ARROW model is 10.7 nm around 1550 nm.

The output interference fringe pattern of the sensor device is displayed in Fig. 3(a), and its corresponding spatial frequency spectrum obtained by use of fast Fourier transform (FFT) is shown in Fig. 3(b). It can be observed from Fig. 3(b) that four distinct peaks exist in the frequency spectrum.

The relationship between the frequency peak and the FP cavity length can be obtained from the following formula