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Temperature-independent refractometer based on fiber-optic Fabry–Perot interferometer

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ABSTRACT

A miniature fiber-optic refractometer based on Fabry–Perot interferometer (FPI) has been proposed and experimentally demonstrated. The sensing head consists of a short section of photonics crystal fiber (PCF) spliced to a single mode fiber (SMF), in which the end-face of the PCF is etched to remove holey structure with hydrofluoric (HF) acid. A Fabry–Perot interference spectrum is achieved based on the reflections from the fusion splicing interface and the end-face of the core of PCF. The interference fringe is sensitive to the external refractive index (RI) with an intensity-referenced sensitivity of 358.27 dB/RIU ranging from 1.33 to 1.38. The sensor has also been implemented for the concentration measurement of λ-phage DNA solution. In addition, the dip intensity is insensitive to the ambient temperature variation, making it a good candidate for temperature-independent bio-sensing area.

1. Introduction

The detection of biological parameters is of great importance for its applications in various fields, such as medical monitoring, food safety and environmental science [1,2]. Since the biological samples exist in aqueous solutions, their growth, death and other activities are inevitably associated with refractive index (RI) changes of solutions. The refractometer with high sensitivity is capable to monitor the micro-RI change of solution, making it as a good candidate for biological sample detection. To date, numerous fiber-optic refractometers have been developed for real-time RI measurement owing to advantages of compact size, high sensitivity and ultra-fast response [3]. The traditional LPGs have been generally employed as the transmission device for sensing applications [4–9]. Recently some post-process techniques, such as phase-shift LPG assisted with coating silver film [10], have been utilized to make LPG-based configuration as reflection probe. LPGs have been reported for RI measurement. However, the sensor depends on the complex grating incorporation and film coating techniques. Fiber Bragg grating (FBG), unlike LPG, is a typical reflection-type component; however, it is inherently insensitive to RI change due to the thick cladding. Post-processing techniques including chemical etching [11], tapering [12] and diameter mismatching [13] have been employed to induce the recoupling of the core-to-cladding modes in FBGs, enabling FBGs to be sensitive to ambient RI change. In addition, FBGs inscribed in micro-structured fibers and D-shaped SMFs were also effective cases for coupling the guided core mode to cladding modes, and measuring RI [14–17]. These devices mentioned above presented excellent sensing performance in the RI measurement, but there also exists a bit complication in the structure fabrication (e.g. weak mechanical strength, and FBG inscriptions). As another group of fiber devices, some fiber interferometers, such as Mach–Zender interferometers (MZIs) [18,19] and Michelson interferometers (MIs) [20,21], have also been widely developed for RI based bio-sensing applications. The fringe patterns of these configurations are generated by the interference between core and cladding modes, which are sensitive to RI change. However, these wavelength-referenced configurations are also sensitive to temperature that brought in sensitivity cross-talk.

Fiber Fabry–Perot interference (FFPI), as another typical reflection-type component, has been widely developed for the various applications [22]. To date, there have been many techniques for forming diverse FP cavity on the fiber tip with the compact size and good stability. For example, Femtosecond laser has been employed to inscribe a FP cavity on the fiber tip for RI sensing applications [23–25]. However, these component fabrications are complex and cost-expensive. Fusion splicing technique is another typical way to fabricate a FP cavity [26–28]. For example, an all-fiber FPI formed by fusion splicing conventional fiber and hollow-core photonic crystal fiber (PCF) has been proposed for highly sensitive temperature, refractive index, and load sensing [28]. Modified FP

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principle operation was obtained as a result of the interaction between the cavities which were formed at the fiber tip using arc discharges. The structure exhibits advantages like compactness, robustness and stability measurement. However, it suffers from the drawbacks of complex fusion process in fabrication, which makes it difficult for mass production. Besides that, using a segment of PCF to create the FP cavity is also an effective way, which has been reported in the past years [29–31]. For example, a compact fiber-optic FPI constructed by splicing a section of HOF between a SMF and a PCF has been proposed for measuring liquids and gases, in which the measurands flow in and out the air cavity through the holey cladding of the PCF [30]. Although this device exhibits a high sensitivity, it suffers from some downsides of complex structure which needs the splicing operations among the three fibers, and the small channels (the diameters of the holes locating at the cladding are too small to allow the measurands flowing in or out the cavity fast, disturb its real-time responses to measurands).

In this paper, we proposed and experimentally demonstrated a microfiber based FFPI sensor for highly sensitive biosensing application. The sensor head consisting of a short section of PCF with the hexagonal array of air holes is etched for creating a suspended core. The splicing point and the end face of the suspended core function as two reflectors, and therefore the PCF region forms a FP cavity. The similar structure was presented in our previous work [32] and was demonstrated for temperature measurement using a wavelength tracking interrogation technique. Here, we improve this structure to realize simultaneously measuring RI and temperature by interrogating both the dip intensity and the wavelength of the interference fringe. The sensor was applied to measure the concentration of λ-phage DNA solution, and the intensity of the interference dip shows good response to the concentration vibration with a detection limit of 0.075 μg/μL.

2. Sensors fabrication

A short section of end cleaved PCF was spliced to a standard SMF by using a commercial fusion splicer (FSM-60S, Fujikura) in the manual mode (with the discharge parameters: arching time, 600 ms; and power, -30 bit), as the microscope image shown in Fig. 1(a). The SMF used in the experiment is Corning SMF-28 fiber with the core/cladding diameters of 9/125 μm and RI of 1.4502/1.445. The PCF used in the experiment is single mode endless fiber made by Yangtze Optical Fiber and Cable Company (SM-7.0-PCF), which consists of a pure silica core (core diameter and RI are 7 μm and 1.467, respectively) and a microstructure cladding with a micrometer-spaced hexagonal array of air holes. To remove the porous cladding, we immerse the sensing head into a HF acid solution with the concentration of 49%. During the etching process, there are three main factors contributing to the final etching result; the concentration of the HF acid solution, the temperature of the ambient environment and the etching time. Among them, the concentration of the HF acid solution we use in the experiment is determined as 49% (mass fraction), and the temperature in the laboratory is rather stable with a variation less than 1 °C. Thus, the etching result is contingent upon the etching time. With etching the PCF head with different times separately, we found that 140 s of the etching time is the optimal. Fig. 1(b) shows the microscope image of the configuration after etching for 140 s. We can see that most of the holey cladding has been removed and the suspended core length has been reduced to be 151.57 μm with a diameter of 2.6 μm.

It is worth noting that, there is no fluctuation of interference spectrum observed during the manipulation and transfer in the laboratory. It means that the proposed sensor head is stable, even though the diameter of the suspended core is down to 2.6 μm and

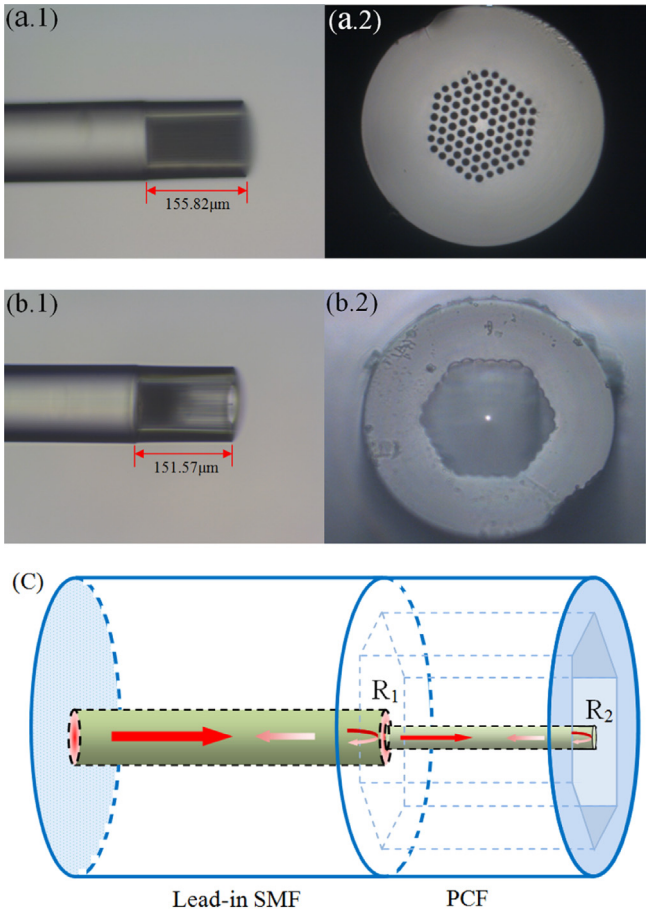

Fig. 1. Microscope image of the sensor head (a) before etching, (b) after etching, and (c) schematic diagram of the SMF–PCF structure.

the length is 151.5 μm. In order to theoretically analyze its mechanical characteristic, we consider the suspended core as a cantilever and the calculated resonance frequency is up to 85 Hz. Therefore, the manipulation induced vibration with low frequency will not affect the reflective spectrum of the microfiber. The sensor head is proved to be robust against manipulation and transfer within the laboratory, and its spectrum is always stable.

Fig. 1(c) demonstrates the schematic diagram of the proposed SMF–PCF structure. The splicing point and the end-face of the suspended core act as two reflective mirrors R_1 and R_2, which form the FP cavity. The operation principle can be described as follows. When the incident light reaches the interface of the SMF and PCF, it will be partially reflected owing to the RI mismatch between the two fiber cores, and the rest part of light will be coupled into the PCF and transmitted along the suspended core. At the end-face of the suspended core, a fraction of light is reflected. The fusion interface and the end-face work as two reflective mirrors, and thus the suspended core in the PCF region performs as a FP cavity. The interference intensity can be given as follows:

$$I = R_1 + (1-A)^2(1-R_1)R_2 + 2\sqrt{R_1R_2}(1-A)(1-R_1)\cos\ \Phi \quad (1)$$

where R_1 and R_2 are the reflection coefficients of two reflection surfaces, A is the transmission loss factor at the fusion interface, and Φ is the phase delay of the two reflected light beams.

According to the Fresnel equation, R_1 and R_2 can be calculated as [33,34]

$$R_1 = \frac{(n_{Sc}-n_{Pc})^2}{(n_{Sc}+n_{Pc})^2}, R_2 = \frac{(n_{Pc}-n_s)^2}{(n_{Pc}+n_s)^2} \quad (2)$$