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Temperature insensitive refractive index sensor based on a combination interference structure

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ABSTRACT

A sensing head consisting of fiber loop mirror inscribed with a highly birefringence photonic crystal fiber (HiBi-PCF) was proposed and experimentally demonstrated. The HiBi-PCF was completely collapsed near the splicing points, thus the cladding mode in the HiBi-PCF would be excited, which was sensitive to the refractive index (RI) of surrounding medium. Owing to the low thermo-optic and thermo-expansion coefficient of the HiBi-PCF, the sensing head in our design was temperature insensitive. High sensitivity of 306.6 ± 0.2 nm/RIU (refractive index unit) and a resolution of 6.5×10^{-5} RIU have been achieved for the proposed liquid refractive index sensor.

1. Introduction

Optical fiber sensors hold numeral advantages over conventional electrical-based sensors. The former are inexpensive, compact, light weight, immune to electromagnetic interference. This resulted in a great demand for fiber sensors in biochemical sensing applications. In recent years, optical fiber refractive index (RI) sensors have attracted lots of attention, because they are useful in many kinds of areas ranging from environmental monitoring to biomedical sensing. Both fiber Bragg gratings (FBGs) and long-period gratings (LPGs) have been used in RI fiber sensors. For an FBG-based RI sensor, the FBG is often etched or polished to gain the access of the evanescent field of the guided mode to the surrounded material to be measured [1–3]. Compared with RI sensors of FBG type, sensors based on LPGs [4–7] are more applicable because of their intrinsical coupling mechanism. A RI sensor based on Fabry–Perot (F–P) interferometers has been also reported [8]. Such a sensing structure makes use of the variation of the maximum contrast of the interference fringes to measure RI. Frazão [9] proposed a refractometer based on high birefringence etched D-type fiber loop mirror. The evanescent field for RI measurement was increased by using the etched D-type structure fiber. Optical refractometers based on photonic crystal fibers were also proposed [10]. However, the measurement principles of those refractometers are using the wavelength shifts to detect the external RI variation, which was faced with a big problem of temperature cross sensitivity. Thus, a temperature compensation part was necessary. Meanwhile, the obtained sensitivity was not high enough in the RI sensing structure which was reported previously. Therefore, fiber refractometer which can realize high sensitivity without the needing of an additional temperature compensation part was desirable in practical applications.

In this work, a sensing head consisting of fiber loop mirror inscribed with a highly birefringence photonic crystal fiber (HiBi-PCF) was proposed and experimentally demonstrated. The HiBi-PCF was completely collapsed near the splicing points, thus the cladding mode in the HiBi-PCF would be excited, which was sensitive to the refractive index (RI) of surrounding medium. Owing to the low thermo-optic and thermo-expansion coefficient of the HiBi-PCF, the sensing head in our design was temperature insensitive. The collapsed HiBi-PCF worked just like a Mach–Zehnder interferometer (MZI), considering the FLM structure, a combination interferometer was formed, which result in a high sensitivity. The RI value of the liquid can be measured by detecting the interference fringes shift corresponding to the FLM and MZI.

2. Sensor fabrication and operation principle

The schematic diagram of the proposed sensor head was shown in Fig. 1. An amplified spontaneous emission (ASE) source of

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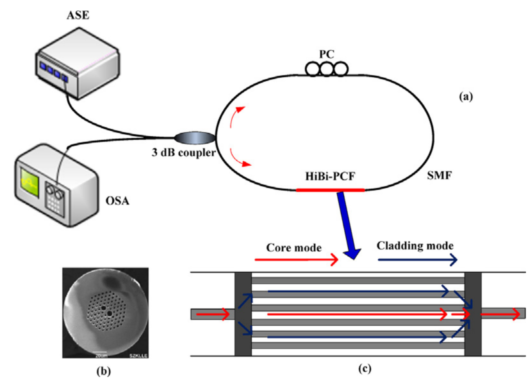

Fig. 1. (a) Schematic diagram of the proposed RI sensor; (b) SEM of the used HiBi-PCF and (c) the partial enlarged drawing of the sensing head.

1450–1650 nm wavelength range is connected to the input of the FLM, and the output spectrum is detected with an optical spectrum analyzer (OSA, AQ6370, Advantest, Japan). The maximum resolution of the OSA is 20 pm. The FLM is formed by splicing (using a commercial fusion splicer (Fujikura FSM-40S)) a sections of HiBi-PCF (LMA-10) to the arms of a 2 × 2.3 dB coupler. The HiBi-PCF with the length of 5 cm and both ends of it was collapsed fusion splicing between two identical single mode fibers (SMF-28) with was in the arms of the coupler. The inset of Fig. 1 shows the cross sectional view of the HiBi-PCF, which has a solid core of diameter of 11 μm surrounded by four layers of air-holes with an outer diameter of 125 μm.

Splicing of the PCF to SMF was carried out by using a commercial fusion splicer (Fujikura FSM-40S). Strong electronic arc discharges caused localized heating on the PCF, leading to collapse of the air-holes in the cladding area of the heated PCF section. It can be seen from the micrograph of the fabricated splicing point, where the air-hole structure of the PCF was collapsed near the splicing point over a short length of ∼140 μm. The PCF was no longer single mode since the fiber had no core–cladding structure any more at the region of the collapsed area. When the fundamental mode of the lead-in SMF propagates into the collapsed region of PCF, its mode field diameter would be broadened due to the diffraction, allowing the excitation of core and cladding modes in the intact PCF section [11,12]. Then, the excited core and cladding modes are further diffracted and recoupled back to the core mode of the lead-out SMF at the second splicing point. Therefore, it worked just like a kind of MZI.

The input light from the ASE is equally splits into two counter-propagating light by the 3 dB coupler, and subsequently they recombine at the coupler after clockwise and counterclockwise light beams propagating around the loop. A polarization controller (PC) is used to adjust the polarization states of the two lights. The counter-propagating light beams introduced a relative phase difference due to the birefringence property of the inserted HiBi-PCF. So interferences generate when they recombine at the coupler. The transmission optical intensity I_t in terms of the phase difference can be described as,

$$I_t = \frac{1-\cos\phi}{2} \tag{1}$$

with

$$\phi = \frac{2\pi LB}{\lambda} \tag{2}$$

where ϕ is the phase difference. λ is the center wavelength of the light source. L is the length of the HiBi-PCF. $B = n_s - n_f$ is the birefringence index of the HiBi-PCF. n_s and n_f are the effective refractive index of the slow and fast axis, respectively. The resonant dip wavelength satisfies the equation of $\phi = 2k\pi$, where k is a random integer.

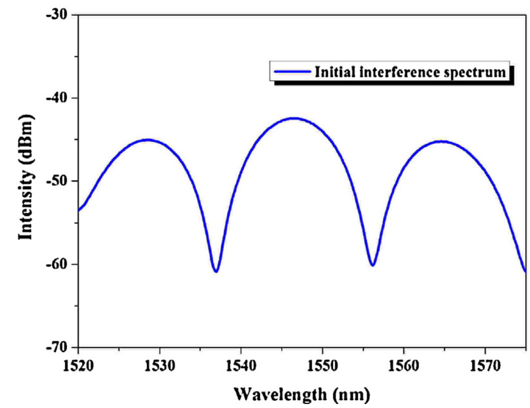

Fig. 2. Initial interference spectrum of the RI sensor.

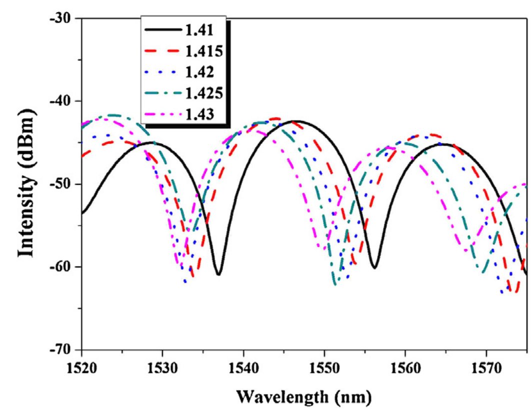

Fig. 3. Interference spectrum variation of the FLM was subject to liquid with different RI.

Therefore, the resonant dip wavelength can be described as,

$$\lambda = \frac{BL}{k} \tag{3}$$

The interference fringes corresponding to the FLM and MZI with different resonant dip wavelengths which result in a spectrum overlap as shown in Fig. 2.

3. Experiment and discussions

To test the HiBi-PCF-FLM based liquid RI sensor, the collapse fusion spliced HiBi-PCF was immersed in the sample of liquid combine with different percentages of glycerin. The liquid samples were calibrated through an Abbe refractometer with a nominal accuracy of ±0.0001. We can get Eq. (2),

$$\Delta\lambda = \frac{L}{k}\cdot(B+\Delta B) \tag{4}$$

where $\Delta\lambda$ is the wavelength shift as put PCF in liquid with varying refractive index. $\Delta\equiv$ is the change of the birefringence index caused by the effective refractive index variation of the fast and slow axis corresponding to PCF. From Eq. (4), it can be seen that $\Delta\lambda$ is directly proportional to $\Delta\equiv$. External RI variation can be detected by measuring the wavelength shift of the interference spectrum.

As the HiBi-PCF was immersed in liquid with RI value variation in a range of 1.41–1.43 at a room temperature (25 °C), the variations of the interference spectrum for the FLM were shown in Fig. 3. It can be seen that the resonant dip wavelength λ_2 of the interference fringes were shifted from 1556.11 nm to 1549.66 nm. The resonant dip wavelength shifts of interference spectrum of the