High-sensitivity refractive index sensors based on fused tapered photonic crystal fiber*

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In this paper, a novel liquid refractive index (RI) sensor based on fused tapered photonic crystal fiber (PCF) is proposed. It is fabricated by fusing and tapering a section of PCF which is spliced with two single-mode fibers (SMFs). Due to the fused biconical taper method, the sensor becomes longer and thinner, to make the change of the outside RI has more direct effects on the internal optical field of the PCF, which finally enhances the sensitivity of this sensor. Experimental results show that the transmission spectra of the sensor are red-shifted obviously with the increase of RI. The longer the tapered region of the sensor, the higher the sensitivity is. This sensor has the advantages of simple structure, easy fabrication, high performance and so on, so it has potential applications in RI measurement.

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Among many refractive index (RI) sensing devices, the fiber-based RI sensors stand out for their small size, high sensitivity, fast response and good stability[1-3]. Nowadays, a number of fiber-based RI sensors have been reported, including long period fiber grating (LPFG)[4,5], fiber Bragg grating (FBG)[6,7], core offset[8], imbedded micro air-cavity[9] and many other structures[10,11]. All of them can be applied to the RI sensing field. However, these approaches still have some disadvantages, such as low performance, complicated fabrication and cross sensitivity. Thus, a further research that aims to find a high performance special structure with low complexity is necessary.

In this paper, a Mach-Zehnder interference fiber sensor is demonstrated for liquid RI measurement. It is fabricated by just splicing a few-centimeter-long segment of tapered photonic crystal fiber (PCF) between two standard single-mode fibers (SMFs). Utilizing the double beam interference principle, the principle of the sensor is analyzed, and the relationship between the shift of interference spectrum and the change of the liquid RI is obtained. In order to verify the RI sensitivity, five sensors with different tapered lengths were fabricated and applied in a straightforward experiment. The experimental results show that the interference patterns of different sensors have a large red shift as increasing RI. Moreover, the RI sensitivity can be enhanced by increasing the tapered PCF length.

As shown in Fig.1(a), the used PCF is the SM-7 solid core PCF, which is fabricated by Yangtze Optical Fiber and Cable Joint Stock Limited Company. It has a pure-silica core with air holes with micro-structured five-layer hexagonal concentric rings in silica. The core and outer diameters of the PCF are 7 μm and 125 μm, respectively. The diameter of the air holes and the spacing-distance of the holes are 2.82 μm and 5.43 μm, respectively. Fig.1(b) is the structural schematic diagram of the proposed RI sensor. The light from the light source propagates through the input SMF, and it splits into two transmission modes when it reaches the first splicing point, due to the mismatched mode field and the tapered structure. One is along the core, and the other is along the surface of the PCF. After transmitting for a distance, the optical paths of the core and surface modes are different because the effective refractive indices of them are different. Thus, when they recombine together at the second splicing point, an interference spectrum will be obtained. Based on the double beam interference principle, the intensity of the interference spectrum and the *m*-order peak wavelength[12] can be expressed as

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\frac{2\pi\Delta n_{\text{eff}}L}{\lambda} + \varphi_0\right), \quad (1)$$

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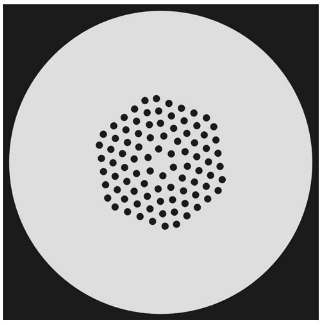
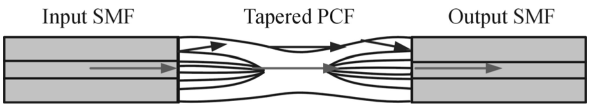
$$\lambda_m = \frac{\Delta n_{\mathrm{eff}} L}{m}, \tag{2}$$

where I_1 and I_2 are the light intensity of the core mode and surface mode, respectively, L is the distance between the two splicing points, Δn_{eff} is the effective RI difference between the two modes, λ is the spatial wavelength, and φ_0 is the initial phase difference of the two modes.



(a)



(b)

Fig.1 (a) Microscope image of cross section of PCF; (b) Structural schematic diagram of the proposed fiber sensor

When the sensor is applied to RI sensing, the optical path difference will changes for liquid RI variations, and there will be a big difference between the effective refractive indices of the two modes due to the tapered structure. Based on Eq.(2), the variation of the wavelength dip is given by

$$\Delta\lambda_m = \frac{(\Delta n_{\mathrm{eff}} + \Delta n) L}{m} - \frac{\Delta n_{\mathrm{eff}} L}{m} = \frac{\Delta n L}{m}, \tag{3}$$

where Δn is the variation of effective RI difference between the two modes. From Eq.(3), we can see that the shift of wavelength dip is directly proportional to the length of the sensor. Therefore, the longer the tapered region of the sensor, the higher the sensitivity will be.

Five sensors with different lengths of tapered region are prepared, and the lengths of their tapered region L are 10 mm, 11 mm, 12 mm, 13 mm and 14 mm, respectively. In order to investigate the RI sensing of these sensors, a straight experiment is performed. The experimental setup is shown in Fig.2.

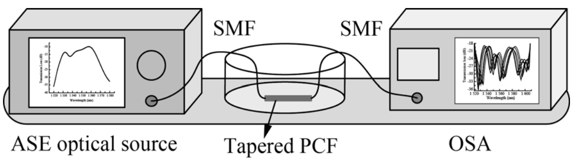
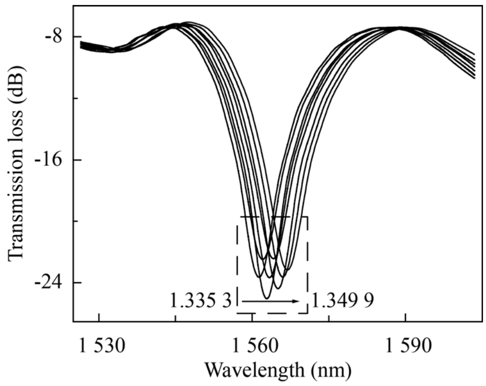
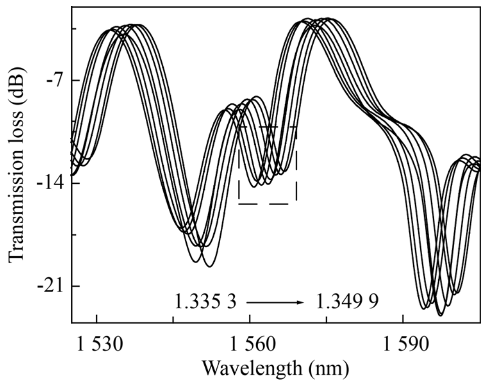


Fig.2 Experimental setup for RI measurement

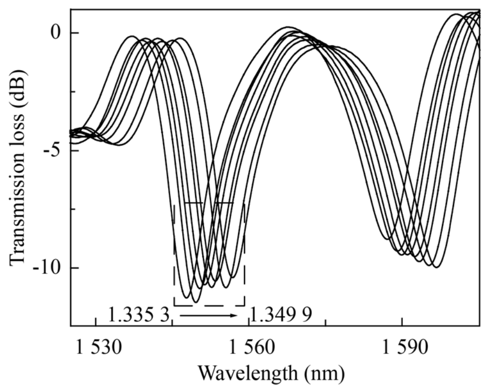
An amplified spontaneous emission (ASE) optical source ranging from 1 520 nm to 1 610 nm and an optical spectrum analyzer (OSA, YOKOGAWA AQ6375) are used to detect the interference spectrum. During the whole experiment, the sensor is mounted on a sample pool with glue to keep it straight, and it is immersed in the different solutions of sodium carbonate. There are eight sodium carbonate solutions with the concentration changing from 10 mg/mL to 80 mg/mL, and their refractive indices are 1.335 3, 1.337 6, 1.339 7, 1.341 5, 1.344 1, 1.345 9, 1.348 1 and 1.349 9, respectively. The resonance spectrum of the sensor is not recorded until it is stabilized by observing from the OSA. The entire measurement is carried out under a constant temperature to avoid the impact of temperature, and it is carefully cleaned by alcohol and water for more than once to ensure the accuracy of experiment after each RI measurement. Thus, the interference spectra of these sensors immersed in the solution with different refractive indices are shown in Fig.3.



(a) L=10 mm



(b) L=11 mm



(c) L=12 mm

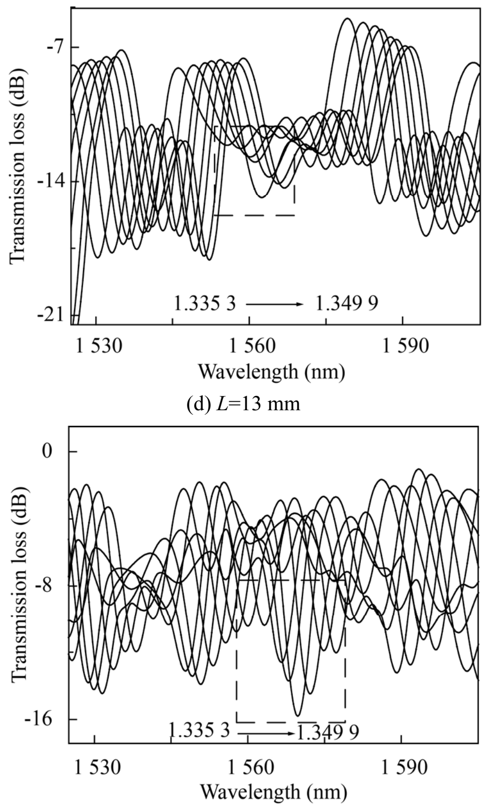


Fig.3 Transmission spectra of different sensors with different lengths of tapered region corresponding to different liquid refractive indices

As shown in Fig.3, with the increase of RI, the interference spectra of five sensors all shift toward longer wavelength, and the longer the tapered region of sensor, the larger the shift will be. In order to illustrate the changes of the spectrum with different refractive indices more intuitively, a wavelength dip of each interference spectrum is selected as the observation point which is located in the dotted box. Then the relationship between the RI and the wavelength shift of these observation points can be obtained, which is shown in Fig.4.

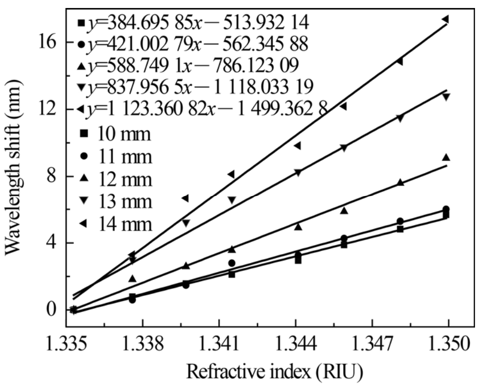


Fig.4 Relationships between wavelength shift and RI of sodium carbonate solution for the five sensors

As shown in Fig.4, there is a good linear relationship between wavelength shift and RI of the solution. The RI sensitivity of the five sensors are 384.695 85 nm/RIU, 421.002 79 nm/RIU, 588.749 1 nm/RIU, 837.956 5 nm/RIU and 1 123.360 82 nm/RIU in the RI range of 1.335 3—1.349 9, respectively. It indicates that the sensitivity of the sensor can be enhanced by increasing the tapered PCF length. Moreover, it has been found that this sensor also has the temperature insensitivity in previous study[13]. Therefore, this sensor is able to overcome the problem of cross sensitivity of temperature in the measurement, and can be better used for the RI sensing.

A RI sensor with high sensitivity is proposed based on tapered PCF. The relationships between interference spectrum and RI for five sensors with different tapered PCF lengths are analyzed. Experimental results show that the transmission spectra shift with the change of RI, and a linear response of 1 123.360 82 nm/RIU is obtained for the sensor with a 14 mm-long tapered region in the RI range of 1.335 3—1.349 9. Also, the longer the tapered region of the sensor, the higher the sensitivity will be. Therefore, it has potential applications in RI measurement field.

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