Temperature sensor based on an isopropanol-sealed photonic crystal fiber in-line interferometer with enhanced refractive index sensitivity

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We fabricate a simple, compact, and stable temperature sensor based on a liquid-sealed photonic crystal fiber (PCF) in-line nonpolarimetric modal interferometer. Different from other reported PCF devices, it does not need expensive polarimetric devices, and the liquid is sealed in one fiber. The device consists of a stub of isopropanol-filled PCF spliced between standard single-mode fibers. The temperature sensitivity (−166 pm/°C) increases over an order of magnitude compared with those of the previous sensors based on air-sealed PCF interferometers built via fusion splicing with the same mechanism. In addition, the refractive index sensitivity also increases. Higher temperature sensitivity can be realized by infiltrating some liquid having a higher thermo-optic coefficient into the microholes of the PCF.

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Fiber-optic interferometric sensors have found numerous sensing applications due to their outstanding advantages over conventional electrical sensors, such as immunity to electromagnetic interference, versatility, linear response, and small size. A lot of efforts have been made to develop different types of fiber Fabry–Perot and modal interferometers with standard single-mode fibers (SMFs), multimode fibers, and photonic crystal fibers (PCFs), also known as microstructured optical fibers. In recent years, PCF based in-line modal interferometers (PCFMIs) built via fusion splicing and microhole collapsing in PCFs have been demonstrated and are attracting more and more attention [1–7]. This kind of device typically consists of a stub of large-mode-area PCF spliced between standard SMFs (SMF-PCF-SMF). The key element in these interferometers is a region in which the voids of the PCF are fully collapsed [1–3]. Two modes (core and cladding modes) are excited and recombined through the PCF because of the collapsing. This technique is really simple and popular since it only involves cleaving and splicing processes that can be carried out in any fiber-optics laboratory [1–3]. The appeal of the interferometers fabricated with this approach is that the devices can be used for a variety of applications ranging from sensing strain to refractive index without infiltration of a liquid/gas sample into the holes of the PCFs [1–3]. However, the temperature sensitivity of such a device is always very low, as PCF is made of silica and air with low thermo-optic and thermal expansion coefficients. In order to enhance the device temperature dependence, it is necessary to modify the materials and components in PCF. A simple and effective method is to infiltrate liquids that have a high thermo-optic coefficient into the microholes of the PCF. There has been much work on liquid-filled PCF devices, and they are mostly less compact and complex polarimetric devices using expensive polarization maintaining PCF [8] or liquid-crystal that has higher refractive index than that of silica and is mostly not sealed in the PCFs [9–13]. However, to our knowledge, there is no report on liquid-sealed PCFMIs based on this nonpolarimetric and simple SMF-PCF-SMF structure. The main challenge is to optimize the splicing condition to control low loss level, miniature collapsed region, and good mechanical performance.

In this Letter, we fabricate a nonpolarimetric PCFMI by cleaving and splicing a short isopropanol-filled PCF between two SMFs. Because isopropanol has a high thermo-optic coefficient and its refractive index is lower than that of the silica core region, this in-line modal interferometer can realize a high temperature sensitivity by measuring the wavelength shift of the resonant dips. Of course, the transmission mechanism of this in-line modal interferometer is still modified total internal reflection (m-TIR). Then, we also measure its refractive index sensitivity and find it is larger than that of an in-line modal interferometer without filling any liquid [2,4]. Higher temperature sensitivity can be acquired if we infiltrate some liquid having a gher thermo-optic coefficient into the microholes of the PCF.

A commercial single-mode PCF (LMA-8, NKT Photonics) is employed to fabricate this modal interferometer. As shown in Fig. 1(a), this type of fiber consists of a solid core surrounded by six rings of air holes. From our measurement, the core diameter is 8.4 μm, the average diameter of air holes is 2.17 μm,and the average pitch (hole-to-hole distance) is 5.3 μm. Compared with other larger-sized PCFs, the diameter of the LMA-8 PCF is the same as SMF-28 fibers, and it is easier and cheaper to be spliced to SMF-28 fibers with higher stability and better repetition.

In our experiment, to begin with, we cut one piece of 11.5 mm-long LMA-8 PCF with a mechanical cleaver. Next we immersed it in isopropanol for a few minutes. Because of the well-known capillarity effect, the isopropanol was infiltrated into the microholes of the PCF gradually. Then the two ends of the isopropanol-filled PCF were spliced to standard SMFs using a commercial fusion

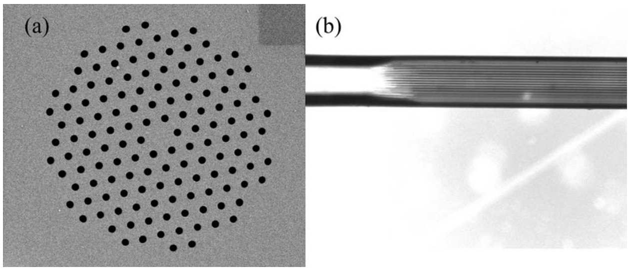

Fig. 1. (Color online) (a) Scanning electron microscope image of the cross section of the PCF used for the experiment. (b) Microscopic image of the PCF-SMF splicing area showing the collapsed region at the end of the PCF.

splicer [14]. As the PCF is filled with isopropanol, the splicing condition needs to be adjusted in order to guarantee minimal air-hole collapsing at the splicing point and simultaneously provide adequate mechanical strength for manual fiber handling. Figure 1(b) shows the microscopic image of the isopropanol-sealed PCF-SMF splicing area. Part of the isopropanol will possibly evaporate during the splicing operation.

As shown in Fig. 2, a broadband amplified spontaneous emission source (1525 ~ 1610 nm) and an Ando AQ6317B optical spectrum analyzer (OSA) were employed during the whole experiment in real time in order to detect the interferometric behavior of the isopropanol-sealed PCFMI. In our experiment, we keep the PCF straight in a temperature-controlled device to avoid bending and torsion. When the light transmits from the SMF to the isopropanol-sealed PCF (Fig. 2), the fundamental SMF mode begins to diffract and excites core and cladding modes in the isopropanol-sealed PCF section with different propagation constants [2,3,15]. After accumulating a phase difference along the isopropanol-sealed PCF, the modes will further diffract and will be recombined through the filtering of the subsequent SMF. Therefore the interference spectrum can be modeled with the following two-beam optical interference equation [16]:

$$I = I_{co} + I_{cl} + 2\sqrt{I_{co} I_{cl}} \cos(2\pi \Delta n_{eff} L/\lambda), \qquad (1)$$

where I is the intensity of the total interference signal, and I_{co} and I_{cl} are the intensities of the core and cladding modes, respectively. Δn_{eff} is the difference between the effective refractive indices of core and cladding modes. L is the length of the isopropanol-sealed PCF section, and λ is the wavelength. It can be noted that the maxima of transmission will appear when $2\pi\Delta n_{eff}L/\lambda = 2k\pi$, where

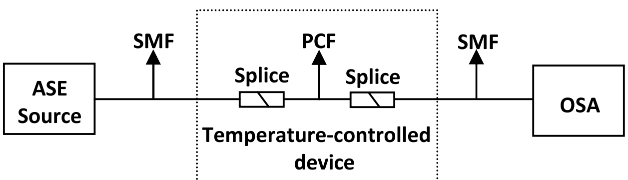

Fig. 2. (Color online) Schematic diagram of the experimental setup used for temperature and refractive index sensing measurement. The PCF length is about 11.5 mm.

k is an integer. Therefore the transmission spectra exhibit peaks at wavelengths given by $\lambda_k = \Delta n_{eff} L/k$.

In our experiment, compared with pure silica, the refractive index of isopropanol changes much more when temperature changes because the thermo-optic coefficient of isopropanol ($\sim -4.5 \times 10^{-4}$/K) is much higher than that of silica ($\sim 8.6 \times 10^{-6}$/K). And this will cause the core mode and the cladding mode to vary quickly and differently when the temperature varies. Therefore, the difference between the effective refractive indices of core and cladding modes will change with temperature and cause the transmission spectra to shift as shown in Fig. 3(a).

Figure 3(a) shows the transmission spectra of the isopropanol-sealed PCFMI under different temperatures. It looks more like a multimode interference, possibly with several cladding modes. However, Eq. (1) can still be used to investigate the evolution of interference peaks. The fringe visibility is 5–10 dB, which is enough for sensing application. As shown in Fig. 3(a), dip A and dip B both blueshift when the temperature increases from 23.7 °C to 66.1 °C gradually. We think this is because the fraction of field inside the holes of the PCF of cladding mode is larger than that of core mode, as shown in [17]. And this will cause the effective refractive index of cladding mode to increase less than that of core mode when the temperature increases, because of the negative thermo-optic coefficient of isopropanol. Therefore, the difference between the effective refractive indices of core and cladding modes decreases when the temperature increases and dips blueshift.

Figure 3(b) shows the relationship between temperature and the resonant dip wavelength of dip A and dip B. From this figure, we can see the response of the sensor keeps good linearity in the measured temperature range, and the linear fitting curves can be expressed as $y = 1571.479 - 0.133x$ for dip A and $y = 1610.616 - 0.166x$ for dip B. This means the temperature sensitivities of dip A and dip B are −133 pm/°C and −166 pm/°C, respectively, which are an order of magnitude higher than previous results [2,4,18]. The experimental result corresponds to our expectation, as the thermo-optic coefficient of isopropanol is more than an order of magnitude larger compared with the thermo-optic coefficient of pure silica. If we can infiltrate some liquid having a higher thermo-optic coefficient into the microholes of the PCF, we think higher temperature sensitivity can be realized in the future. Here for the application, we do not need to consider the polarization effect. In fact, the holes

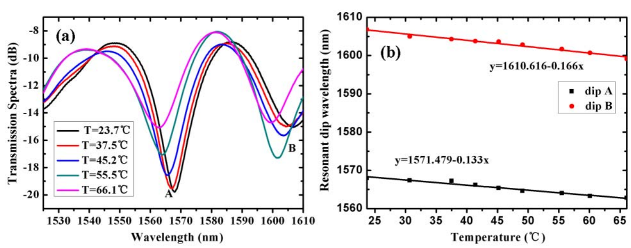

Fig. 3. (Color online) (a) Transmission spectra of the isopropanol-sealed PCF interferometer under different temperatures. (b) Relationship between temperature and the resonant dip wavelength of dip A and dip B.

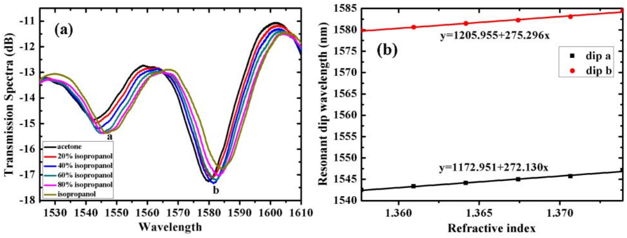

Fig. 4. (Color online) (a) Transmission spectra of the isopropanol-sealed PCF when immersed in different liquids. (b) Relationship between outer liquid refractive indices and the resonant dip wavelength of dip A and dip B.

of the PCF may become elliptic in shape with random orientation in the splicing region between SMF and PCF and will cause random parasitic birefringence and polarization dependent loss. This may be a good research orientation and will promote the development of new polarimetric-related applications in the future.

In our experiment, we also measure the refractive index sensing property of this interferometer. Figure 4(a) shows the transmission spectra of the isopropanol-sealed PCF when immersed in acetone, isopropanol, and mixtures of acetone and isopropanol, respectively. As the refractive index of pure isopropanol (1.3739 at 1.55 μm) is higher than that of pure acetone (1.3577 at 1.55 μm) [19], we can see the interference fringes shift to the right with the outer refractive index increasing, which is because the difference between the effective refractive indices of core and cladding modes increases when the outer refractive index increases.

Figure 4(b) shows the relationship between outer liquid refractive indices and the resonant dip wavelength of dip A and dip B. From this figure, we can see the response of the sensor also keeps good linearity in the measured refractive index range and the refractive index sensitivities are 272.130 nm/RIU and 275.296 nm/RIU for dip A and dip B, respectively, which are larger than the sensitivities of the previous PCFMIs whose PCFs were not filled with any liquid [2,4]. But it is well known that temperature variation usually distorts the performance of fiber-optic sensors. So if we want to make a refractive index sensor based on a PCFMI, we should use some temperature compensation methods.

In conclusion, we fabricate a miniature temperature sensor based on an isopropanol-sealed nonpolarimetric PCFMI and demonstrate its sensing property. Different from other reported PCF devices, it does not need expensive polarimetric devices, and the liquid is sealed in one fiber. It is one kind of in-line modal interferometer resulting from the interference among the core mode and excited cladding modes, and it has advantages of simplicity and compactness compared with other types of interferometers. Because the refractive index of isopropanol is lower than that of the silica core region, the transmission mechanism of this in-line modal interferometer is still m-TIR. The experimental results indicate that there is a linear relationship between temperature and the resonant dip wavelength, and the temperature sensitivities of dip A and dip B are −133 pm/°C and −166 pm/°C, respectively, which are an order of magnitude higher than previous results. This result corresponds to our expectation, as the thermo-optic coefficient of isopropanol is more than an order of magnitude larger compared with the thermo-optic coefficient of pure silica. In addition, the response of the sensor also keeps good linearity in the measured refractive index range, and the refractive index sensitivity also increases. If we can infiltrate some liquid having a higher thermo-optic coefficient into the microholes of the PCF, we think higher temperature sensitivity can be realized in the future. We can also consider building a point and sensor array just as mentioned in Ref. [6].

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