Ultrasensitive temperature sensor based on an isopropanol-sealed optical microfiber taper

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We demonstrate an ultrasensitive temperature sensor based on an isopropanol-sealed optical microfiber taper (OMT) in a capillary. The OMT is highly sensitive to ambient refractive index (RI) with a maximum sensitivity of 18989 nm/RI unit in the range of 1.3955–1.4008. The thermo-optic effect of isopropanol and the thermal expansions of the sealant and sealed liquid turn the OMT into an ultrasensitive temperature sensor with the maximum sensitivity of −3.88 nm/°C in the range of 20°C–50°C. The temperature sensitivity contributions from different mechanisms are also investigated theoretically and experimentally. © 2013 Optical Society of America

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Fiber-optic sensors for temperature measurement have been extensively studied in scientific research and industrial application due to their outstanding advantages of immunity to electromagnetic interference, small size, fast response, durability against harsh environment, and remote monitoring. In recent years, various configurations and fabrication techniques have been proposed and demonstrated to construct fiber temperature sensors, such as fiber Bragg gratings [1], long-period fiber gratings [2], varieties of optical fiber interferometers [3–6], and other interesting structures [7]. The grating-based temperature sensors have high resolution and large measurement windows, but they always require precise and expensive fabrication technologies, including phase mask and laser source. The fiber interferometer temperature sensors, such as Fabry–Perot- [3], Michelson- [4], and Mach–Zenhnder-interferometers [5,6], are simply structured and inexpensive, but they usually have a low sensitivity. Recently, a temperature sensor based on selectively infiltrated photonic crystal fiber has an ultrahigh sensitivity, which reaches up to 54.3 nm/°C [7]. However, the corresponding temperature measurement window is relatively narrow and the fabrication process is complicated, involving femtosecond laser micromachining [8].

In this Letter, we demonstrate a simple, low cost, and ultrasensitive temperature sensor based on a liquid-sealed optical microfiber taper (OMT). The OMT is fabricated by a fusion splicer with additional tension on one side. It is highly sensitive to ambient refractive index (RI) with the maximum sensitivity of 18989 nm/RI unit (RIU) in the RI range of 1.3955–1.4008. The high temperature sensitivity of the liquid-sealed OMT is mainly derived from the ultrahigh RI sensitivity. With temperature increasing, the RI value of the sealed liquid decreases rapidly due to the thermo-optic effect, resulting in an obvious transmission spectrum shift. The RI liquid we choose is isopropanol, which possesses a high thermo-optic coefficient of $-4.5 \times 10^{-4}/°C$ [6]. The isopropanol-sealed OMT has a temperature sensitivity up to −3.88 nm/°C in the temperature range of 20°C–50°C. To the best of our knowledge, this temperature sensor is the most sensitive device among the single-mode fiber (SMF)-based temperature sensors. The simple fabrication process, cost effectiveness, and ultrahigh sensitivity make it a competitive fiber sensor in highly sensitive temperature and/or RI sensing.

The experimental setup of the OMT for sensing measurement is illustrated in Fig. 1(a). Two ends of the fiber sensor are connected to an optical spectrum analyzer (OSA)(Yokogawa AQ6370B) and a supercontinuum broadband light source (Superk Compact, NKT Photonics, Inc.), respectively, to monitor the transmission spectrum change. The microfiber taper was fabricated on a standard telecom SMF (SMF-28e, Corning, Inc.) in a fusion splicer (Ericsson FSU-975). A user-defined fiber-tapering program was created and the discharge current was set as 10 mA. In the fiber tapering process, a certain additional tension was applied manually on one side of the fiber sample, leading to a longer taper waist length and a significant asymmetric morphology. The tapering process was terminated when the desired transmission spectrum appeared on the OSA. Later, the obtained OMT was inserted in a capillary tube with the length and inner diameter of 2 cm and 300 μm, respectively. A drop of isopropanol was added to one end of the capillary and

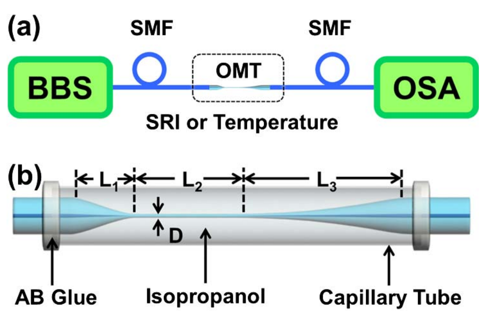

Fig. 1. (Color online) (a) Experimental setup for sensing measurement. (b) Schematic diagram of the isopropanol-sealed OMT in a capillary.

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soon it was filled with the RI liquid via capillarity. The liquid-filled tube was sealed immediately by AB glue on both sides. Figure 1(b) shows the schematic diagram of the isopropanol-sealed OMT. It has a total length L, which consists of three sections represented by L_1, L_2, and L_3. The taper-waist diameter of L_2 is represented by D.

A typical optical microscope image of the OMT is shown in Fig. 2(a). The total length L is 2350 μm, which involves $L_1 = 650$ μm, $L_2 = 300$ μm, and $L_3 = 1400$ μm, and the waist diameter D is 7.2 μm. The minimum insertion loss of the OMT is less than 2 dB and the maximum interference extinction ratio is over 35 dB in the air. Before the OMT liquid sealing, we investigated its RI response experimentally. It was straightly glued on a glass slide and then immersed in different RI solutions. Figure 2(b) shows the transmission spectrum changes in different RI solutions. With the increase of RI, the transmission spectrum has a significant red shift. The relationships between surrounding RI (SRI) and wavelength shift of different loss peaks are shown in Fig. 2(c). For loss peak c, the highest sensitivity reaches up to 18989 nm/RIU in the RI range of 1.3955–1.4008, which is similar to [9]. The highest RI sensitivity of peak b is 13977 nm/RIU in the range of 1.3829–1.3872. For the linear response range of 1.3605–1.3775, the RI sensitivity is

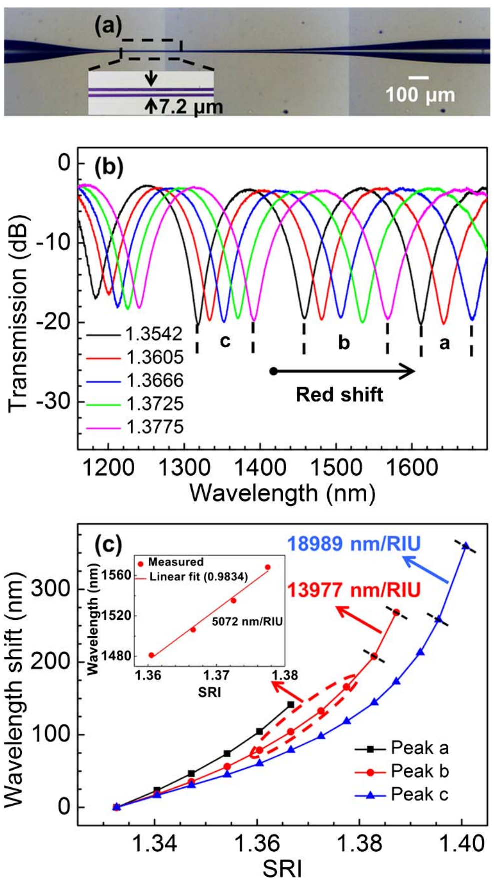

Fig. 2. (Color online) (a) Optical microscope image of the OMT. (b) Typical transmission spectrum of the unsealed OMT under different RI solutions. (c) Wavelength shift of the resonant peaks with different RI solutions. The inset shows the linear fitting result of peak b in the RI range of 1.3605–1.3775.

5072 nm/RIU, as shown in the inset figure of Fig. 2(c). It should be noted that the asymmetric structure of the OMT has no significant effect on its sensing properties. We carried out the RI experiments on both directions and obtained the same results. Moreover, we also theoretically simulated the asymmetric and symmetric OMT with the same geometrical parameters of L, L_2, and D and got the similar RI sensitivity. We think that the taper waist plays the decisive role in the spectrum formation and sensing properties. The ultrahigh RI sensitivity of the OMT is mainly due to the relatively longer and thinner taper waist and not related to the asymmetric structure. In addition, we checked the polarization response of the OMT and found that the device is insensitive to polarization due to its good symmetrical cross-section.

Owing to the low thermo-optic coefficient of silica, the OMT has a low temperature sensitivity of less than 15 pm/°C, which is obtained in our experiments. However, the OMT is highly sensitive to SRI. As is known, the isopropanol has a high thermo-optic coefficient of -4.5×10^{-4}/°C. In the temperature range of 20°C–50°C, the RI value of isopropanol changes in the range of 1.3766–1.3631, where the OMT has a high RI sensitivity, linear response, and good extinction ratio [Figs. 2(b) and 2(c)]. With temperature augmentation, the RI around OMT decreases rapidly, leading to the transmission spectrum blue shift. An isopropanol-sealed OMT (structure parameters: $L_1 = 687.5$ μm, $L_2 = 400$ μm, $L_3 = 1587.5$ μm, $D = 7$ μm) was immersed into an oil bath with the resolution of 0.01°C to test its temperature response. As shown in Fig. 3(a), the significant blue shifts of 115, 79, and 60 nm were observed for resonant peaks A, B, and C, respectively, in the transmission spectrum as temperature increases from 20°C to 50°C in step of

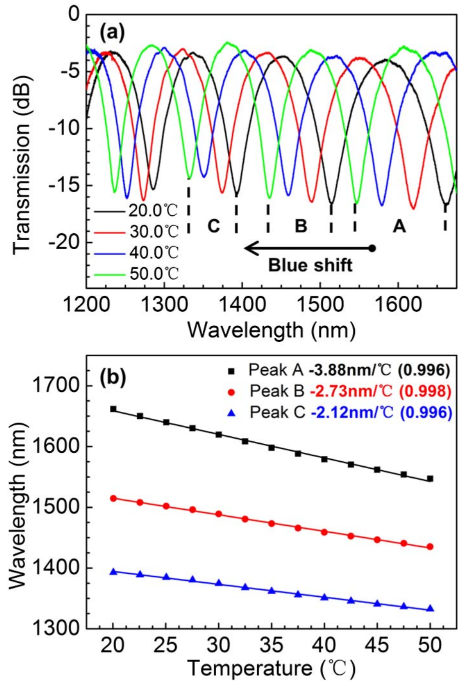

Fig. 3. (Color online) (a) Typical transmission spectrum of the isopropanol-sealed OMT under different temperatures. (b) Relationships between temperature and wavelength of different resonant peaks. The numbers in brackets represent Adj. R-Square.

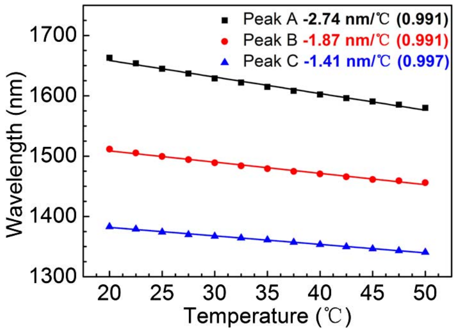

Fig. 4. (Color online) Simulation results of TSCs from thermo-optic effect of isopropanol for different resonant peaks.

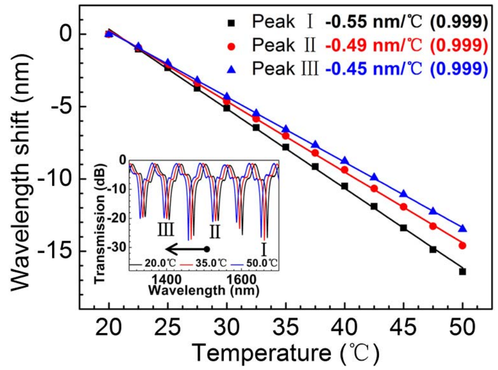

Fig. 5. (Color online) Relationships between temperature and wavelength shift of different resonant peaks for the air-sealed OMT. The inset shows the typical transmission spectrum under different temperature.

2.5°C. The relationships between temperature and wavelength shift of these resonant peaks are presented in Fig. 3(b). The linear fitting results give the temperature sensitivities of about −3.88 nm/°C, −2.73 nm/°C, and −2.12 nm/°C, respectively, with excellent linearity (given in brackets). To the best of our knowledge, the isopropanol-sealed OMT is the most sensitive sensor compared with the other all-SMF-based temperature sensors.

We theoretically investigated the temperature sensitivity contributions (TSCs) from thermo-optic effect of the isopropanol with commercial software Rsoft. The microfiber taper structure parameters were the same as the isopropanol-sealed OMT, except that the uniform waist length L_2 is set to be 500 μm. A linear profile and a quadratic profile were constructed for L_1 and L_3, respectively. The simulated transmission spectrum in isopropanol was in good agreement with the experimental result. Relationships between temperature and wavelength shift of different resonant peaks are shown in Fig. 4. The linear fitting results give the temperature sensitivities of peaks A, B, and C, which are −2.74 nm/°C, −1.87 nm/°C, and −1.41 nm/°C, respectively, less than the experimental results. We believe that the difference between the simulation and experimental results is owing to the influence of AB glue.

In order to validate our conjecture, another OMT (structure parameters: $L_1 = 750$ μm, $L_2 = 425$ μm, $L_3 = 1700$ μm, $D = 6.5$ μm) was fabricated and sealed in a capillary with AB glue. The sealed medium in the capillary was just air to compare with the case of isopropanol-sealed device. The temperature sensing results of the air-sealed OMT is shown in Fig. 5. With temperature increasing, thermal expansion effect of the AB glue will produce tension in the microfiber taper, making the resonant peaks shift to short wavelength [Fig. 5, inset]. There are six resonant peaks in the wavelength range of 1300–1700 nm. The temperature sensitivities given by linear fitting results for peaks I, II, and III are −0.55 nm/°C, −0.49 nm/°C, and −0.45 nm/°C, respectively. We take the average value −0.49 nm/°C of these six loss peaks as the TSC from thermal expansion of the AB glue. Take the loss peak A, for example. Its TSCs from the thermo-optic effect of isopropanol and thermal expansion effect of AB glue are −2.74 nm/°C and −0.49 nm/°C. The summation is −3.23 nm/°C, still less than the temperature sensitivity of −3.88 nm/°C, corresponding to the isopropanol-sealed OMT. The difference value of −0.65 nm/°C may be caused by the hydraulic pressure from the liquid volume expansion. With temperature augmentation, the volume expansion of the isopropanol will produce hydraulic pressure on the AB glue, increasing the axial tension in the OMT and further enhancing the sensor's temperature sensitivity.

In conclusion, we have demonstrated an ultrasensitive fiber sensor based on the OMT for RI and temperature measurement. The highest RI sensitivity of 18989 nm/RIU is achieved in the RI range of 1.3955–1.4008. The highly sensitive temperature sensor is constructed by sealing the OMT into a capillary within isopropanol. The thermo-optic effect of isopropanol and the thermal expansions of the AB glue and sealed liquid turn the OMT into a ultrasensitive temperature sensor with the maximum sensitivity of −3.88 nm/°C. The sensing mechanism of the device has been analyzed in detail. Additionally, theoretical simulation of the isopropanol-sealed OMT and temperature sensing experiments of the air-sealed OMT are also implemented to get the TSCs from thermo-optic effect of isopropanol and thermal expansion effect of the AB glue, respectively. This ultrasensitive sensor is very simple, easily fabricated, cost-effective, and compact, making it a promising fiber sensor in biological sensing field.

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