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Min Li(李敏)[1], Biao Feng(冯彪)[2], Jiwen Yin(尹辑文)[1]
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Highly sensitive optical fiber temperature sensor based on resonance in sidewall of liquid-filled silica capillary tube*

Min Li(李敏)[1,†], Biao Feng(冯彪)[2], and Jiwen Yin(尹辑文)[1]

[1] College of Physics and Intelligent Manufacturing Engineering, Chifeng University, Chifeng 024000, China
[2] Department of Optoelectronics Science, Harbin Institute of Technology at Weihai, Weihai 264209, China

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A highly sensitive optical fiber temperature sensor based on a section of liquid-filled silica capillary tube (SCT) between single mode fibers is proposed. Two micro-holes are drilled on two sides of SCT directly by using femtosecond laser micromachining, and liquid polymer is filled into the SCT through the micro-holes without any air bubbles and then sealed by using ultra-violet (UV) cure adhesive. The sidewall of the SCT forms a Fabry–Perot resonator, and loss peaks are achieved in the transmission spectrum of the SCT at the resonant wavelength. The resonance condition can be influenced by the refractive index variation of the liquid polymer filled in SCT, which is sensitive to temperature due to its high thermo-optical coefficient (-2.98×10^{-4} °C^{-1}). The experimental result shows that the temperature sensitivity of the proposed fiber structure reaches 5.09 nm/°C with a perfect linearity of 99.8%. In addition, it exhibits good repeatability and reliability in temperature sensing application.

Keywords: optical fiber sensors, liquid filling, temperature measurement

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1. Introduction

Optical fiber temperature sensor is increasingly popular for its compactness, immunity to electromagnetic interference, and potential low cost. Various optical fiber temperature sensors based on optical fiber tapers,[1,2] special optical fibers,[3–6] and fiber gratings[7,8] have been fabricated. However, most of them based on pure optical fiber material cannot achieve high temperature sensitivities (only about 10 pm/°C–200 pm/°C) due to the limitation of both low thermo-optical coefficient (TOC, about 10^{-7} °C^{-1}) and low thermal expansion coefficient (TEC, about 10^{-5} °C^{-1}) of silica. Recently, fiber optofluidic interferometer based on an optical microbubble-on-tip structure was developed.[9] The optical microbubble-on-tip is a hybrid solid/liquid/gas microstructure generated by heating a fiber tip with laser. The diameter of the optical microbubble-on-tip interferometer increases with time, leading the free spectral range (FSR) to decrease. By measuring the FSR, the temperature sensitivity is demonstrated to be −1146 pm/°C. Although the temperature sensitivity of this sensor is improved, it is still not high enough.

To further enhance the temperature sensitivity, the materials with high TOC and TEC are employed to fabricate fiber optical temperature sensors, such as by infiltrating liquid into photonics crystal fibers,[10,11] sticking organic material on the end face of optical fibers to form a Fabry–Perot (FP) cavity,[12–14] immerging the sensor in liquid,[15,16] and imbedding the sensor in metal V-shaped groove.[17] Most of these sensors usually have much higher sensitivities because of the sensitive temperature response of the material.

In recent years, the silica capillary tube (SCT) has been used for making optical fiber humidity[18] or magnetic field[19] sensors through depositing particular material on the outer surface of SCT based on the resonance in its sidewall.[20] Owing to the unique hollow structure of SCT, the material with high TOC can be filled and sealed inside the SCT to achieve a highly sensitive temperature sensor based on a similar resonance phenomenon. In this paper, we splice a section of SCT between single mode fibers (SMFs) and drill two micro-holes on its two sides by using femtosecond laser. Liquid polymer (HASUNCAST RTVS 901 PT-B) is filled into the SCT through the micro-holes without any air bubbles and then sealed by using UV cure adhesive. For the refractive index (RI) of the liquid polymer is lower than that of the sidewall of SCT, the sidewall of the SCT forms an FP resonator. The resonance wavelength can be influenced by the refractive index variation of the liquid polymer, which is sensitive to temperature due to its high TOC. The proposed fiber structure attains a high temperature sensitivity of 5.086 nm/°C with a linearity of 99.8%. The experimental results also show its good repeatability and reliability in temperature sensing. Therefore, the Fabry–Perot resonator has a bright prospect in the applied domain of medical, biology, and environmental science.[21]

2. Fabrication and principle

The fabrication process of the proposed sensor is shown in Fig. 1. A section of SCT (internal diameter 50 μm, external

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†Corresponding author. E-mail: phdlimin@163.com
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diameter 124 μm) was spliced between two sections of SMFs by using a commercial fiber fusion splicer. The optical image is shown in Fig. 1(a). The length of SCT is 980 μm, and the thickness of the sidewall is about 37 μm. The two interfaces at the splicing points are parallel to each other. Two micro-holes (14 μm in its length and width) were drilled on two sides of SCT directly by using femtosecond laser (120 fs, 800 nm, 1 kHz) micromachining. One hole is used for infiltrating polymer, and the other is used as a vent. The image of the structure with the micro-holes is shown in Fig. 1(b). Each micro-hole is about 15 μm away from the nearby splicing surface between SCT and SMF.

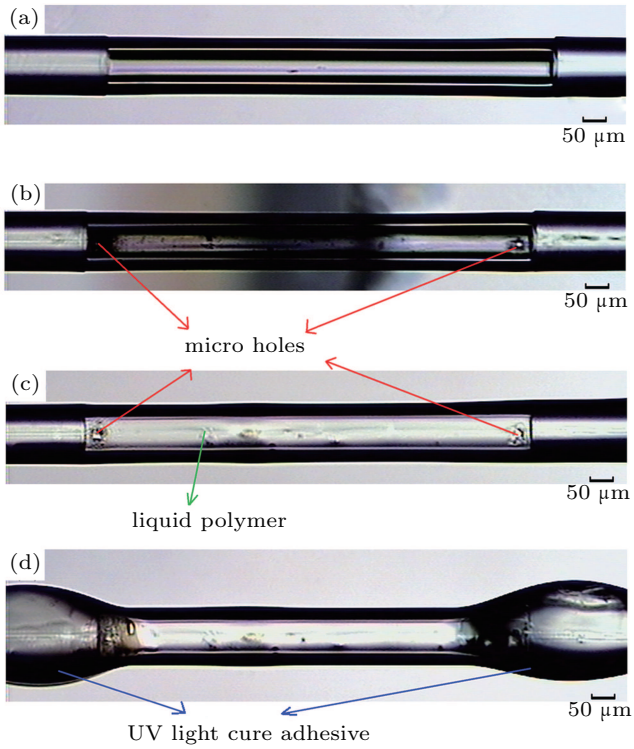


Fig. 1. (a) A section of SCT spliced between two sections of SMFs, (b) image of structure with micro-holes, (c) image of SCT filled with liquid polymer, and (d) image of final fabricated fiber structure.

Then, a kind of liquid polymer (HASUNCAST RTVS 901 PT-B) was filled into the hollow core of SCT. This material was chosen because of its lower RI than that of silica, small coefficient of viscosity, ultralow volatility, and low light absorption coefficient. Besides, the TOC of the polymer is high, which makes the sensor possess high temperature sensitivity. In practice, the liquid polymer can work stably at least between −30 °C and 100 °C, the proposed sensor based on the polymer is mainly used for low temperature sensing. In this process, the left micro-hole was immerged into the liquid polymer, and the right micro-hole was kept out of the liquid polymer. The liquid polymer flowed into the silica capillary tube through the left micro-hole immediately due to liquid siphon effect. Meanwhile, the air in the silica capillary tube was expelled to the outside environment through the right micro-hole. The image of the SCT filled by liquid polymer is shown in Fig. 1(c). From Fig. 1(c) we can see that the whole region of hollow core is fully filled with liquid polymer without any air bubbles due to the two well-designed micro-holes. Finally, ultraviolet (UV) curable adhesive (HASUNCAST 3220) was dipped on the two micro-holes and then solidified by UV light exposure to seal the liquid polymer into the SCT. The image of the final fabricated fiber structure is shown in Fig. 1(d). In order to avoid generating microbubbles, the polymer with low volatility was selected. The low volatility makes it much easier to avoid generating the air bubbles in the sealing process. Besides, we placed the polymer in ultrasound environment with power 40 W for one hour, and then set it for about two hours. Because of the self-leveling function of the polymer, the microbubbles can be avoided as much as possible. In addition, in the fabrication process, the left micro-hole was emerged into the liquid polymer, and the right micro-hole was kept out of the liquid polymer. The liquid polymer can flow into the silica capillary tube through the left micro-hole immediately due to liquid siphon.

Since the refractive index (RI) of the liquid polymer filled in the hollow core of SCT is lower than that of the sidewall, the sidewall of SCT forms an FP resonator[18–20] as shown in Fig. 2. Part of the propagating light is coupled into the sidewall of SCT in the way of grazing incidence, and then reflected at the outer wall of SCT. As a result, the core modes oscillate through the cladding, and FP interference can occur between the light reflecting from the inner wall and that from the outer wall of SCT respectively. Single reflection from the inner and outer walls of SCT is considered to simplify the calculation. As shown in Fig. 2, h is the thickness of the sidewall, θ and θ_1 are the incident and refractive angles of the light respectively, n_1 and n_2 are the refractive indices of liquid polymer and silica sidewall respectively.

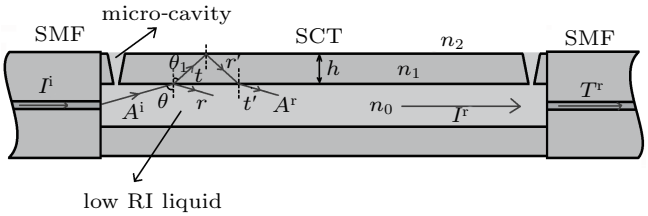


Fig. 2. Diagram of FP resonator based on sidewall of SCT.

The central wavelengths of the interference peaks corresponding to the resonant condition, λ_m, can be expressed as[18]

$$\lambda_m = \frac{2h\sqrt{n_1^2 - n_0^2}}{m}, \quad m = 1, 2, 3, \ldots, \tag{1}$$

where m is the order of the interference peaks. The guided light at these wavelengths would transmit through the resonator and leak out of the sidewall of the SCT. Therefore,

periodic and narrow loss peaks at these wavelengths appear in the transmission spectrum. Besides, from Eq. (1) it can be seen that the central wavelengths of the interference peaks are determined by the thickness of the sidewall, if n_1 and n_2 are fixed. The length of SCT is unrelated to the central wavelength of the interference peak, which can be verified by the experimental results shown in the next section.

By taking the derivative of Eq. (1) with respect to temperature T, we can obtain the temperature sensitivity of the proposed fiber structure based on the central wavelength shift of the interference peak as follows:

$$S_T = \frac{2h\sqrt{n_1^2-n_0^2}}{m}\alpha + \frac{2h}{m\sqrt{n_1^2-n_0^2}}(n_1\varepsilon_1 - n_0\varepsilon_0)$$
$$= \lambda_m\alpha + \frac{\lambda_m}{n_1^2-n_0^2}(n_1\varepsilon_1 - n_0\varepsilon_0), \quad (2)$$

where α is the TEC of silica, ε_1 and ε are TOCs of the silica and the liquid polymer respectively. Here, $\alpha = 5.5\times10^{-7}/^{\circ}\mathrm{C}$, $\varepsilon_1 = 1.1\times10^{-5}/^{\circ}\mathrm{C}$, $n_1 = 1.4598$, and $h = 37$ μm. To estimate the value of n and ε, we measured the RI values of the liquid polymer at different temperatures by using an optical fiber liquid RI senor reported by us before.[22] The results are shown in Fig. 3. We can easily obtain $\varepsilon = -2.98\times10^{-4}/^{\circ}\mathrm{C}$ and $n = 1.4045$ at 22 °C. Assuming $\lambda_m = 1550$ nm, the temperature sensitivity of the proposed fiber structure can be calculated to be 4.1 nm/°C. The numerical calculation also shows that n and ε contribute to the majority of temperature sensitivity, which means that the temperature sensitivity is largely improved by filling high TOC liquid into the hollow core of SCT.

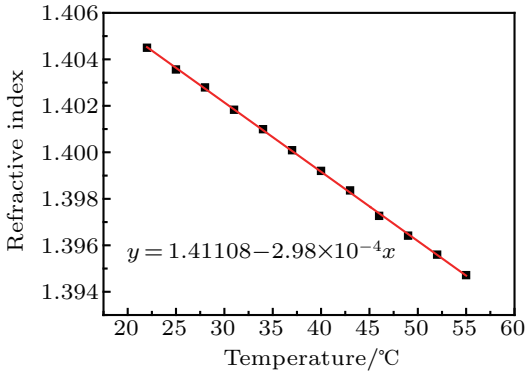


Fig. 3. Plot of RI *versus* temperature of the liquid polymer, measured by using optical fiber liquid RI sensor.

3. Experimental results and discussion

In the experiment, the broadband light with a wavelength from 1250 nm to 1650 nm is launched into the fabricated fiber structure. The transmission spectrum is measured by using an optical spectrum analyzer (OSA, YOKOGAWA, AQ6370B). The result is shown in Fig. 4. There are obvious interference peaks in the transmission spectrum. The transmission loss of the fabricated structure is about −5 dB, and the contrast of the interference peak near 1450 nm reaches about 30 dB. To prove that these loss peaks are induced by the resonance in the sidewall of liquid-filled SCT, another two similar fiber structures (the lengths of the liquid-filled SCTs are 1490 μm and 1650 μm respectively) are fabricated by using the same method, and their transmission spectra are also measured as shown in Fig. 4. From Fig. 4 it follows that though the SCT sections of three fabricated structures are different in length, their loss peaks in the spectra are located at nearly the same wavelength positions. The experimental results accord well with the results from the resonance theory in the sidewall of the SCT that central wavelengths of the interference peaks only depend on the thickness of the sidewall. What needs explaining is that the minute difference between the central wavelengths of the loss peaks of three different fiber structures may be induced by the nonuniform thickness of the SCT sidewall.

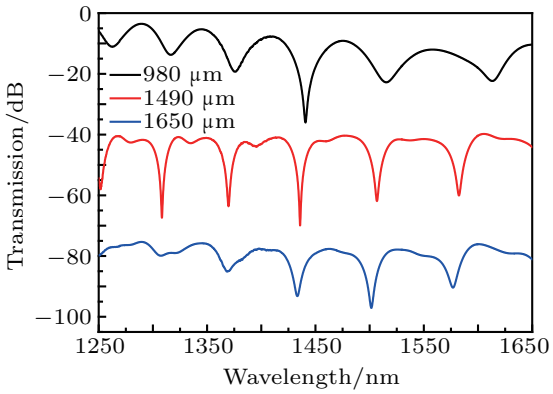


Fig. 4. Transmission spectra of proposed fiber structures based on liquid-filled SCTs with lengths of 980 μm, 1490 μm, and 1650 μm respectively.

To investigate the response of the proposed fiber structure to temperature, the fabricated structure with an SCT length of 980 μm is placed inside a glass tubewith an inner diameter of 3 mm, which is then placed in a thermostat water bath. The transmission spectrum of the structure is measured in real time by using the broadband light source (BBS) and OSA. The whole experiment setup is shown in Fig. 5. The lower and higher threshold temperature of this sensor mainly depend on the temperature characteristic of the polymer material. The high temperature resistance and low temperature resistance properties of the polymer determine the temperature sensing range of the sensor. In practice, the liquid polymer sensor can work stably at least between −30 °C and 100 °C. In our experiment, the tested range is only from 25 °C to 55 °C, as the temperature range is usually around room temperature in the application of environmental science. At each temperature increment point, the transmission spectrum is recorded after the temperature has been stabilized for 10 min.

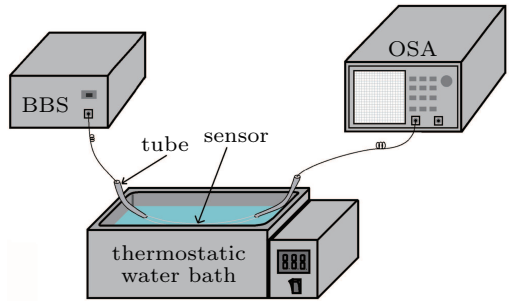


Fig. 5. Setup for temperature response experiment.

To clearly show the shift of the interference peak near 1450 nm with temperature increasing, plotted is only a small range of each spectrum where the interference peak is located. The result is shown in Fig. 6(a). It can be seen that the interference peak shifts to longer wavelength direction with temperature increasing. Then the central wavelength values of the interference peak at different temperatures are read and linearly fitted. The result is shown in Fig. 6(b). From Fig. 6(b) we can see that there is perfectly linear relationship (R-square = 0.998) between the central wavelength and temperature. Meanwhile, the temperature sensitivity based on the central wavelength shift reaches as high as 5.086 nm/°C, which is in agreement with the theoretical expectation.

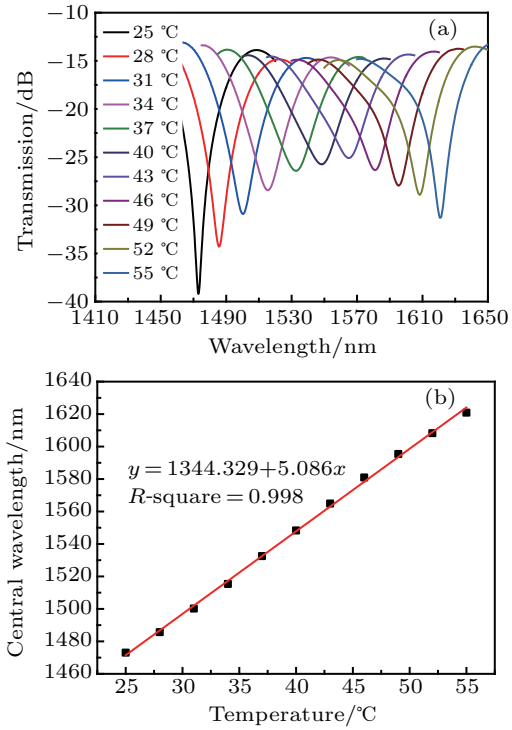


Fig. 6. (a) Shift of the interference peak near 1450 with temperature increasing, and (b) linear fitting result of central wavelength values.

The repeatability is also an important parameter to evaluate the performance of the sensor. To show the repeatability of the fabricated fiber structure in temperature sensing, it is heated and cooled between 25.0 °C and 55.0 °C in steps of 5 °C for three runs which are finished separately in three different days. In the same way as that mentioned above, the transmission spectrum at each temperature is measured after 10 min of temperature stabilization. The central wavelength values of the interference peak at different temperatures in three repeated experiments including heating and cooling process are shown in Fig. 7.

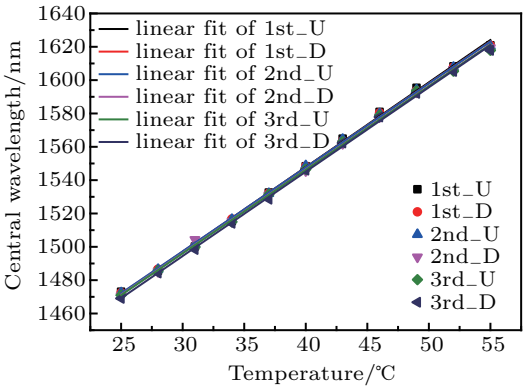


Fig. 7. Plots of central wavelength value of the interference peak *versus* temperature in three repeated experiments.

From Fig. 7 it can be seen that the central wavelength values of the interference peak are nearly identical in the three runs of heating and cooling process. There is no obvious hysteresis in the forward and backward curves. These results prove that the fabricated fiber structure has good repeatability and reliability in temperature sensing application.

4. Conclusions

In this work, a highly sensitive optical fiber temperature sensor is fabricated by infiltrating liquid polymer into the SCT between SMFs. As the RI of the used liquid polymer is lower than that of silica, its transmission spectrum shows obvious lossy peaks induced by the resonance in the sidewall of SCT. Due to the high TOC of the liquid polymer, the proposed fiber structure obtains a high sensitivity of up to 5.086 nm/°C, which is in agreement with the theoretical expectation. The experimental results also show that the proposed fiber structure can have actual application in temperature sensing due to its good linearity and repeatability.

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