Highly sensitive temperature sensor using packaged optical microfiber coupler filled with liquids

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Abstract: A novel temperature sensor based on a Teflon capillary encapsulated 2 × 2 optical microfiber coupler (OMC) filled with refractive index matching liquids is described. The sealed capillary and the filling liquid are demonstrated to enhance the temperature sensing performance, achieving a high temperature sensitivity of 5.3 nm/°C. To the best of our knowledge, the temperature sensor described in this article exhibits the highest sensitivity among the OMC structure based fiber optic temperature sensors. Experimental results also show that it has good repeatability along with a fast response time of 243 ms.

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1. Introduction

Rapid recent progress in micro optical fiber processing technology has resulted in the correspondingly rapid development of novel micro/nano optical devices. The associated optical fiber sensors have attracted much attention because of their small size, excellent immunity to external electromagnetic interference and capability of providing a long sensor to interrogation system distance. With the improvement of micro/nanofiber fabrication technology, micro/nano optical devices have achieved rapid development in recent years [1, 2]. Temperature sensors are widely used as micro/nano optical fiber sensors and recent improvements in the technology has resulted in greatly improved performance and reliability. Most of the proposed optical fiber temperature sensors are based on micron scale processing of single-mode fiber (SMF) optical fiber, fiber gratings [3–6], couplers and ring resonators [7–9], tapered fibers coated by thermo-sensitive material [10, 11], and high birefringence photonic crystal fibers (HBFs) with liquid-filled cores [12, 13]. Considering fabrication cost and difficulties, a microfiber coupler may be a more favorable candidate for fabricating temperature sensors.

For most micro/nano temperature sensors based on traditional silica fiber structures, their temperature sensitivity is normally below 0.3 nm/°C [14], which is mainly limited by the small thermo-optic coefficient difference between the fiber core and cladding. To overcome these limitations, Qian et al have selectively filled a temperature sensitive liquid, such as alcohol in the air holes of a photonic crystal fiber to improve the thermo-optic coefficient, and achieved an extra-high sensitivity of 6.6 nm/°C [15].

In this paper, an optical temperature sensor based on an optical microfiber coupler is described, which is encapsulated in a Teflon capillary, and immersed in a refractive index matching liquid. The fabrication method of the temperature sensor is described in detail, including the fabrication of the microfiber coupler, capillary encapsulation and syringe based liquid filling. To ensure that the fabricated temperature sensor has a relatively high sensitivity, different capillary materials and filling liquids were investigated for fabricating the temperature sensor. Through a comparison of the experimental results, the highest sensitivity of 5.3 nm/°C was achieved when a Teflon capillary and index matching liquid was deployed, which is several times greater than similar sensors previously published [16–19]. The repeatability and response time of the fabricated sensor have also been investigated. This proposed temperature sensor provides a favorable choice for applications including industrial production and environmental monitoring.
2. Theory

The strongly fused coupler theory was applied to this model because of the strong fusion of microfibers [20]. The interference between the lowest-order even and odd modes at the coupling region was considered. A simple analytical method was chosen to carry out a preliminary approximate theoretical analysis.

Under these conditions, the coupling coefficient between two single-mode parallel microfibers is given by:

\[
C(\lambda) = \frac{3\pi\lambda}{3\lambda a^2 n_1} \left( \frac{1}{1 + \frac{1}{V^2}} \right)
\]

In the formula, \(\lambda\) is the wavelength of incident light, \(V\) is the normalized frequency where \(V = \frac{2\pi a}{\lambda} \sqrt{n_1^2 - n_2^2} \cdot n_1\) and \(n_2\) are the RIs of the silica fiber and the surrounding medium, \(a\) is the diameter of the microfiber.

The output power of the coupled port of the MFC is given by:

\[
P = P_0 \sin^2(CL)
\]

Where \(P_0\) and \(P\) are the input power and the output power respectively and \(L\) is the effective coupling length. The two equations above show that the output power depends on the RI of the surrounding medium \(n_2\), coupling length \(L\), and microfiber diameter \(a\).

If an external medium is chosen such that its refractive index varies with the temperature of the local environment, then the dip wavelength and transmission loss of the output spectrum will become sensitive to temperature. Thus a temperature sensor can be realized by detecting wavelength shift of the output spectrum, assuming a suitable calibration is in place.

3. Experiment and results

An Optical Microfiber Coupler (OMC) was fabricated from two identical standard singlemode optical fibers (SMF-28, Corning, NY, USA) by employing a fiber tapering system as shown in Fig. 1(a), which consists of a ceramic micro-heater (NTT-AT, Japan) and two high accuracy translation stages. For the fabricated OMC, the diameter of each coupled microfiber is 1.6 \(\mu\)m and the length of the coupling waist is 1.3 cm. A Teflon capillary was used to encapsulate the fabricated microfiber coupler, which has a length of 80 mm and an inner diameter of 1.5 mm, as illustrated in Fig. 1(b). The waist region of the microfiber coupler was completely encapsulated by the Teflon capillary. A refractive index matching liquid (mixture of glycerin and water) was injected into the capillary using a syringe, and the microfiber coupling region was therefore completely immersed into the index matching liquid. An ultraviolet light source was employed to cure the low refractive index ultraviolet (UV) epoxy to seal both ends of the Teflon capillary.
Fig. 1. (a). Schematic of experimental setup for fabricating optical microfiber coupler; (b) Schematic of the fabricated packaged microfiber coupler filled with liquid, inset illustrates microscope image of the fabricated temperature sensor.

In order to investigate the stabilities of the temperature sensing measurements, the fabricated temperature sensor was fixed on a glass slide. Figure 2 illustrates the experimental setup for measuring the temperature sensing performance of the sensor. A temperature controlled environmental chamber was used to adjust the surrounding temperature. Port 1 was connected to a supercontinuum (SC) generation light source (YSL SC-series) with an emission in the wavelength range of 750-1650 nm, and port 2 was connected to the optical spectrum analyzer (OSA) (AQ6317C, Yokogawa, Japan). Figure 3 shows the measured output transmission spectrum of the fabricated temperature sensor at room temperature when the capillary and the infilled liquid were Teflon and index matching liquid respectively.
Fig. 2. Schematic of the experimental setup for measuring the temperature sensing performance of the sensor.

Fig. 3. Transmission spectrum of the fabricated microfiber coupler sample at a room temperature.

The transmission spectrum of the Teflon encapsulated microfiber coupler filled with index matching liquid is shown in Fig. 4(a), illustrates the response of the sensor when the temperature was increased from 35 °C to 45 °C with an increment of 2 °C. From this figure, it can be observed that a resonance dip around the wavelength of 1460 nm has a significant blue shift when the surrounding temperature increases. Any error due to temperature fluctuation in the environmental chamber was minimized as the measured transmission spectrum was recorded only after the temperature had been allowed to stabilize for one minute at each temperature value. The relationship between the measured resonance dip wavelength and the temperature is shown in Fig. 4(b). It can be clearly seen that the transmission spectrum is very sensitive to temperature variations, a linear equation was used to fit to the experimental data.
This linear analysis shows an excellent fit with an $R^2$ value of 0.99, and the average temperature sensitivity was calculated to be 5.3 nm/°C, which is much larger than other similar optical fiber temperature sensors as illustrated in Table 1.

**Table 1. Similar structure fiber sensors.**

| Reference source | The range of temperature (°C) | Sensitivity |
|------------------|-------------------------------|-------------|
| References 16    | −50 to 100                    | 0.17 nm/°C  |
| References 17    | 27 to 54                      | 3.86 nm/°C  |
| References 18    | 247 to 1283                   | 11.96 pm/°C |
| References 19    | 22 to 60                      | 1.5 nm/°C   |
| This work        | 35 to 45                      | 5.3 nm/°C   |

A comparison with earlier demonstrated coupler structure based sensors on the basis of temperature sensitivities and measurement range shows that while the temperature measurement range of the proposed sensor is not superior to that of other sensors the sensitivity achieved is much higher. D. J. J. Hu has proposed a sensor based on directional coupler structure which was formed by a nematic liquid crystal filled photonic crystal fiber [17]. The sensitivity reached 3.86 nm/°C, which means that the performance is comparable to the sensor investigated in this work. However a comparison based on the design of the structure of the sensor of this investigation shows that the sensor of this investigation is not only superior in terms of sensitivity, but also lower in complexity, and hence manufacturing cost and manufacturing difficulty.

In order to investigate the influence of the packaged capillary material and the injected external media on the sensitivity of the sensor, several samples were prepared as illustrated in Table 2. As shown in Table 2, the sample described above was designated as sample 1, which was constructed using a Teflon capillary and index matching liquids. Sample 2 was encapsulated in a Teflon capillary and the injected external medium was anhydrous ethanol. Sample 3 was encapsulated in a silica capillary and the injected external medium was index matching liquid. Figures 5(a) and 5(b) represent the measured transmission spectra of sample 2 and sample 3 over the temperature range of 35 °C – 45 °C. It is clear that there exists a different transmission spectral response to the same temperature variation for the three samples by comparison of Figs. 4(a), 5(a), and 5(b). In order to evaluate the temperature sensitivities of the three samples, the relationship between resonance dip shifts and temperature is illustrated in Fig. 5(c). It can be clearly seen from Fig. 5(c) that sample 1 has the highest sensitivity of 5.3 nm/°C. The temperature sensitivities of sample 2 and sample 3 are 2.19 nm/°C and 0.18 nm/°C, respectively. It can therefore be concluded that the index matching liquid has a greater influence on the temperature sensing performance than anhydrous ethanol, and that the use of Teflon as the capillary material also enhances the temperature sensitivity compared to silica.

**Table 2. Sensing properties of the three samples.**

| Sample number | Capillary material | Liquid material                  | Sensitivity (nm/°C) |
|---------------|--------------------|----------------------------------|---------------------|
| Sample 1      | Teflon             | Index matching liquids           | 5.3                 |
| Sample 2      | Teflon             | Anhydrous ethanol                | 2.19                |
| Sample 3      | Silica             | Index matching liquids           | 0.18                |
Based on the experimental results above, it is clear that the sensitivity of the sensor depends on both the capillary material and the filling liquid. This can be attributed primarily to the expansion (or shrinkage) coefficients of the capillary and the photo-elastic effect of the index matching liquid. When the temperature changes, the thermo-optic effect of the refractive index matching liquid results in a small change in its refractive index and as the...
refractive index of the liquid usually decreases with an increase of temperature, this leads to a red shift in the spectrum. Some of the previously reported sensors use this principle to implement temperature measurement [21, 22]. Also the liquid refractive index usually increases with the increase of external pressure and the resulting spectrum is blue shifted. The response of the sensor described in this investigation therefore simultaneously depends on the temperature and pressure. However pressure changes within the sensor package dominate the sensitivity of the device, as the temperature effect on the filling liquid RI is negligible, and thus any red shift caused by the temperature change is minor and the blue shift caused by pressure dominates the spectral response. Due to the variation of the surrounding temperature, the volume of the capillary and filling liquid are changed due to thermal expansion (or contraction), which also results in a change of pressure inside the capillary, which is also experienced by the sensor element. At this point, the photo-elastic effect occurs and the refractive index of the matching liquid varies linearly with the change of pressure inside the capillary. By adjusting the impact of the thermal expansion (or contraction) effect and photo-elastic effect on the sensor, the sensitivity to temperature is greatly enhanced. It can be seen from the experimental results that the effect of the combination of the thermal expansion (or contraction) effect and photo-elastic effect on the refractive index of the matching liquid is significantly better than that of ethanol. This conclusion explains the result of sample 2. The special Teflon capillary at ambient temperatures higher than 35 °C shrinks with the increase of temperature, this material is used in the manufacture of fiber heat shrinkable capillary. While the glass capillary expands with the increase of temperature, the pressure change inside the glass capillary is far less than in the case of the Teflon capillary, and thus the sensitivity of the sensor packaged with the Teflon capillary is superior. This conclusion explains the result of sample 3 in Fig. 5(c). Based on the above comparison, the fabricated sample 1 can be considered as a good candidate for temperature sensing.
To investigate the repeatability of this temperature sensor, six temperature reference points were used to observe the stability of the sensor at different temperatures, and then any resulting wavelength shift was recorded for a large number (24) of identical but separate temperature cycles. If the sensor has good temperature stability, the reference point location will have a relatively small shift range. The process of heating and cooling between 35 °C and 45 °C in the environmental chamber can be viewed as a temperature changing process, and the two processes together are called a cycle. The cycles were repeated two times, and thus each temperature result was recorded four times over the duration of the two cycles. Finally,
six separate temperature points produced six experimental results which included four repeated values as described above. The results are shown in Fig. 6. Each of the data points represents four separate measurements with the error bar indicating one standard deviation. The values of the relative standard deviations are 0.48 nm, 0.51 nm, 0.44 nm, 0.52 nm, 0.39 nm and 0.58 nm for the six successive measurements. The low standard deviation value strongly support the conclusion that this method has excellent repeatability.

![Figure 6](image.png)

Fig. 6. Six batches of experimental measurements, the error bars in this figure represent the standard deviation of four experimental measurements.

Furthermore, the response time was also measured in the experiments. A tunable laser source (Santec TSL-710), a photo amplifier and an oscilloscope (Tektronix MDO4034C) were employed to launch and receive the optical signal. The fabricated temperature sensor was placed in the environmental chamber, for which the temperature was maintained constant at 37.5 °C. The cover of environmental chamber door was then briefly opened to expose the sensor to the external environment in the lab. A rapid temperature variation was achieved in this manner. The temperature in the environmental chamber was measured using its reference temperature sensor, the temperature quickly reduced to 37 °C, then the door was closed again to keep the temperature constant at this value. The response curve in this interval was recorded using a photodetector and an oscilloscope. The time-dependent response of the sensor is shown in Fig. 7. The response time was calculated as the time interval from the beginning of the change to the new point of stability, resulting in a measured response time of 243 ms.
4. Conclusion

A highly sensitive temperature sensor based on a Teflon capillary encapsulated microfiber coupler filled with index matching liquid has been demonstrated experimentally. Through employing a different capillary material and filling liquid, a maximum sensitivity of 5.3 nm/°C was achieved, which is several times greater than other temperature sensors based on similar microfiber coupler structures. Experimental results also demonstrated that this temperature sensor has a fast response time of 243 ms. The fabricated highly sensitive temperature sensor shows good potential for applications in environmental monitoring, biomedical applications and industrial production.

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