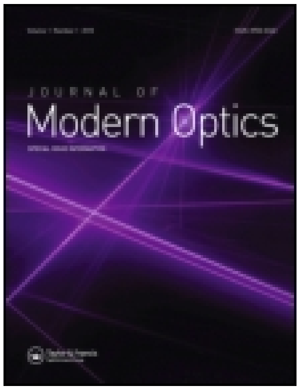

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Lead silicate fiber-based, refractive index-independent temperature sensor

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Thee fabrication is reported of a simple, compact, and stable refractive index (RI)-independent temperature sensor based on a soft glass fiber (SGF) interferometer. Because the SGF has a high thermal expansion coefficient and a high RI, it is sensitive to temperature change but not sensitive to the RI change of liquids with lower RI. It thus can be used to detect the temperature change of aqueous solutions accurately. As an example, a temperature sensor with a temperature sensitivity of ∼17 pm/°C and a negligible RI sensitivity of only about −1 nm/RIU (RI unit) in the range 1.32–1.43 is demonstrated. In addition, our SGF interferometer has potential applications and advantages in detecting liquids such as liquid crystals with higher RI.

Keywords: soft glass fiber; interferometer; temperature sensitivity; refractive index sensitivity

1. Introduction

Fiber-optic technologies have experienced an immense improvement in the past 30 years. A lot of interest has been focused on developing high performance interferometric fiber-optic sensors due to their significant advantages over conventional electrical sensors, such as immunity to electromagnetic interference, small size, and versatility [1]. In recent years, many different fiber temperature sensors have been fabricated based on in-line modal interferometers [2–4]. But these fiber in-line modal interferometers are also sensitive to the surrounding refractive index (RI) change because of the large mode field diameter and low RI of silica, which will interfere with the temperature measurement in aqueous solutions.

In this letter, we propose a simple, compact, and stable RI-independent temperature sensor by splicing a high RI soft glass fiber (SGF) between two single mode fibers (SMFs). Because the RI (1.8) of the glass (Schott SF57 glass) used for SGF is higher than that of the conventional silica fiber (1.45) [5], the mode field diameter of the SGF is lower and it is not sensitive to the surrounding RI change when immersed in liquids with lower RI. But it can be used to detect liquids such as liquid crystals with higher RI. Moreover, as the SGF has a higher thermal expansion coefficient compared with pure silica fiber, it can be utilized as a good temperature sensor.

2. Theory and experiment

In our experiment, we employ a piece of 14 mm-long lead silicate SGF (a wagon-wheel (WW) holey fiber (HF)) with a small core diameter fabricated by the University of Southampton (UK). As shown in Figure 1(*a*), the core and cladding diameters of the SGF are 1.34 μm and 92.4 μm, respectively. The inset in the top right corner of Figure 1(*a*) is a magnification of the core of the SGF. As the softening point of the SGF (<600°C) is much lower than that of silica fiber (>1600°C), an asymmetric fusion splicing method as illustrated in [6] is utilized to splice the two fibers. The offset distance and the fusion splicing parameters need to be groped and optimized repeatedly. Figure 1(*b*) shows the microscopic image of the fiber fusion splicing area. The voids of the SGF collapse completely over a short region, typically less than 200 μm long.

Figure 2 shows a schematic of the experimental setup. A supercontinuum source (SuperK Versa, NKT Photonics) and an optical spectrum analyzer (OSA, AndoAQ6317B) are employed during the whole experiment in real time in order to detect the interferometric behavior of the SGF. In our experiment, we use two clamps to keep the SGF straight to avoid bending and torsion. When the light transmits from the SMF to the collapsed SGF region in the interferometer, the fundamental SMF mode begins to diffract and it excites

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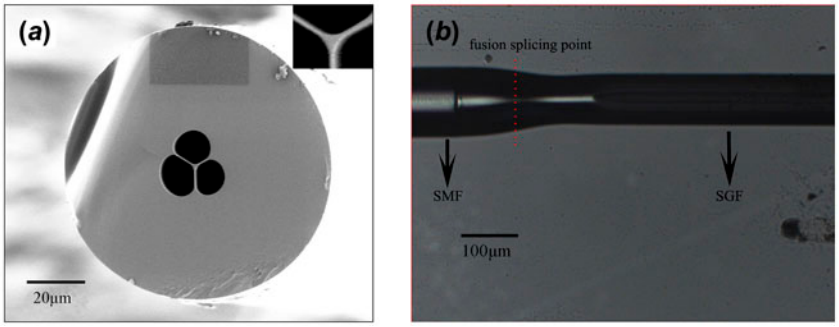

Figure 1. (*a*) Scanning electron microscope image of the cross-section of the SGF. The insert is a magnification of the core of the SGF. (*b*) Microscopic image of the fiber fusion splicing area showing the collapsed region at the end of the SGF. The dotted line denotes the fusion splicing point. (The color version of this figure is included in the online version of the journal.)

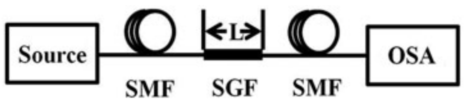

Figure 2. Schematic of the experimental setup. The SGF length is about 14 mm.

fundamental and high order modes in the SGF section with different propagation constants [7–9]. After the modes reach the other collapsed end of the SGF, they will further diffract and will be recombined through the filtering of the subsequent SMF. Therefore, there exists multi-mode interference in our interferometer and the OSA will show the interference fringes with peaks and valleys alternately, as shown in Figure 3. If we assume n_1 and n_2 are the effective indices of the fundamental and one high order modes in the SGF section, the resonant wavelengths λ_k can be expressed as $\lambda_k = (n_1 - n_2) L/K$, where L is the SGF length and K is a integer. More detailed theoretical explanation can be found in our previous work [7].

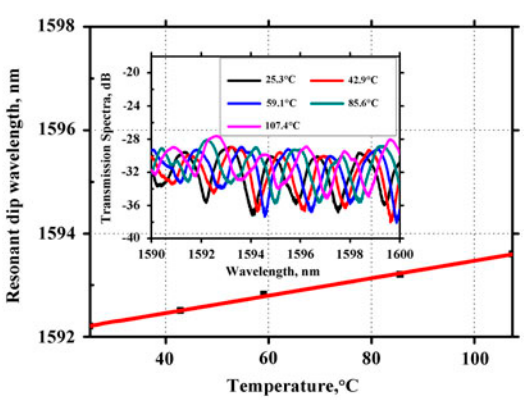

Figure 3. Relationship between temperature and the resonant dip wavelength. The inset shows the transmission spectra of the SGF interferometer under different temperatures. (The color version of this figure is included in the online version of the journal.)

Figure 3 (inset) shows the transmission spectra of the SGF interferometer under different temperatures. From the inset, we can see the interference spectra have a red-shift when the temperature increases and the fringe visibility is 5–8 dB, which is enough for sensing application. Figure 3 shows the relationship between temperature and the resonant dip wavelength. 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 $y = 1591.7906 + 0.0168x$. This means the temperature sensitivity is ∼17 pm/°C, which is higher than photonic crystal fiber (PCF) based temperature sensor as the SGF has a higher thermal expansion coefficient [2,3].

In our experiment, we also measure the RI sensing property of this interferometer at room temperature. As shown in the inset in Figure 4, the transmission spectra of the SGF interferometer have no obvious changes when immersed in deionized water and ethylene glycol, respectively. Figure 4 shows the relationship between outer liquid RI and the resonant dip wavelength. From this figure, we can see the RI sensitivity is only

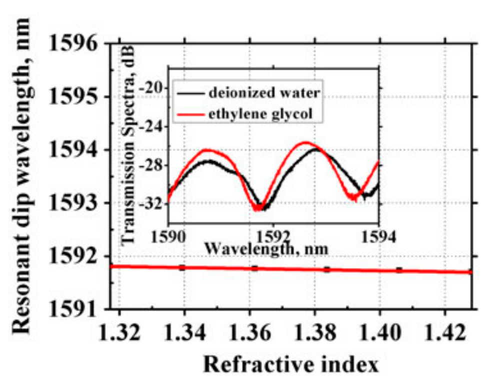

Figure 4. Relationship between outer liquid RI and the resonant dip wavelength. The inset shows the transmission spectra of the SGF interferometer when immersed in different liquids. (The color version of this figure is included in the online version of the journal.)

about −1 nm/RIU in the RI range 1.32–1.43 because the SGF has a very high RI. This sensitivity is two orders of magnitude lower than PCF based RI sensor [3,7–9], which is negligible and does not interfere with the temperature measurement in aqueous solutions.

3. Discussion

Our SGF interferometer can be used to detect the temperature change of aqueous solutions accurately. If the temperature change 1°C in aqueous solutions, it will cause 0.0001 RIU change of aqueous solutions because the thermo-optic coefficient of water is about -10^{-4}. As the RI sensitivity is only about −1 nm/RIU in aqueous solutions for our interferometer, the 0.0001 RIU change will cause the resonant dip wavelength to shift 0.1pm, which will cause temperature measurement error of less than 0.01°C. For this reason, the temperature measurement error rate is less than 1%.

From Figure 3, it can be seen that the temperature range we measured is not very high. This is because the free spectral range (FSR < 2 nm) is very narrow when we use a 14 mm-long SGF. If we increase the FSR through decreasing the SGF length, we can measure higher temperature range. The maximum temperature the SGF interferometer can detect is decided by its softening point. In addition, though our SGF interferometer is not sensitive to outer liquid refractive indices in the range 1.32–1.43, it has potential applications in detecting liquids like liquid crystals with higher RI because the RI of the SGF reaches up to 1.8. This is another advantage of our SGF interferometer over other conventional fiber interferometers.

4. Conclusion

We have demonstrated a simple, compact, and stable RI-independent temperature sensor based on a SGF interferometer. The temperature sensitivity is ∼17 pm/°C and the RI sensitivity is only about −1 nm/RIU in the RI range of 1.32–1.43, which is negligible and does not interfere with the temperature measurement in aqueous solutions. Our SGF interferometer also has potential applications in detecting liquids such as liquid crystals with higher RI because the RI of the SGF reaches up to 1.8, which is the maximum RI we can measure with this SGF interferometer. We believe if we insert the SGF interferometer into a liquid crystal cell filled with liquid crystal, it can be used as an electric field sensor with good performance in the future.

Acknowledgements

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