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Highly sensitive liquid-sealed multimode fiber interferometric temperature sensor

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ABSTRACT

A highly sensitive optical fiber temperature sensor based on liquid-sealed coreless multimode fiber (also called no core fiber, NCF) interferometer is proposed and experimentally demonstrated. By inserting the interferometer into a liquid-sealed capillary, a simple and highly sensitive fiber temperature sensor can be implemented. Owing to the high thermo-optic coefficient of the liquid and thermal expansion of the sealant, the interferometric spectra of the proposed sensor are shifting obviously with the variation of temperature; temperature response of the sensor can be effectively modulated through this way. Experimental results show that the sensitivity of the temperature sensor can be improved by tuning the refractive index (RI) value of the sealed liquid; a maximum value of 5.15 nm/°C has been obtained when the RI value of the sealed liquid is 1.450, it is close to the RI of the NCF.

1. Introduction

Multimode fiber interferometers (MMFIs) have been extensively studied and widely developed in a variety of research areas and industrial applications owing to their simple fabrication, fast response, corrosion resistance, anti-electromagnetic interference properties, etc. So far, there have been plenty of MMFI-based structures proposed to monitor environmental factors, such as temperature [1–3], refractive index (RI) [4,5], displacement [6,7], curvature [8,9], and others [10,11].

Conventional MMFI-based all optical fiber temperature sensors could only achieve a relatively low sensitivity (~10 pm/°C), which was restricted by the relatively low thermo-optic and thermal expansion coefficients of the silica basis components. Techniques which are aiming at improving the sensitivity are essential; some attempts have been made to enhance the temperature response, such as employment of specially designed multimode fiber and micro/macro-bending of multimode fiber structure in MMFI-based sensors. For instance, Li et al. presented a MMFI-based temperature sensor with a special multimode fiber used instead. Owing to its high thermo-optic coefficient polymer cladding, the sensitivity could reach up to 3.19 nm/°C, however, the measured temperature range was limited from 28 to 38 °C for its broad free spectrum range [12]. Moreover, a dual-cascaded MMFI structure temperature sensor was proposed with a sensitivity of 88 pm/°C [13], and micro/macro-bending of MMFIs were implemented and successfully improved the temperature sensitivity to 31.97 pm/°C and 11.6 pm/°C [6,14]. But all these attempts merely made a slight increase on temperature sensitivity. Recently, a new liquid-sealed packaging scheme has been designed in MMFI structures to enhance the temperature sensitivity. Fuentes et al. proposed a liquid-core multimode interference device for temperature sensing, namely, enclosure of the liquid of appropriate RI value into a capillary fiber, which was connected with two sections of single-mode fibers (SMFs) by fiber ferrules. A sensitivity of 20 nm/°C was achieved at the cost of easy operation and broad-range measurement [15]. Meanwhile, Lee et al. presented a simple leaky-guided multimode fiber interferometer by usage of a liquid material as the cladding of the multimode fiber, and the maximum sensitivity of about 50 nm/°C was achieved with the temperature range from 24 to 32 °C, however, it needs special liquid material with an appropriate and flat material dispersion profile to act as the fiber cladding [16].

In this paper, a highly sensitive optical fiber temperature sensor based on single-mode-no-core-single-mode (SMS) fiber structure which was embedded in a liquid-sealed capillary has been demonstrated. When the refractive index of the filled index matching

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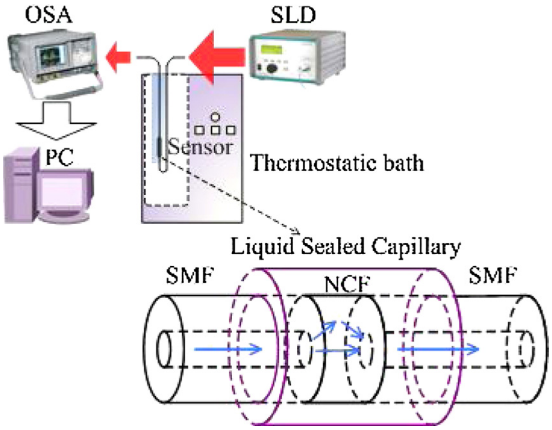

Fig. 1. Experimental setup (inset: schematic diagram of the proposed temperature sensor).

liquid was close to but smaller than that of the no-core fiber (NCF), the proposed sensor exhibited high sensitivity to temperature variation. In the experiment, the refractive index matching liquids with specific RI values of 1.420, 1.430, 1.440 and 1.450 respectively were chosen to calibrate the temperature response of our sensor.

2. Sensor design and principle

The proposed interferometer contains an SMS fiber structure, i.e., a coreless multimode fiber (MMF) segment sandwiched between two single-mode fibers (SMFs). After inserting and fastening the structure into a liquid-sealed capillary tube, a temperature-sensitive sensor is realized, and it is interrogated in a transmission mode as schematically shown in Fig. 1. The operating mechanism of the sensor relies on multimode interference and refractometry of the interferometer. More specifically, when the light field propagating along the lead-in SMF enters into the MMF section, a number of guided modes, including core and cladding modes, are excited in the MMF section, the excited cladding and core modes propagate further and re-couple back to the core mode of the lead-out SMF afterwards. Therefore, multimode interference can be formed by the excitation and re-coupling of the modes. Because the longitudinal propagation constants for the excited modes are associated with the cladding refractive index of the MMF, the interference spectrum will change with the refractive index. In our case as the ambient temperature rises, the refractive index matching liquid acting as the cladding of the coreless MMF (NCF) will reduce its RI value effectively as a result of the high negative thermo-optic coefficient, therefore resulting in a wavelength shift in the interferometric spectrum. It exhibits a red wavelength shift of the spectrum to refractive index for such a MMI structure, as experimentally demonstrated in [4,17,19]. Moreover, thermal expansion of the stainless steel capillary tube also contributes to the temperature response of the sensor. With an increment ΔT in the ambient temperature, the introduction of an additional axial tensile strain to the interferometer will also shift the interference pattern to short wavelengths, with the wavelength variation expressed as [18]

$$\Delta\lambda = -\lambda_0(1 + 2\nu + p_e)\beta(T)\Delta T \quad (1)$$

where λ_0 is the concerned initial valley wavelength; ν and p_e are the Poisson's ratio and the strain-optic coefficient of the NCF, respectively; $\beta(T) = \Delta L/(L\cdot\Delta T)$ is the thermal expansion coefficient of the tube (L is the initial length of the tube, ΔL is the length variation of the tube under the temperature change ΔT). Obviously, the combination of these two effects will absolutely increase the interaction between temperature and wavelength shift of the interference pattern, so the temperature sensitivity of the sensor is enhanced. Besides surrounding RI and strain, temperature also affects optical multimode fiber interferometer by itself through thermal expanding and thermo-optic effects of the fiber material. It has been proved that the output spectrum of the interferometer shifts to longer wavelengths as the temperature increases, which will decrease the temperature sensitivity of the proposed MMI sensor [20]. Compared with the above two factors, however, the reduction in temperature sensitivity about 10 pm/°C of the sensor is relatively small and can be ignored.

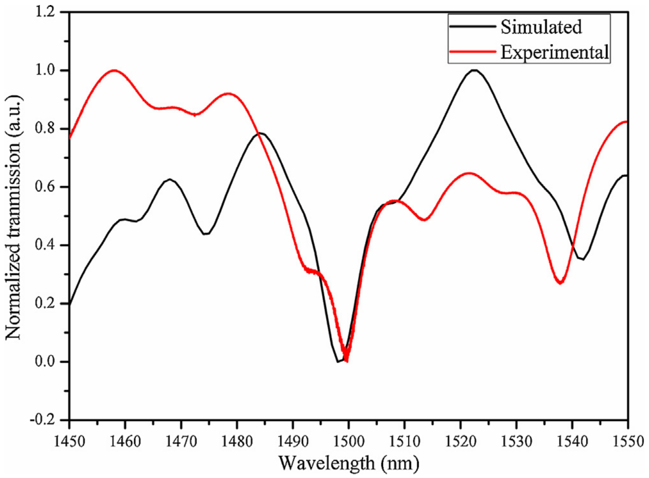

Fig. 2. Experimental and simulated transmission spectra of the MMFI-based interferometer in air. (For interpretation of the references to color in the text citation of this figure, the reader is referred to the web version of this article.)

Herein, a NCF-based interferometer was fabricated by fusion-splicing of a 40 mm NCF with a core diameter of 125 μm between two stubs of SMFs. The output spectrum of the fabricated interferometer, with two continuous periods ranging from 1450 to 1550 nm, was shown up by the red curve in Fig. 2. The figure also shows the simulated transmission spectrum in the black curve of the NCF-based interferometer by using the beam propagation method (BPM). The parameters of the NCF used in our simulation are set as follows: 125 μm in diameter, 1.4570 in refractive index, and 40 mm in length. Both the spectra were normalized for better comparisons. Neglecting the optical spectral power fluctuations, which may result from different coupling coefficients of manually fusion-spliced SMS sections, the experimental results were well consistent with the simulation ones.

After that the interferometer was inserted into a 60 mm long stainless steel capillary tube with an inner diameter of 800 μm. Refractive index matching liquid of specific RI was carefully filled through one end of the tube, and then the tube was stuffed without any bubbles inside. With the interferometer kept straightforward along the tube, we sealed two ends of the tube with AB glue, and thus in this way the NCF-based temperature sensor was finally obtained.

3. Experimentations and discussions

3.1. Influence of RI on temperature response

Prior to the temperature response test, the interferometer was immersed into glycerin solutions with different concentrations to ascertain the temperature dependence in a high-sensitivity RI range. Device connection for RI measurement was the same as that described in Fig. 1 with the sensor replaced by the interferometer. Light from a super-luminescent diode (SLD) propagated through the interferometer, and the transmission spectrum was measured by an optical spectrum analyzer (OSA). Fig. 3 shows