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High temperature fiber sensor based on spherical-shape structures with high sensitivity

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ABSTRACT

An optical fiber high temperature sensor is proposed and fabricated by cascading two spherical-shape structures, which are built by a section of single mode fiber (SMF). The spherical-shape structures can realize the coupling and recoupling between the core mode and the cladding modes. Experimental results show that the sensor is capable of monitoring temperature change from 25 °C to 735 °C with sensitivity of 0.1193 nm/°C and the sensitivity of microstrain is −0.0012 nm/με which is beneficial for encapsulation. The characteristics of the proposed sensor indicate compact, high sensitive and inexpensive properties, which can be widely applied in many fields.

1. Introduction

High temperature sensors based on inline Mach–Zehnder interferometers (MZI) have attracted considerable interest due to the advantages of small size, high sensitivities, anti-electromagnetic interference and flexibility of integration with the system which have potential applications in oil and petrochemical industry, engine health monitoring and so on [1,2]. Many kind of configurations and different techniques have been proposed to form inline MZI, including mismatched core diameter [3,4], small-waist fiber taper [5], waist-enlarged fiber taper [6,7], single mode-multimode-single mode fiber structure (SMS) [8,9] and peanut-shape structure [10]. For inline MZI temperature sensors, in order to improve the sensitivity, a large thermal coefficient difference between the two optical arms is needed [6]. The SMS structure has low sensitivity because the interference is confined in the same core of the multimode fiber which has the identical thermal properties [9]. Recently, a strain insensitive high temperature fiber sensor based on the modal interferometer was proposed, which is constructed by splicing a piece of small-core photosensitive fiber (SCPSF) between two pieces of SMF. Although the temperature sensitivity is up to 0.106 nm /°C, the special SCPSF is needed [4]. Based on concatenated down-tapers, Lu et al. presented a temperature fiber sensor with sensitivity of 0.071 nm/°C, but the structure was very fragile due to the small-waist taper [5]. Geng et al. proposed a MZI built by two waist-enlarged fusion bitapers, which had a good physical strength and a high sensitivity of 0.070 nm /°C [6]. A simple and low-cost MZI was formed by cascading two peanut-shape structures with temperature sensitivity of 0.0468 nm /°C, and had a good mechanical strength [10]. In addition, cascaded long period gratings (LPG) can be also used for temperature sensor. The sensitivity may be different (a positive or a negative value) due to the different design for LPG [11].

In this paper, a novel high temperature sensor based on two spherical-shape structures MZI is proposed. The first spherical-shape structure can excite high-order cladding modes and the second spherical-shape structure will recombine the core and cladding modes; therefore a comb interference spectrum can be obtained. Experimental results show the device is capable of monitoring temperature change from 25 °C to 735 °C with temperature sensitivity of 0.1193 nm/°C, meanwhile the microstrain experiment shows that the sensitivity of −0.0012 nm/με is little relative to the temperature sensitivity. So the effect of microstrain is small and it is beneficial for encapsulation.

2. Fabrication of spherical-shape structure

The schematic diagram of the proposed sensor is shown in Fig. 1. It consists of two spherical-shape structures with a section of SMF. A commercial fusion splicer is used to fabricate the MZI sensor head employing manual splicing mode. Firstly, a section of

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SMF (8.2 μm /125 μm) is cleaved and put into the fiber fusion splicer to fabricate the spherical-shape end. The end face of the SMF is set beyond the electrode rod 180 μm. The parameters of the first discharge are as follows: the discharge time is 1300 ms, and the discharge intensity is 200 bit. After discharging, the fiber tip is softened and becomes a sphere. Then this spherical-shape end is spliced to a section of SMF to form the spherical-shape structure. The parameters of the fusion splicing are as follows: the distance between the spherical-shape end and the face of the SMF is 15 μm, the arc power is 65 bit, and the discharge time is 1300 ms. Fig. 2 shows two spherical-shape structures made under the above parameters. The parameters of the first spherical-shape structure are $Z_1=206.7$ μm and $D_1=187.5$ μm. The parameters of the second spherical-shape structure are $Z_2=215$ μm and $D_2=192$ μm. The error of the size is less than 4%, and the fabrication process is repeatable. The proposed MZI sensor can be achieved by cascading two spherical-shape structures.

3. Properties and analysis

The transmission intensity of the proposed MZI can be expressed as follows,

$$I_{out}=k_1k_2I_{in}+\eta(1-k_1)(1-k_2)I_{in} +2I_{in}\sqrt{\eta k_1k_2(1-k_1)(1-k_2)}\cos(\Delta\varphi+\varphi_0) \quad (1)$$

where k_1 and k_2 are the couple efficiency of the first and the second spherical-shape structure, η is the transmission loss at the cladding, φ_0 is the initial phase difference which is affected by the spherical-shape structure and I_{in} is the input light intensity.

The incident light is split into core mode and cladding modes at the first spherical-shape structure and then recombined at the second spherical-shape structure. $\Delta\varphi$ is the phase difference between the core mode and cladding modes after a certain distance transmission, which can be expressed as [12] follows:

$$\Delta\varphi=2\pi\frac{(n_{core}-n_{clad})L}{\lambda} \quad (2)$$

where n_{core} and n_{clad} are the effective refractive indices of the core mode and the cladding modes, L is the interaction length between the two spherical-shape structures, and λ is the operating wavelength. When $\Delta\varphi=(2m+1)\pi$, $m=0, 1, 2\ldots$, the wavelength values with minimum output light intensity are located at

$$\lambda_{dip}=\frac{2}{2m+1}(n_{core}-n_{clad})L \quad (3)$$

The dip shift with the variation of temperature and strain change at the same time can be expressed as follows:

$$\lambda_{dip}+\Delta\lambda=\frac{2}{2m+1}[(n_{core}+\Delta n_{core})-(n_{clad}+\Delta n_{clad})](L+\Delta L)$$

where

$$\Delta n_{core}=n_{core}\xi_{core}\Delta T+n_{core}p_{core}\varepsilon,$$
$$\Delta n_{clad}=n_{clad}\xi_{clad}\Delta T+n_{clad}p_{clad}\varepsilon,$$
$$\Delta L=L\alpha\Delta T+L\varepsilon \quad (4)$$

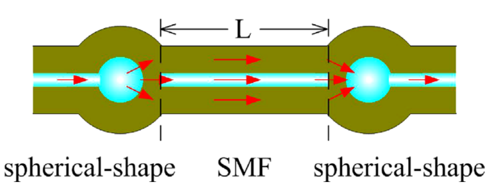

Fig. 1. Schematic diagram of the proposed sensor.

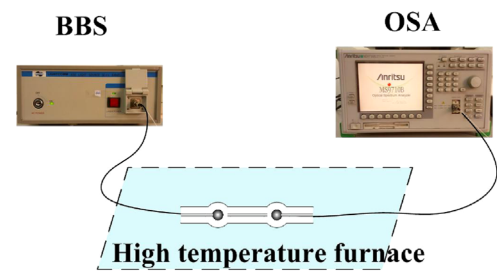

Fig. 3. Experimental setup.

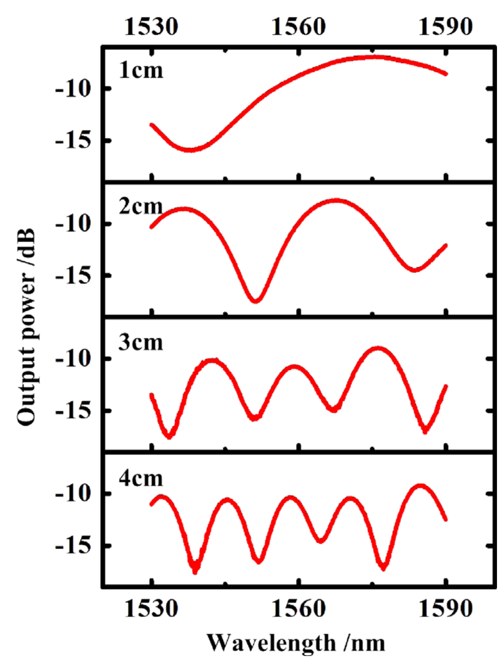

Fig. 4. Transmission spectra of the proposed MZI sensor with different *L*.

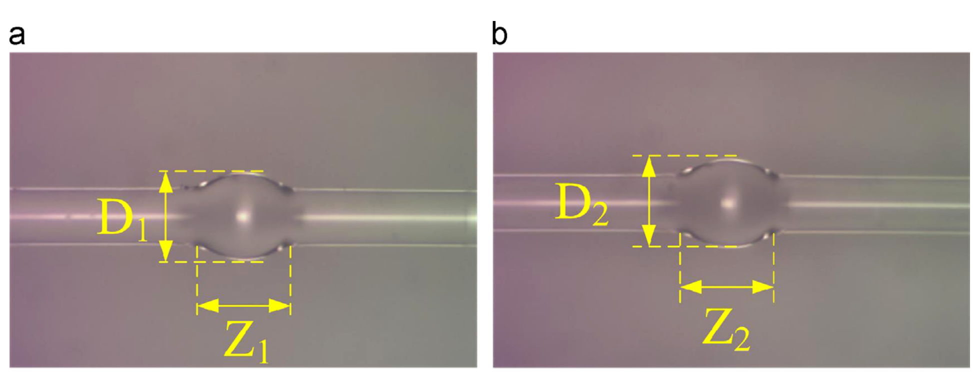

Fig. 2. The image of the spherical-shape structures: (a) structure 1 (b) structure 2.