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Optical modal interferometer fiber strain sensor based on waist-enlarge fusion splicing

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ABSTRACT

A novel strain sensor based on all-fiber modal interferometer is presented and experimentally demonstrated. It is formed by splicing a section of polarization-maintaining fiber (PMF) between two waist-enlarge fusion tapers. When the strain increased from 0 $\mu\varepsilon$ to 1764 $\mu\varepsilon$, the sensitivities of sensors with lengths of 34 mm, 40 mm and 47 mm are −1.36 pm/$\mu\varepsilon$, −1.22 pm/$\mu\varepsilon$, −1.06 pm/$\mu\varepsilon$, respectively. The absolute value of sensitivity will increase with the decrease of the length. The temperature response of the sensor is also discussed. The sensor has merits of simple fabrication, low cost, and good robustness.

1. Introduction

Optical fiber strain sensors have been widely used in sensing and monitoring of constructions and buildings, such as bridges and tunnels. Recently, a great number of Fabry–Perot structures sensors have been applied to strain measuring. For example, the sensor with a short section of hollow-core photonic crystal fiber(PCF) [1], the sensor with cavity formed by a microscopic air bubble [2–4], and the sensor using laser etching or chemical etching to form cavity in the fiber [5,6]. However, the Fabry–Perot structures have disadvantages of low coupling efficiency and high cost. Modal interferometers have attracted a lot of intention because of the advantages of small size, low cost and high sensitivity, such as a pair of long period fiber gratings (LPGs) [7], air-hole collapsing of PCF [8,9], small-waist fiber tapers [10,11]. However, the fabrication of fiber gratings uses photolithography, UV radiation and post-annealing, which is complicate and highly cost; the PCF is expensive and difficult to splice, which limits the practical application; the small-waist tapers are very fragile, so it is easy to be damaged. Recently, fiber sensors based on waist-enlarge splicing have attracted much attention with the merits of easy fabrication and good robustness [12–14]. But these sensors have relatively low sensitivities, and the sensitivities of different length sensors have not been discussed in the above papers.

In this paper, we proposed and experimentally demonstrate a novel in-line modal interferometric sensor, which is formed by splicing a section of PMF between two waist-enlarge splicing tapers. At the first splicing taper, the high-order cladding modes can be excited, and then be coupled back into the SMF at the second splicing taper, therefore a comb interference spectrum can be obtained. The experimental result demonstrates that the proposed sensor has strain sensitivities of −1.36 pm/$\mu\varepsilon$, −1.22 pm/$\mu\varepsilon$ and −1.06 pm/$\mu\varepsilon$ for the length of 34 mm, 40 mm and 47 mm, respectively. Moreover, the temperature sensitivity of the sensor with length of 34 mm is 126 pm/°C.

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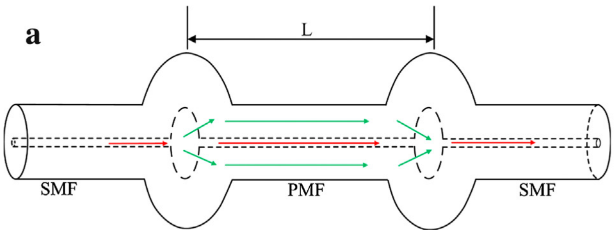

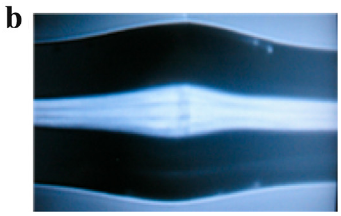

Fig. 1. (a) The schematic diagram of the proposed sensor; (b) The image of waist-enlarge fusion taper.

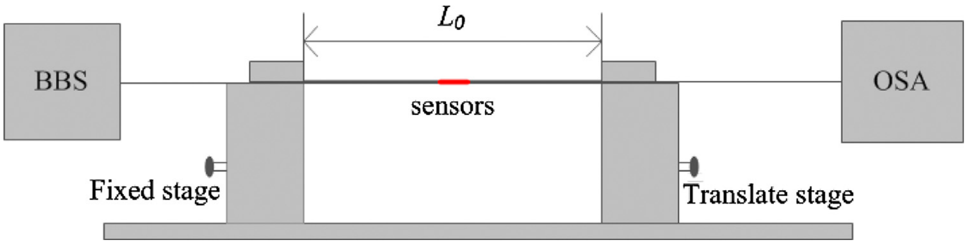

Fig. 2. Schematic diagram of the experimental setup for the strain measurement.

2. Sensor fabrication and principle

The presented strain sensor head is showed in Fig. 1(a). It is formed by splicing a section of PMF between two waist-enlarge fusion tapers. The birefringence index and the mode field diameter of the PMF (Panda, PM 1550) are 7.7×10^{-4} and 10.5 μm. A fusion splicer (FSM-60S) is used to fabricate the sensor. The end of PMF was spliced towards the lead-in/out SMF employing automatic splicing mode. To form such a waist-enlarge fusion taper, the splice parameters are set as follows: the discharge time is 2000 ms, the overlap is 150 μm. After discharging, the fiber tips are soften and pushed together, and then the fiber diameter is gradually enlarged and becomes a waist-enlarged fusion taper. Fig. 1(b) shows the image of the fusion taper. The diameter of the waist-enlarge taper is increased to about 165 μm, and the length of the taper is about 270 μm.

When the light transmits in the core mode and launched into the first waist-enlarged fusion taper, part of the light is coupled to the cladding modes. These cladding modes enter the PMF and travel a short optical path along the sensing segment, finally re-coupled back to interfere with the core mode at the second waist-enlarged fusion taper. Thus a modal interferometer is formed. Strain measurement can be achieved by calculating the phase difference between the core mode and the cladding modes.

The transfer function of the interferometer can be expressed as:

$$I = I_{core} + I_{clad} + 2\sqrt{I_{core}I_{clad}}\cos(\Phi) \qquad (1)$$

where I_{core} and I_{clad} are the intensities of the core mode and the cladding mode, respectively. And Φ is the phase difference between the core mode and the cladding mode, which can be defined as:

$$\Phi = \frac{2\pi\Delta n_{eff}L}{\lambda} \qquad (2)$$

where L is the length of the sensor, Δn_{eff} is the effective index difference between the core mode and the cladding mode. λ is the resonant dip wavelength. According to the interference condition, the resonant dip wavelength can be described as:

$$\lambda = \frac{2\Delta n_{eff}L}{2m+1} \qquad (3)$$

where m is an integer. When strain is applied to the PMF, the effective index difference and the fiber length will change, and thus the transmission dips will shift. So the strain can be measured by the shift of the dips wavelength.

3. Experimental results and discussion

The schematic diagram of the experimental device is shown in Fig. 2. A broadband light source (BBS) with wavelength range from 1500 nm to 1600 nm is used to generate the incident light. The sensing fiber was clamped by two clips on a displacement platform. Then translate the stage on the right to change the separation distance accurately. And the transmission spectra are observed by optical spectrum analyzer (OSA) with a minimum resolution of 10 pm.

To analyze the performance of the modal interferometer, the sensors with different PMF lengths between the two tapers were fabricated, which are L_1 = 34 mm, L_2 = 40 mm and L_3 = 47 mm. The transmission spectra of the proposed sensors with