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Simultaneous strain and temperature sensor based on polarization maintaining fiber and multimode fiber

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A novel, simultaneous strain and temperature sensor utilizing polarization maintaining fiber (PMF) and multimode fiber (MMF) is proposed and experimentally demonstrated in this paper. The sensing head of this sensor can be obtained by splicing PMF and MMF in the structure of PMF-MMF-PMF. The extinction ratio of the transmission spectrum can be over 30 dB. The strain sensitivities of sensor by two spectrum dips can be 1.01 pm/με and 1.27 pm/με in the range from 0 to 2000 με. Meanwhile, the temperature sensitivities of 49 pm/°C and 41 pm/°C can be achieved by two spectrum dips in the range from 30 °C to 70 °C. The sensitivity difference between the two spectrum dips can be used to realize dual parameters fiber sensing. This sensor exhibits the advantages of simple fabrication, compact structure and multipurpose measuring. It may have the great potential in fields of robot arms and artificial limbs.

1. Introduction

Recently, all-fiber sensors have attracted much attention for the advantages such as compact size, low weight, and free from electromagnetic interference. The sensing measurement of physical quantities can be refractive index [1–5], strain [6–8], curvature, temperature [9–11], vibration, etc. Among the optical fiber sensing, the strain measurement has been widely studied in many fields [12,13]. The strain fiber sensors can be realized by different kinds of optical techniques, including long-period grating (LPG) [14–17], multimode interference (MMI) [18] and brillouin frequency shift [19–21]. The traditional fiber structure is unable to satisfy the practical applications and new methods are investigated to fulfill the goals, such as the fiber splice methods of taper [22,23], core-offset and erosion fiber appear in the fiber sensor production process. The laser is applied in the fiber sensing system to acquire high accuracy [24] and the dual-frequency optoelectronic oscillator also is used in strain sensor to achieve high resolution.

Zhu et al. [25] have studied the properties of PANDA-FBGs for simultaneous distribution measurement of strain and temperature, and the relationship of the measurement accuracy and the birefringence. However, the PANDA-FBGs are difficult to manufacture and have high cost in the manufacturing. Zhang et al. [26] have proposed a Z-shape fiber structure fabricated by CO_2 laser for the simultaneous measurement of axial strain and temperature. Heng et al. [27] have investigated and experimentally demonstrated a hybrid multimode fiber laser configuration for simultaneous measurement of strain and temperature based on radio-frequency demodulation. Nevertheless, these strain sensor systems are designed in great complexity and are difficult to be applied in practice.

In this paper, we propose a strain all-fiber sensor based on polarization maintaining fiber and large diameter multimode fiber by the method of mismatching outer diameter. The variational axial stress on the fiber sensor influences the birefringence and the multimode interference. Therefore, the strain sensing can be realized by measuring spectral drift. The strain sensitivities of sensor by two spectrum dips can be 1.01 pm/με and 1.27 pm/με in the range from 0 to 2000 με and the temperature sensitivities of 49 pm/°C and 41 pm/°C can be achieved in the range from 30 °C to 70 °C. The dual parameters sensing of strain and temperature can be realized by using the sensitivities difference between the two spectrum dips. Moreover, this sensor is simple and easy to fabricate, which reveals potential applications in environmental monitoring, biological and mechanical sensing.

2. Structure and principles

The schematic diagram of proposed all-fiber sensor for simultaneous axial strain and temperature measurement is shown in Fig. 1 (a). The sensing head consists of a section of multimode fiber (MMF) spliced with two short segments of polarization maintaining fiber (PMF). The single mode fibers (SMF) are concatenated

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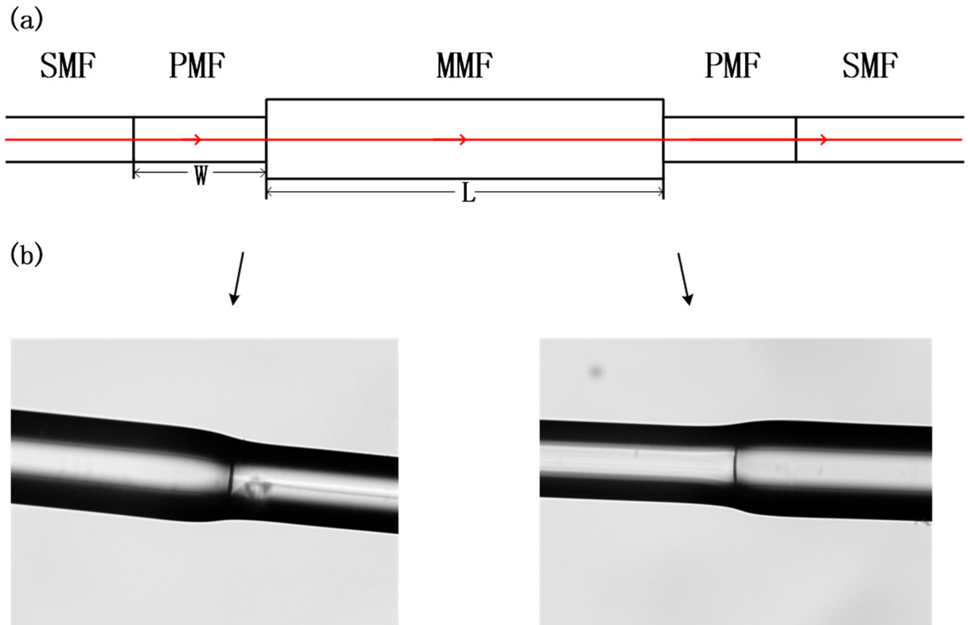

Fig. 1. (a) The structural schematic of the proposed all-fiber sensor for axial strain. (b) The photographs of the two fusion splices between PMF and MMF under microscope.

with the two sides of sensing head. The photographs of the two fusion splices between PMF and MMF under microscope are shown in Fig. 1(b). The length of PMF and MMF are $W = 1$ cm and $L = 6$ cm, respectively. The PMF and the SMF both are commercial standard. The MMF is homemade fiber with the outer diameter 150 μm and core diameter 44 μm. The type of PMF in the proposed sensor is PANDA fiber and its beat length is 4.06 mm at the operating wavelength of 1550 nm. The sectional views of PMF and MMF under electron microscope are shown in Fig. 2.

The propagating mode in PMF will split into two orthogonal polarized modes (fast and slow mode) due to the property of birefringence [28]. The strength of birefringence is defined as

$$B = n_s - n_f, \tag{1}$$

where n_s and n_f separately are the refractive indices for slow and fast modes. The phase difference is caused as the incident light travels through the PMF. It can be written as:

$$\theta_{PMF} = \frac{2\pi BW}{\lambda}, \tag{2}$$

where λ is the vacuum wavelength. While the incident light enters into MMF from PMF, high order modes will be excited. The effective refractive indices difference between low order modes and high order modes in the MMF can be expressed as:

$$\Delta n = n_{low}^{eff} - n_{high}^{eff}, \tag{3}$$

where n_{low}^{eff} and n_{high}^{eff} is the effective refractive indices of the low order modes and high order modes. The high order modes are sensitive to the axial strain and changing temperature. The phase difference between low order modes and high order modes can be expressed as:

$$\theta_{MMF} = \frac{2\pi L\Delta n}{\lambda}. \tag{4}$$

When the sensing head is applied by an axial tension, an axial strain can be achieved and the length of sensing head will have a slight increase. Then the phase difference in PMF and MMF will have an additional increment. They can be written as:

$$\Delta\theta_{PMF} = \frac{2\pi B\Delta W}{\lambda}, \tag{5}$$

$$\Delta\theta_{MMF} = \frac{2\pi\Delta L\Delta n}{\lambda}, \tag{6}$$

where ΔW and ΔL are the axial deformation quantities of PMF and MMF. Comparing with SMF, the two short segments of PMF increase the strain and temperature sensitivities of sensor due to the axial tension or the temperature influencing the phase difference $\Delta\theta_{PMF}$ of fast and slow mode in PMF.

The light intensity in MMF can be expressed as:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} cos(\theta_{MMF} + \Delta\theta_{MMF}), \tag{7}$$

where I_1 is the sum of light intensity of low order modes and I_2 is the sum of light intensity of the high order modes. The multimode interference will be caused at the fusion splice between MMF and PMF, when the light propagates from MMF into PMF in the output side. When $(\theta_{MMF} + \Delta\theta_{MMF})$ equals to $(2N+1)\pi$ (N is integer), the intensity of interference is minimum.

3. Experiment and discussion

The schematic configuration of the sensing system is shown in Fig. 3. The optical broadband source (BBS) is used as the light source and the transmission spectrum is monitored by an optical spectrum analyzer (OSA, YOKOGAWA AQ6375). The SMF is fixed on the two–dimensional adjusting frames and the sensing head is straightened. The optical spectrum of the sensor system is shown in Fig. 4. The maximum of extinction ratio of the transmission spectrum can be over 30 dB. The dip1 and dip2 of transmission spectrum around 1680 nm and 1750 nm are used to measure the axial strain and temperature sensitivities of the proposed sensor. To achieve a precise strain sensing result without the effect of temperature, the sensor is placed in the temperature constant cabinet of 30 degrees centigrade. The two–dimensional adjusting frames provide the axial tensile force to sensing head with a step of 0.01 mm, which is equal to the span 200 με of each step. The transmission spectrum of the sensor under different strain as functions