Optical Fiber Technology 40 (2018) 52–55

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte

Transverse load sensor based on Mach-Zehnder interferometer constructed by a bowknot type taper

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ARTICLE INFO

Keywords:
Fiber optics sensor
Transverse load
Bowknot-type taper
Mach-Zehnder interferometer
Polarization maintaining fiber

ABSTRACT

A transverse load fiber sensor based on Mach-Zehnder interferometer constructed by a Bowknot-type taper between a single mode fiber (SMF) and a polarization maintaining fiber (PMF) was proposed. Due to the polarization maintaining fiber's birefringence, intensities of the two peaks which are corresponding to the fast and slow axis modes changed with the transverse load applied on the PMF. The experimental results showed that the structure with a 2 cm-long PMF has the sensitivities of 104.52 and −102.94 dB/(N/mm) for the fast and slow axis spectral dip wavelengths of 1485 and 1545 nm in the interference pattern, respectively, which are almost 7 times higher than that of the current similar existing transverse load sensor.

1. Introduction

Conventional electromechanical sensors, such as electrical strain and pressure monitors, are often adequate for measuring the strain or pressure. However, the electromechanical sensors always exhibit intrinsic temperature sensitivity and vulnerable to electromagnetic interference [1–3]. Compared with the electrical-based sensors, optical fiber sensors hold many advantages, such as well-adapted, compact, and immune to electromagnetic interference [4–12]. Therefore, there are many optical fiber sensing application demands in health monitoring of the bridge, building, dam and so on. In these applications, the load or strain monitoring are very important. Many related researches are carried out. For example, some high sensitivity transverse load sensor based on fiber Bragg grating (FBG) and tilted Fiber Bragg gratings (TFBG) have been reported [8–15]. Wieduwilt et al. [12] inscribed a FBG in the waist of tapered photosensitive fibers for transverse load sensing application. Shao et al. [13] proposed a lateral force sensor based on a core-offset tilted FBG. Suo et al. [14] proposed an in-fiber directional transverse load sensor based on an excessively tilted FBGs. Another highly sensitive lateral force sensor has also been demonstrated by the use of the polarization properties of π-phase-shifted FBG with a laser frequency locking technique [15]. For these kinds of FBG-based load sensors, however, they require the wavelength measurement which can be slow and uses expensive interrogation equipment. In addition, they usually suffer from the drawback of temperature-cross sensitivity. Polarization maintaining fiber (PMF) has good polarization maintaining properties and been widely used in optical fiber communication and optical fiber sensing [16]. As a transverse load is applied on the PMF, the couple efficiency between the two orthogonal modes on the fast and slow axes directions will change. Rong et al. [17] proposed an in-line optic fiber polarimetric transverse strain sensor based on the coupling of the two orthogonal modes. The E-field intensities of two modes can be expressed as the linear-fitting functions of transverse strain, and two sensitivities of −7.74 and 15.42 dB/(N/mm) were obtained. However, the sensitivities are not high enough.

In this paper, a transverse load fiber sensor based on a Mach-Zehnder interferometer (MZI) constructed by a bowknot-type taper (BTT) and a PMF was proposed. The core mode in the PMF has different effective indices corresponding to the two orthogonal polarization-modes for the birefringence of the PMF. Therefore, the interference patterns of the MZI corresponding to the two orthogonal polarization modes have different spectral dip wavelengths. By detecting the intensity's changing of the interference spectral dips, the transverse load variation on the MZI can be obtained. At the range of 0 to 0.098 N/mm, the sensitivities of 104.52 and −102.94 dB/(N/mm) for the two orthogonal polarization spectral dip wavelengths are obtained, which are almost 7 times higher than that of the current similar existing transverse load sensor[17]. Thanks to the similarity of two orthogonal polarization-modes for temperature variation, by using a differential method [19], the low temperature sensitivity of 0.0084 dB/°C was obtained, which means that the proposed sensor is near insensitive to the temperature.

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https://doi.org/10.1016/j.yofte.2017.11.013
Received 2 April 2017; Received in revised form 9 November 2017; Accepted 12 November 2017

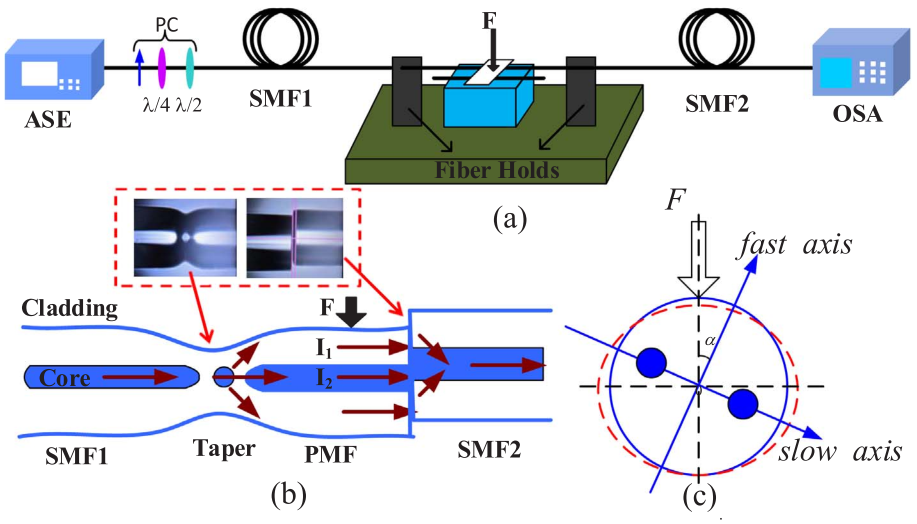

Fig. 1. (a) Schematic of the proposed transverse load sensor, (b) the cross-section of PMF and the showing of the transverse load, (c) the partial enlarged drawing of the MZI.

2. Experimental method and theoretical analysis

The schematic diagram of the proposed transverse load sensor is shown in Fig. 1(a). An amplified spontaneous emission (ASE) source with a wavelength range of 1450–1650 nm is used as the light source. The output spectrum is detected with an optical spectrum analyzer (OSA, AQ6370, Japan). The resolution of the OSA is 20 pm. The length of the PMF is 2 cm. The birefringence index of the PMF is 7.7024×10^{-4} (PANDA, 1017-C, YOFC) and the beat length of the PMF L_b is 2.01 mm. The length between the center of the taper and the offset is 2.0 cm. The core and cladding diameters of the SMF are 9 and 125 µm, respectively. A polarization controller (PC) was used to adjust the polarization states of the input lights. The PC contains one polarizer, a half-wave plate and a quarter-wave plate. This combination allows the preparation of arbitrary polarization states at the fiber input, which can compensate for any change of polarization state induced by fiber loops and twists in the optical path leading to the PMF.

The MZI is formed by a BTT connecting a core-offset fusion splicing of a SMF2. The schematic of BTT is shown in Fig. 1(b). The BTT is formed by using a commercial electric-arc fusion splicer (Fujikura FSM-60 s) through an insufficient-tapered fusion splicing method [18]. By setting a longer fusion distance (about 10 µm) between the ends of the SMF1 and PMF, with an inadequate fusion, and after discharging, a BTT and a little sphere will be formed at the left part of the fiber core. The inset of Fig. 1(b) shows the microscope pictures on the splicer's screen. The measured diameter and length of the taper area are 80 and 95 µm, respectively. And the diameter of the little sphere is about 6.5 µm.

As shown in Fig. 1(b), due to the existence of the little sphere on the center of the BTT structure, the light propagating from the left side of the taper will be coupled into the little sphere, and then be coupled into the fiber core of the right side of the taper, just likes the function of a telescope, which is benefit to improve the sensitivity of the sensor. By adjusting the taper diameter to match the propagating constant of the modes in the taper to that of the resonant modes of interest, one can couple most of the light into the sphere. After propagating through the BTT, the light will be coupled into the cladding and core of the PMF. Because of the core-offset fusion splicing between the PMF and the SMF2, after the light propagating through the PMF, the light in the core and the cladding will be coupled into the core of the SMF2, and a MZI forms.

In experiment, a glass slide (width × length × thickness = 9 × 50 × 2 mm) was set on the PMF and a supporting fiber to hold the transverse load. As shown in Fig. 1(b) and (c), the intensity of the light I_1 propagating in PMF's cladding is orthogonal, which can be decomposed to two orthogonal polarization modes in fast axis (I_f) and slow axis (I_s) directions. When the transverse load was applied on the PMF, the PMF will be a tiny deformation (the red dotted line ellipse in Fig. 1(c)). Therefore, the intensities of the fast axis polarization mode I_f and the slow axis polarization mode I_s will couple to each other with the increasing or decreasing of the transverse load. Consequently, the intensity of the light propagating along the fiber cladding I_1 will change with the variation of I_f and I_s After the light propagating through the BTT, the phase difference between the core and the cladding modes can be described as,

$$\Delta\Phi = 2\pi\Delta n_{eff}^{m} L/\lambda \tag{1}$$

where Δn_{eff}^{m} is the effective refractive index difference between the core and the m_{th} cladding mode, λ is the wavelength of the input light, L is the length of the PMF. Because of the refractive index difference between the core and the cladding of the PMF, there will be a phase difference between them after the light propagating through the PMF. The output intensity of the MZI can be described as,

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\Delta\Phi) \tag{2}$$

where I_1 and I_2 are the intensities of the light propagating along the fiber core and cladding, respectively. The pattern fringe visibility K can be described as,

$$K = 2\sqrt{I_1 I_2}/(I_1 + I_2) \tag{3}$$

The spectral dip wavelength satisfies the expression of $\Delta\Phi = (2k + 1)\pi$, where k is natural number. Therefore, the spectral dip wavelengths corresponding to fast axis polarization mode (λ_f) and slow polarization mode (λ_s) can be described as,

$$\lambda_f = 2(n_{eff,f}^{core} - n_{eff,f}^{clad})L/(2k + 1) \tag{4}$$

$$\lambda_s = 2(n_{eff,s}^{core} - n_{eff,s}^{clad})L/(2k + 1) \tag{5}$$

where $n_{eff,f}^{core}$ and $n_{eff,f}^{clad}$ are the effective refractive index of the core mode and excited cladding mode on the fast axis of the PMF, respectively. $n_{eff,s}^{core}$ and $n_{eff,s}^{clad}$ are the effective refractive indices of the core mode and excited cladding mode on the slow axis of the PMF, respectively.

For this MZI, in order to obtain the maximal interference patterns variations, the light energy in the fiber cladding and the fiber core should nearly be equal. Fig. 2 shows the simulation results of the core and cladding's intensities under different degree of core-offset by Rsoft. It can be seen that the best core-offset size is about ~4 µm, where the energy coupled into the fiber cladding is nearly equal to that coupled into fiber core.