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Orientation-dependent fiber-optic inclinometer based on core-offset michelson interferometer

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Abstract. An in-fiber Michelson interferometer (MI) inclinometer, which consists of misalignment-spliced fiber with end coating, is proposed and experimentally demonstrated. The incident light divided at the misalignment-spliced joint is reflected at the end coating, and then re-coupled into the core of the fiber. Due to the phase difference between the core mode and the cladding mode, a typical Michelson interference is obtained. The fiber near the misalignment-spliced joint is inserted in two capillary quartz tubes. The inclination of the capillary quartz tube leads to a significant deformation and curvature of the misalignment-spliced joint, which causes the wavelength and amplitude of the MI spectrum to change. The experimental results indicate a good response within the angle range of 0° to 50°. Both the wavelength modulation and intensity modulation are realized, with sensitivities of 0.55 nm/deg and 0.17 dB/deg, respectively. Moreover, the sensor shows a strong orientation dependence due to the asymmetric structure in the misalignment-spliced joint.

Keywords: MI, the wavelength modulation, the intensity modulation, sensor.

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1 Introduction

Tilt sensors (also known as inclinometers) are widely used in many applications, including structural health monitoring, landslide prediction, geotechnical/civil measurement and gesture sensing. In recent years, fiber-optic inclinometers are of great interest due to their unique advantages of compact size, remote monitoring, insensitivity to flammable and explosive gasses,^{1,2} etc. Various schemes of fiber-optic inclinometers have been developed, which can be mainly classified into two types: the grating-based and the interferometer-based.³⁻⁶ Take fiber Bragg grating (FBG) as an example, pre-processing such as polishing and tapering can couple light from the core to the cladding, making the FBG sensitive to angle changes.⁷⁻⁹ However, the pre-processing weakens the mechanical strength of the fiber and the sensors usually suffered from instability. Both tilted fiber Bragg grating (TFBG) and long period fiber grating (LPFG) are typical structures to couple core modes to the cladding modes, which can be applied as inclinometers.¹⁰⁻¹² However, the sensing characteristics based on the transmission spectrum limit their application where a single-ended probe would be preferable (in vivo applications, for instances).¹³ As another type of fiber-optic device, in-fiber interferometers with separate interference arms are also sensitive to tilt.¹⁴ For example, the fused taper is employed for the coupling of core-to-cladding modes, in which the interference spectrum is obtained.¹⁵ As the tapered region is soft and easy to bent, many inclinometers based on fused taper have been proposed.¹⁶⁻¹⁸ The drawback of this structure is that the fused taper is easy to be broken and the

measurement range is small. In addition, different fibers with core-mode-field misalign are also spliced to form an interferometer for tilt measurement, such as thin-core fiber,¹⁹ hollow-core photonic crystal fiber,^{20,21} multicladding fiber,²² etc. This type of sensor exhibits high sensitivity, however, these special fibers are expensive and the manufacturing process is complicated.²³

In this paper, we propose and experimentally demonstrate a Michelson interferometer (MI)-based inclinometer using a simple configuration: a misalignment-spliced single mode fiber (SMF) with end coating. different from the reported misalignment-spliced structures used for curvature,²⁴ bending,^{25,26} and strain measurement, the proposed sensing probe is inserted in two capillary quartz tubes near the misalignment spliced joint. The tilt of the quartz tube changes the coupling ratio between the core mode and the cladding mode, resulting in the shift of the reflection spectrum. In this way, a highly sensitive tilt measurement is achieved. This inclinometer shows a high sensitivity of 0.55 nm/deg, which makes it a good candidate for tilt measurement.

2 Sensing System and Thoretical Analysis

2.1 The Schematic of Experimental Setup

The schematic diagram of the experimental setup is shown in Fig. 1 (a). A broad band source (BBS), an optical spectrum analyzer (OSA), and an optical circulator are employed to monitor the interference spectrum. Fig. 1(b) shows the schematic diagram of the MI-based inclinometer. The fiber axis is defined as the z-axis. Two sections of fiber are misaligned spliced, where the y-axis is offset and the x-axis is aligned. The left side of the misalignment-spliced joint is defined as “lead-in fiber”, and the right side is defined as “misalignment-spliced fiber”, as indicated in Fig. 1 (b). A copper film is plated on the end of the misalignment-spliced fiber. The lead-in fiber and the misalignment-spliced fiber are inserted in two capillary quartz tubes, respectively. The distance between these two capillary tubes is a few millimeters. The left capillary tube is fixed and the right capillary tube could be rotated freely so that the fiber can be bent. The image of the misalignment-spliced joint is shown in Fig. 1(b).

Fig. 1 (a) Schematic diagram of the experimental setup. (b) Schematic diagram of the inclinometer.

As shown in Fig. 1(b), the incident light from the lead-in fiber is divided into two parts at the misalignment-spliced joint. A part of the light is coupled into the core of the misalignment-spliced fiber, and another part is coupled into the cladding of the misalignment-spliced fiber. These two parts of light are reflected at the copper film, and then re-coupled into the core of the lead-in fiber at the misalignment-spliced joint.

2.2 The Working Principle of Sensing System

Due to the phase difference of the core mode and the cladding mode, a typical Michelson interference is obtained in the core of the lead-in fiber. The interference fringe can be observed in the reflection spectrum, which can be expressed as:

$$I = (I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \Delta\varphi) \cdot R, \quad (1)$$

where I_1 and I_2 are the light intensity of the core mode and the cladding mode. R is the reflectivity of the copper film, and its value is usually greater than 0.8. $\Delta\varphi$ is the phase difference between the core mode and the cladding mode, which can be written as:

$$\Delta\varphi = 2\pi(n_{\text{eff}}^{\text{co}} L_{\text{co}} - n_{\text{eff}}^{\text{cl}} L_{\text{cl}}) / \lambda, \quad (2)$$

where L_{co} and L_{cl} are the propagating length of the core mode and the cladding mode. λ is the incident light wavelength of the MI. n_{eff}^{co} and n_{eff}^{cl} are the effective refractive indexes of the core mode and the cladding mode, respectively. When the phase difference satisfies the condition:

$$\Delta\varphi = (2m+1)\pi, \quad m = 0, 1, 2, 3, \dots, \quad (3)$$

where m is the interference order, a transmission dip appears at:

$$\lambda_m = 2(n_{eff}^{co}L_{co} - n_{eff}^{cl}L_{cl}) / (2m+1), \quad (4)$$

when the capillary quartz tube is rotated, the incident angle of light at the misalignment-spliced joint is changed, so the phase difference between the core mode and the cladding mode is changed accordingly. In this way, a wavelength shift of the interference spectrum has occurred. In addition, as the curvature of the misalignment-spliced fiber increases, more light is coupled from the core to the cladding, so the intensity of the interference spectrum is reduced accordingly.

3 Sensor Fabrication

Two sections of SMF (Corning, SMF-28e) are inserted in two capillary quartz tubes, and then, misaligned spliced using a commercial fusion splicer (FURUKAWA, S178) in a customized mode. The diameters of the fiber core and cladding are 9.2 μm and 125 μm , respectively. A copper film is plated on the cleaved end of the misalignment-spliced fiber using magnetron sputtering (ULVAC, ACS-4000-C4). The film thickness is 60 nm. The quartz tube is fixed to the fiber by epoxy resin adhesive (Henkel, E-120HP). The distance between these two capillary tubes is ~ 3.5 mm.

According to the Michelson interference theory, the fringe contrast depends on the coupling ratio and transmission loss of light. Therefore, it is important to improve the length of the misalignment-spliced fiber and the core offset of the splice joint, so as to enhance the fringe contrast.

Four MI samples with core offset of 6 μm and different lengths of 1, 2, 4, and 8 cm are fabricated. Each MI sample exhibits distinct fringe contrast and free spectrum range in the interference spectrum, as shown in Fig. 2. It can be found that the MI sample with a shorter fiber length has smaller fringe contrast. The MI sample with a fiber length of 1 cm has the

largest fringe contrast. However, the short fiber is difficult to operate on the fusion splicer, so the misalignment-spliced fiber with a length of 2 cm is selected in the following experiment.

Fig. 2 Interference spectra of the four MI samples with core offset of 6 μm and different lengths of 1, 2, 4, and 8 cm.

Furthermore, the core offset of the misalignment-spliced joint is improved by moving the X- and Y-directional motors in the fusion splicer. Six MI samples with a fiber length of 2 cm and different core offsets of 1, 2, 4, 8, 10, and 12 μm are fabricated. The interference spectra are shown in Fig. 3. The MI sample with an offset of 12 μm gets the maximum contrast ratio but endures large insertion loss. So there is a trade-off between the core offset and insertion loss. In the following experiment, the core offset of the misalignment-spliced joint is selected to be 8 μm .

Fig. 3 Interference spectra of the MI samples with length of 2 cm and core offsets of 1, 2, 4, 8, 10 and 12 μm .

4 Experiment and Discussion

4.1 The Tilt Performance of the Incliomoter

With the experimental setup depicted in Fig. 1(a), the tilt performance of the inclinometer is characterized. The optimized parameters, i.e. misalignment-spliced fiber length of 2 cm and core offset of 8 μm are selected. As shown in Fig. 4, the interference spectrum exhibits a fringe contrast of about 12 dB. The insertion loss is about -31 dB, which is approximate to other fiber devices based on the Sagnac interferometer (about -42 dB) and Mach-Zehnder interferometer (about -32dB).²⁷ The wavelength and fringe contrast of the interference valley near 1553.2 nm is used as indicators for the tilt measurement, as shown in the dashed box in Fig. 4.

Fig. 4 Interference spectrum of the sensor with misalignment-spliced fiber length of 2 cm and core offset of 8 μm .

Fig. 5 Some interference valleys of the inclinometer with the angle from 0° and 50°.

The experiment is carried out at constant room temperature (22.5°C). The tilt angle is varied from 0° to 50°, with a step of 5°. An electronic angle meter (RION, DMI410) with an accuracy of 0.05° is used to provide a standard angle. The interference valleys with increasing angle are shown in Fig. 5, which show the strong angle feature. The angle direction is along the y-axis, as shown in the inset.

The wavelength and intensity of the interference valleys are plotted as the function of angle, as shown in Fig. 6 (a) and 6 (b), respectively. When the angle increases from 0° to 50°, the interference valley shifts toward a longer wavelength, and the intensity increases. In the range from 0° to 20°, the wavelength sensitivity of 0.55 nm/deg and intensity sensitivity of 0.17 dB/deg is obtained. When the angle is larger than 20°, the sensitivity increases obviously. It is because that more light is coupled from the core to the cladding, and the cladding modes are comparatively sensitive to surrounding bending. Moreover, the misalignment-spliced joint endures an extra strain as the angle becomes larger, which increases the phase difference between the core mode and the high-order cladding mode. The response curves of the wavelength and intensity are obtained by quadratic fitting, the fitting equation is given in the figure.

Fig. 6 The wavelength(a) and intensity(b) response with respect to different tilt angles.

4.2 The Orientation Dependence of the Inclinator

To study the orientation dependence of the inclinometer, the angle response over the orientations ranging from 0° to 360° are demonstrated. The orientation along the y-axis is set to be 0°. Fig. 7 plots the wave-length sensitivity and intensity sensitivity at different orientations, which clearly

shows the strong orientation dependence of the inclinometer. The maximum sensitivity is at the y-axis, and the minimum sensitivity is at the x-axis.

Fig. 7 Angular dependence of the inclinometer with respect different orientations.

This is easy to understand since the y-axis direction has the largest misalignment at the misalignment-spliced joint, whereas the x-axis direction has little misalignment. There are still some errors in Fig. 7, which may result from the following reasons: the two capillary tubes are incompletely set on the same horizon plane due to the fiber off-set, which may add a walk-off angle to the tilt; the mechanical turning of the sensor may bring in errors. For the in-field applications, the ambient temperature fluctuation always leads to sensor performance deterioration and large measurement error.

4.3 The Temperature Response of the Proposed Inclinometer

Therefore, the temperature response of the proposed inclinometer is characterized. The inclinometer is placed in a tube furnace (SIGMA, OTF60). The temperature in the furnace rises gradually from 20°C to 60°C with a step of 5°C and is maintained at each temperature for ~30 minutes. As shown in Fig. 8 (a), the wavelength of the interference valley shifts linearly toward a longer wavelength with a sensitivity of 36.7 pm/°C. The spectral shift is caused by the difference of effective refractive index between the core mode and the cladding mode, which is induced by the temperature rise.²⁸ Since the wavelength increases linearly, the temperature influence can be eliminated effectively by introducing a commercial FBG. Fig. 8 (b) shows the intensity of the interference valley at different temperatures. The maximum intensity variation over the whole heating process is less than 0.42 dB. It means that the temperature-angle cross-sensitivity of intensity demodulation is only ~0.062 deg/°C.

Fig. 8 Temperature response of the inclinometer from 20°C to 60°C.

5 Conclusion

The in-fiber interferometer based on misalignment-splicing is a classic structure for curvature, bending, and strain measurement. In our research, a compact and reflective in-fiber MI-based inclinometer is demonstrated. The proposed device is fabricated by means of misalignment-splicing and end coating. The fiber is inserted in two capillary quartz tubes near the misalignment-spliced joint, which makes it highly sensitive to tilt angle. The inclinometer presents a strong orientation dependence due to the asymmetric structure. The temperature response of the inclinometer is also characterized, and temperature compensation can be used to eliminate the temperature-induced error. The inclinometer has the advantages of compact size, high sensitivity and can provide remote sensing as a reflection probe, making it a good candidate for tilt measurement in many applications.

Disclosures

The authors declare no competing interests.

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