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Temperature-insensitive torsion sensor with sensitivity-enhanced by processing a polarization-maintaining photonic crystal fiber

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A B S T R A C T

We propose an optical fiber twist sensor by employing a Sagnac interferometer based on polarization-maintaining photonic crystal fiber (PM-PCF). To enhance the torsion sensitivity, a short length of PM-PCF is processed by heating-torsion using carbon dioxide laser. It is demonstrated experimentally that the birefringence of PM-PCF is decreased after processed, and the torsion sensitivity is improved in varying degrees for different lengths of heating-torsion. The maximum sensitivity can achieve 7.09 nm/(rad/m) after post-processing, which is two times higher than that of unprocessed one (3.75 nm/(rad/m)). In addition, the temperature sensitivity of twist sensor drops significantly after post-processing. The result shows that heating-torsion is a novel method to improve the torsion sensitivity of PM-PCF.

1. Introduction

In recent years fiber optics sensors have been widely used in engineering applications such as energy and biological, spaceflight, environment and the security monitoring, due to their compact structures, high sensitivity and immunity to environmental interferences [1,2]. Torsion is an important parameter for practical applications in security monitoring of buildings, bridges, and many other structures [3]. Traditional torsion sensors based on optical encoders and magnetic always have big electromagnetic interference and easier to be affected by temperature [4]. Currently Most studies about torsion sensors are based on fiber long period gratings(LPGs) [5–7] and fiber Bragg gratings (FBGs) [8–10] photonic crystal fiber(PCF) [11], Sagnac interference [12–14] and multi-mode interference [15], such as J.M.Sierra-Hernandez propose a good device performance and easy device fabrication torsion sensing arrangement based on a three beam path Mach–Zehnder interferometer [16]. Quan Zhou present a Fiber torsion sensor based on a twist taper in polarization-maintaining fiber [4] and ChiChiu Chan propose a twist sensor using solid core low birefringence photonic crystal fiber based Sagnac interferometer [17]. Among the various researches on twist sensor, the optical fiber Sagnac interferometers device based on polarization-maintaining photonic crystal fibers(PM-PCF) attracts more and more attention, because it can be easily obtained and the free spectral range(FSR) of the spectrum depends only on the length of the polarization-maintaining fiber [17]. Moreover the unique characteristics and high flexibility designs of PCF lead the torsion sensor employing Sagnac interference device based on PM-PCF to have more advantageous such as excellent temperature stability and high flexibility [4]. There are so many studies to improve the torsion sensitivity using Sagnac interference device based on PM-PCF have been reported O. Frazão et al. proposed a measurement of torsion using a Sagnac interferometer with polarization maintaining side-hole fiber [14]. Youngjoo Chung et al. presented a highly birefringence photonic crystal fiber-based Sagnac interferometer to enhance torsion sensitivity, which measured to be high with 1.03 nm/(rad/m) [18]. B. B. Song and H. Zhang et al. proposed a twist sensor using PM-elliptical core fibers based Sagnac interferometer the torsion sensitivity can reach up to 15.83 nm/(rad/m) [2]. W.G. Chen et al. proposed a highly sensitive torsion sensor based on Sagnac interferometer using side-leakage PCF [19]. However, most of these researches have stressed on the structure of the polarization-maintaining fiber to control the torsion sensitivity and not focused on the possible method of post-processing for the improvement of fiber torsion sensitivity.

In this paper, we propose an optical fiber twist sensor by employing a Sagnac interferometer based on polarization-maintaining photonic crystal fiber. In addition, we enhance torsion sensitivity significantly by processing the PM-PCF with heating-torsion, and the reason causes

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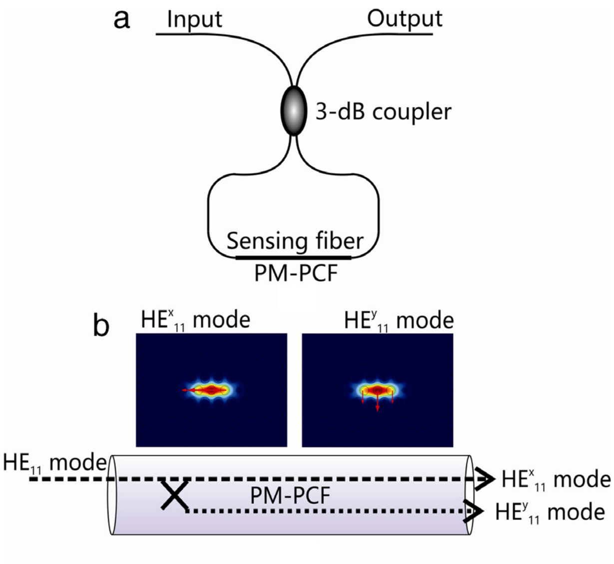

Fig. 1. (a) The Sagnac interferometer loop; (b) The two orthogonal polarization modes propagating along the PM-PCF.

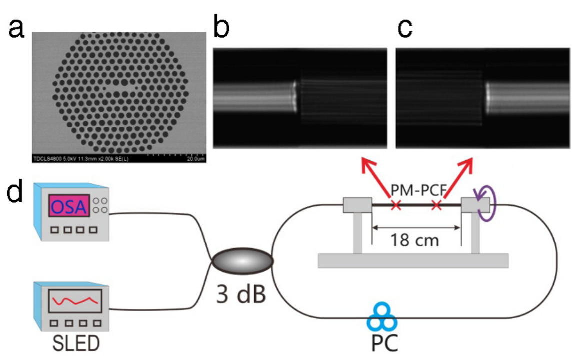

Fig. 2. (a) The SEM of polarization-maintaining photonic crystal fiber; (b)(c) Microscopic images of the fusion splicing joints; (d) Sensing scheme for torsion sensing with the fabricated PM-PCF.

the increase of sensitivity has been analyzed. Moreover, the effect of temperature on torsion sensor has been decreased after post-processing.

2. Principle and experiment setup

The principle of Sagnac interferometer(SI) which consists of an optical fiber loop is shown in Fig. 1(a). The input light will be split into two beams propagating in counter directions by the 3 dB fiber coupler and the two beams are combined again at the same coupler. Unlike other fiber optic interferometers, the phase difference of Sagnac interferometer is related to the propagating speed of the polarization mode [20]. As the difference of the effective refractive along the slow and fast axes of PM-PCF, the two orthogonal polarization modes HE^x_{11} and HE^y_{11} will propagate at different velocities along the length of the PM-PCF, as shown in Fig. 1(b). Clearly this will bring a difference in phase delay in each of the two directions. Therefore, the weighted phase of HE^x_{11} and HE^y_{11} added together will be different in each direction when the two beams are combined at the 3 dB fiber coupler [21]. Under the influence of the external environment such as twist, temperature and so on, the variations of birefringence will lead to the change of the phase difference.

Fig. 2(a) shows the scanning electron microscopy (SEM) images of the whole cross-section of the PM-PCF, the core is composed of three silica rods which are doped germanium to introduce the fiber birefringence and improve the torsion function The core diameter is 1.85 μm (vertical) and 10.56 μm (horizontal) the diameter of fiber and the normal air holes are 125 μm and 2.1 μm, respectively. Two small air holes are introduced on both sides of the core to raise the fiber birefringence and the size of small air holes are 1.25 μm. The pitch of PM-PCF is 2.9 μm. Fig. 2(d) shows the schematic diagram of our proposed torsion sensor based on SI, which consists of a 3 dB coupler with two output ports and a short length of PM-PCF spliced between two SMFs. The light source is launched from a broadband resource (SLED, Shenzhen Golight Technology Co., Ltd., Shenzhen, China) with wavelength in range of 1250–1650 nm and the transmission spectrum is monitored by an optical spectrum analyzer(OSA, Yokogawa AQ6370D) with a resolution of 0.02 nm. A polarization controller (PC) is used to optimize the interferometer spectrum. Two SMFs are spliced with the PM-PCF, one end of the SMF is fixed using a fiber hold, and the other end is fixed with the rotator which can rotate 360 °, the microscopic images of the fusion splicing joints between PM-PCF and SMF as shown in Fig. 2(b)(c). The distance between the two fiber holds is 18 cm, which is fixed in the experiment. We investigate the change of torsion sensitivity using different lengths of PM-PCF before and after post-processing, respectively.

3. Experiment and analysis

Neglecting the insertion loss of SI, the transmission spectrum T can be given as $T = [1-\cos(\varphi)]/2$ where $\varphi = 2\pi LB/\lambda$ is the phase difference, L and λ are the length of PM-PCF and the operating wavelength, respectively [18]. $B = n_s - n_f$ is the birefringence between the effective refractive indexes of slow and fast axes, or $B = n_0 + n_g$ is the sum of the fiber birefringence where n_0 is the instinct linear birefringence in PM-PCF and the n_g is the circular birefringence induced by torsion [19]. When the PM-PCF is twisted, the core deformation and shearing stress will be introduced by torsion, and the mechanical stress can change the effective refractive of slow and fast axis due to the photoelastic effect [22]. The variations in the effective refractive indices can be given by the photoelastic coefficient along the slow axes and fast axes, respectively [2]:

$$\Delta n_s = g_s n_s \tau, \quad \Delta n_f = g_f n_f \tau. \tag{1}$$

Where, τ is the torsion change rate per unit length of fiber, g_s and g_f are the photo-elastic coefficient along the slow and fast axes, respectively. Accordingly, the change of birefringence is $\Delta B = \Delta n_s - \Delta n_f$ when the PM-PCF is twisted. The phase change $\Delta\varphi$ can be given approximately by:

$$\Delta\varphi = \frac{2\pi}{\lambda}(\Delta LB + \Delta BL). \tag{2}$$

Assume the length of PM-PCF has no change, the interference trough shift can be described as $\Delta\lambda = S\Delta\varphi/2\pi$, where $S = \lambda^2/BL$ defined as the FSR of PM-PCF [22]. Therefore, according to the above analysis the wavelength shift can be approximated as $\Delta\lambda = \lambda\tau\left(n_s g_s - n_f g_f\right)/B$. As a result, the transmission spectrum shifts to longer wavelengths, when the PM-PCF is twisted, as shown in Fig. 3. The torsion angle changes from minus 60 degrees to 100 degrees, and the interference trough shift from a_1 to a_3 respectively.

In the experiment, three different lengths (20 mm, 16 mm 13 mm) of PM-PCF are intercepted to measure the torsion sensitivity before and after post-processed. When the PM-PCF is unprocessed, The interference trough shift into a shorter wavelengths as the fiber is twisted clockwise and moved to longer wavelengths as the fiber is twisted anticlockwise. We conduct several experiments for each different length of PM-PCF and the average torsion sensitivities of linear fitting are 1.85 nm/(rad/m), 2.57 nm/(rad/m) and 3.75 nm/(rad/m) respectively, as shown in Fig. 4. The torsion sensitivity is related to the length of PM-PCF, because there is a negative correlation between the variation of torsion per unit length of PM-PCF and the total length of PM-PCF.

The change of fiber length and the variation of instinct birefringence can be ignored, when the fiber is twisted. The wavelength shift of