Fiber-Optic Interferometric Torsion Sensor Based on a Two-LP-Mode Operation in Birefringent Fiber

Orlando Frazão, Carlos Jesus, José M. Baptista, José L. Santos, and Philippe Roy

***Abstract*—A fiber-optic sensor for torsion measurement, based on a two-linearly polarized (LP)-mode operation in ultrahigh birefringent photonic crystal fiber is described. The structure of the photonic crystal fiber presents two large asymmetric holes adjacent to the core fiber. When linearly polarized light is injected in x- and y-directions, respectively, two separate interferometers can be obtained. In one of these cases, as torsion is applied to the sensing head a beat between the two interferometers is formed due to the simultaneous excitation of the two polarization states. The detection technique to read the torsion sensor is based on the analysis of the fast Fourier transform, which proved to be an effective and simple solution. The sensor exhibited reduced sensitivity to temperature.**

***Index Terms*—Optical fiber sensor, two-mode operation interferometer.**

I. Introduction

TWO-LINEARLY polarized (LP)-MODE (TM) operation in optical fibers has been used for optical sensing namely for strain and temperature sensors, allowing the discrimination of these two parameters [1], [2]. Elliptical-core two-LP-mode optical-fiber sensors have been investigated for sensing different physical parameters. Blake *et al.* reported longitudinal strain measurement, using a two-LP-mode fiber interferometer [3]. In this case, a large differential phase shift between LP_{01} and LP_{11} modes was observed. Recently, with the advent of photonic crystal fibers (PCFs) several researchers have studied two-LP-mode operation interferometry in highly birefringent (Hi-Bi) PCF. Jin *et al.* using a full-vector finite-element method (FEM) observed that the two-LP-mode PCF sensor shows higher sensitivity at longer wavelengths [4]. The same authors also investigated axial strain and temperature sensitivities, using a Hi-Bi PCF fabricated by Blaze-Photonics, concluding it was possible to perform temperature insensitive strain sensors [5], [6]. Torsion measurement is important for civil engineering applications such as bridges, buildings, and many other civil structures. Optical torsion sensors have been reported using different fiber devices. For instance, a long period grating (LPG) is able to measure torsion [7]. However, LPGs present cross-sensitivities between different physical parameters (temperature, strain, pressure, refractive index, load, etc.). Recently, a simultaneous measurement of multiparameters (strain, temperature, and torsion) using a Sagnac interferometer with polarization maintaining side-hole fiber was reported [8].

In this letter, a torsion sensor based on a two-LP-mode interferometer using a highly birefringent photonic crystal fiber is presented. The Hi-Bi PCF has two large holes with different diameters, showing sensitivity to torsion and reduced sensitivity to temperature. When a twist angle is applied to the Hi-Bi PCF, the amplitude modulation of the interferometer changes and a simple processing analysis using the fast Fourier transform (FFT) is applied to obtain the torsion measurement.

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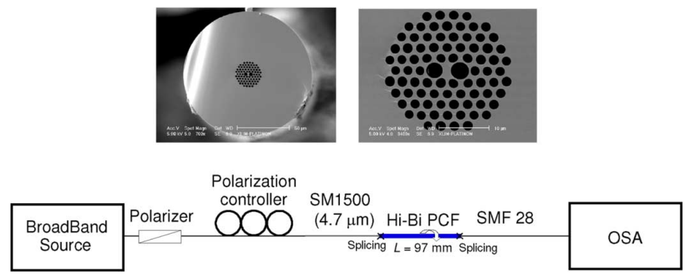

Fig. 1. Experimental setup using Hi-Bi PCF for torsion measurement. In the inset, photos of the cross section of the Hi-Bi PCF are shown.

II. Sensing Configuration and Results

Fig. 1 presents the sensor configuration. Light from a broadband source in the window of 1550 nm is linearly polarized and injected into the Hi-Bi PCF. To enhance the launching efficiency, a special single-mode fiber was used (SM 1500 with a core diameter of 4.7 μm). The Hi-Bi PCF was designed and fabricated in XLIM laboratory, employing the stack and draw technique. Besides birefringence targets, the fiber design looked for two spatial modes (LP_{01} and LP_{11}) propagation at 1550 nm, turning viable spatial modal interferometry at this wavelength. The fiber cross section is shown in the inset of Fig. 1. The Hi-Bi PCF has the following characteristics: all-silica, 5 layers, 82 small holes with 1.85 μm diameter, and two large holes with 3.3 and 3.6 μm diameters, respectively, 2.6 μm pitch, 79 mm length, and a group birefringence of 8.1×10^{-3}. The Hi-Bi PCF was spliced using a conventional splicing machine, and the total loss of the two splicing points was ~5 dB. Calculating the

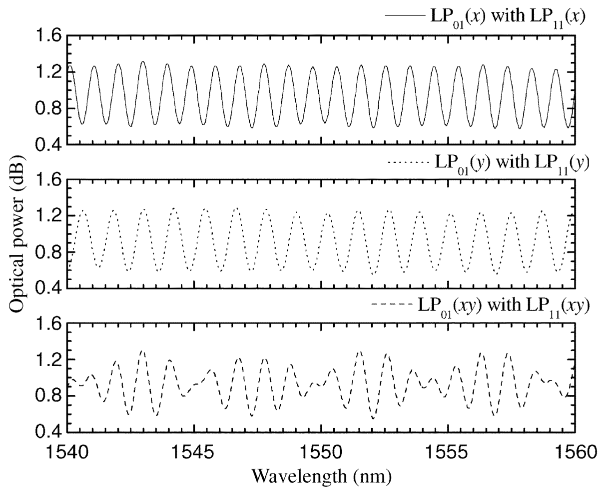

Fig. 2. Spectral response of the TM interferometer untwisted for polarization azimuths of 0° ($LP_{01}(x)$ and $LP_{11}(x)$), 90° ($LP_{01}(y)$ and $LP_{11}(y)$), and 45° ($LP_{01}(xy)$ and $LP_{11}(xy)$).

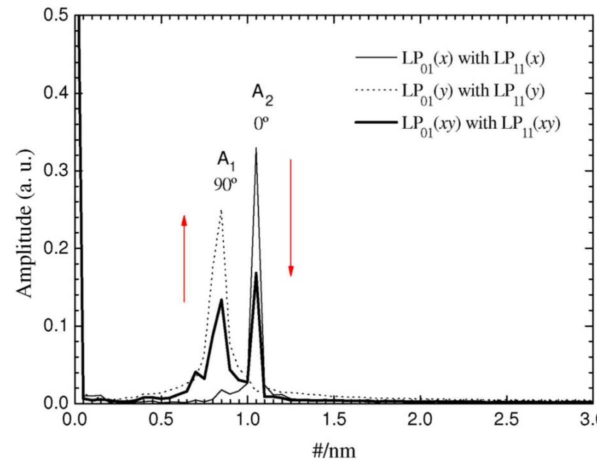

Fig. 3. FFT of the TM interferometer for the three polarization orientations: 0° (line), 90° (dotted line), and 45° (dashed line).

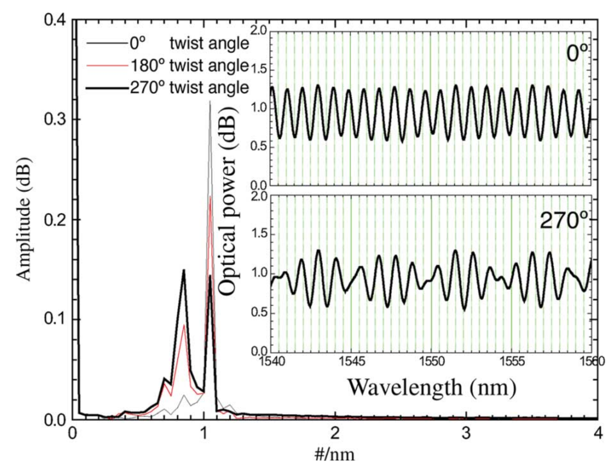

Fig. 4. FFT of the channeled spectrum of the sensing head when it is subjected to torsion for three different twist angles (0°, 180°, 270°). The figure inset shows the interference fringes for the twist angles of 0° and 270°.

spatial beat length for the x-polarization state (between $LP_{01(x)}$ and $LP_{11(x)}$) and for the y-polarization state (between $LP_{01(y)}$ and $LP_{11(y)}$) the values obtained were 47 and 31 μm, respectively. The difference is expected due to the geometry of the core. The two-LP-mode operation can be understood as a system that is analogous to an Mach–Zehnder interferometer. The two arms of the interferometer are replaced by the two spatial modes propagating in one polarization state. Therefore, when the two first spatial modes are excited, the fundamental (LP_{01}) and the second (LP_{11}) modes, a pattern fringe is formed due to the relative phase of the interfering waves. Such arrangement has two discrete interferometers. One of them is obtained when the modes $LP_{01(x)}$ and $LP_{11(x)}$ are simultaneously excited. The other interferometer corresponds to the excitation of the $LP_{01(y)}$ and $LP_{11(y)}$ modes. When LP light is launched at 45° relatively to the eigenaxes of the Hi-Bi PCF, both polarization states x and y of the two spatial modes are simultaneously excited, generating multibeam interference. The azimuth of the polarized light injected into this fiber can be adjusted using a polarization controller. Fig. 2 shows the relationship between the measured intensity variation with the wavelength, without torsion, when the launching direction is set to: 0° ($LP_{01(x)}$ and $LP_{11(x)}$ only); 90° ($LP_{01(y)}$ and $LP_{11(y)}$ only); and 45° ($LP_{01(xy)}$ and $LP_{11(xy)}$). Fig. 3 gives the FFT of these data and presents the relationship between the frequency of the fringes of the channeled spectrum and their amplitude. The two set of peaks represent the two-LP-mode interferometer (A_1 between $LP_{01(x)}$ and $LP_{11(x)}$ and A_2 between $LP_{01(y)}$ and $LP_{11(y)}$). The amplitude of these signatures changes with the orientation of the input polarization, as can also be observed in Fig. 3 for the case of polarization at 45° (dashed line). In Fig. 4, the inset shows the superposition of the LP_{01} and LP_{11} when the Hi-Bi PCF fiber is untwisted and with a twist of 270°, respectively. When a twist angle is applied to the sensing head, a beat between the two interferometers appears due to the simultaneous excitation of the two polarization states. The FFT of the channeled spectrums is also shown in Fig. 4. When the twist is applied, the first frequency peak increases and the second frequency peak decreases. The beat modulation obtained by the 270° twist angle is similar to the beat modulation obtained when the light is launched at an angle of 45° relatively to the eigenaxis of the Hi-Bi PCF. Fig. 5(a) shows the relationship between the twist angles and the FFT amplitudes. The result associated to the second peak (A_2) presents more sensitivity when compared with the first peak (A_1) [9]. The two results are nonsymmetrical due to the asymmetry of the two large holes of the Hi-Bi PCF. As it can be observed, the output changes ≈0.2 dB when the twist angle is varied in the range of $[-270°, 270°]$. Due to the characteristics of the optical spectrum analyzer, the resolution of the torsion sensor was estimated to be $\sim 2.7°$. This value is essentially determined by the amplitude resolution of the optical spectrum analyzer and by the error $(\sim 1°)$ associated with the rotation mount. To eliminate possible light source fluctuations, the difference between the two amplitude peaks $(A_2 - A_1)$, when expressed in logarithmic values, as function of the torsion angle can be used. The result is shown in Fig. 5(b), presenting two linear regions associated with the torsion ranges $[-270°, -90°]$ and $[90°, 270°]$. The slopes correspond to a twist angle sensitivity of approximately ± 8.25/degree. It was observed that the rotation of the splice region between the input standard fibre and the Hi-Bi PCF is critical for the sensor operation (the best performance was achieved with the standard fibre clamped just before the splice).

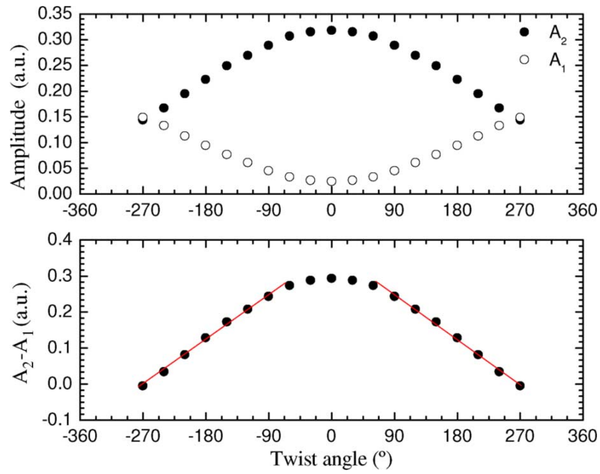

Fig. 5. (a) Torsion response of the sensing head. (b) Difference of the two FFT peaks (log scale) as a function of the torsion angle.

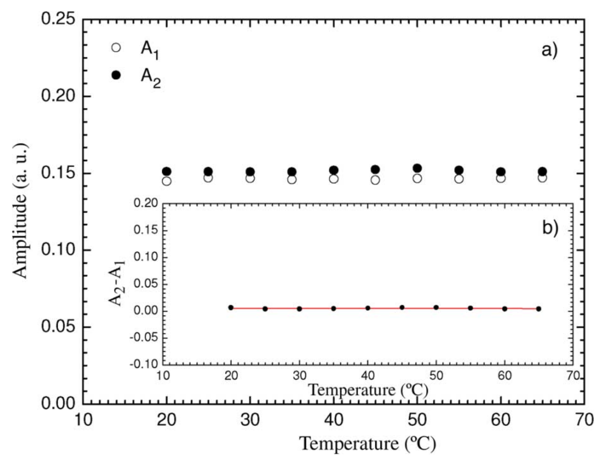

Fig. 6. (a) Temperature response of the sensing head; (b) difference of the two FFT peaks (log scale).

Indeed, it is this rotation that changes the polarization state at the input of the Hi-Bi PCF and therefore the excitation conditions of the polarization modes. The Hi-Bi PCF converts these twist-induced polarization variations into channelled spectrum changes, from where the measurand information can be recovered. In a practical implementation of this sensing structure, optimal operation would require a well-defined linear polarization state for the light that inputs the splice region, which can be readily achieved with a fibre polarizer. The temperature dependence of the sensing head was also investigated. The sensing head was placed inside a tubular oven, and the temperature was changed in the range $[20\,^\circ\mathrm{C}–60\,^\circ\mathrm{C}]$ for a twist angle of $\sim 220^\circ$. The phases of the two interferometers vary, but not its relative phase, which means it is not expectable temperature-induced variation of the FFT peaks. Fig. 6 shows the obtained results. The two peaks of the FFT were observed simultaneously, and their amplitude as function of temperature were plotted [Fig. 6(a)]. On the other hand, Fig. 6(b) shows the difference between the two FFT peaks (logarithmic values), which indicates a very small sensitivity to temperature $(8 \times 10^{-6}/^\circ\mathrm{C})$. Therefore, for a small temperature range, the torsion sensor can essentially be considered temperature independent. When these results are compared with those obtained with the Blaze-Photonics Hi-Bi PCF PM-1550-01 fiber [10], the sensing structure presented here permits a higher measurement range (180° for each torsion direction with the fibre shown in Fig. 1, while for the PM-1550-01 fiber this value is reduced to 90°). It must be emphasized that it is the fact of the fibre investigated in this work to guide two spatial modes at 1550 nm that is in the core of the performance of the reported sensing head. In addition, it brings extra flexibility for other sensing arrangements, particularly when dealing with simultaneous multiparameter measurement (standard Hi-Bi fibres, such Panda or Bow-Tie, are single mode at 1550 nm).

III. Conclusion

This work presented a sensing head to measure torsion with low sensitivity to temperature. An interferometric configuration based on a two-mode operation was used for determination of the twist angle in a Hi-Bi PCF with two large asymmetric holes. Fourier analysis of the channeled spectrum obtained by beating the interference of the two lowest spatial modes at each polarization allows obtaining torsion measurement by monitoring the amplitude of the FFT peaks. This proved to be an efficient and cost-effective interrogation approach of this sensing head when applied to torsion measurement, providing a measurand resolution of $\sim 2.7^\circ$. This value can be increased if the configuration is optimized, particularly in what concerns the FFT processing.

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