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# Large range linear torsion sensor based on a suspended-core fiber loop mirror

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**Abstract.** A fiber loop mirror containing a section of high-birefringence suspended-core fiber is used for torsion sensing. The suspended-core fiber section has a triangular-shaped core with an in-circle diameter of approximately 1.8  $\mu\text{m}$ . Due to its small dimensions and geometric structure, it presents high birefringence and intermodal interference simultaneously. A torsion sensitivity of 59.0 pm/deg is obtained in a very large linear range of 900 deg with a resolution of 1.2 deg. © 2013 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.52.2.020501]

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Fiber loop mirrors (FLMs) are frequently used devices in optical communications and sensing.<sup>1</sup> This device has attracted attention due to its easy manufacture. It is formed by a splice between the output ports of a 3-dB optical coupler. In this configuration, two waves travel inside the fiber loop in opposite directions but following the same optical paths, which assures constructive interference when the waves recombine at the coupler. This way, all the light is reflected back into the input port with reflectivity limited only by losses in the fiber, the splices, and the coupler. This mirror-like property is the reason why this device is frequently used to form a resonant cavity in fiber lasers.<sup>2</sup> This interferometric configuration is not a new concept, but with the emergence of novel microstructured optical fibers, such as photonic crystal fibers (PCFs), it has again been subject of intense research. When a section of high-birefringence fiber is introduced inside the fiber loop, obtaining a high-birefringence fiber loop mirror (HiBi-FLM), several advantages arise: independence of input polarization and the fact that the periodicity of the spectral filter produced is only dependent on the length of the HiBi fiber and not on the total length of the FLM.<sup>3</sup>

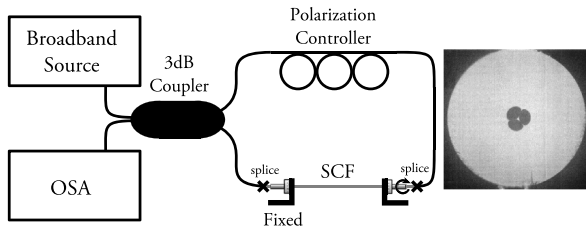
In optical sensing, HiBi-FLMs have been used for strain,<sup>4</sup> temperature,<sup>5</sup> and liquid-level measurement.<sup>6</sup> They have also been combined with long period gratings (LPG)<sup>7</sup> or fiber

Bragg gratings<sup>8</sup> for simultaneous measurement of strain and temperature. A physical parameter that is very important in structural monitoring that has not been given full attention is torsion. Fiber torsion sensors were originally based on LPGs where the resonant peaks could be shifted when a twist is applied to the fiber.<sup>9,10</sup> Other configurations are based on the change in visibility of a particular feature.<sup>11</sup> More recently, torsion sensors based on polarization maintaining (PM)-PCF or HiBi-FLM have been studied. Nalawade et al. created a torsion sensor based on a modal interferometer with PM-PCF that is insensitive to strain and temperature.<sup>12</sup> More recently, HiBi-FLMs have been employed for the measurement of applied torsion. Usually, when a very high torsion sensitivity is obtained (1 nm/deg), the measurement range of validity is very small 65 deg.<sup>13</sup> The opposite is also true; when the sensor is linear in a larger range 180 deg, the sensitivity is smaller (59 pm/deg).<sup>14</sup>

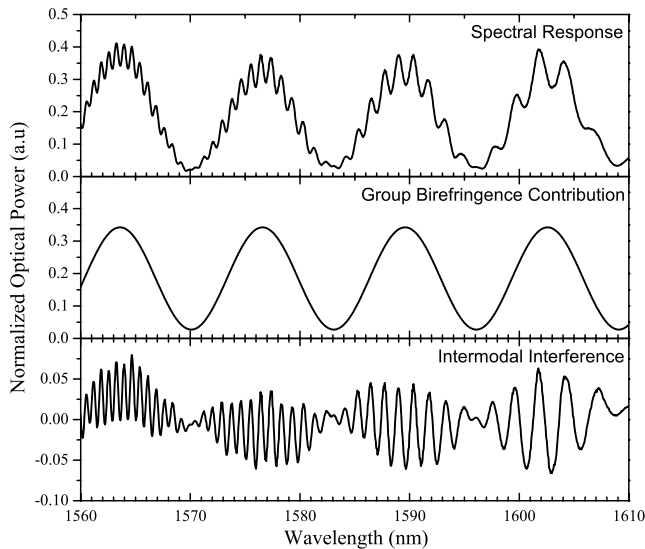
In this letter, a torsion sensor based on a high-birefringence suspended-core fiber (SCF) with a microcore diameter of 1.8  $\mu\text{m}$  is presented. This sensor has a very large linear measurement range of 900 deg. The sensor was also characterized in strain and temperature.

Figure 1 illustrates the experimental setup used in this work. It consists of an optical broadband source, a fiber loop mirror, and an optical spectrum analyzer (OSA) with a maximum resolution of 0.05 nm. The optical source is an erbium-doped broadband source, with a central wavelength of 1550 nm and a large spectral bandwidth of 100 nm. The FLM was adapted for the measurement of torsion by setting the suspended-core fiber section in between two twist stages. It is formed by a commercial 3 dB ( $2 \times 2$ ) optical coupler with low insertion loss (3.32 dB) from Thorlabs Inc., a section of suspended-core fiber with approximately 0.05 m in length, and an optical polarization controller. The three-hole suspended-core fiber was fabricated at Marie Curie-Skłodowska University and has a triangular-shaped core with an in-circle diameter of approximately 1.8  $\mu\text{m}$  (see Fig. 1). Due to core asymmetry, the fiber presents a high birefringence.<sup>15</sup> All measurements of torsion were performed with the suspended-core fiber coated and with torsion applied on a section between the two splices. The splices between single-mode fiber (SMF) and suspended-core fiber were performed using a conventional electric-arc splicer and applying a simple technique. The technique consists in applying the electric arc in the SMF region. With this technique low-loss splices with high reproducibility are obtained.<sup>16</sup>

Figure 2 presents the spectral response and spectral decomposition of the fiber loop mirror signal. The top signal is the original signal where several interferometers are clearly present. Processing this signal one can easily separate the birefringence contribution (middle signal) and what is left is the bottom signal. The middle signal results from the interference between light that propagates in the two polarization modes of the birefringent fiber: the fast and slow modes. The bottom signal, with much smaller fringes, results from the intermodal interference between the few modes that propagate in the SCF core (silica-air waveguide). This intermodal interference can be explored for multiparameter sensing as it presents different sensitivities to physical parameters when compared with the birefringence pattern.<sup>17</sup> For torsion analysis, the suspended-core fiber is subjected to torsion on one end while the other is fixed. A twist of 900 deg, half

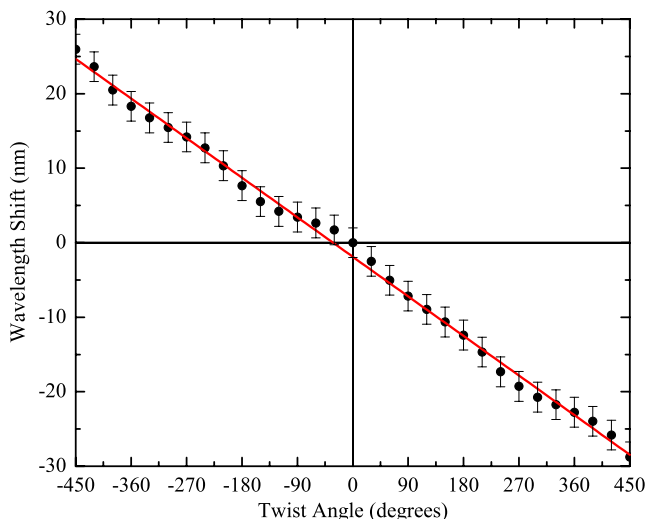


**Fig. 1** Fiber loop mirror setup adapted to the measurement of torsion and cross-section photograph of the microcore suspended-core fiber.

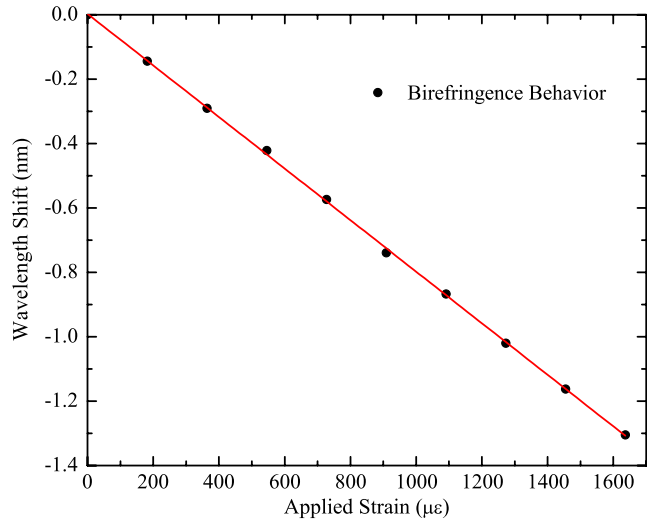


**Fig. 2** Spectral response and spectral decomposition of the fiber loop mirror signal.

clockwise (450 deg) and half counterclockwise (450 deg), is applied while the wavelength shift of the birefringence pattern is monitored as a function of twist angle. Torsion is applied to a 0.30 m section of suspended-core fiber where the splices to SMF are not included. A linear fit to the experimental data with a good squared correlation coefficient ( $r^2$ ) of 0.995 can be seen in Fig. 3. A high torsion sensitivity of



**Fig. 3** Wavelength shift as a function of applied twist angle.



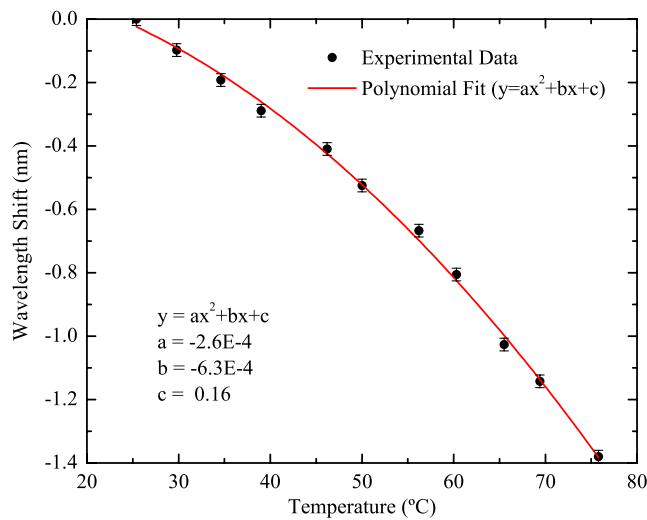
**Fig. 4** Wavelength shift as a function of applied strain for the birefringence pattern.

59.0 pm/deg was obtained. Since the suspended-core fiber has a high linear birefringence, when it is twisted, an elliptical birefringence results from the circular twist induced birefringence and the intrinsic linear birefringence.<sup>18</sup> The torsion induced elliptical birefringence is proportional to the twist angle and the birefringence vector depends on the twist direction, clockwise or anticlockwise. The visibility of the birefringence pattern varies in the range 0.7 to 0.8.

Strain was applied to a total length of 0.55 m in which the 0.50 m SCF section is included. Analyzing the spectral responses of the fiber loop mirror (see Fig. 4), a sensitivity of  $-0.8 \text{ pm}/\mu\epsilon$  was obtained when considering the shift of the birefringence pattern. The shift to shorter wavelengths derives from the dominance of the photo-elastic effect over the extension of the fiber. The sensitivity to applied strain is very small, which leads to a small wavelength shift that cannot explain the torsion sensitivity results. The wavelength shift ranges are completely different when torsion or strain is applied.

As for temperature, a nonlinear response was found (see Fig. 5). A shift toward shorter wavelengths was found as temperature increases, which results from the fact that the dominant effect is the birefringence dependence on temperature. Since the birefringence is generated by the core geometry and the stresses there induced during fabrication, when temperature is increased, these stresses are relaxed, resulting in a shift to shorter wavelengths. Considering a linear section in the range of 25°C to 50°C, a sensitivity of 21.3 pm/K is determined.

In conclusion, a large-range (900 deg) linear response, torsion sensor was built using a high-birefringence suspended-core fiber in a fiber loop mirror. A sensitivity of 59.0 pm/deg was obtained. The resolution of the sensor is 1.2 deg and is limited by the resolution of the optical spectrum analyzer. This sensor was also characterized in strain and temperature. As for strain, a sensitivity of  $-0.8 \text{ pm}/\mu\epsilon$  was obtained. A strong nonlinear temperature response is the down-side of this sensor resulting in a mean sensitivity of



**Fig. 5** Birefringence pattern wavelength shift as a function of temperature variations.

21.3 pm/K in the range of 25°C to 50°C. Albeit having small strain and temperature sensitivities when compared with torsion sensitivity, it is possible to use the intermodal interference present in the spectral response for the simultaneous measurement of several physical parameters.<sup>17</sup>

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