Temperature- and strain-independent torsion sensor using a fiber loop mirror based on suspended twin-core fiber

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Received May 18, 2010; revised June 16, 2010; accepted July 2, 2010; posted July 23, 2010 (Doc. ID 128705); published August 13, 2010

In this Letter, we present a fiber loop mirror configuration based on a suspended twin-core fiber for sensing applications. Using the suspended twin-core fiber, the fringe pattern is due to the differential optical patch of the light in the two cores associated with a refractive index difference of ~10^{-3}, which indicates an advantage of this approach compared with those based on high-birefringent fibers, namely, the possibility of using a small length of fiber. The sensing configuration was characterized for torsion, temperature, and strain. Using the fast Fourier transform technique, it is possible to obtain measurand-induced amplitude variations of the fringe pattern. The results obtained indicate the viability of a temperature- and strain-independent torsion sensor.

OCIS codes: 060.2310, 060.2370, 060.4005.

An all-fiber loop mirror or Sagnac interferometer can be implemented in different configurations. The traditional fiber loop mirror has been used for gyroscopes, hydrophones, geophones, and current measuring systems [1]. The other type of fiber loop mirror is one in which the loop contains a section of a high-birefringent (Hi-Bi) fiber. The advantages are input polarization independence and periodicity of the formed spectral filter, which depends only on the length of the Hi-Bi fiber and not on the total length of the fiber loop mirror [2].

In optical sensing, the Hi-Bi fiber loop mirror has been used for strain [3], temperature [4], liquid level [5] and displacement [6] measurement, and also as a spectral filter for fiber Bragg gratings demodulation [7]. Moreover, the Hi-Bi fiber loop mirror combined with a Bragg grating [8] or with a long period grating [9] was also demonstrated for simultaneous measurement of strain and temperature.

Photonic crystal fibers (PCFs) are made of a single type of glass and have air holes in their structure, and thus the PCF birefringence is induced by its asymmetric geometry and the PCF is also highly insensitive to temperature changes. Michie *et al.* [10] investigated the independence of the modal birefringence with temperature in highly birefringent PCF fibers. Furthermore, it has been reported that the PCF did not exhibit temperature dependence due to the existence of a single material in their structure and used in a fiber loop mirror [11–13]. Different types of PCF are used in the fiber loop mirror and applied in specific applications, namely, for displacement [14], strain [15–17], or curvature [18].

The first demonstration of the suspended core fiber was proposed in 2001 [19]. The core, with 1 μm diameter, was single-mode, and it was predicted to have 17% of the mode located in the air at 1550 nm. This degree of overlap between the fundamental mode and the holes suggested this fiber was suitable as an evanescent field device sensor. Several authors have studied this novel geometry for gas sensing and biosensing [20]. Because of the triangular geometry, this type of fiber presents high birefringence owing to the stress geometry created by the fabrication and was also demonstrated in a fiber loop mirror when a suspended core fiber section with three holes was spliced inside the loop [21].

In this Letter, the authors present a suspended twin core in a fiber loop mirror. Because of the difference of stress geometry of the core, the refractive index difference between the two cores is high, and therefore it is possible to use a small section as an element sensing device. The sensing head was characterized in torsion, temperature, and strain.

The fiber cross section is shown in the inset of Fig. 1. The suspended twin-core fiber with four holes made of pure silica was fabricated at the Institute of Photonic Technology (Jena, Germany). The distance between the two cores is approximately 7.6 μm, making it possible to illuminate simultaneously the two cores using a standard single-mode fiber (SMF-28). The core diameter is 1.5 μm, the cladding is 124 μm, and the big/small holes are 10/5 μm, respectively. Other characteristics can be obtained in the literature [22]. Figure 1 presents the mode profile of the suspended twin-core fiber. The splice loss is approximately 3.5 dB, the propagation loss is 0.3 dB/m, and the effective refractive index difference for the light propagating in the two cores is 7.6×10^{-4} (x polarization) and 8.1×10^{-4} (y polarization).

Figure 1 presents the fiber loop mirror configuration adapted to measure torsion, strain, and temperature.

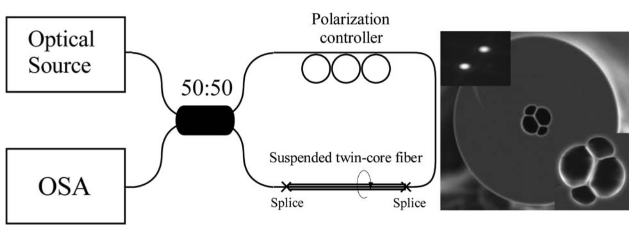

Fig. 1. Setup of the sensing head.

It consists of a 3 dB (2×2) optical coupler with low insertion loss, an optical polarization controller, and a suspended twin-core fiber section with a length of 0.26 m. The fiber loop mirror is illuminated by a broadband source (erbium-doped fiber) with a central wavelength of 1550 nm, and the fringe pattern was read by an optical spectrum analyzer (OSA) with a maximum resolution of 0.05 nm. All measurements were performed with the coated suspended twin-core fiber.

The suspended twin-core fiber section corresponding to a Mach–Zehnder interferometer was incorporated into a fiber loop mirror. The wavelength spacing $(\Delta\lambda)$ is given by $\Delta\lambda = \lambda^2/\Delta n L$, where $\Delta n = n_{\mathrm{core1}} - n_{\mathrm{core2}}$ is the effective refractive index difference between the two cores and L is the fiber length.

The value is approximately 1×10^{-3}, and this difference results from several factors, namely different bridge widths and differential tensions in the two cores associated with the fiber fabrication process.

For the torsion measurement, the twist is applied only in the region of the suspended core fiber and the consequence is a variation of the channeled spectrum fringe amplitude (and consequently variation of the fringe visibility) associated to a variable polarization state of the light guided in the cores due to the stress created in the core when the torsion is applied. This variation can be observed in the inset of Fig. 2, which gives also the fast Fourier transform (FFT) analysis of the obtained results for torsion angles 0°, 45°, and 90°. Figure 3 shows the torsion response of the sensing head using the FFT technique and the visibility measurement. The sensitivities are 1.2×10^{-2} dB/° and 5.1×10^{-4}/° using the FFT technique and the visibility approaches, respectively.

For the temperature measurement, the sensing head containing the twin suspended core fiber was placed in a tubular oven, which permitted the temperature of the sensing head to be set with an error smaller than 0.1 °C. Figure 4 (inset) presents the fringe pattern when the sensing head was subjected to temperatures of 25 °C and 65 °C. In this experiment, the thermo-optic effect on the fiber was dominant, decreasing with the increase of temperature. Similar results were observed for twin-core PCF [22,23]. The sensitivity observed is −19.9 pm/°C. It

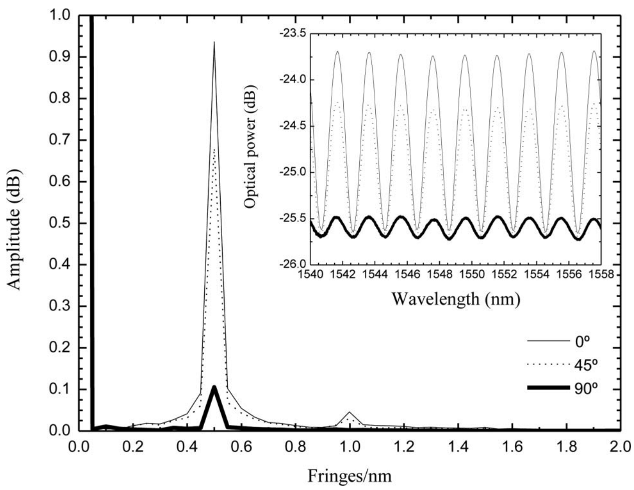

Fig. 2. Channeled spectrum of the sensing head when the torsion was applied for 0°, 45°, and 90° (inset) and FFT analysis.

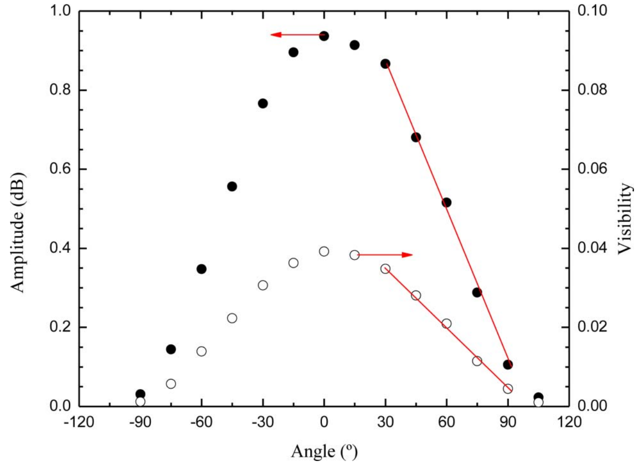

Fig. 3. (Color online) Torsion measurement using the FFT and the visibility measurement techniques.

can be noticed that the fringe amplitude presents very low dependence when the temperature is applied. This result is confirmed by the FFT analysis.

For the strain measurement, the sensing head was attached to a translation stage with a resolution of 1 μm. Figure 5 (inset) shows the response of the structure in the situations of no applied strain and applied strain of 775 $\mu\varepsilon$. Observed is a blueshift of the channeled spectrum (−0.9 pm/$\mu\varepsilon$), an indication that the effective refractive index difference between the two core modes decreases with the increase of strain. On the other hand, the amplitude of the channeled spectrum fringes is negligible when strain is applied.

The invariance with strain and temperature of the fringe amplitude of the channeled spectrum indicates that this sensing configuration shows measurement parameter torsion sensitivity without cross sensitivity to strain and temperature, an important characteristic in view of its application as a torsion sensor.

In summary, a sensing configuration based on a fiber loop mirror incorporating a suspended twin-core fiber was demonstrated. The sensing head was characterized in torsion, strain, and temperature. We observed that the amplitude of the fringes of the channeled spectrum is

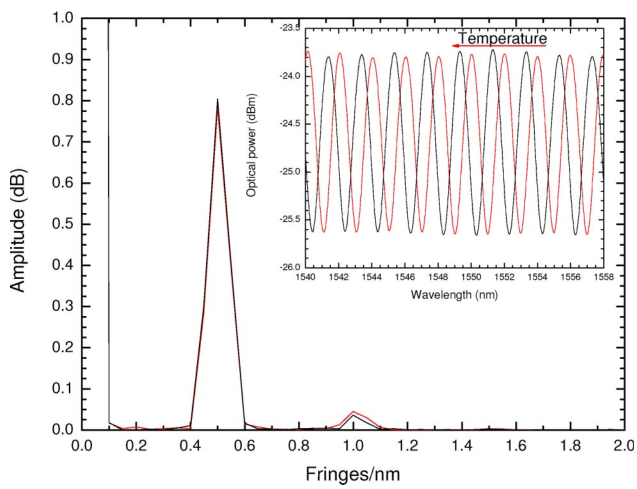

Fig. 4. (Color online) Channeled spectrum of the sensing head for the temperatures of 25 °C and 65 °C (inset figure) and FFT analysis.

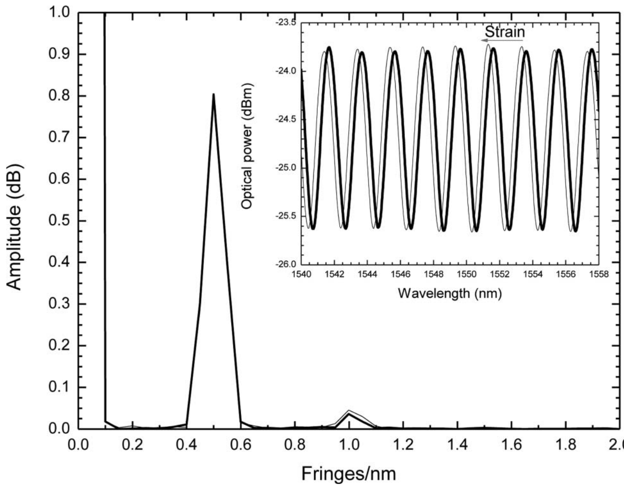

Fig. 5. Channeled spectrum of the sensing head in conditions of no strain and 775 $\mu\varepsilon$ (inset) and FFT analysis.

sensitive only to torsion, indicating the viability of implementing with this structure a strain- and temperature-independent torsion sensor. The stability is guaranteed owing the high birefringence of the cores where the polarization states are constant when torsion is applied. However, the splice region is critical, and to solve this problem a splice protector can be used.

This work was supported by the European Cooperation in Science and Technology Action 299—Optical Fibres for New Challenges Facing the Information Society.

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