LETTERS

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Highly sensitive torsion sensor based on directional coupling in twisted photonic crystal fiber

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We demonstrate a novel torsion sensor based on a twisted photonic crystal fiber with an embedded liquid rod waveguide. Only one resonant dip appears in the transmission spectrum in the range of 1,350–1,650 nm, which is associated with the directional coupling between the core and rod modes. The relative position of the fiber core with respect to the liquid rod waveguide is altered owing to the torsion stress, which changes the phase-matching condition and leads to a resonant-wavelength shift. The helical structure of the liquid rod waveguide can improve the torsion sensitivity of the device and provide an ability to distinguish the rotation direction. The measured torsion sensitivities were as high as ∼203 and ∼208 nm·mm·rad⁻¹ in the clockwise and counterclockwise rotations, respectively. © 2018 The Japan Society of Applied Physics

Fig. 1. Illustration of the setup for PCF twisting.

Fig. 2. (a) Side-view photograph of the SFTPCF spliced with an SMF. (b) Cross-section of the SFTPCF, where the red dotted circles outline the hole filled with a standard RI liquid. (c) Illustration of the SFTPCF (non-scaled) comprising a central solid core and helical liquid rod waveguide.
and air hole decreased to 108 and 2.7 µm, respectively, owing to the velocity difference (0.22 mm/s) between \( \nu_1 \) and \( \nu_2 \).

As shown in Fig. 2(b), one of the air holes located in the cladding of the twisted PCF was selectively filled with a 1.49-RI liquid using a femtosecond-laser-assisted selective filling method.\(^{17}\) The selectively filled twisted PCF (SFTPCF) sample is expected to exhibit an improved torsion sensitivity, as it combines the advantages of helical structures and embedded directional coupler in the PCF. In Fig. 2(c), the three-dimensional (3D) geometry (non-scaled) of the SFTPCF shows that the RI liquid rod can form a waveguide in the air hole and wrap around the PCF core.

In general, in twisted solid-core PCFs, the resonant dips in the transmission spectrum originate from the resonant coupling between the PCF core mode and cladding modes, as observed in LPFGs.\(^{18}\) In order to obtain a unique dip for tracing, we increased the twisting period of the PCF to avoid the dips resulting from the LPFG. A series of twisted PCF samples with different periods were prepared; transmission spectra were recorded until no apparent resonant dips could be observed. A PCF sample with a twisting period of 1,200 µm and twisting rate \( \alpha = 5.2 \text{ rad·mm}^{-1} \) satisfied this requirement.

The twisted PCF was then spliced with a section of a single-mode fiber (SMF) that was cut off, and only a 10-µm-long SMF was preserved. One hole in the cladding was drilled from the cross-section of the SMF using a femtosecond-laser beam. The selectively opened end of the twisted PCF was immersed into the RI liquid; the liquid filled the opened hole of the twisted PCF owing to the capillary force. A filled sample with a twisted section length of 4.2 cm was prepared; both ends of the sample were fusion-spliced with an SMF and connected to a super-continuum light source (NKT Photonics Super K Compact) and optical spectrum analyzer (Yokogawa Test and Measurement AQ6370C), respectively.

The transmission spectrum of the twisted PCF sample is plotted in Fig. 3. In the wavelength range of 1,350–1,650 nm, no obvious lossy dips can be observed in the spectra of the unfilled sample (black curve), which indicates that no resonant dip of the LPFG is formed, implying that the method of fabricating twisted PCFs is reliable. The same twisted PCF was then used to prepare a selectively filled sample. The spectrum of this sample shows an apparent resonant dip at approximately 1,550 nm, which originates from the coupling between the fiber core mode and liquid rod mode. The strength of the directional coupling resonance is \( \sim 7 \text{ dB} \). The strength of the weak interference fringes caused by the splicing joints between the twisted PCF and SMF is \( \sim 1 \text{ dB} \), which does not interfere with the performance of this device. The resonant dip is sufficiently unique to be traced for torsion tests.

The novel device was placed in a torsion test system\(^{19}\) to observe the shift of the resonant dip with the increase of the torsion angle. One rotator was fixed, while the other one was rotated in the clockwise (+) or counterclockwise (−) directions, which were equal to or opposite to the direction of the twisting PCF, respectively. The distance \( L \) between the two fiber holders was 55 mm. Therefore, the applied torsion \( \tau \) can be estimated by \( \tau = \theta / L \) (rad·mm\(^{-1}\)). It is worth noting that the device is highly sensitive to temperature. In order to eliminate the temperature influence, the device was covered under a protective shield, which maintained the sample at a constant temperature of 22 °C during the torsion test, yielding stable spectra.

The unique resonant dip could be traced in the spectra, where the angle of rotation \( \theta \) was varied from 0 to \( \pm 240° \) (±0.076 rad·mm\(^{-1}\)) in this case, in intervals of 30° (0.0095 rad·mm\(^{-1}\)). Larger rotation angles were not applied to avoid damage to the fiber. A series of spectral responses for different angles of rotation is plotted in Fig. 4. It is evident that the resonant dip shifts to the opposite direction when the sample is rotated oppositely. The SFTPCF can distinguish opposite rotations without the need for pre-twisting owing to the helical structure.

It is well known that mode coupling can only occur around the phase-matching point, where the effective RI of the core mode overlaps with that of the rod waveguide mode. The shift of the phase-matching point is mainly caused by the relative position change of the liquid rod waveguide with respect to the fiber core with the rotation. As shown in Fig. 5, when the SFTPCF rotates, the angle \( \Phi \) between the liquid rod waveguide and fiber core changes, which can be expressed as\(^{20}\).
During the torsion test, when the direction of rotation was equal to that of the PCF twisting, under a torsion stress, the angle $\Phi$ between the fiber core and liquid rod waveguide increased (Fig. 5), which implies that the twist rate $\alpha$ improved with a constant $\rho$. According to Eq. (2), the resonant wavelength $\lambda_R$ shifted towards longer wavelengths with the increase of $\alpha$.

During the torsion test, the wavelength variation of the lossy dip with the applied torsion ($\tau$) is plotted in Fig. 6 to demonstrate the linear fitting between the torsion and wavelength shift for the SFTPCF.

In conclusion, we proposed a novel fiber device based on an SFTPCF for torsion measurements. The operation principle of the device is based on the directional coupling between the fiber core mode and liquid rod mode. The shift of the resonant wavelength was caused by the change of the angle between the fiber axis and liquid rod waveguide. The measured torsion sensitivities were as high as $\Delta \omega = 208$ rad·mm$^{-1}$ in the clockwise and counterclockwise rotations, respectively. This device has significant potentials for ultra-sensitive torsion measurements.

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