Simultaneous multi-parameter measurement using Sagnac loop hybrid interferometer based on a highly birefringent photonic crystal fiber with two asymmetric cores

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Abstract: We have experimentally investigated the multi-parameter sensing characteristics in a novel all-fiber Sagnac loop hybrid interferometer based on a highly birefringent photonic crystal fiber with two asymmetric cores. The sensor device was based on a combination of two types of in-fiber interferences, the intra-core-mode Sagnac interference and the inter-core-mode Mach-Zehnder interference due to the distinct birefringent properties associated with the asymmetric cores. Fast Fourier transform analysis on the transmission spectra of the device exhibited six clear peaks in the spatial frequency domain. By examining the phase shift responses of two distinct Sagnac and one Mach-Zehnder interference peaks, the response matrix that enable simultaneous measurement of torsion, strain, and temperature could be obtained. The proposed all-fiber Sagnac loop hybrid interferometer has the advantages such as simplicity of the device structure, compact device size, and capability for simultaneous sensing of multiple parameters.

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1. Introduction

There has been much interest in developing multi-parameter all-fiber sensors for simultaneous measurement of strain, temperature, torsion and other environmental parameters [1–7]. Simultaneous monitoring of multiple parameters by use of a fiber sensor with a simple structure offers many advantages in terms of the size, cost and simplicity of the sensor system. Besides, it also helps in resolving the cross-sensitivity problems among different external parameters to improve the sensor performance. For the simultaneous measurement, it usually requires complex sensing head having multiple detection features and each of them should exhibit unique response to the external parameter to be measured.

All-fiber Sagnac loop interferometer (SLI) based on highly birefringent photonic crystal fiber (HB-PCF) is one of the most widely used fiber sensor device due to its unique properties such as easy construction, large flexibility in the sensor fiber design and characteristics, compactness due to the high birefringence property of the fiber, and low temperature sensitivity [4–10]. Recently, various sensing systems have been investigated with single-structured SLIs made by HB-PCFs for the simultaneous measurement of multiple parameters. For the discrimination of strain and temperature, different sensing methods based on HB-PCFs were applied as follows: cladding-mode resonance in the SLI made by a HB-PCF [4], inter-modal interference in a small-core PCF-based loop mirror [5], and the SLI incorporated with a HB-PBG Bragg fiber [6]. SLI based on highly-birefringent PCF with the side-leakage [7] structure was also investigated for simultaneous measurement of torsion and temperature. The measurement schemes dealt with polarization modes and dispersion properties of the single-core HB fibers to obtain the multi-parameter sensing responses. Therefore, their applications were generally limited to dual-parameter sensing systems although they have shown the advantages such as enhanced resolutions and simultaneous measurement capabilities for the sensor systems.

More recently, attractive characteristics of twin-core fibers, where two parallel cores are integrated in a single fiber structure, have been exploited for multi-parameter sensing applications [11–16]. Most of the sensing applications were investigated by using the twin-core fibers as the sensing elements in the in-line Mach-Zehnder interferometers (MZIs) [12–

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14]. Using a polarimetric interferometer made by a polymer microstructured fiber having a dual core with the similar birefringent property, individual sensing characteristics of the cores on hydrostatic pressure, strain, and temperature were investigated [15]. A fiber loop mirror based on a suspended twin-core fiber has been demonstrated for a strain- and temperature-independent torsion sensing device [16]. The fringe visibility of the Mach-Zehnder interference from the twin-core in the fiber loop was found to be strongly affected by torsion, while it was insensitive to strain and temperature. However, these fiber interferometers were made by birefringent fibers integrated with two nearly symmetric cores exhibiting nearly similar birefringence and dispersion properties, thus their potential in multi-parameter sensing applications would be limited by the restriction in the fiber properties.

In this paper, we experimentally investigate multi-parameter sensing characteristics in a novel all-fiber Sagnac loop hybrid interferometer (SLHI) based on a newly designed highly birefringent photonic crystal fiber with two asymmetric cores. The all-fiber SLHI could be made by combining the Sagnac interferometers based on the birefringent properties of the cores and the Mach-Zehnder interferometers comprising the two cores, and the resulting multiple interferences from the hybrid structure was used for the multi-parameter sensing application. A demodulation method based on the FFT analysis was used to examine the phase shift responses of the integrated distinct Sagnac interferences and Mach-Zehnder interference for simultaneous measurement of torsion, strain and temperature. The proposed all-fiber SLHI is simple in device construction and has the capability for simultaneous multi-parameter sensing applications.

2. Experiments

An all-silica highly-birefringent asymmetric twin-core PCF (HB-ATCPCF) was fabricated by the conventional stack-and-draw method whose detailed procedure was given in [12]. The fiber was designed to have two index-guiding elliptic cores with different birefringent properties. Two highly asymmetric cores were separated by a single layer of air holes and the surrounding cladding was made to have a high air-filling fraction, thus the light beams propagate along the cores with strong confinement and the power transfer between the cores would be negligible. Figure 1 shows the scanning electron micrograph (SEM) image of the fiber microstructure. The smaller core was designated by core 1 and the larger one by core 2, and the slow axes of the cores were aligned to approximately 65° with each other. On average, the diameter of air holes and the air-filling fraction were measured to be ~3.7 μm and 0.84, respectively. The core sizes along the slow/fast axis were ~2.90/1.90 μm and ~6.0/1.60 μm for cores 1 and 2, respectively. The total size of the microstructured region comprising the two cores and the air holes was smaller than 10 μm, thus the light from a conventional single mode fiber (SMF) can be well coupled to both cores of the HB-ATCPCF.

Figure 2(a) describes the schematic diagram of a SLHI made by using the HB-ATCPCF inside a fiber Sagnac loop. The 12.3 cm-long HB-ATCPCF was manually fusion-spliced to the arms of the Sagnac loop made by SMFs. It should be noted that the light coupling between the core of single mode fiber and the twin-core of the HB-ATCPCF is an important step
which determines the device performance. Since the cores of the birefringent fiber are highly asymmetric in terms of the size and the birefringent axis orientation, the fringe contrasts and hence the sensitivities of multiple interferences in the SLHI strongly depend on the light coupling condition and the insertion loss at the spliced points. Thus, the fusion splicing was carefully performed by manual control on the lateral motion of the V-grooves in a conventional splicing machine (Fitel, s174). For the splicing between the lead-in SMF and HB-ATCP CF, the transmission spectrum was continuously monitored to optimize the fringe contrast. The fiber joint was fusion-spliced when the optimized fringe spectrum with a maximum contrast was achieved. The same procedure was applied for the splicing between the opposite end of the birefringent fiber and the lead-out SMF. The splicing loss of the single splicing joint was found to be less than 3 dB, and it would be further minimized by optimizing the splicing conditions. In the optical characterization, the broad-band light beam (Throlabs, ASE730) launched at the input port (port 1) was coupled to the Sagnac loop through a polarization insensitive 3 dB fiber coupler. In the fiber coupler, the light beam splits into two parts with equal intensity and propagates to the ports 3 and 4 in the clockwise (CW) and counter-clock wise (CCW) directions, respectively. Upon reaching the ends of the HB-ATCP CF, the two light beams further split into the two cores and excite a pair of polarization modes in each core, where they travel along the same length of the birefringent fiber and couple out from the Sagnac loop at port 2. A fiber polarization controller (PC) was used to optimize the output spectrum of the SLHI. In the measurement of the sensing responses on torsion and strain variations, we used a pair of mechanical stages equipped with fiber holders. The HB-ATCP CF was tightly fixed to the fiber holders using glue after removing the fiber coating. One fiber holder was stationary, whereas the other one was movable for the measurement. For torsion sensing, the holder was rotated in the range of –150 to 320°, and to apply axial strain in the range up to ~3000 με, the holder was linearly translated using the mechanical stage. For the measurement of sensing responses on temperature variation, the HB-ATCP CF was heated in the temperature range of 25 to 145 °C using an electrically controlled oven. The output spectra of the SLHI were measured by an optical spectrum analyzer (OSA) (Ando, 6317B) upon applying the external variations to the sensor fiber.

Figure 2(b) shows the simulated electric-field patterns of the fundamental core modes of the HB-ATCP CF with two polarization directions, where s and f stand for the slow and fast birefringence axes of the cores, respectively. The simulation was obtained by the full-vector
finite element analysis in the COMSOL using the same geometric structure shown in Fig. 1. The polarization modes of the birefringent cores with the structural asymmetry can interfere with each other and make four-beam interference patterns after transmitting through the fiber loop. The multiple interferences in the SLHI are classified into two categories, i.e. the intra-core mode Sagnac interferences originated from the birefringent property of each core and the inter-core mode Mach-Zehnder interferences due to modal index contrast between the cores.

3. Operation principle of the SLHI

The transmission characteristics of an all-fiber SLHI can be investigated using the Jones matrix analysis [17, 18]. The SLHI is composed of a 3 dB coupler with the $2 \times 2$ single-mode fiber ports and a section of the HB-ATCPCF.

Let’s consider a light beam with the field amplitude of $E_1 = xE_{1x} + yE_{1y}$ launched at port 1 of the SLHI. By the 3 dB fiber coupler, the light is divided into two transmitted ports with the coupling ratios of $k$ (port 3) and $1-k$ (port 4), and they travel the common fiber loop in the CW and CCW directions, respectively. The field amplitudes at the ports 3 and 4 are respectively given by

$$E_3 = \sqrt{k} E_1, \quad E_4 = \sqrt{1-k} HE_1; \quad H = \begin{pmatrix} e^{i\pi/2} & 0 \\ 0 & e^{-i\pi/2} \end{pmatrix},$$

(1)

where the matrix $H$ reflects the phase-delay occurred when the light cross-couples from port 1 to port 4. It is assumed that the Sagnac loop is in the x-z plane and the birefringent fiber is straightened along the z-axis as described in Fig. 2(a). The birefringence orientations of the propagating beams with respect to the x-axis at both sides of the birefringent fiber are given by $\theta_1$ and $\theta_2$, respectively. The field amplitudes of the CW and CCW propagating beams at each input ends of the birefringent fiber are respectively expressed as

$$E_{3in} = R_1 E_3, \quad E_{4in} = R_2^{-1} E_4; \quad R(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix},$$

(2)

where $R_r = R(\theta_r) \quad (r = 1, 2)$ indicates the rotation matrix for the polarization state in the CW propagation, and the inverse matrix $R_r^{-1} = R(-\theta_r)$ can be used for the light beam in the CCW propagation.

At the input ends of the birefringent fiber, the each light beam splits into the fundamental modes of two cores with the field splitting ratios of $s_1$ for core 1 and $s_2$ for core 2 (see the inset of Fig. 2(a)) and they are expressed as

$$E_{3in} = s_1 E_{3lin} + s_2 E_{3lin}, \quad E_{4in} = s_1 E_{4lin} + s_2 E_{4lin},$$

(3)

Then, the field amplitudes of the light beams at each output ends after propagating the birefringent fiber would be

$$E_{3out} = s_1 M_1 E_{3lin} + s_2 M_2 E_{3lin}, \quad E_{4out} = s_1 M_1 E_{4lin} + s_2 M_2 E_{4lin},$$

(4)

In the equation, the transfer matrix $M_m$ ($m = 1$ for core 1, 2 for core 2) includes the phase-delay introduced to the polarization modes during propagating each core along with the additional rotation of the polarization state induced by the axis orientation of the birefringent core with respect to the input light polarization. Figure 2(c) describes the schematic diagram of the axis orientation, $\beta_m$, of the core $m$ with respect to the input polarization of the propagating beam. The transfer matrix $M_m$ for the core $m$ is expressed by
where $J(\Phi_m)$ is the phase-delay matrix with the phase difference, $\Phi_m$, between the polarization modes [17], $k_0 = 2\pi/\lambda$, $\lambda$ is the wavelength of the light beam, $L$ is the length of the birefringent fiber, and $n'_m$ and $n''_m$ are the effective refractive indices of the fundamental polarization modes of the core $m$ along the fast and slow axes, respectively. It is assumed that beam coupling to the higher order modes of the birefringent cores is negligible.

Then, we can define the transfer matrix $M_f$ for the light beam at the output end after propagating the birefringent fiber as $M_f = s_1 M_1 + s_2 M_2$. The axes of two cores in the birefringent fiber are aligned with the mutual orientation of $\beta_1 - \beta_2 (-65^\circ)$. By fixing the plane of the input polarization along with birefringence axes of core 2 (see Fig. 1(b)), the axis rotation ($\beta_2$) of core 2 becomes zero with respect to the axis of the input polarization. Since the mutual axes orientation is sufficiently larger than $45^\circ$, we can assume that it is nearly $90^\circ$ for simplicity in analysis i.e. $\beta_1 \sim 90^\circ$ for core 1 and $\beta_2 \sim 0^\circ$ for core 2. The matrix $M_f$ is thus given as

$$M_f = s_1 e^{-ik_0 n'_1 L} \begin{pmatrix} 1 + \frac{s_1}{s_2} e^{ik_0 \alpha L} & 0 \\ 0 & e^{-ik_0 n'_2 L} + \frac{s_1}{s_2} e^{ik_0 \alpha L} \end{pmatrix}$$

where $B_m = n'_m - n''_m$ ($m = 1, 2$) is the birefringence of the core $m$, and $\alpha = n'_2 - n'_1$ is the effective index difference between two core modes with the alternative polarization axes for the input light polarization along with x-axis. The schematic of the effective indices for the polarization modes of the two cores in the HB-ATCPCF is shown in Fig. 2(d). After propagating the cores in the directions of CW and CCW and passing through the fiber coupler individually, the field amplitudes of the transmitted beam at the output port (port 2) is given by the summation of the beams as follows [17],

$$E_{out} = \left[ k R_1 M_f R_1 + (1-k)HR_2^{-1}M_f R_2^{-1}H \right] E_i,$$

Using the coupling ratio of $k = 0.5$ for the 3 dB fiber coupler and the orientation of $\theta' = \theta_1 + \theta_2$, the transmission intensity ($I$) of the SLHI is given in the final form,

$$I = \frac{(E_{out} \ast \overline{E_{out}})}{(E_i \ast \overline{E_i})} = \frac{1}{2} \sin^2 \theta' \begin{bmatrix} s_1^2 + s_2^2 + s_1^2 \cos k_0 B_1 L + s_2^2 \cos k_0 B_2 L + s_1 s_2 \cos k_0 (\alpha + B_1) L + s_1 s_2 \cos k_0 (\alpha + B_2) L \\ s_1 s_2 \cos k_0 (\alpha + B_1) L + s_1 s_2 \cos k_0 (\alpha + B_2) L \end{bmatrix}.$$
fiber attenuation, the insertion loss, the birefringence of the single mode fiber inside the loop, and the light coupling between two cores of the HB-ATCPCF are assumed to be negligible.

Therefore, we can expect that the SLHI will exhibit complex transmission spectrum involving two Sagnac interferences characterized by the birefringence of $B_1$ and $B_2$ in the cores individually, and four Mach-Zehnder interferences characterized by the effective index differences of $\alpha, \alpha + B_1, \alpha + B_2$, and $\alpha + B_1 + B_2$ between the core modes.

4. Results and discussion

4.1 Fast Fourier transform analysis on the interference spectra of the SLHI

In the two-beam interference for the transmission properties of SLI and MZI [20], the relative phase difference ($\Phi$) is given by $\Phi_y = 2\pi \Delta n y L / \lambda$, where $\Delta n y$ is the effective index difference between the mode $i$ and mode $j$ along the arbitrary polarization directions in the SLHI. The phase shift of an interference spectrum can be expressed using the effective index difference and the effective group index difference in the alternative forms of [2, 15]

$$\phi y = 2\pi L \delta \left( \frac{\Delta n y (\lambda)}{\lambda} \right) = -2\pi \left( \frac{\Delta n_{y/y} L}{\lambda_0^2} \right) \delta \lambda.$$  (9)

where $\Delta n_{y/y} = \Delta n - \lambda_0 \frac{\partial \Delta n}{\partial \lambda}$ is the effective group index difference between the modes, $\lambda_0$ is the center wavelength of the interference fringe, and $\delta \lambda$ indicates the wavelength shift from $\lambda_0$ to $\lambda$ ($\delta \lambda \equiv \lambda - \lambda_0$). The spatial frequency ($\xi$) of the interference spectrum in the spatial domain can be thus defined as

$$\xi = \frac{\Delta n_{y/y} L}{\lambda_0^2}.$$  (10)

Firstly, we examined the transmission spectrum of an in-line MZI made by the 12.3 cm-long HB-ATCPCF using the same experimental setup as described in [12]. The light launched from the lead-in SMF splits into two birefringent cores of the fiber and they experience different optical paths due to associated modal index difference between the cores, and finally they recombine and make interference at the lead-out SMF. The polarization state was controlled by a PC at the lead-in SMF. Figure 3 shows the transmission spectra of the MZI with different input polarization states. It was found that the interference patterns have strong polarization dependence. The fringe spacing for the x-polarization was larger than that for the y-polarization, and also the fringe contrast (~8 dB) for the x-polarization was slightly larger than that (~6 dB) for the y-polarization. The different interference characteristics along with the different polarization states are caused by the associated high birefringences properties of the asymmetric cores. From the measured fringe spacing ($S$) of ~3.27 and ~1.74 nm for the x- and y-polarizations at $\lambda_0$ ~1550 nm, the modal group index differences between the cores were obtained to be $-5.97 \times 10^{-3}$ and $-1.13 \times 10^{-2}$, respectively, using the relation, $S = \xi^{-1} = \lambda_0^2 / (\Delta n_{y/y})$, from Eq. (10). The large group index difference observed in the HB-ATCPCF is at least one order magnitude higher than those of the twin-core fibers previously reported in [13, 14], and this would be an advantageous property for reduction of the device size in sensing applications.
Fig. 3. Transmission spectra of the in-line Mach-Zehnder interferometer made by 12.3 cm-long HB-ATCPCF with the different input polarization states; (a) for x-polarization and (b) for y-polarization.

Fig. 4. (a) Transmission spectrum of the SLHI made by the 12.3 cm-long HB-ATCPCF in the wavelength domain, and (b) its corresponding FFT spectrum in the spatial frequency domain. The FFT spectra obtained from the transmission spectra of the MZI shown in Fig. 3 were also plotted as references.

Figure 4(a) shows the characteristic transmission spectrum of the all-fiber SLHI made by the 12.3 cm-long HB-ATCPCF. The interference pattern looks very complicated. The transmission spectrum is a combination of high frequency modulations superimposed with low frequency envelopes that result from the multiple intra-core and inter-core mode interferences taking place together in the hybrid interferometer. In order to understand the transmission characteristics of the hybrid interferometer, the interference patterns were examined by the demodulation method based on the fast Fourier transform (FFT), and the results are shown in Fig. 4(b).

In the FFT spectrum of the SLHI, six spatial frequency peaks are clearly found at 0.0235, 0.2471, 0.3059, 0.5350, and 0.5765 nm⁻¹, and designated by P1 to P6, respectively. Using Eq. (10), the group index differences at the wavelength of 1550 nm are estimated to be $4.59 \times 10^{-4}$, $4.83 \times 10^{-3}$, $5.98 \times 10^{-3}$, $6.43 \times 10^{-3}$, $1.08 \times 10^{-2}$, and $1.13 \times 10^{-2}$ for the spatial peaks, respectively. Two lowest spatial peaks, P1 ($0.0235$ nm⁻¹) and P2 ($0.2471$ nm⁻¹), are from the Sagnac interferences of core 1 with the group birefringence of $B_1 = 4.59 \times 10^{-4}$, and core 2 with the group birefringence of $B_2 = 4.83 \times 10^{-3}$, respectively, and the other higher spatial peaks, P3 to P6, come from the Mach-Zehnder interferences between the inter-core modes of the two birefringent cores. The spatial peak P3 at 0.3059 nm⁻¹ is induced by the beating between the polarization modes along with the fast axis of core 2 and the slow axis of core 1, and thus the group index difference for the peak is $\alpha = 5.98 \times 10^{-3}$. It is noted that the position of P4 at 0.3294 nm⁻¹ is well matched with the combination of P3 + P1 = 0.3059 +
0.0235 \times 0.3294 \text{ nm}^{-1} \text{ with group index difference of } \alpha + B_1 = 6.43 \times 10^{-3}. \text{ The other peaks from Mach-Zehnder interferences are also matched with the combination values, } P_3 + P_2 = 0.3059 + 0.2471 = 0.5530 \text{ nm}^{-1} \text{ for } P_5 \text{ with } \alpha + B_2 = 1.08 \times 10^{-2}, \text{ and } P_3 + P_1 + P_2 = 0.3059 + 0.0235 + 0.2471 = 0.5765 \text{ nm}^{-1} \text{ for } P_6 \text{ with } \alpha + B_1 + B_2 = 1.13 \times 10^{-2}. \text{ The observations are in agreement with the theoretical expectation from Eq. (8), i.e. the positions of the spatial peaks from Mach-Zehnder interferences are determined by the combination of the birefringence properties of the two cores and } \alpha . \text{ As shown in the figure, it is also observed that the positions of the spatial frequencies of the in-line MZI along with the x- and y-polarizations from Fig. 3 exactly match to those of } P_3 \text{ and } P_6 \text{ of the SLHI, respectively. Because the corresponding inter-core modal index contrasts for the peaks } P_3 \text{ and } P_6 \text{ are } \alpha = n_{1}^{e} - n_{1}^{o} \text{ and } \alpha + B_1 + B_2 = n_{1}^{e} - n_{1}^{o} , \text{ the fringe patterns in the transmission of the in-line MZI are formed by the core modes propagating along with the alternative birefringence axes for the fixed polarization state, and this validates our assumption that the axes of two cores in the HB-ATCPCF are nearly orthogonal.}

The existence of multiple spatial peaks in the hybrid interferometer is another advantageous property, and this is discriminated from those of previously reported fiber loop interferometer made by the twin core fiber with nearly symmetric structure [16]. In the case of symmetric core structure with a small birefringence ( \( B_1 = B_2 \approx 5 \times 10^{-3} \) ), the number of spatial peaks was limited to only one and this was from the Mach-Zehnder interference by the index difference between two cores. In the SLHI with the highly birefringent and asymmetric core structure in this study, on the other hand, six spatial peaks are made and their sensing responses can be used for multi-parameter sensor applications.

### 4.2 Multi-parameter sensing characteristics of the HB-ATCPCF based SLHI

In order to characterize the sensing responses of the SLHI on the external variations such as torsion (\( \tau \)), strain (\( \varepsilon \)), and temperature (\( T \)), the changes in the phase spectra for the three selected spatial peaks of \( P_1, P_2, \) and \( P_6 \), corresponding to the Sagnac interferences of core 1 and 2 and the highest-order Mach-Zehnder interference between the cores, were investigated using the FFT analysis [2]. By applying FFT on the measured transmission spectra, the phase shift of each interference in the multiplexed spectra can be extracted from the location of the spatial peak in the frequency domain. From Eq. (9) and Eq. (10), the phase shift for a specific spatial peak can be written as

\[
\varDelta \Phi_{ij} = -2 \pi \frac{\delta \xi_{ij} \delta \lambda}{\delta \lambda}
\]

where \( \delta \lambda = \left( \frac{\delta (\Delta n_{ij})}{\Delta n_{ij}} \frac{\delta L}{L} \right) \lambda \) is the associated wavelength shift for the \( l \)-order (\( l \) is an integer) sensing peak of an interference spectrum in the wavelength domain [2]. It is noted that the positive phase shift in the spatial domain corresponds to the negative shift of the interference spectrum in the wavelength domain and vice versa.

Figure 5(a) shows response of the interference fringe to the torsion in the wavelength domain. The torsion was applied in the counter clockwise direction with the angle ranging from 150° to 210°. The enlarged view of the fringe spectra given in the inset represents the fringe change in the wavelength region of 1540 to 1548 nm. The variation of the fringe with the applied torsion looks very complicated since the multiple interferences are involved in the fringe spectra, though the variation of the fringe position and envelope reflects effect of torsion. Figure 5(b) shows the corresponding phases in the spatial frequency domain. For the Sagnac interferences, the phase of \( P_1 \) gradually increased from 1.52 to 1.93 radians, while the phase of \( P_2 \) slightly decreased from 1.72 to 1.44 radians with the torsion increasing from 150° to 210°. In the case of \( P_6 \) from the Mach-Zehnder interference, the phase change was positive from \(-3.03 \) to \(-1.62 \) radians and much larger than that of \( P_1 \) for the given torsion range.
The phase shifts of the spatial peaks, P1, P2, and P6, with the torsion in the broad measurement range of −150 to 320° are described in Fig. 6(a). It was found that, with the increasing torsion angle, the phase of P1 continuously increased, whereas the phase for the P2 continuously decreased. Interestingly, the periodic step-like phase shifts were found at the torsion angles near −100, 100, and 300°. This periodic quasi-discontinuity property can be explained by the singularity characteristic of the torsion induced retardation observed in high birefringent fibers. It is known that the retardation linearly changes with the torsion. However, singularity periodically happens at the torsion angles given by the products of the twisting rate and the length of the birefringence fiber, $\gamma(2q+1)\pi/B_\gamma$ [21], where $\gamma$ is the twisting rate and $q$ is an integer. It is also noted that the directions of the shifts for P1 and P2 are opposite to each other in the whole applied torsion range. This characteristic might be originated from the structural asymmetry between the birefringent cores, which will result in the discrepancy in the phase shift properties. The stress is induced in the core region by the applied torsion. Since the axes of the cores were almost orthogonally aligned with each other, the stress imposed on the slow axis of core 1 will be applied to the fast axis of core 2 at the same time. Therefore, the signs of the retardation would be opposite in the cores even though the torsion-induced stress was applied in a common direction, and finally this gives the opposite phase shift response. In the peak P6, a sinusoidal phase shift with a periodicity of ~360° was observed in overall range of the torsion with the exception of drastic fluctuations found at the corresponding singularity points.

The absolute phase-shift sensitivities to torsion are investigated in the ranges of −40 to 40° (zone-I) and 140 to 220° (zone-II) showing the linear responses and the results are shown in
Fig. 6(b). The sensitivities of P1 and P2 were measured to be $5.87 \times 10^{-3}$ rad/° (R² ~0.955) and $-1.73 \times 10^{-3}$ rad/° (R² ~0.90) respectively in the zone-I. In the zone-II, the corresponding sensitivities were $7.88 \times 10^{-3}$ rad/° (R² ~0.941) and $-4.12 \times 10^{-3}$ rad/° (R² ~0.982), respectively. The sensitivities of the peak P6 in zone-I and zone-II were measured to be $-1.77 \times 10^{-2}$ rad/° (R² ~0.993) and $2.14 \times 10^{-2}$ rad/° (R² ~0.985), respectively. The regression coefficients (R²) nearly equal to 1 from the fittings indicate the phase shifts exhibit very linear response.

Figure 7(a) shows the transmission spectra of the SLHI subjected to the axial strains of 0 με, 353 με, and 706 με, and the phase shifts of the three spatial peaks by the applied axial strain are given in Fig. 7(b). The result shows that the phase shift response to the axial strain is very linear in the strain range up to ~3000 με. In comparison with the case of torsion, the variation of the intensity envelope in the fringe spectra was negligible. The sensitivities for the Sagnac interference peaks of P1 and P2 were measured to be $5.47 \times 10^{-5}$ rad/με (R² ~0.981) and $-1.91 \times 10^{-4}$ rad/με (R² ~0.992), respectively. In a similar manner to the case of torsion, the opposite phase shift response to strain can be explained by the structural asymmetry between the cores. Stretching the fiber would decrease the fiber diameter as well as increase the fiber length. This will induce stress in the core region, and the stress develops retardation through the photoelastic effect of the core material [9]. The axes of the cores are aligned with the relative angle near to the orthogonal, thus an opposite retardation would be induced by the strain-induced stress. Consequently, it will result in different directions of the phase shifts. In the P6, the phase shift sensitivity was the positive $2.15 \times 10^{-3}$ rad/με (R² ~0.998) which implies the negative wavelength shift in the wavelength domain. Similar negative wavelength shift property was founded in the MZIs made by other twin-core fibers [12, 16].

Fig. 8. (a) Transmission spectra of the SLHI under different applied temperatures, and (b) phase shifts of the spatial peaks, P1, P2, and P6, with the temperature in the range of 25 to 145 °C.
Figure 8(a) shows the transmission spectra of the SLHI under the different temperatures of 25, 50, and 75 °C, and the phase shifts of the spatial peaks with the temperature in the range of 25-145 °C are shown in Fig. 8(b). Interestingly, the opposite phase shift response to temperature was also observed in the Sagnac interference peaks. The temperature sensitivities of P1 and P2 were $5.58 \times 10^{-4}$ rad/°C ($R^2 \sim 0.81$) and $-9.26 \times 10^{-4}$ rad/°C ($R^2 \sim 0.954$), respectively. In comparison with the conventional SLIs, the relatively low temperature sensitivity of the SLHI is explained by the thermal expansion property of the HB-ATCPCF. Since silica was commonly used for the core and cladding materials, it does not exhibit differential thermal expansion property and this gives the low sensitivity [8, 9]. For the opposite phase shift response, we carefully guess that this results from the asymmetry in the temperature induced stress-optic effect. The elevation of the temperature will induce stress in the core region by thermal expansion property of the fiber material. Like the strain, the temperature induced stress will result in the discrepancy in the direction and magnitude of the phase shift because of the structural asymmetry in the birefringent cores. On the other hand, the temperature sensitivity of P6 was much larger to be $-2.67 \times 10^{-2}$ rad/°C ($R^2 \sim 0.989$).

Compared with the sensitivities of the Sagnac interferences, the large temperature sensitivity of the MZI might be attributed to the large group index contrast between the cores originated from the asymmetry in core size and shape, and this would increase with the increase of the temperature by the thermo-optic and thermal expansion properties of the core material, leading to positive wavelength shift sensitivity in the wavelength domain.

The opposite phase shift response to torsion, strain, and temperature observed in the Sagnac interference peaks is another advantage in the simultaneous measurement scheme, and this is originated from the orthogonal orientation in the axes of two cores. According to the transfer matrix for the HB-ATCPCF as given in Eq. (6), the phases of the Sagnac interferences for core 1 and 2 will have the same sign if the birefringent axes of the cores are parallel ($\beta_1 = \beta_2 \sim 0$). On the other hand, the signs would be opposite when they are orthogonal ($\beta_1 \sim \pi/2$ and $\beta_2 \sim 0$) as for the case of the present study. Therefore, during the SLHI subjected to the external variations, the phases for the Sagnac interferences of core 1 and 2 were found to shift in the opposite directions and this would help in resolving the cross-sensitivity problems and improving the sensor performance during the measurement of different external parameters [22].

From the measured phase shift sensitivities of the three spatial peaks P1, P2 and P6, simultaneous sensing characteristic of the SLHI for the multi-parameters of torsion, strain and temperature are investigated using the matrix method [1, 2]. The phase shift of the system for the $q^{th}$ order frequency peak in the spatial domain is given by the sum of the individual responses to the multiple parameters in the form,

$$\Delta \Phi_q = \frac{\partial \Phi}{\partial \tau} \Delta \tau + \frac{\partial \Phi}{\partial \varepsilon} \Delta \varepsilon + \frac{\partial \Phi}{\partial T} \Delta T; \quad q=1, 2, \text{ and } 6. \quad (12)$$

where $\Delta \tau$, $\Delta \varepsilon$ and $\Delta T$ are the variations in torsion, strain and temperature, respectively, and the matrix form is given as,

$$\begin{pmatrix}
\Delta \Phi_1 \\
\Delta \Phi_2 \\
\Delta \Phi_6
\end{pmatrix} = \begin{bmatrix}
5.87 \times 10^{-3} & 5.47 \times 10^{-4} & 5.58 \times 10^{-4} \\
-1.73 \times 10^{-3} & -1.91 \times 10^{-4} & -9.26 \times 10^{-4} \\
-1.77 \times 10^{-2} & 2.15 \times 10^{-3} & -2.67 \times 10^{-2}
\end{bmatrix} \begin{bmatrix}
\Delta \tau \\
\Delta \varepsilon \\
\Delta T
\end{bmatrix} \quad (\text{zone-I}). \quad (13)$$

Consequently, multi-parameters of torsion, strain, and temperature can be determined from the phase shifts observed in the spatial frequency domain using the inverted matrix form. From the coefficient matrix and the spectral resolution (10 pm) of the OSA as an example, the sensing resolutions for torsion, strain, and temperature in the zone-I (II) are estimated to be $1.49 \ (1.17)$ °, $68.98 \ (82.9)$ με, and $7.18 \ (6.46)$ °C, respectively. In addition, we investigated the sensing performance of the SLHI for simultaneous measurement of two parameters of...
torsion and strain using the Sagnac interference peaks of P1 and P2. In the investigation, torsion was varied under a constant strain of 353 με and strain was varied under a fixed torsion of 0° at room temperature, respectively, and the results are shown in Fig. 9. The solid lines indicate the applied values that should be matched for the ideal sensor performance. The rms deviations between the measured and the applied values are obtained to be ± 11° for torsion and ± 201 με for strain limited by the resolution of OSA (0.1 nm) and measurement accuracies of the devices such as translation and rotational stages. The sensing resolution and accuracy of the present sensor system could be further improved by optimization in the design of fiber structure and material of the HB-ATCPCF. Furthermore, the proposed system has shown the possibility for application in simultaneous measurement of more than three parameters since the system exhibited six clearly-divided spatial peaks.

![Fig. 9. Sensing performance of the SLHI for simultaneous measurement of two parameters of torsion and strain using the Sagnac interference peaks of P1 and P2.](image)

5. Conclusion

An all-fiber Sagnac loop hybrid interferometer based on a newly designed highly-birefringent PCF with two asymmetric cores was demonstrated for application in simultaneous multiple-parameter sensing devices. The demodulation method based on the fast Fourier transform analysis was used to investigate the optical characteristics of the sensing system. It was found that the interferometer exhibited six clear peaks in spatial frequency domain and they were resulted from the two types of in-fiber interferences: the intra-core mode Sagnac interference and the inter-core mode Mach-Zehnder interference. The phase shift responses of the three spatial peaks were investigated and the coefficient matrix of the sensing system could be obtained for simultaneous measurement of torsion, strain, and temperature. The proposed all-fiber SLHI has shown several advantageous properties such as simplicity in the device structure, compact device size and the possibility for simultaneous sensing applications for more than three parameters of interest.

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