<table>
<thead>
<tr>
<th><strong>Title</strong></th>
<th>Control and design of fiber birefringence characteristics based on selective-filled hybrid photonic crystal fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author(s)</strong></td>
<td>Han, Tingting; Liu, Yan-ge; Wang, Zhi; Guo, Junqi; Wu, Zhifang; Luo, Mingming; Li, Shuo; Wang, Jing; Wang, Wei</td>
</tr>
<tr>
<td><strong>Citation</strong></td>
<td>Han, T., Liu, Y.-g., Wang, Z., Guo, J., Wu, Z., Luo, M., et al. (2014). Control and design of fiber birefringence characteristics based on selective-filled hybrid photonic crystal fibers. Optics Express, 22(12), 15002-..</td>
</tr>
<tr>
<td><strong>Date</strong></td>
<td>2014</td>
</tr>
<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10220/20273">http://hdl.handle.net/10220/20273</a></td>
</tr>
<tr>
<td><strong>Rights</strong></td>
<td>© 2014 Optical Society of America. This paper was published in Optics Express and is made available as an electronic reprint (preprint) with permission of Optical Society of America. The paper can be found at the following official DOI: <a href="http://dx.doi.org/10.1364/OE.22.015002">http://dx.doi.org/10.1364/OE.22.015002</a>. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.</td>
</tr>
</tbody>
</table>
Control and design of fiber birefringence characteristics based on selective-filled hybrid photonic crystal fibers

Tingting Han,1 Yan-ge Liu,2,* Zhi Wang,2 Junqi Guo,2 Zhifang Wu,3,4 Mingming Luo,2 Shuo Li,2 Jing Wang,2 and Wei Wang1

1College of Electronic and Communication Engineering, Tianjin Normal University, Tianjin, 300387, China
2Key laboratory of Optical Information Science and Technology, Ministry of Education, Institute of Modern Optics, Nankai University, China
3School of Electrical and Electronics Engineering, Nanyang Technological University, Singapore
4CINTRA CNRS/NTU/THALES, UMI 3288, Research Techno Plaza, 50 Nanyang Drive, Singapore

*ygliu@nankai.edu.cn

Abstract: We demonstrated a kind of birefringence-controllable hybrid photonic crystal fibers (HPCFs) by selectively infiltrating air holes of PCFs with index-tunable liquids processing higher index than silica background. Detailed theoretical investigations on mode couplings from fundamental core mode to high-index-liquid-rod modes and birefringence properties of several HPCFs were presented. Strong wavelength dependence of phase and group birefringence was found, and HPCFs with different arrangements of high index liquid rods possess distinct birefringence characteristics. Then, the Sagnac interferometers (SIs) based on two typical HPCFs with different liquid-rod arrangements were theoretically and experimentally studied. The results indicated the SIs exhibit different transmission spectra and temperature responses due to the distinct birefringence features of HPCFs. A temperature sensitivity of $-45.8 \text{ nm/}^\circ\text{C}$ at $56.5 \ ^\circ\text{C}$ was achieved using one HPCF, and a sensitivity of $-11.6 \text{ nm/}^\circ\text{C}$ from $65 \ ^\circ\text{C}$ to $85 \ ^\circ\text{C}$ was achieved using the other HPCF. The thermal tunable HPCFs with birefringence-controllable properties will provide great potential for a variety of tunable optical devices and sensors.

©2014 Optical Society of America

OCIS codes: (060.5295) Photonic crystal fibers; (060.2420) Fibers, polarization-maintaining; (060.2370) Fiber optics sensors.

References and links

Photonic crystal fibers (PCFs) [1,2] are a class of optical fibers constituting wavelength-scale microstructure running along fiber length. They possess a number of novel properties and significant applications owing to novel guiding mechanisms and flexible design. Among the properties, there have been more interests to explore birefringence property. By use of an asymmetric cladding or core structures in PCFs, high-birefringent (Hi-Bi) PCFs can be implemented. Due to the polarization characteristics, Hi-Bi PCFs were widely used as in-fiber polarizing devices in optical fiber communication, and the Hi-Bi PCFs based Sagnac interferometers (SIs), as a kind of interferometer devices, also played an important role in fiber sensing for measuring temperature, strain, refractive index and so on. High performance Hi-Bi PCFs with unique birefringence characteristics need to be produced and developed. Generally, in index-guiding Hi-Bi PCFs [3,4], the dependence of birefringence on wavelengths is linear. While, Hi-Bi photonic bandgap fibers (PBGFs) exhibit extraordinary and various birefringence features due to the influence of bandgap effects and different fiber structures [5–7]. For example, both the phase and group birefringence have higher absolute value at two edges of bandgaps in a non-circle hollow-core Hi-Bi PBGF investigated by Alam et al in 2005 [5] and in a highly birefringent all-solid PBGF with elliptical cladding rods studied by Yu et al [6]. But, in another birefringent solid-core PBGF assisted by interstitial air holes reported by Pureur et al [7], the group birefringence has lower value at the edge of the bandgap. In addition, in 2006, Cerqueira presented a hybrid PCF in which a guided mode is confined simultaneously by modified total internal reflection from an array of air holes and antiresonant reflection from a line of high-index inclusions [8]. Based on the hybrid guiding mechanisms and asymmetric fiber structures, hybrid PCFs [8–11] share properties of both index-guided and photonic bandgap structures, and have potential to be a high birefringence fiber with novel birefringence properties. For two kinds of hybrid PCFs with different high
index inclusions proposed in [9], the phase birefringence increases with the increase of wavelength, and increases at the short wavelength edge of the bandgap. An all-solid Hi-Bi PCF with two stress applying lower index rods [11] has phase birefringence with lower absolute values and group birefringence with higher absolute values at both edges of a bandgap. The birefringence of the Hi-Bi PCFs above mentioned is induced through the fiber fabrication process. In addition, the air-hole structures of PCFs provide new opportunities to achieve novel birefringent PCFs by filling certain air holes with functional materials, such as liquid and metal. In 2008, Tyagi et al [12] rendered fiber birefringence by pumping pure molten Ge at high pressure into one air channel of silica-air PCFs and achieved strongly polarization-dependent transmission losses with extinction ratios as high as 30 dB in the visible range. Based on the index-tunable properties of the liquid, birefringence tunable Hi-Bi PCFs were developed [13–17] and widely used in SIs for high sensitive sensors. In 2002, Kerbage et al first achieved birefringence-tunable index-guiding Hi-Bi microstructured fiber (MOF) by infiltrating polymer into selected air holes of a grapefruit MOF [13,14]. Based on the reports in [4,13–18], there are several ways to realize the filling Hi-Bi PCFs. One way is by fully filling or selectively filling air holes of original index-guiding HiBi-PCFs with functional materials, thus improving PCF’s functionality [4,15]. In 2011, Qian et al [4] infiltrated alcohol into an index-guiding Hi-Bi PCF and achieved another index-guiding Hi-Bi PCF based SI with a high temperature sensitivity of 6.6 nm/°C [18]. In 2012, Zheng et al [15] selectively infiltrated a high index liquid into the same index-guiding Hi-Bi PCF as the work in [4] and achieved a bandgap-guiding Hi-Bi PCF based SI with a high temperature sensitivity of 0.4 nm/°C which is 100 times higher than the sensitivity of 3.97 pm/°C in a hollow-core PBGF [19]. Furthermore, due to different guiding mechanisms of the two achieved Hi-Bi PCF in [4] and [15], the two SIs appeared distinct transmission spectra and temperature response. Another way is by fully filling or selectively filling anisotropic materials into PCFs including index-guiding [16,17] and bandgap-guiding PCFs. In 2007, Wolinski et al [16] presented tunable Hi-Bi PBGFs by selectively infiltrating liquid crystals into an index-guiding Hi-Bi PCF and full infiltrating liquid crystals into an index-guiding PCF. In 2008, Du et al [17] demonstrated an electrically tunable Sagnac filter based on a PBGF that was realized by infusing liquid crystal into all air holes of a solid-core index-guiding PCF. The last way is by selectively filling air holes of the non-birefringent PCFs with functional materials, and the asymmetry is introduced. The Hi-Bi PCFs in [13,14] were achieved by this way. In terms of the above mentioned Hi-Bi PCFs, the interference dips of their SIs all presented same variation tendency with the environment factors changing due to the monotonous linear dependence of birefringence on wavelengths, except for the Hi-Bi PCF in [15]. But, the Hi-Bi PCF in [15] have lower sensitivity. Recently, based on the third way above mentioned, we proposed a Hi-Bi PCF [20] by selectively infusing a high index liquid into two adjacent air holes near the core of an index-guiding PCF. The Hi-Bi PCF possesses birefringence nonlinear change with wavelength. What is more, the modal group birefringence has a zero value at a certain wavelength and an ultra-high sensitivities of 26.0 nm/°C (63,882 nm/RIU) at 50.0 °C was experimentally achieved. For this kind of PCFs having several air holes filled with high index liquids [21–23], the fundamental core mode can couple with high-index-liquid-rod modes. The arrangements of high index rods influence the mode couplings, and further decide fiber birefringence characteristics. How to control and design fiber birefringence by selective-infusion method is the emphasis of this paper. In this paper, we demonstrated several types of birefringent hybrid PCFs (HPCFs), which were implemented by filling different selected air holes of an index-guiding silica PCF with thermal tunable liquid having higher index than silica background. The introduction of high-index rods causes mode couplings between fundamental core mode and high-index-rod modes. The detailed mode couplings and their resulting various birefringence properties of the HPCFs with different liquid-rods arrangements were investigated theoretically. Then, the transmission spectra and temperature responses of two proposed HPCFs based SIs were studied theoretically and experimentally. Due to distinct birefringence features of the two
HPCFs, the two SIs presented different transmission spectra and temperature responses. A sensitivity of $-45.8 \text{ nm/°C}$ at $56.5 \text{ °C}$ was achieved using one HPCF, and a sensitivity of $-11.6 \text{ nm/°C}$ from $65 \text{ °C}$ to $85 \text{ °C}$ was achieved using the other HPCF.

2. Theoretical analysis of birefringence characteristics of several types of HPCFs

The cross-section of the PCF used in our paper, which was fabricated by Yangtze Optical Fiber and Cable Corporation Ltd. of China, is shown in Fig. 1(a). This pure silica PCF includes five rings of air holes arranged in a regular hexagonal pattern. The effective index of silica background is 1.444 at 1.550 $\mu m$. The diameters of the air holes, the adjacent holes distance, and the diameter of the core are 3.7 $\mu m$, 5.8 $\mu m$, and 7.9 $\mu m$, respectively. The achieved HPCFs were achieved by infusing an index-tunable liquid into selected air holes of fiber cladding. The isotropic liquid produced by Cargille Laboratories Inc. possesses a refractive index of 1.52 (@ 0.5893 $\mu m$ and @ 25 °C) and a thermal coefficient of $-0.000407/\text{°C}$. Due to the introduction of high index rods, the HPCFs can confine light by both total internal reflection from air holes and antiresonant reflection from high index rods which is central to the photonic bandgap effect in PBGFs. Large birefringence and novel birefringence features for the HPCFs are expected. We fully discussed the birefringence features of several types of HPCFs with various filling structures in theory.

For a birefringent fiber, phase birefringence $B$ and group birefringence $B_g$ are two major factors characterizing birefringence, which can be expressed as follows:

$$B = n_x - n_y, \quad B_g = B - \lambda \frac{dB}{d\lambda},$$  \hspace{1cm} (1)

Where, $n_x$ and $n_y$ are the effective indices of the $x$-polarized and $y$-polarized fundamental core modes, and $x$-polarization and $y$-polarization directions are shown in Fig. 1.

Fig. 1. (a) Cross-section of the PCF used in this paper; (b)-(d) Theoretical models for simulation, where the white holes are air holes and the black holes are infiltrated with high index liquids, and they are called HPCF1, HPCF2, HPCF3 in turn.

Firstly, we studied the HPCF with only one air hole adjacent to fiber core filled, called HPCF1, and its theoretical simulation model was shown in Fig. 1(b). The white holes are air holes, and the black hole is the index tunable liquid. Then, utilizing finite-element method [24] by Comsol Multiphysics 3.4 software and considering material dispersion of the silica and liquid, the fundamental core mode and high-index-rod modes were analyzed in detail. Figure 2(a) represents the effective refractive indices of fundamental core mode and high-index-rod modes at $x$-(black solid curves) and $y$-polarizations (red dashed curves), respectively. The inset shows the fundamental core mode intensity distribution at the wavelength of 1.700 $\mu m$, which is well confined in the core. While, at wavelength ranges from 1.270 $\mu m$ to 1.450 $\mu m$ and from 2.500 $\mu m$ to 2.900 $\mu m$, the mode energy in fiber core couples to the high index liquid rod. In practice, silica is hardly transparent at wavelength range longer than 2 $\mu m$. But, according to the antiresonant reflection [25] of high index rods, the antiresonant wavelength ranges shift to short wavelength with liquid index decreasing. Meanwhile, the birefringence feature curves also shift to the short wavelength, and possess similar variation tendency. Hence, in practice, we can tune the wavelength range over which silica has lower loss by choosing proper liquid. Figure 2(b) shows the mode intensity distributions of $x$- (upper) and $y$-polarized (below) modes at points of A, B, C, D, E and F,
respectively. It is clearly seen that fundamental core mode couples with higher order mode LP_{21}-like in the high index rod at points A and B, with LP_{02}-like mode at C and D and with LP_{11}-like mode at E and F points, respectively.

According to Eq. (1), using the dispersion curve 1 in Fig. 2(a), the modal phase birefringence $B$ and group birefringence $B_g$ of HPCF1 were further calculated, as shown in Fig. 3. The $B$ exhibits some unique features: 1) non-monotone variation with wavelength; 2) a decrement near both edges, i.e. mode coupling areas; 3) a zero value at a longer wavelength of 2.160 $\mu$m. Among the features, the decrement of $B$ at both edges can be explained using the features of dispersion curves for fundamental mode and high-index-rod mode at coupling areas. At short wavelength coupling region, the fundamental mode at one polarization with lower mode effective index will first couple with high-index-rod mode, thus lifting its mode effective index. This finally results in the decrement of birefringence near the short wavelength coupling region. At long wavelength coupling region, the fundamental mode at one polarization with higher mode effective index will first couple with high-index-rod mode, thus lowering its mode effective index. This similarly results in the decrement of birefringence near the long wavelength coupling region. The zero value of $B$ results from co-effects between antiresonant reflection effect and total internal reflection effect of the HPCF. The $B_g$ is deduced by $B$. It has two zero values at wavelengths of 1.490 $\mu$m and 2.490 $\mu$m, respectively, near two edges, positive values at wavelength range from 1.490 $\mu$m to 2.490 $\mu$m and negative values at wavelength ranges from 1.400 $\mu$m to 1.490 $\mu$m and from 2.490 $\mu$m to 2.600 $\mu$m. These birefringence features are very different from that of index-guiding Hi-Bi PCFs [3,4] and Hi-Bi PBGF [5–7], which are mainly because of the introduction of high index rod.

![Fig. 2. (a) The effective refractive indices of core fundamental mode and high index rod modes at x-(black solid curves) and y-polarized modes (red dashed curves) for HPCF1. The inset shows the core fundamental mode intensity distribution at wavelength of 1.700 $\mu$m. (b) The mode intensity distributions of x-(upper) and y-polarized modes (below) at points of A, B, C, D, E and F, respectively.](image)
Fig. 3. Variation of modal phase birefringence $B$ (black curves) and group birefringence $B_g$ (red curves) of HPCF1 versus wavelength. Black dashed line represents zero $B$, and red dashed line represents zero $B_g$.

Secondly, we analyzed another HPCF with two air holes located at first and second layer filled, called HPCF2, as shown in Fig. 1(c). Similarly, the mode dispersion curves were simulated. Figure 4(a) presents the effective refractive indices of fundamental core mode with wavelength at $x$-(black solid curves) and $y$-polarizations (red dashed curves), respectively. Compared with that of HPCF1 in Fig. 2(a), there exist four coupling areas from 1.250 $\mu$m to 1.450 $\mu$m and two coupling areas from 2.400 $\mu$m to 3.000 $\mu$m. This is because the two filled high index rods can be seen as a twin-core waveguide in which each mode has two eigen-modes: odd mode and even mode. And the four coupling regions at shorter wavelengths come from couplings between fundamental core mode and high index rod modes $LP_{21}$-like even mode, $LP_{21}$-like odd mode, $LP_{02}$-like even mode and $LP_{02}$-like odd mode, respectively. The two couplings areas at longer wavelengths come from couplings between fundamental core mode and $LP_{11}$-like even mode and $LP_{11}$-like odd mode, respectively. Using the dispersion curve 1 in Fig. 4(a), the variation of $B$ (black curve) and $B_g$ (red curve) versus wavelength of HPCF2 were calculated as shown in Fig. 4(b). The $B$ also has decrements at both edges and a zero value at a wavelength of 2.090 $\mu$m. The $B_g$ has positive values at wavelength range from 1.450 $\mu$m to 2.300 $\mu$m, and has higher value at longer wavelength edge than that at shorter wavelength edge.

Thirdly, we analyzed the filling structure as shown in Fig. 1(d), called HPCF3. With the number of filled holes increasing, the number of high index rods modes also increases. According the mode coupling theory as shown in Ref [26], $N$ high index-rod waveguides form $N$ different modes and has $N$ dispersion curves of the high-index-rod modes. Hence, in HPCF3, there are totally 10 dispersion curves for $LP_{21}$-like mode and $LP_{02}$-like mode. We didn’t study the complex mode couplings of HPCF3 in detail and only calculated the effective refractive index of fundamental core mode at $x$-polarization, as shown in Fig. 5 (black curves). For clear comparison with HPCF1 and HPCF2 above studied, the wavelength range is broken into two parts as shown in (a) and (b). The blue and red curves represent the...
effective refractive indices of fundamental core mode of HPCF1 and HPCF2, respectively. It can be clearly seen that with the number of filled rods increasing, the cut-off wavelength at short wavelength edge becomes longer, while, that at long wavelength edge becomes shorter. This, firstly, results in narrower wavelength range for the HPCF with more high index rods. Figure 6 shows the comparison of $B$ and $B_g$ of HPCF3 (black curves), HPCF2 (red curves), and HPCF1 (blue curves). With the number of filled rods increasing, the decrement of $B$ at both edges becomes smaller, even is zero (at short wavelength edge of HPCF3). This is because for different arrangements of high index rods, the high-index-rod waveguides develop different high-index-rod modes whose dispersion curves have diverse slopes. The slopes of dispersion curves for the coupled high-index-rod mode and fundamental core mode have impact on the coupling wavelength ranges. According to the features of dispersion curves for fundamental core mode and high-index-rod mode at coupling areas, at short wavelength region, if the coupled high-index-rod mode has steeper dispersion curve, the dispersion curve of fundamental mode near the coupling region is steeper, which results in the coupling wavelength region narrower. This further leads to the wavelength range in which the phase birefringence decreases narrower. For coupled high-index-rod mode with smaller slope dispersion curve, the situation is exactly opposite. Hence, from the coupling situations of HPCF1, HPCF2, HPCF3 as shown in Fig. 5(a) at short wavelength coupling region, the slopes of dispersion curves for the fundamental core modes are HPCF1 < HPCF2 < HPCF3. This results in the width of wavelength ranges where the phase birefringence decreases HPCF1 (from 1.400 μm to 1.500 μm) > HPCF2 (from 1.425 μm to 1.45 μm) > HPCF3 (no decrement), as shown in Fig. 5(b). And the same interpretation is for the variation of birefringence near long wavelength coupling region. In addition, the wavelength at which $B$ equals zero exhibits blue shift. The $B_g$ of HPCF1 has zero values, positive values and negative values, while, HPCF2 and HPCF3 both only have positive values at their low loss transmission wavelength ranges.

![Fig. 5. Effective refractive indices of core fundamental modes of HPCF3 (black curves), HPCF2 (red curves) and HPCF1 (blue curves) at x-polarization.](image1)

![Fig. 6. Comparison of $B$ (a) and $B_g$ (b) of HPCF3 (black curves), HPCF2 (red curves), and HPCF1 (blue curves).](image2)
Next, we studied another four kinds of HPCFs, called HPCF4, HPCF5, HPCF6, and HPCF7, as shown in Figs. 7(a)–7(d), respectively. Different from HPCF2, HPCF4 has two filled air holes located on either side of core. Figure 8(a) shows the effective indices of fundamental core mode and high-index-rod mode of HPCF4 versus wavelength at x- (black solid curves) and y-polarizations (red dashed curves). And we can see that at short wavelength edge there exist two couplings, and at long wavelength edge one coupling. This is because, for HPCFs, the fundamental core mode only can couple with the even mode of high index rods. This coupling situation is different from that of HPCF2 also with two air holes infiltrated. Then, using the dispersion curve 1 in Fig. 8(a), the variation of $B$ (black curves) and $B_g$ (red curves) with wavelength were calculated, as shown in Fig. 8(b). The $B$ also has a decrement at short wavelength range, and has zero value at 2.360 µm. With wavelength increasing, the $B$ increases from the negative values to positive values gradually, reaching the highest value at 2.260 µm, and then turns down. For comparing to HPCF1, we show the mode dispersion curves of fundamental core mode of HPCF1 and HPCF4 at x-polarization near short wavelength region in the inset of Fig. 8(a). The slope of the dispersion curve at coupling region (as the black circle shown) of HPCF4 is lower than that of HPCF1, according to the above explanation, the width of wavelength ranges where the phase birefringence decreases in HPCF4 (from 1.400 µm to 1.700 µm) is larger than that in HPCF1. In addition, the wavelength where $B_g$ equals zero is 1.590 µm, located nearer to the short wavelength edge.

![Simulation models of the other four kinds of HPCFs](image1)

**Fig. 7.** Simulation models of the other four kinds of HPCFs, called (a) HPCF4, (b) HPCF5, (c) HPCF6, and (d) HPCF7, where the white holes are air holes and the black holes are high index liquids.

![Effective indices of core fundamental mode and high-index-rod modes](image2)

**Fig. 8.** (a) Effective indices of core fundamental mode and high-index-rod modes of HPCF4 versus wavelength at x-(black solid curves) and y-polarizations (red dashed curves). The inset shows the comparison of mode dispersion curves between HPCF1 and HPCF4 at short wavelength region for x-polarization. (b) Variation of the phase birefringence $B$ (black curve) and group birefringence $B_g$ (red curve) of HPCF4 versus wavelength.

For HPCF5, HPCF6 and HPCF7, the mode couplings are more complex due to more high index rods. Here, we didn’t study the mode couplings in the three HPCFs in detail and directly gave the variation of birefringence with wavelength. Figure 9(a) shows the variation of phase birefringence $B$ with wavelength in HPCF5 (black curves), HPCF6 (red curves) and HPCF7 (blue curves). For HPCF6 and HPCF7, the effective index at x direction is smaller than that at y direction, which is different from HPCF5. For convenient comparison, the $B$ of HPCF6 and HPCF7 were taken as $n_y-n_x$. It can be clearly seen, firstly, the wavelength ranges...
where valid fundamental core modes exist are different based on different numbers of the filled rods. Then, the $B$ all have maximum values in the middle of the wavelength range and decrements at short wavelength edge. However, the reduced values are different. In addition, the $B$ of HPCF6 is positive at the wavelength range from 1.420 $\mu$m to 2.600 $\mu$m, while, the $B$ of HPCF5 and HPCF7 both have zero values at wavelengths of 2.100 $\mu$m and 2.120 $\mu$m, respectively. Figure 9(b) shows the variation of group birefringence $B_g$ of the three HPCFs. They have distinct wavelengths where $B_g$ equals to zero. And the $B_g$ of HPCF5 and HPCF7 are higher at long wavelength edge than that of HPCF6.

![Fig. 9. Variation of (a) the phase birefringence $B$ and (b) group birefringence $B_g$ with wavelength of HPCF5 (black curves), HPCF6 (red curves) and HPCF7 (blue curves).](image)

Taken all the HPCFs above studied together, we conclude that the existence of high index rods makes this type of HPCFs have specific birefringence characteristics different from index-guiding Hi-Bi PCF [3,4], the elliptical hollow core birefringent PBGF [5] and all-solid PBGF with elliptical cladding rods (the $B$ has smaller values in the middle and higher values at both edges) [6]. Furthermore, different arrangements of high index rods lead to distinct birefringence properties. For example, the $B$ either only have positive values for wavelength range from 1.420 $\mu$m to 2.600 $\mu$m (HPCF6) or process zero values, positive values and negative values at certain wavelength ranges which are different for various HPCFs (HPCF1-HPCF5, HPCF7). Due to the influence of mode couplings between high-index-rod mode and fundamental core mode, the $B$ exhibit decrements nearby the coupling wavelength ranges, and the reduced values relate to the position and number of high index rods. The diverse characteristics of $B$ directly lead to distinct group birefringence $B_g$ properties. The $B_g$ either only have positive values for HPCF3 and HPCF2, or have zero values, positive values and negative values at certain wavelength ranges which are different for HPCF1, HPCF4, HPCF5, HPCF6 and HPCF7. The SI is one important application based on Hi-Bi PCF, and the birefringence properties of Hi-Bi PCF directly influence the features of SIs. Based on the unique properties of the achieved HPCFs, the SIs may present specific features in transmission spectra and sensing. In turn, the birefringence features can be concluded by the characteristics of the SIs.

3. Theoretical analysis of temperature characteristics of two HPCFs based SIs

In this section, we chose two typical HPCFs: HPCF3 having positive values of $B_g$ at wavelength range from 1.470 $\mu$m to 2.170 $\mu$m; HPCF4 having a zero value of $B_g$ at wavelength of 1.580 $\mu$m, positive values at wavelength range from 1.580 $\mu$m to 1.600 $\mu$m and negative values at wavelength range from 1.400 $\mu$m to 1.580 $\mu$m, to theoretically studied the transmission and sensing characteristics of SIs.

Figure 10 illustrates the schematic diagram of the proposed HPCF based SI, which consists of a 3 dB optical coupler (OC) with a splitting ratio of ~50:50 at a wavelength range from 1.300 $\mu$m to 1.600 $\mu$m, a polarization controller (PC), and a section of HPCF. The light from a supercontinuum source (SCS) (0.600 $\mu$m-1.700 $\mu$m) propagates around the fiber loop,
and the transmission interference spectrum is measured by an optical spectral analyzer (OSA) with the highest resolution of 0.02 nm. The transmission $Tr$ can be expressed as the equation:

$$Tr(\lambda) = \frac{1 - \cos(\delta)}{2},$$  

(2)

where, $\delta = 2\pi LB/\lambda$ is the phase difference. The position of the interference dip $\lambda$ satisfies the phase-matched condition:

$$\frac{2\pi B(\lambda)L}{\lambda} = 2m\pi, \quad m = 0, \pm 1, \pm 2, \ldots,$$

(3)

where, $L$ is the filling length, $m$ is any integer. If applying temperature changes onto HPCFs, the interference dip wavelength $\lambda$, phase birefringence $B$ and filling length $L$ will be influenced by temperature. Taking the deviation with respect to temperature on both sides of Eq. (3), we obtained [15,19]:

$$\left[ L \frac{\partial B(\lambda, T)}{\partial T} + L \frac{\partial B(\lambda, T)}{\partial \lambda} \frac{d\lambda(T)}{dT} + B(\lambda, T) \frac{dL}{dT} \right] \lambda(T) - B(\lambda, T)L \frac{d\lambda}{dT} = 0,$$

(4)

The temperature related $d\lambda/dT$, i.e. temperature sensitivity $S$ is expressed by:

$$S(T) = \frac{d\lambda}{dT} = \frac{\partial B(\lambda, T)}{\partial T} \lambda(T) + B(\lambda, T) \alpha_{\lambda, T} \frac{dL}{dT} L \frac{d\lambda}{dT}.$$

(5)

Where, $\alpha = dL/LdT$ is the thermal expansion coefficient of the filled liquid, which is about $8 \times 10^{-4}$ °C$^{-1}$. Sensitivity $S$ is related to $\partial B(\lambda, T)/\partial T$, $B_{\lambda}(\lambda, T)$, and the position of interference dips $\lambda$. Then, we considered all these factors overall to obtain the temperature sensitivities of two SIs based on HPCF3 and HPCF4, respectively.

Fig. 10. Schematic diagram of the proposed HPCF based SI.

Firstly, we studied the temperature response of the HPCF3 based SI. According to the thermal coefficient of the infiltrated liquid, the temperature-dependent $B$ was calculated. Figure 11(a) shows the variation of $B$ versus wavelength at temperatures 25 °C (black curve) and 30 °C (red curve), respectively. With temperature increasing, the index of the filled liquid decreases, resulting in blue shift of transmission spectra. Meanwhile, the $B$ decreases with wavelength increasing. The variation of the factor $\partial B(\lambda, T)/\partial T$ dependence on wavelength at 25 °C was calculated as well, as shown in Fig. 11(b). We can see $\partial B(\lambda, T)/\partial T$ only has negative values from 1.470 μm to 2.470 μm, and also has higher absolute values at both...
edges. Combining with the characteristics of $B_g$ of HPCF3 (as shown in Fig. 6(b)), which only has positive values, the temperature sensitivity $S$ was obtained according to Eq. (5), as shown in Fig. 12. All the values of $S$ are negative, and the absolute values in middle wavelengths are larger than that in both edges. The $S$ ranges from $-6.8 \, \text{nm}^{\circ}\text{C}$ to $-11.4 \, \text{nm}^{\circ}\text{C}$.

Secondly, we studied the temperature response of the HPCF4 based SI. Similarly, the $B$ of HPCF4 at temperatures 25 °C and 30 °C were also calculated, as shown in Fig. 13(a). Different from HPCF3, with temperature increasing, the $B$ show different changing variation tendency. It increases at spectral range from 1.450 μm to 1.470 μm and decreases at wavelength range from 1.470 μm to 2.570 μm. Figure 13(b) further shows the variation of $\partial B(\lambda, T)/\partial T$ versus wavelength at 25 °C, which has negative values in the middle wavelengths, has positive values at both edges and process zero value at wavelengths of 1.480 μm and 2.520 μm. Combined with the $B_g$ of HPCF4 (as shown in Fig. 8(b)), the temperature sensitivity $S$ at 25 °C was calculated based on Eq. (5), as shown in Fig. 14. It is clearly seen, the $S$ has positive values, negative values and zero values at different wavelengths. Especially, due to the existence of zero value at 1.590 μm for $B_g$, as the denominator of Eq. (5), the $S$ has infinite values at 1.590 μm, as the vertical dashed line shown. Furthermore, near the vertical dashed line, the $S$ has higher values. Comparing with the HPCF3 based SI, the $S$ of HPCF4 based SI has higher values.

Thus, according to different birefringence properties of HPCFs, two SIs were obtained. One has negative temperature sensitivities when the HPCF has $B$ with monotonic variation and $B_g$ with positive values. The other one has positive, negative and zero temperature sensitivities when the HPCF has $B$ with non-monotonic variation and $B_g$ with positive, negative and zero values. The latter SI has very high temperature sensitivities due to the small values of $B_g$, especially the existence of zero value of $B_g$. 

Fig. 11. (a) Variations of $B$ at temperatures 25 °C (black curves) and 30 °C (red curves) for HPCF3, respectively. (b) Variation of $\partial B(\lambda, T)/\partial T$ at 25 °C dependence on wavelength for HPCF 3.

Fig. 12. Calculated temperature sensitivity $S$ versus wavelength of HPCF3 based SI at 25 °C.
4. Experimental measurement of transmission and sensing characteristics of two HPCFs based SIs

Based on the different birefringence characteristics of two typical HPCFs, two SIs with diverse spectra and temperature response were above theoretically achieved. In the experiments, we produced two typical HPCFs with birefringence similar to that of HPCF3 and HPCF4, and measured the transmission and sensing characteristics.

Firstly, we experimentally produced HPCF4 by the manual gluing method described in detail in [26], and a 25 cm length of HPCF4 was achieved with two ends spliced fusion to single mode fibers (SMFs). We measured the transmission spectrum of HPCF4, as shown in Fig. 15(a) (black curve). The resonant dip at 1.216 μm comes from the mode coupling between fundamental core mode and LP_{02}-like even mode, and in theory this coupling occurs at about 1.300 μm as shown in Fig. 8(a). The theoretical and experimental results reveal resonant wavelength difference of about 84 nm. This is caused by the derivation in the diameter and index of high index rods between theoretical model and actual experimental measurements. In addition, the experimental long wavelength edge is smaller than the theoretical edge, which results from the absorption of the liquid. Then, HPCF4 was placed into the SI device and meanwhile was located into the temperature chamber with a temperature stability of ± 0.1 °C for temperature sensing measurement, as shown in Fig. 10. Figure 15(b) shows the interference spectra at different temperatures from 38.0 °C to 41.0 °C. We can see a series of interference dips with unequal spacing occur, and the spacing of dips at short wavelength edge are more intensive. This is because the spacing (s) between adjacent
interference dips is decided by \( s = \frac{\lambda^2}{|B_g|L} \), which is inversely proportional to \( B_g \). Seen from Fig. 15(b), interference dips A-F all shift to shorter wavelength with temperature increasing, and from 39.0 °C to 39.5 °C dip D turn to shift to longer wavelength. Until 41.0 °C, dips A and D disappear, and a wide loss dip appears. Figure 16(a) further shows the specific wavelengths variation of interference dips A-F from 25 °C to 56.5 °C (the circles). It can be clearly seen dips A, B and C experience similar change tendency, meanwhile, dips D, E and F experience similar change tendency. Then, to directly observe the temperature sensitivity, the experimental results are analyzed and fitted with 6-order polynomial, as shown with the solid curves. By the first-order derivative of the fitting curves, the temperature sensitivity \( S \) is obtained, as shown in Fig. 16(b). It is clearly seen that the sensitivities change nonlinearly with temperature. Meanwhile, they have positive, negative and zero values, which matches well with the theoretical simulation in Fig. 14. The \( S \) of dip A increases from −10.0 nm/°C at 27.0 °C to −32.1 nm/°C at 39.5 °C, that of dip B increase from −11.5 nm/°C at 33.0 °C to −33.5 nm/°C at 48.0°C and that of dip C increase from −13.8 nm/°C at 43.0 °C to −45.8 nm/°C at 56.5 °C. The \( S \) of dips D, E and F decrease gradually from negative values to zero, then to positive values. The variations of interference dips for HPCF4-based SI can be explained in detail by Eq. (5). The highest \( S \) occurs beside the wavelength where \( B_g \) equals to zero.

Then, with the number of the filled air holes increasing, the time spent on manual gluing the air holes are longer. For increasing the work efficiency, we utilized another method, CO₂ laser’ side irradiation, to produce another HPCF. We fixed the PCF on a stage and used high frequency CO₂ laser (CO2-H10, Han’s laser) to expose one side of the PCF. The pulse frequency of the CO₂ laser is fixed at 5 kHz, and the average power is attenuated to 0.6 W for practical use. After CO₂ laser’s side-exposure for a few circles, partial air holes of the
Then, we cut off the PCF at the exposed part, and the PCF with cross-section of partial air holes collapsed was then immersed into the liquid. Thus, the opened air holes were infused into liquid, and the selective-filled HPCF was achieved, called HPCF8. The inset of Fig. 17(a) shows the cross-section of HPCF8 illuminated by the visible light and the bright holes represent the liquid-filled holes. Comparing the cross-section of HPCF8 with HPCF3, they both have the five holes (as the red box shown) filled. We simulated the birefringence properties of HPCF8 (black curves), as shown in Fig. 17. The variation of $B$ and $B_g$ characteristics of HPCF3 (red curves) are also shown in Fig. 17 for comparison. We can see the $B$ and $B_g$ of HPCF8 have similar change tendency to that of HPCF3, except that HPCF8 has narrower wavelength range than HPCF3. The $B$ decreases monotonically with wavelength, and the values of $B_g$ are all positive and the values are higher at both edges than that in the middle wavelengths. Hence, we studied the transmission and temperature characteristics of this type HPCF utilizing HPCF8.

![Fig. 17. Calculated (a) phase birefringence $B$ and (b) group birefringence versus wavelength for HPCF8 (black curves) and HPCF3 (red curves). The inset is the cross-section of HPCF8 illuminated by the visible light, and the bright holes represent the liquid-filled holes.](image)

Then, the temperature characteristics of HPCF8 based SI were measured. Figure 18(a) shows the transmission spectra of HPCF 8 based SI at 25 °C and 60 °C, and the specific variations of interference dips A-D with temperature increasing are shown in Fig. 18(b). The solid lines are the linear fitting. It is clearly seen that the interference dips all shift to shorter wavelengths, and the dip wavelengths change approximately linearly with temperature within certain temperature limits. Furthermore, the sensitivities of dips in the middle wavelength are larger than that of dips at both edges. This variation tendency matches with the theoretical simulation of $S$ in Fig. 12, while, the $S$ in experiment and in theory have certain deviation, which may come from the mismatches between the fiber model in experiment and in theory. The sensitivities of all dips are higher than $-8.0$ nm/°C, and sensitivity of $-11.6$ nm/°C from 65 °C to 85 °C is achieved for dip C.

![Fig. 18. (a) Transmission spectra of HPCF8 based SI at temperatures 25°C and 60°C. (b) Variations of interference dips A-D shown in (a) with temperature increasing. The solid lines are the linear fitting.](image)
5. Conclusion

In conclusion, we proposed and demonstrated a kind of birefringence controllable hybrid photonic crystal fibers (HPCFs) by selectively infiltrating air holes of PCFs with index tunable liquids having higher index than silica background. By detailed theoretical simulation of mode couplings between core fundamental mode and high index rod mode and birefringence properties of several HPCFs, we found that coupled high-index-rod modes have impacts on the birefringence properties. The HPCFs presented unique birefringence properties different from traditional index-guiding Hi-Bi PCFs and Hi-Bi PBGF. Furthermore, distinct birefringence properties were achieved for HPCFs under different arrangements of high index rods. Then, the temperature response of two HPCFs (called HPCF4 and HPCF8) based SI were theoretically and experimentally investigated. Based on different birefringence properties of the two HPCFs, the SIs presented different transmission spectra and temperature characteristics. For HPCF4 with two filled air holes located on either side of core, the values of $B_g$ are positive, negative and zero for different wavelengths. This birefringence features result in the HPCF4 based SI possessing temperature sensitivities with positive, negative or zero values at different wavelengths and nonlinear change versus wavelengths. Especially, due to the existence of zero value for $B_g$, higher temperature sensitivity can be achieved for the interference dip near the wavelength at which the $B_g$ equals zero. And a sensitivity of up to $-45.8$ nm/°C at 56.5 °C was achieved for HPCF4 based SI. For HPCF8, near half of all the air holes mainly including five holes located in a line at one side of fiber core were filled, the values of $B_g$ for HPCF8 are all positive, which result in the HPCF8 based SI having temperature sensitivities with negative values and nearly linear change versus wavelengths. And a sensitivity of up to $-11.6$ nm/°C from 65 °C to 85 °C was achieved for HPCF8 based SI. The thermal tunable birefringent HPCFs with distinct birefringence properties will provide great potential possibilities for a variety of tunable optical devices and sensors for different situations.

Acknowledgments

This work was supported by the National Key Basic Research and Development Program of China (Grant No. 2010CB327605 and 2011CB301701), the National Natural Science Foundation of China (Grant No. 61322510, 11174154 and 11174155), the Tianjin Natural Science Foundation (Grant No. 11JCZDJC16800), and the Doctor Foundation of Tianjin Normal University (Grant No. 52XB1307).