Highly Birefringent Photonic Crystal Fibers with a High-index Doped Rod

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Abstract— This article designs and theoretically investigates a highly birefringent photonic crystal fiber (HB-PCF) for reducing the effect of polarization-mode dispersion (PMD) in high-speed optical communication system. To achieve a high modal birefringence in the proposed HB-PCF, we designed four types of HB-PCF by adding some birefringence-enhancing factors step by step in sequence. Ultimately, from the simulation results, the numeric value of modal birefringence of the proposed HB-PCF is up to 25.008×10^{-3} at the habitual wavelength $\lambda = 1.55\,\mu$m of optical-fiber communications.

1. INTRODUCTION

Some imperfections of a single mode fiber (SMF) are produced due to variations in geometric shape or impurity-introducing in practical fiber-fabrication processes, and anisotropic stress acting on the fiber due to the fiber-installation in an optical communication system. These imperfections result in an uncontrolled and unpredictable modal birefringence in the SMF and bring about polarization-mode dispersion (PMD). The PMD induces pulse broadening and seriously restricts the data rates in a high-speed optical communication links. The polarization-maintaining fibers (PMF) were used to significantly reduce the governing factor of small random birefringence fluctuations. Conventional PMFs (such as elliptical core fibers, bowtie structured fibers, and PANDA fibers) have a modal birefringence with a value of about 10^{-4} order typically. Recently many articles used photonic crystal fibers (PCF) to realize a highly birefringent photonic crystal fiber (HB-PCF) [1–8]. Modal birefringence of about 10^{-3} order was achieved typically for these HB-PCFs at a wavelength of 1550 nm.

To enlarge the modal birefringence, one can destroy the six-fold symmetry of the fiber to the best of one's ability and strongly split the degenerated doublet pair. The modal birefringence B of a fiber is defined as the difference in effective index of the split modes

$$B = \left| n_{\mathit{eff}}^{x} - n_{\mathit{eff}}^{y} \right|, \tag{1}$$

where n_{eff}^{x} and n_{eff}^{y} are the effective indices of the x- and y-polarization mode, respectively. In this paper, by overlapping some birefringence-enhancing factors step by step, and then the difference between the effective indices of the degenerated fundamental mode is enlarged. According to Eq. (1), a HB-PCF with ultra high birefringence is designed. Ultimately, the numeric results reveal that the value of modal birefringence of the proposed HB-PCF is up to 25.008×10^{-3} at a wavelength of $1.55\,\mu$m.

2. SIMULATION MODEL AND PRINCIPLES

The cross-sectional view of a regular index-guiding PCF is shown in Fig. 1(a). The cladding of the PCF consists of a triangular lattice of air-holes, referred to as cladding holes in this paper, each one with a diameter of $D_c = 0.5\,\mu$m and a pitch (center-to-center distance between the holes) Λ of $0.8\,\mu$m in a background of undoped silica (refractive index of about $n = 1.444$ at a wavelength of $1.55\,\mu$m). The solid core is formed by removing the central air hole.

To destroy the six-fold symmetry of the fiber and split the degenerated doublet pair for enlarging the modal birefringence, the first birefringence-enhancing factor is introduced — two air holes at the innermost layer of the PCF were replaced with larger holes with a diameter of $D_1 = 0.74\,\mu$m. This type of structure is named as Type 1 in this article and indicated in Fig. 1(b). In addition to the two larger holes, the second birefringence-enhancing factor in Type 2 is a removal of two holes in appropriate orientation at the innermost layer of the PCF, which is shown in Fig. 1(c). To enhance the birefringence more, one can confine the splitting degeneration modes in a smaller core region. Therefore, as shown in Fig. 1(d), the third birefringence-enhancing factor is added, Type 3 was designed by inserting a circular Ge-doped rod with a cladding diameter of $D_c = 0.5\,\mu\text{m}$ while a higher refractive index of $n_{\text{core}} = 1.7$ at a wavelength of $1.55\,\mu\text{m}$ in the center of the core. Ultimately, the fourth birefringence-enhancing factor is that the circular Ge-doped rod was replaced with elliptic one with the same refractive index to even more enlarge the modal birefringence. The lengths of major axis and minor axis of the central elliptic rode are $D_y = 0.755\,\mu\text{m}$ and $D_x = 0.54\,\mu\text{m}$, respectively. The final structure is named as Type 4 and exhibited in Fig. 1(e).

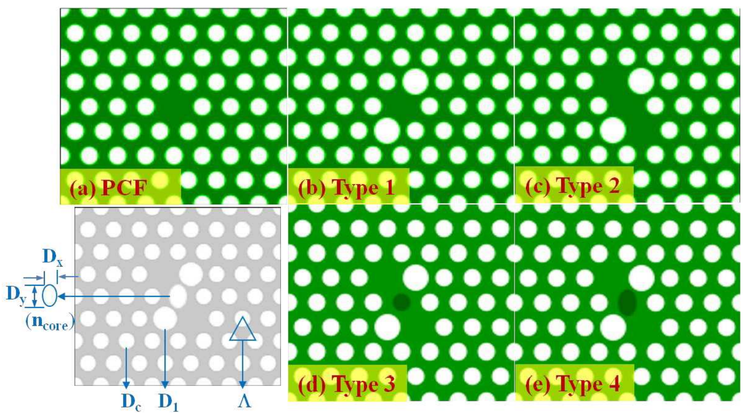

Figure 1: Cross-sectional view of (a) a regular PCF and the HB-PCFs, (b) Type 1, (c) Type 2, (d) Type 3, and (e) Type 4.

3. NUMERICAL RESULTS AND DISCUSSIONS

The refractive indices of the split modes n_{eff}^x and n_{eff}^y were estimated by means of the plane-wave expansion (PWE) method, and then the modal birefringence was deduced by using Eq. (1). Fig. 2 compares the modal birefringence of these four types of HB-PCF. As shown in Fig. 2, the birefringence values increase in sequence for adding the birefringence-enhancing factors as mentioned previously. However, the maximum values of birefringence for the majority of HB-PCF types occurred at a wavelength that is far from the habitual wavelength of optical-fiber communications ($1.55\,\mu\text{m}$). To shift the maximum birefringence wavelength toward a shorter wavelength while still keeping its birefringence at an original maximum value, one can shrink the whole structure with a scale-down factor [7]. On the other hand, one can expend the whole structure to shift the maximum birefringence wavelength toward a longer wavelength. In this work, the birefringence curves (B-curves) of some types of HB-PCF need to red-tune (to be tuned toward a longer wavelength) and the B-curves of some types need to blue-tune toward a shorter wavelength. To shift the maximum birefringence wavelength of all the HB-PCF types toward a wavelength of $1.55\,\mu\text{m}$, we defined a scale-adjust factor of m. For $m < 1$, the structure is modified by shrinking the whole structure, and the B-curve is blue-tuned. For $m > 1$, on the contrary, the structure is modified by expanding the whole structure, and the B-curve is red-tuned.

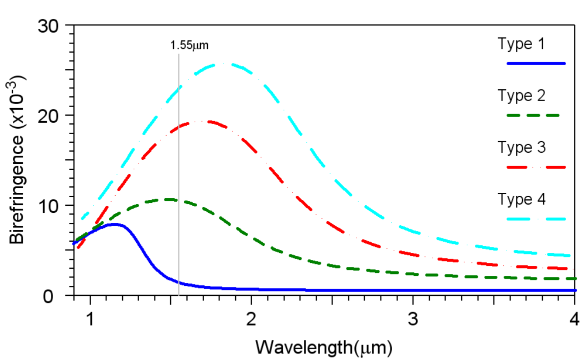

Figure 2: Dependence of birefringence on wavelength for the HB-PCF Type 1 to 4.

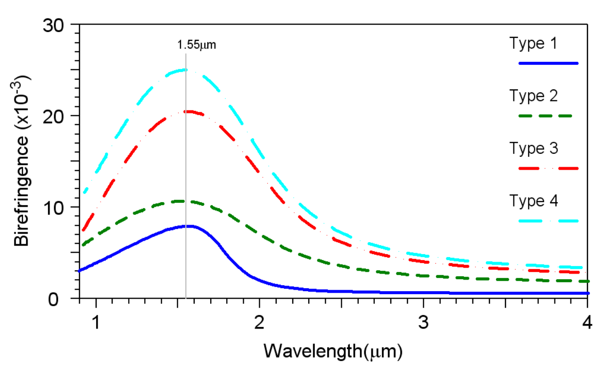

Figure 3: Dependence of birefringence on wavelength for the modified HB-PCF types.

For different types of HB-PCF, according to Fig. 2, the B-curves of Type 1 and 2 need to red-tune and those of Type 3 and 4 need to blue-tune. Particular values of m were designed to be 1.35, 1.03, 0.9 and 0.85 for Type 1 to 4, respectively. Fig. 3 indicates the dependence of birefringence on wavelength for the four types of modified HB-PCF. For the habitual wavelength $\lambda = 1.55\,\mu\text{m}$ of optical-fiber communications, for ultimate result, the numeric values of modal birefringence are 7.926×10^{-3}, 10.625×10^{-3}, 20.473×10^{-3}, and 25.008×10^{-3} with respect to Type 1 to Type 4. Table 1 exhibits the designed geometric and optical parameters of the modified HB-PCF Type 1 to 4.

Table 1: Geometric and optical parameters of the modified HB-PCF types.

HB-PCF types	scale-adjust factor m	Λ (μm)	D_1 (μm)	D_c (μm)	D_x (μm)	D_y (μm)	n_{core}
Type 1	1.35	1.08	0.999	0.675	–	–	–
Type 2	1.03	0.824	0.762	0.515	–	–	–
Type 3	0.9	0.72	0.666	0.45	0.45	0.45	1.7
Type 4	0.85	0.68	0.629	0.425	0.459	0.642	1.7

4. CONCLUSIONS

This study systematically designs and theoretically investigates a highly birefringent photonic crystal fiber (HB-PCF) by adding some birefringence-enhancing factors step by step in sequence. The modal birefringence is increased even more whenever a birefringence-enhancing factor is introduced. By adding all the four birefringence-enhancing factors, the modal birefringence of the HB-PCF Type 4 is up to 25.008×10^{-3} at a wavelength of about 1.57 μm. To shift the maximum birefringence wavelength toward the habitual wavelength of optical-fiber communications (1.55 μm), we introduced a scale-adjust factor m. Finally, the proposed HB-PCF with a high-index Ge-doped elliptic rod in the central core was designed. The numeric value of modal birefringence of the proposed HB-PCF is up to 25.008×10^{-3} at the habitual wavelength $\lambda = 1.55\,\mu\text{m}$ of optical-fiber communications.

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