Highly birefringent extruded elliptical-hole photonic crystal fibers with single defect and double defects

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Highly birefringent elliptical-hole photonic crystal fibers (PCFs) with single defect and double defects are proposed, which are supposed to be achieved by extruding normal circular-hole PCFs based on a triangular-lattice photonic crystal structure. Comparative research on the birefringence and the confinement loss of the proposed PCFs with single defect and double defects is presented. Simulation results show that the proposed PCFs with single defect and double defects can be with high birefringence (even up to the order of 10^{-2}). The confinement loss increases when the ellipticity of the air hole of the PCFs increases, which nevertheless can be overcome by increasing the ring number or the area of the air holes in the fiber cladding.

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Photonic crystal fibers (PCFs)[1−10] have attracted increasing interest over the past decade because of their unique properties such as high birefringence, high nonlinearity, endlessly single-mode operation, single-polarization single-mode operation, and tailorable chromatic dispersion. Highly birefringent PCFs are one kind of extemely important PCFs which have promising applications in, e.g., fiber sensors[11], fiber lasers[12−15], and fiber filters[14−16]. So far, various highly birefringent PCFs have been proposed[17−21]. Elliptical-hole PCFs have been proved to be with high birefringence possibly up to the order of 10^{-2}[19−21]. However, it is difficult to control the shape and keep the uniformity of elliptical air holes in the fabrication process.

In this letter, we introduce a highly birefringent elliptical-hole PCF which is supposed to be achieved by extruding a normal circular-hole PCF based on a triangular-lattice photonic crystal structure. Since the previously reported highly birefringent PCFs are typically based on single defect or double defects[22,23], we focus on the comparative investigation of the characteristics of the proposed extruded elliptical-hole PCFs with single defect and double defects.

Figure 1 shows cross sections of normal PCFs based on a triangular-lattice photonic crystal structure of circular air holes with one and two missing holes as the fiber core (encompassed by five rings of circular air holes in the fiber cladding). For such kind of PCFs, the hole pitch Λ (the center-to-center distance between the two adjacent air holes) is the key parameter for the basic crystal lattice. The air holes are characterized by the normalized area $S = \pi D^2/(4\Lambda^2)$, where D is the diameter of the circular air hole. Supposing the normal PCF is extruded in horizontal direction and expanded in perpendicular direction (but remains the same area of the cross section), we can find that the circular air holes become elliptical air holes with the same area. Thus, we achieve the extruded elliptical-hole PCFs, as shown in Figs 1(c) and (d). We define the extruding ratio η as X/X', which is also the ellipticity of the elliptical air hole after extrusion, and X (X') is the length in horizontal direction before (after) extrusion. By employing this extrusion method, uniform elliptical air holes with well-controlled ellipticity can be achieved and good consistency can be ensured. However, it is quite difficult to ensure good consistency for the fabrication of the elliptical PCFs based on the fiber perform, where there are some fluctuations of some parameters of the elliptical holes.

A full-vector finite-element method (FEM) and the anisotropic perfectly matched layers[24] are employed to simulate the guided modes of the proposed PCF. In what follows, the refractive index of fused silica and the normalized area S of the air holes in the PCF are assumed to be 1.45 and 0.2, respectively. The calculated results are expressed in terms of the normalized frequency $\nu = \Lambda/\lambda$, where λ is the operation wavelength in free space. We will consider the phase-index birefringence (PIB) which is defined as[21]

$$\Delta n = n_y - n_x, \quad (1)$$

where n_i $(i = x, y)$ is the phase modal index. The dispersion curves of the y-polarized and

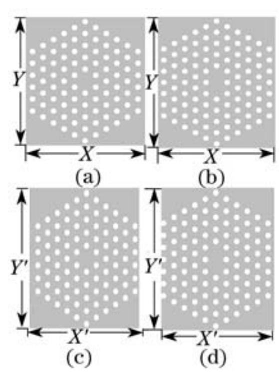

Fig. 1. Cross sections of (a) the normal circular-hole PCFs with single defect and (b) double defects based on a triangular-lattice photonic crystal structure, and (c) the proposed extruded elliptical-hole PCF with single defect and (d) double defects.

x-polarized fundamental modes of the extruded elliptical-hole PCF with a single defect as the fiber core and 5 rings of air holes in the fiber cladding are shown in Fig. 2. Evidently, the y-polarized mode has a higher effective index than the x-polarized one, resulting in a high birefringence of the PCF. The inset of Fig. 2 shows the major electric field component of the y-polarized fundamental mode at the normalized frequency of 1.5. The birefringence behavior of this extruded elliptical-hole PCF is shown as solid curve with parameters of $\eta = 1$, and ring number of air holes $N = 5$ in Fig. 3. Similar characteristics can also be found for the extruded elliptical-hole PCF with double defects. Figure 3 shows birefringence of the proposed extruded elliptical-hole PCFs with single defect and double defects when the ellipticities of the elliptical air hole are 1, 1.5, and 2, respectively. When there is no extrusion, the PCF with double defects remains a birefringence because of the asymmetry of the fiber core, which is higher than that of the PCF with a single defect by more than one order of magnitude. For the proposed PCFs with single defect and double defects, the birefringence has been greatly enhanced when the ellipticity increases (i.e., extrusion ratio increases). High birefringence up to 10^{-2} at low frequencies is achieved. The high birefringence at low frequencies is mainly due to the asymmetry of the fiber cladding because of the extruded elliptical air holes, which can be inferred from the fact that a larger proportion of the modal energy is distributed in the fiber cladding at a lower frequency. For example, considering the case with η=2, when the normalized frequency is lower than 0.78, the extruded elliptical-hole PCFs with single defect and double defects possess high birefringence around 10^{-2} (the birefringence of the PCF with single defect is a little higher than that of the PCF with double defects). But when the normalized frequency is higher than 0.78, the birefringence decreases and the birefringence of the extruded elliptical-hole PCF with double defects becomes higher than that of the extruded elliptical-hole PCF with single defect. These comparative characteristics can be understood by the fact that elliptical air holes in the fiber cladding contribute to the birefringence at low normalized frequency and the asymmetry of the fiber core contributes to the birefringence at high normalized frequency. We have also found that the birefringence of the extruded elliptical-hole PCF is higher than that of the normal elliptical-hole PCF based on the triangular-lattice photonic crystal structure at the high normalized frequency because the extrusion results in the asymmetry of the fiber core of the extruded PCF, which enhance the birefringence at the high normalized frequency.

We also study the confinement loss of the proposed extruded elliptical-hole PCFs. Confinement loss can be deduced from the imaginary part of the complex effective index by[5]

$$\alpha = \frac{40\pi}{\ln(10)\lambda}\mathrm{Im}(n_{\mathrm{eff}}), \tag{2}$$

where n_{eff} is the complex effective index. Figure 4 shows the confinement loss of the proposed extruded elliptical-hole PCFs with single defect and double defects when the ellipticities of the elliptical air hole are 1 and 1.5, respectively. The confinement loss of the

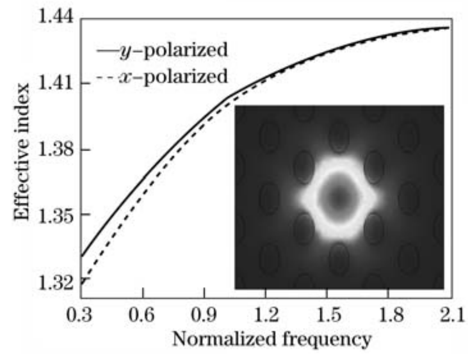

Fig. 2. Effective indices of the y-polarized (solid curve) and x-polarized (dotted curve) fundamental modes as a function of normalized frequency when the ellipticity of the elliptical air hole is 1.5. Inset shows the major electric field component of the y-polarized fundamental mode.

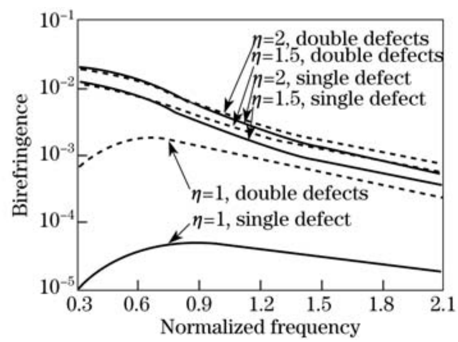

Fig. 3. Birefringence of the proposed extruded elliptical-hole PCFs with single defect (solid curves) and double defects (datted curves) when the ellipticities of the elliptical air hole are 1, 1.5, and 2, respectively.

extruded elliptical-hole PCFs with a single defect is larger than that of the extruded elliptical-hole PCFs with double defects. For comparison, the confinement loss of the normal elliptical-hole PCF based on a triangular-lattice photonic crystal structure is also shown with the ellipticity of the elliptical air hole being 1.5, which indicates a much larger confinement loss of the extruded elliptical-hole PCF is much larger than that of normal elliptical-hole PCF. Thus, for the extruded elliptical-hole PCFs, there is a tradeoff between birefringence and confinement loss. However, the confinement loss can be greatly reduced when the ring number or the area of the air holes increases[19]. Considering the extruded elliptical-hole PCFs with 5 and 6 rings of air holes in the fiber cladding, the confinement loss is effectively reduced (with about two orders of magnitude at high normalized frequency) by employing more air holes in the fiber cladding. For example, the extruded elliptical-hole PCF with 15 rings of air holes in the fiber cladding has the confinement loss less than 0.1 dB/km (good enough for transmission use) when the normalized frequency is higher than 0.6. Thus the confinement loss of the extruded elliptical-hole PCF cannot remain a big obstruction.

In conclusion, we have investigated the extruded elliptical-hole PCFs with single defect and double defects, which are believed to have the ease to keep the

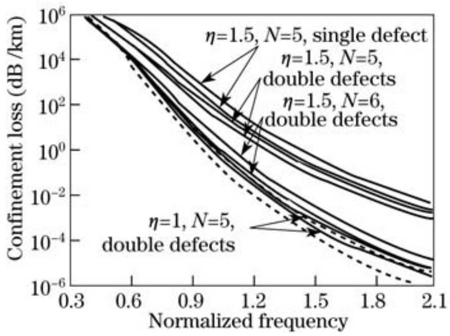

Fig. 4. Confinement loss of the proposed extruded elliptical-hole PCFs with single defect and double defects when the ellipticities of the elliptical air hole are 1 and 1.5, respectively. Dotted curve shows the confinement loss of the normal elliptical-hole PCF based on a triangular-lattice photonic crystal structure when the ellipticity of the elliptical air hole is 1.5.

uniformity of elliptical air holes in the fabrication process of PCFs. Simulation results have shown that the extruded elliptical-hole PCFs with single defect and double defects possess high birefringence up to the order of 10^{-2} at low normlized frequency. For the extruded elliptical-hole PCFs, the normal triangular-lattice photonic crystal structure is destroyed, which results in the relatively larger confinement loss. However, the confinement loss of the proposed extruded elliptical-hole PCFs can be effectively reduced by increasing the ring number or the area of air holes in the fiber cladding. To achieve a highly birefringent PCF, the extruded elliptical-hole PCFs with single or double defects are a good choice, since high birefringence can be achieved at low normalized frequency for both kinds of extruded elliptical-hole PCFs and the confinement loss cannot remain a big obstruction.

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