Versatile control of geometric birefringence in elliptical hollow optical fiber

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A novel optical fiber fabrication technique was developed by converting the symmetry of the silica substrate into the germanosilicate ring core to efficiently introduce geometric birefringence in an elliptical hollow optical fiber. Due to high ellipticity in the hollow ring core, the fiber provides an extremely high group birefringence of $2.35 \times 10^{-3}$ at 1550 nm. Single-mode single-polarization guidance was also experimentally confirmed, with a bandwidth of $\sim 35$ nm. The generic adiabatic mode conversion capability in the taper also provided a stable fusion splice to conventional single-mode fiber with low loss and high tensile strength. © 2006 Optical Society of America

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Varieties of optical waveguide structures have been proposed to introduce high birefringence in optical fibers for polarization-maintaining (PM) or single-mode single-polarization (SMSP) applications. Conventional high-birefringent (Hi-Bi) fibers, such as bow-tie, panda, elliptical stress applying member, elliptical core, and side tunnel fibers, have utilized either geometric or stress-induced birefringence. These configurations have been intensively investigated over the years, and optical fibers with an order of magnitude higher birefringence than those of conventional single-mode fibers (SMFs) are commercially available. However, recent developments in high-resolution fiber sensor and SMF lasers require higher birefringence and thermal stability than in commercial Hi-Bi fibers.

We recently proposed and theoretically analyzed a novel design of a highly birefringent elliptical hollow optical fiber (EHOF) composed of a triple-layer structure; a central elliptical air hole, a circumferential elliptical ring core, and a circular cladding. Due to the large refractive index contrast between the ring core and the air hole (0.45) as in photonic crystal fiber, high birefringence has been theoretically predicted with a relatively small index difference between the core and the cladding ($\Delta n$). In this study, we developed a novel fabrication process for EHOFS and experimentally demonstrated its high birefringence and generic compatibility with conventional optical fibers, for the first time to the best knowledge of the authors.

Figure 1(a) shows a schematic design of the proposed EHOFS. An elliptical air hole at the center is concentric to the circumferential elliptical ring core. As theoretically discussed in Ref. 3, the birefringence in the EHOFS arises mainly from the boundary conditions for electromagnetic fields at the elliptical core–hole interface. The diameters of the major axis ($2a_{\text{hole}}$) and the minor axis ($2b_{\text{hole}}$) of the air hole characterize the geometric birefringence of EHOFS.

Solid elliptical core fibers, in general, have been fabricated by drawing a preform whose sides are removed to a certain depth at a high temperature. Above the softening point, the flat side surfaces of the preform flow to form a circular shape because of the surface tension and low-viscosity silica cladding, which results in an elliptical germanosilica core. In the case of EHOFS, however, the high drawing temperature tends to seal the central air hole, and the hole, if it is not sealed, is prone to have a circular shape due to built-in positive pressure. To cope with these problems, we developed a new fabrication technique to provide anisotropy in both a hollow air hole and its circumferential ring core. A schematic of the process is shown in Fig. 1(b). First, a hollow silica substrate tube is cut to provide two flat surfaces, then the germanosilica core layers are deposited over...
the prepared tube by the conventional modified chemical vapor deposition process. The tube is then partly collapsed to deform the prepared tube into a round cross section, leaving behind an elliptical hole and an elliptical ring core. Note that the ellipticity in the hole and ring core is already introduced at the preform stage, which eliminates high-temperature drawing requirements. The final preform is then drawn to fiber at a low-temperature with optimal pressure and tension control.

The cross sections of the fiber drawn from the preform are shown in Fig. 2 for Fig. 2(a) high drawing temperature with a fully collapsed solid core, and Fig. 2(b) low drawing temperature with an open elliptical air hole and a ring core. The proposed fabrication process was found to effectively produce high ellipticity in the ring core and the air hole and to flexibly control the air-hole size as well. As shown schematically in the ideal case in Fig. 1(a), the fabricated fiber showed a thinner ring along the minor axis, shown in Fig. 2(b), along with elliptical hole. With this developed technology, the ellipticity can be routinely controlled by the cut volume of the silica tube, and the air-hole diameter can be managed by the temperature and tension at the drawing process. In this experiment, the index difference between the ring core and cladding was set as 0.01, and the ellipticity factor \( e = a/b \) of the hole and core was kept as 1.3.

The near-field beam patterns of both the elliptical solid-core fiber [inset in Fig. 2(a)] and the EHO [inset in Fig. 2(b)], measured by a CCD camera, are shown. Due to the very thin EHO along the minor axis, the guided mode showed a unique intensity distribution. The near field of EHO, Fig. 2(b), has two maxima along the major axis (~1 mm), which is attributed to weak guidance of light along the thin ring core. Note that the intensity profile is similar to that of twin-core fiber, which can be efficiently converted to a solid elliptical core beam in an adiabatic mode transformation with minimal loss. By this novel peculiarity, the EHO can be used as a connector between single- and twin-core fibers.

The overall splicing loss between the EHO and the conventional SMF is less than 1.0 dB, independent of air-hole size, and the tensile strength was as high as 3 GPa, which is comparable with that of conventional SMF–SMF splice.

To further investigate the model guidance, we investigated the transmission spectra of EHO for various elliptical air-hole sizes. As depicted in Fig. 3(a), the EHO had a long wavelength cutoff for the fundamental mode when the air-hole major axis was larger than 8 \( \mu \)m. Generally, the single-mode operation bandwidth is limited by a higher-order mode cutoff \( \lambda_{C, \text{higher order}} \) at short wavelengths and a fundamental mode cutoff \( \lambda_{C, \text{fundamental}} \) at long wavelengths. In this measurement the higher-order mode cutoff moves to a shorter wavelength, from 1517.4 to 975.1 nm, when the air hole is increased from 0 to 10 \( \mu \)m, and the fundamental mode cutoff begins to be effective in EHO over 8 \( \mu \)m air holes. It is noteworthy to confirm that thin elliptical ring core fiber as a result of the larger air-hole size shows a relatively weak guidance property.

For Hi-Bi fibers, we could expect a unique guidance property, SMSP, where only one polarization is guided in the fundamental mode. By varying the polarization state of the incident white light using a lin-
ear polarizer, we could resolve the differences in fundamental mode cutoff for $x$ and $y$ polarization, as shown in Fig. 3(b). For an extinction ratio over 20 dB, the SMSP region was observed in the wavelength range from 1587.6 to 1622.8 nm. As predicted in Ref. 8, the bandwidth for SMSP can be further expanded with optimal design, and experimental investigations are being pursued by the authors.

The birefringence of the fiber is then measured by the wavelength-scanning method. Figure 4(a) show the spectral polarization oscillations with various air-hole sizes of the EHOF for the same fiber length, $l = 260$ mm. We notice that the larger the air-hole diameter becomes, the denser the spectral interference obtained. The separation between two adjacent maxima ($\Delta \lambda$) can be related to the group beat length ($L_B$) and birefringence ($B$) by relation $[L_B = (\Delta \lambda / \lambda)L, B = (\lambda / L_B)]$. Figure 4(b) shows the wavelength dependence of the fiber birefringence on elliptical air-hole size. It is clearly seen that, by introducing an additional elliptical air hole into the center of the elliptical core fiber, high birefringence was achieved, and the EHOF birefringence escalated significantly as the air-hole diameter increased. In particular, the 8 $\mu$m EHOF ($2a_{\text{hole}} = 8 \mu m, e = 1.3$) illustrates an extremely high group birefringence of $2.35 \times 10^{-3}$ at 1550 nm and $3.26 \times 10^{-3}$ at 1650 nm. The birefringence of the order of $10^{-3}$ is an order of magnitude larger than that of conventional PM fibers. In this unique EHOF structure, larger values of birefringence can be further obtained by adopting a greater ellipticity and a higher ring core refractive index. Moreover, the group birefringence increases significantly as the wavelength increases, compared with conventional stress-induced PM fibers. This means that the most important contribution to the EHOF birefringence is the geometrically induced birefringence.

In summary, a Hi-Bi elliptical hollow optical fiber was successfully fabricated by use of a new technique based on the use of a flat-face silica substrate tube for modified chemical vapor deposition, where flexible control of ellipticity and air-hole size was achieved for EHOFs. The large refractive index contrast and ellipticity in both the hole and the ring core resulted in extremely high geometric birefringence of $2.35 \times 10^{-3}$ at 1550 nm, which is an order of magnitude higher than that of conventional PM fibers. The single-mode single-polarization condition was also experimentally confirmed from 1587.6 to 1622.8 nm for the extinction ratio of 20 dB. We expect that the fabrication technique can be widely applicable for creating geometric anisotropy inside solid-cladding optical fiber for a further increase in the birefringence and bandwidth of single-mode single-polarization guidance.

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References