Fabrication and study of microstructured optical fibers with elliptical holes

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We report the fabrication of what are believed to be the first microstructured optical fibers with uniformly oriented elliptical holes. A high degree of hole ellipticity is achieved with a simple technique that relies on hole deformation during fiber draw. Both form and stress-optic birefringence are characterized over a broad wavelength range. These measurements are in excellent agreement with numerical modeling and demonstrate a birefringence as high as $1.0 \times 10^{-4}$ at a wavelength of 850 nm.

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Microstructured optical fibers (MOFs) with elliptical holes have received significant theoretical analysis because of their polarization-dependent interaction with guided electromagnetic waves. In addition to the high-birefringence and polarization-maintaining characteristics of these fibers, a number of properties such as photonic bandgap guidance and dispersion have been investigated. Furthermore, the addition of an elliptical hole in the core region of MOFs has been studied for the prospect of enhancing birefringence even beyond the exceptionally high levels demonstrated in MOFs to date. Fabrication of the first MOFs with uniformly oriented elliptical holes is reported here. Composed of polymer, these fibers provide the first steps toward realizing the variety of elliptical hole structures presented in the literature.

The difficulty in fabricating MOFs with noncircular holes is due to the action of surface tension, viscous stresses, heating, and pressure effects during the fiber draw. These effects typically result in either nonuniformly oriented hole deformations or hole recircularization when the holes are noncircular in the preform stage. It is shown here that with an appropriate geometry some of these effects can be advantageously employed to create oriented elliptical holes.

The preform hole pattern shown in Fig. 1(a) was drilled into a commercially extruded poly(methyl methacrylate) (PMMA) preform with a diameter of 8 cm. This was subsequently drawn to a structured cane with a diameter of 6 mm, sleeved in a PMMA jacket with an outer diameter of 12 mm and drawn again into fiber of three different outer diameters. The deformed hole pattern in the resulting fiber is shown in the electron microscope image in Fig. 1(b).

The values of major hole pitch $\Lambda_a$, as indicated in Fig. 2(a), for the three different diameter fibers are 5.12, 3.82, and 3.14 $\mu$m. The values of the ellipticity of the cores, defined as the ratio of minor to major pitches $\Lambda_b/\Lambda_a$, are 0.61, 0.61, and 0.59, respectively. The averaged hole major diameters $d_a$ of the inner ring are 3.0, 2.1, and 1.6 $\mu$m for these three fibers, with average ellipticity $d_b/d_a = 0.59, 0.54$, and 0.48, respectively. From the reproducibility of these measurements retaken over several perpendicular cleaves the accuracy is estimated to be $\pm 5\%$.

Studying these measurements of structural sizes at various fiber diameters has led to the following understanding of the process of hole deformation: During fiber draw the phenomenon of hole collapse drives the preferential collapse of the holes along the line joining the two giant deforming voids on either side of the microstructure. The interplay among surface tension, viscous stresses, and pressure differentials is thought to be the cause of the partial hole collapse observed in many MOFs. Thus pressurization of the airholes can provide some control over such deformations. However, such collapse is impeded by the viscosity of the material while in its glassy state. For the structure shown in Fig. 1(a) the absence of material in the deforming voids provides less resistance to deformation, and the resultant asymmetric stresses deform the holes to ellipses.

An empirical formula was found by considering appropriate dimensionless quantities to accurately match the reconstruction of microstructured optical fibers with elliptical holes.
describe the deformation process in the inner ring of holes. The formula is given by

\[
\left( \frac{\Delta d_a}{\Lambda_a} \right)^2 = 2.98 \frac{\Delta d_a}{\Lambda_a},
\]

where the notation \( \tilde{x} = x/D \) is used to indicate that these quantities have been scaled by the outer fiber or preform diameter \( D \) and where \( \Delta d_{a,b} = d_{a,b} - \bar{d} \) represents the change in these scaled quantities from the initial preform dimensions \( \bar{d} \). An important finding is that \( \Lambda_a \) scales geometrically with the outer fiber diameter, i.e., \( \Lambda_a \propto D \), and in that sense undergoes no deformation. It is therefore used to represent the structure scale throughout this Letter. The term \( \Delta d_a/\Lambda_a \propto \Delta d_a \) can be simply understood as the magnitude of hole collapse. Measurements taken from the three fibers, initial preform, and intermediate cane are compared with Eq. (1) in Fig. 2(b) and show excellent agreement, demonstrating that an uncomplicated relation exists between hole collapse and the two measures of deformation in the minor direction.

Polarized light from a broadband light source is launched at 45° to the principal axes of the birefringent MOF of known length. The output polarization state is analyzed with a second polarizer also at 45° to the MOF principal axes. An intensity modulation is observed over the broad wavelength range (see Fig. 3), which can be used to characterize the wavelength-dependent modal birefringence, \( B(\lambda) = n_x - n_y = \lambda/L_B(\lambda) \), where \( n_x \) and \( n_y \) are the effective indices of the dominantly polarized modes and \( L_B \) is the polarization beat length. The light source used for the measurements was a high-brightness white-light source. However, for fibers with modulation periods shorter than 5 nm a tunable Ti:sapphire laser operating from 700 to 860 nm was used. Measurements at longer wavelengths were impossible because of very high material absorption; thus measurements were limited to the transparency windows in the visible. All fibers were experimentally found to be single mode. However, the fiber with \( \Lambda_a = 5.12 \) \( \mu \)m was only single mode for lengths greater than 2 m, where higher-order leaky modes are significantly attenuated.

The relative phase difference \( \phi \) between the two polarization modes after length \( L \) is given by \( \phi(\lambda) = 2\piLB/\lambda \). Assuming that \( B = (\lambda/\Lambda_a)^{k_0} \), which is suggested in the literature and is strongly supported here, the use of \( \Delta \phi = \phi(\lambda + \Delta\lambda/\lambda) - \phi(\lambda) \) yields

\[
B(\lambda) = \frac{\Delta \phi}{2\pi L} \left( 1 + \frac{\Delta\lambda}{\lambda} \right)^{k_0-1} - 1 \right]^{-1},
\]

which is accurate for large \( \Delta\lambda/\lambda \). When \( \lambda \) is centered on a peak and \( \Delta\lambda \) represents the distance to a nearby peak, then \( \Delta \phi = 2\pi n \), where \( n \) is an integer. Alternatively, a peak-to-node reading corresponds to \( \Delta \phi = 2\pi(n + 1/2) \). In this way several measurements can be averaged at each sample wavelength to statistically reduce the overall errors. The unknown power \( k_0 \) can be determined efficiently by iteration. That is, after the measured data are graphed with an initial guess for \( k_0 \), its value can then be accurately refined by a power-law fit to the trend.

The resulting birefringence measurements on the three fibers are overlaid in Fig. 4, where the wavelength has been scaled with the major pitch of the
fibers. In good accordance with the size–wavelength scaling law for electromagnetism, the three measurements piecewise construct a distinct functional dependence of birefringence on wavelength. The small discontinuities between measurements are the result of the slightly different deformations at different microstructure sizes and are approximately the same magnitude as the ±5% errors in the data. The measured values of $k_0 = 2.8$ are in excellent agreement between fibers and support the appropriateness of the power-law fit over a broad wavelength range.

Numerical modeling of the real MOF was carried out with a highly efficient, fully vectorial mode solver employing adjustable boundary conditions, with a finite-difference implementation in the radial direction and an azimuthal Fourier decomposition. The confinement losses of the fundamental modes were found to be negligible in comparison with the material losses. Only waveguide-induced (form) birefringence was calculated and the stress-optic contribution was neglected. Most important, the form birefringence was found to be weakly dependent on the measured deformations. The fast polarization axis is in the minor direction of the core, $\lambda_b$.

The numerical results for the MOF with $\lambda_b = 3.82 \, \mu m$ are plotted in Fig. 4 and show poor agreement with the initial measurements. Subsequently, this fiber was annealed at 90 °C (~20 °C below the glass transition temperature) for 25 min to alleviate any material stresses, and the birefringence measurement was retaken (shown in Fig. 4). The annealed results show excellent agreement with numerical modeling and prove that a nonzero stress-optic birefringence was latent in the material in opposition to the form birefringence. The experimental results indicate that the increase in measured birefringence due to eliminating stress was ~25%, which is wavelength independent. The birefringence for these fibers increases strongly with wavelength and beyond 850 nm is comparable in magnitude with conventional polarization-maintaining fibers, for which birefringence is nearly wavelength independent. SEM images of the annealed fiber confirm no discernible change in the microstructure and thus the pure form birefringence of the type investigated here is expected to be largely independent of temperature.

In conclusion, a technique employing hole deformation during fiber draw has been presented for the fabrication of microstructured optical fibers with uniformly oriented elliptical holes. The process of deformation is qualitatively understood through the process of hole collapse and results in a high degree of ellipticity (~0.5). An empirical formula has been accurately fitted to the measured deformations, which relates the minor direction deformations to the magnitude of hole collapse. The birefringence of three fibers with different structure sizes were measured and show consistent agreement in their wavelength trends. Annealing of the fibers has been demonstrated to alleviate a nonzero stress-optic component to birefringence that increased the measured birefringence by ~25%. The subsequent birefringence measurements show excellent agreement with numerical calculations of form birefringence.

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