Small-core single-mode microstructured polymer optical fiber with large external diameter

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A preform sleeving technique is demonstrated that allows the fabrication of single-mode polymer microstructured fiber with the smallest core and hole dimensions yet reported to our knowledge. For a fixed triangular hole pattern a range of fibers is produced by adjustment to the operating conditions of the draw tower. Numerical modeling is carried out for one of the fibers produced with a 570-μm external diameter, a core diameter of 2.23 μm, an average hole diameter of 0.53 μm, and an average hole spacing of 1.38 μm. This fiber was shown to be endlessly single mode.

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Microstructured polymer optical fibers (mPOFs) offer the potential to fabricate fibers with an almost limitless range of internal hole structures.[1–3] This degree of structural freedom is the result of the availability of a range of preform fabrication methods and the diversity of suitable polymeric materials (many of which can be readily doped and chemically modified). These advantages, along with the relatively low draw temperatures associated with polymers, have led to mPOFs being actively examined as an alternative to microstructured glass optical fibers for specific applications.

The material properties of poly(methyl methacrylate) (PMMA), the polymer used in this study, certainly provide advantages relative to silica in the fabrication of microstructured optical fibers when we consider that the drawing of all such fibers is governed by the balance between surface tension and viscosity-related forces. Although the viscosity of PMMA and silica are of similar magnitude at their respective draw temperatures ($\sim 5 \times 10^{-6}$ and 3.6×10^{-6} Pa s, respectively[4,5]), PMMA's surface tension is an order of magnitude lower than that of silica ($\sim$0.032 and 0.30 N/m, respectively[6,7]). Thus, lowering the draw temperature, and hence increasing both the viscosity and the required draw tension, permits hole distortion and collapse caused by surface tension effects to be minimized, allowing fine-scale mPOFs to be drawn while maintaining their structural integrity.

Our fabrication techniques, which are similar to conventional polymer optical fiber fabrication methods,[8,9] generally employ a two-stage process with an intermediate cane being produced to achieve the necessary large reduction in diameter from preform to fiber.[3] This Letter reports the results obtained for fibers drawn with a novel, simple-to-use sleeving technique. The objective here was to produce single-mode, small-core (approximately 2 μm) mPOFs for which the hole sizes were less than 1 μm. To achieve this, the drawing conditions were varied to keep the ratio of hole size to hole spacing (d/Λ) within the final fiber as close as possible to that imposed on the original preform by minimizing the extent of any (surface-tension-induced) hole collapse.

The mPOF used to test our sleeving technique employed a triangular lattice consisting of four rings of holes (60 in total) in a triangular pattern. At the preform stage, the hole size was 1.0 mm and the spacing between hole centers was 1.2 mm, yielding a nominal d/Λ ratio of 0.83. By use of a computer numerical control mill, this hole pattern was drilled into an 80-mm-diameter PMMA rod of 65-mm length. This primary preform was then drawn down to form a microstructured cane with a diameter of approximately 2.5 mm. To form a secondary preform, this cane was surrounded with hollow capillary tubes within a thick-walled sleeving tube. Once formed, the secondary preform was drawn with the tower operating conditions adjusted to provide a range of fibers of varying diameter (D). To control the tension (τ) under which a fiber was drawn, either the oven temperature (T) or the preform feed rate (F) into the oven was adjusted.

Table 1 clearly shows the critical importance of applying sufficient tension during the drawing process. The first two runs had insufficient tension, whereas the next three show that the smaller the diameter, the greater the hole collapse in the fiber. The last run ($D = 570$ μm) used a substantially higher applied tension and yielded the least hole shrinkage. It was difficult to obtain accurate estimates of the hole size and hole spacing with an optical microscope; thus the values provided in Table 1 should be regarded as estimates only, although we believe that the rank order of the data is still meaningful.

Figure 1 is a cross section from the 570-μm fiber clearly showing the sleeving arrangement. Surrounding the sleeved cane are both the large fill capillaries and the sleeving tube that were used to bulk up the cane to create the secondary preform. These large airholes have no influence on the guiding properties of the fiber because the light traveling in the small core interacts with only the four rings of holes directly around it (see Fig. 2). However, one problem that employing a capillary fill may cause is that cladding modes will not couple out of the central section of the fiber as effectively as when the whole surrounding structure is solid. An attractive (but untried) alternative here would be to use *in situ* polymerization rather than capillary stacking as a means of producing a secondary preform. This fiber was found to strongly guide He–Ne light (at 633 nm), and the measured near-field pattern is shown in Fig. 3. This pattern was found to be independent of launch conditions and remained unchanged when the fiber was bent or twisted, indicating single-mode guiding.

Scanning electron microscopy measurements on the 570-μm fiber (see Fig. 2) showed hole diameter and spacing values of 0.53 and 1.38 μm, respectively, yielding a core size of 2.23 μm. With these parameters the confinement losses for the fundamental and second-order modes were determined by use of a hybrid (finite-difference and Fourier decomposition) method employing adjustable boundary conditions.[10] The fiber was found to have a fundamental mode in the central core, as shown in Fig. 4(a), with an effective index of 1.4796 and a confinement loss of 0.24 dB/m. The second-order mode at this wavelength is extremely lossy (see Table 2) with most of the light residing in the gaps between the holes, as shown in Fig. 4(b).

The experimentally measured d/Λ and λ/Λ ratios of 0.38 and 0.46, respectively, indicate that this fiber lies in the endlessly single-mode regime[11,12] with an expected fundamental mode cutoff at approximately 1.3 μm. This was impossible to demonstrate experimentally because of the high material absorption at wavelengths greater than 1 μm. To investigate this upper limit numerically, confinement losses for the fundamental and second-order modes were calculated over a wavelength range (0.40–1.6 μm) around the He–Ne value (see Table 2). For each wavelength all modes look similar to those in Fig. 4. The loss attributable to the second-order mode is substantially greater than that for the fundamental mode in all cases, confirming the predicted endlessly single-mode operation.

In conclusion, we have shown that sleeving is a simple but effective technique by which to draw mPOFs down to hole and spacing sizes of the order of a micrometer. Surface tension effects play a prominent

Table 1. Effect of Drawing Conditions on Fiber Characteristics

D (μm)	τ (g)	F (mm/min)	T (°C)	d (μm)	Λ (μm)	d/Λ	C^a (μm)
600	70	2	205	0	0	–	–
600	80	2	200	0	0	–	–
400	110	4	215	0.37	1.17	0.31	1.97
500	110	4	215	0.71	1.26	0.56	1.81
600	110	4	215	0.53	1.51	0.35	2.49
570	180	4	210	1.12	1.61	0.69	2.10

[a] Core diameter.

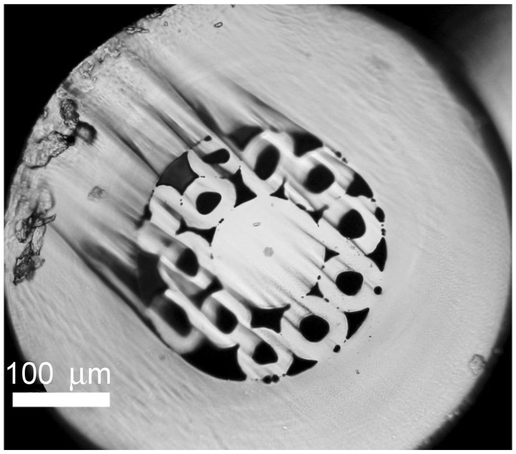

Fig. 1. Microscope image of the 570-μm-diameter small-core microstructured polymer fiber. The microstructure is located in the 118-μm-diameter central region of the fiber (unresolved at this magnification).

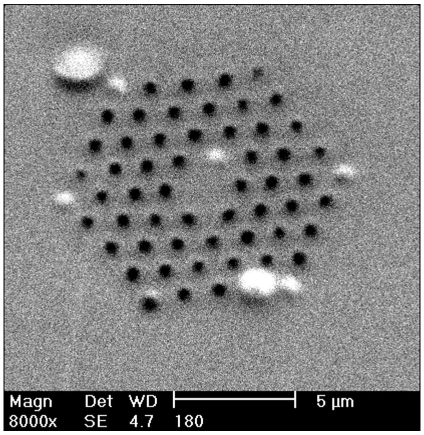

Fig. 2. Scanning electron microscopy image of the central core region of the fiber in Fig. 1. (Image courtesy of the Electron Microscopy Unit, University of Sydney.)

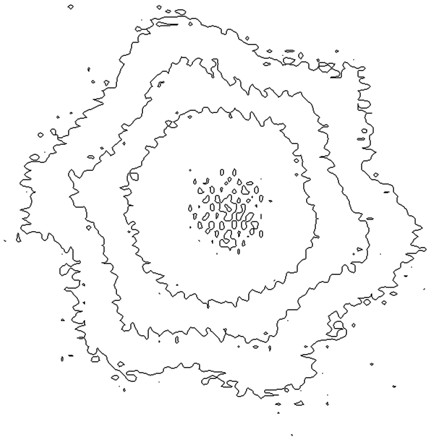

Fig. 3. Measured contour plot of the guided mode profile for the fiber shown in Fig. 1 with a 2.23-μm core diameter. Contours trace the 90%, 70%, 30%, and 5% intensity levels and are all confined within the first ring of airholes that define the core (see Fig. 2).

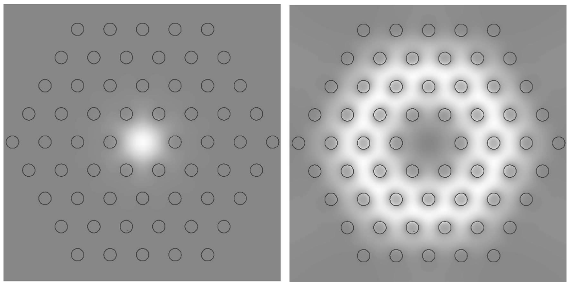

Fig. 4. Calculated intensity profiles at 633 nm for (a) the fundamental mode and (b) the second-order mode.

Table 2. Mode Confinement Losses as a Function of Wavelength

Wavelength (μm)	Fundamental Mode (dB/m)	Second-Order Mode (dB/m)
0.4	1.1×10^{-2}	4.8×10^{2}
0.633	2.4×10^{-1}	9.8×10^{3}
1.0	2.0×10^{1}	26×10^{4}
1.6	2.7×10^{3}	6.4×10^{4}

part in the fiber draw process but are not nearly as problematic as when drawing microstructured glass optical fibers. Lowering the draw temperature, and hence increasing the polymer viscosity, allows the draw tension to be increased to a level at which hole distortion (and ultimately hole collapse) can be held at an acceptable level. Our experiments have shown that keeping the tension above 150 g allows PMMA to be drawn into a fiber with a diameter of ~500 μm with the hole structure in the primary preform being essentially retained. With this sleeving technique, structures with small internal dimensions can be drawn within large-external-diameter fibers, offering possibilities for nonlinear applications and the reduction of microbending losses.[13]

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