Ultrahigh-resolution fiber-optic image guides derived from microstructured polymer optical fiber preforms

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Ultrahigh-resolution fiber-optic image guides—fused image fiber, faceplate, and taper—were fabricated by using microstructured polymer optical fiber (MPOF) preforms composed of two polymers: polymethylmethacrylate and polystyrene. The pixel diameter in the resultant MPOF-based image guides was as small as 3 μm. The imaging capabilities of these types of fiber-optic elements were demonstrated. © 2009 Optical Society of America

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Image guides, such as fused image fiber, faceplate, and taper, have been made from bundles of special glass or polymer optical fibers (POFs) [1–4]. For their single pixel diameter, the special glass is about 5 μm and the polymer is about 10 μm. The drawbacks for the image fiber bundle formed from glass fibers are that it is heavy because of the high density (2.4–2.65 g/cm³), and it has a high processing temperature. Otherwise, it is difficult to get higher resolution from the traditional step-index (SI) polymer image fiber. Recently, an ultrahigh image plate based on graded-index (GRIN) POFs has been reported by researchers at Nanoptics, Inc. [1]. However, it is liable to be considered that the process is time consuming and may be not suitable for mass production of various image guides such as fused image fiber, taper, and so on.

The aims of this study are to fabricate ultrahigh-resolution polymer imaging fiber, faceplate, and taper by resorting to the microstructured polymer optical fiber (MPOF) technology. MPOFs are a relatively recent development in POF technology and support a wide variety of microstructure fiber geometries [5–7]. Several processing methods have been reported for fabricating large preforms of MPOFs, such as stacking [5], drilling [6–9], casting [10], and extrusion [11]. To develop MPOFs into a kind of bread-and-butter optical fiber material, a series of experiments on their mass production and applications in chemical sensing and image transmission has been carried out [5–13].

Traditionally, the number of fibers contained in an image bundle is from several to tens of thousands. It is time consuming to stack thousands of single fibers or multifibers. This problem can be solved by integrating a few pieces of the MPOF preforms filled by another higher refractive index polymer fiber material. The two-polymer-based microstructured optical fiber (MOF) preform is equivalent to a fat fiber bundle that contained several hundreds of single polymer fibers. It is easy to turn this into an ultramultipixel number of image guides with the integration of the MPOF preforms.

The fabrication process of microstructured polymer imaging fiber proposed here could be generalized as follows: designing, extruding, filling, stretching, cutting, machining, fusing, and stretching again. Certainly, there are many important parameters to be controlled.

First, the structure of a MPOF preform with a 631-hole hexagonal array was designed as shown in Fig. 1(a), and then the preform was fabricated by extrusion of optical-grade polymethylmethacrylate (PMMA) (refraction index of 1.49) pellets in a homemade extruder as reported before [11]. The resultant PMMA-based MOF preform has a 70 mm outer diam-

![Fig. 1.](image-url)
eter, 250 mm length, 1.5 mm air-hole diameter, and 1.8 mm hole spacing [Fig. 1(b)]. The next step was to fill all air holes along the preform length with polystyrene (PS) fibers (refraction index of 1.59). Then, the PS-fiber-filled MOF preform was fused together in a vacuum oven at 155°C for 8 h. Because of the approximate thermal processing temperature of PMMA and PS, the PS-PMMA-based MOF (named primary preform) was stretched to form a slender rod with about 25 mm outer diameter and about 1.2 m length. The rod was cut to a fixed length. Then, seven pieces of fixed length rod with the same diameters were machined to six sectorlike cross-section rods and one hexagonal cross-section rod. The machined surfaces of rods were polished one by one to be smooth. Finally, the hexagonal cross-section rod was surrounded by six sectorlike cross-section rods like a plum blossom, and they were fused together at 165°C to form the secondary preform. All of the steps from primary to secondary preform are schematically shown in Fig. 2(a). A photograph of the resultant secondary preform with 4417 pixels was shown in Fig. 2(b). The whole process was carried out in a routine experimental room.

The imaging capability of the resultant fused image fiber sample was primarily observed by using a set of homemade assay systems as shown in Fig. 3(a). The main components in the imaging system are an LED white light source, a collimating lenses, an optical micrometer, a 20× objective lens, an 8× ocular lens, a CCD camera, and a 0.5 m length of the resultant MPOF image fiber sample. An optical micrometer with 10 μm scale as a test specimen was connected to one end of the fused imaging fiber sample. When the LED is turned on, an image of the optical micrometer was inputted to an end of the fused imaging fiber sample, transmitted, and outputted from the other end connected with a CCD camera. In this system, the original image of the optical micrometer was magnified by the 20× objective and the 8× ocular lens, respectively. In this way, imaging capabilities of the resultant PS-PMMA-based MOF sample with 4417 pixels, 3 μm pixel diameter, 0.25 mm outer diameter, and 0.5 m length were demonstrated. A microscopic photograph of the optical micrometer was shown in Fig. 3(b). The minimum scale of 10 μm on the micrometer was clearly discerned. Unfortunately, several hexagonal grids originating from fusing milled sectorlike and hexagonal cross-section rods interfere with the image; this should be improved by a more precise machining process in the future.

For the resultant PS-PMMA-based faceplate and taper, imaging abilities were directly observed by naked eyes. Figure 4(a) shows the photograph of a MPOF faceplate sample with 8 mm outer diameter, 2 mm thickness, and 80 μm pixel diameter. The characters “ABCDEF” were clearly transmitted with 75% transmittance. Figure 4(b) is a photograph of the resultant MPOF taper sample with a 24 mm diameter at the large end and a 12 mm outer diameter at the small end.

The diffraction-limiting resolution for the resultant
MPOF image guides can be obtained by the use of the dimensionless parameter $V$. The relationship between $V$ and fiber diameter $R$ is written as \[ R = V \lambda/(2 \pi \times \text{NA}), \] (1)

where the numerical aperture (NA) is that of the individual fiber of an image fiber and $\lambda$ is the wavelength of light. For a fiber to be of minimum radius, $V$ should be 2.405 in a single-mode fiber. If $\lambda$ is assumed to be 0.5 mm and if the NA is calculated by

\[ \text{NA} = (n_1^2 - n_2^2)^{1/2}, \] (2)
in which $n_1$ and $n_2$ are the refractive indices of PS and PMMA, respectively, here, the minimum radius of the fiber will be 0.62 $\mu$m, which yields about 466 line pairs/mm of limiting resolution for this case.

A simple method for fabricating ultrahigh-resolution fused image fiber, optical faceplate, and taper was demonstrated. This is promising for developing the mass-fabrication technology of the MPOF into the production of fused image optic components. With developments and advances in technology for machining and stretching large fused MPOF preforms, it will be possible to fabricate various lightweight, lower-cost, and high-flexibility image optic components used in medical and other fields [15,16].

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References