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Fabrication of imaging microstructured optical fibers

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ABSTRACT

We demonstrate the fabrication of multi-core (imaging) microstructured optical fiber via soft-glass extrusion through a 3D printed die. The combination of 3D metal printing and extrusion allows for unprecedented control of the optical fiber geometry. We have exploited this to demonstrate a 100 pixel rectangular array imaging microstructured fiber. Due to the high refractive index of the glass used ($n = 1.62$), such a fiber can theoretically have a pixel pitch of less than 2 µm. This opens opportunities for ultra-small, high-resolution imaging fibers fabricated from diverse glass types.

Keywords: Imaging fibers, optical fiber fabrication, glass extrusion, microstructured optical fibers, 3D printing

1. INTRODUCTION

Imaging inside the human body is routinely performed in organs such as the esophagus, lungs, and bowel. There is great interest in miniaturizing in-vivo imaging tools for minimally invasive diagnostics deeper inside the body, such as the far reaches of the lungs. While electronic cameras are commercially available with dimensions approaching 1 mm, there is significant scope for fiber optics to play a role in sub-millimeter imaging, spectroscopic imaging, or where electromagnetic interference is present.

Imaging fibers and fiber bundles are readily available from manufacturers such as Schott Glass, Fujikura, and Asahi. For example, imaging fibers from Fujikura can be provided in dimensions of 0.3 to 2.0 mm outer diameter and feature between several thousand and up to 100,000 pixels. The limitation of such imaging fibers is that the pitch between cores (pixels) is relatively large (approximately 5 µm or greater) due to the comparatively low index contrast possible with solid fibers.

Microstructured optical fibers, such consist of air holes that run along their length, are an alternative design of optical fiber that allows for a large selection in glass, and polymer [1]. These fibers allow for large differences in refractive index, n, in the fiber cross section (e.g. $n = 1.445$ for silica glass and $n = 1.000$ for air). Previous demonstrations to fabricate imaging MOFs have typically focused on polymer fibers. Eijkelenborg fabricated a 112 core imaging fiber from drilled poly(methyl methacrylate) (PMMA), with an outer diameter of 800 µm [2] and Wang *et al.* fabricated a 547 hole PMMA fiber with 320 µm diameter [3]. However, while polymer has good compatibility for biomedical use, it suffers from difficulty in cleaving and relatively poor transmission properties compared to glass. In a recent demonstration, 11,000 cores were demonstrated in a silica capillary stacked microstructured optical fiber [4].

Due to the large refractive index contrast, microstructured optical fibers can be fabricated with extremely small core diameters. In 2009 we demonstrated a lead-silicate glass suspended-core optical fibers with core diameters as small 420 nm [5]. Such fibers have found applications in sensing [6-8] and nonlinear optics [9].

In this paper we demonstrate the fabrication of an array version of the suspended-core fiber from soft-glass. This has been achieved though extrusion of soft-glass through a 3D printed titanium die to fabricate a preform with four cores, which was then caned and stacked, before drawing into a 100 core fiber.

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2. FIBER FABRICATION

2.1 Extrusion

We have fabricated a 100 core imaging microstructured optical fiber by first 3D printing a four-core titanium extrusion die. A high-index lead-silicate glass billet (n=1.62, F2, Schott) was then extruded through the die at high temperature and force (575°C at 2,500 N), with the extrusion process shown schematically in Fig. 1(a) and the target preform geometry shown in Fig. 1(b) The resulting cross-section of the extruded preform is shown in Fig. 1(c). Some distortion compared to the target geometry is seen, due to die swell effects in the extrusion process. Further refinement of the 3D geometry of the extrusion die may be used in future to counter these effects.

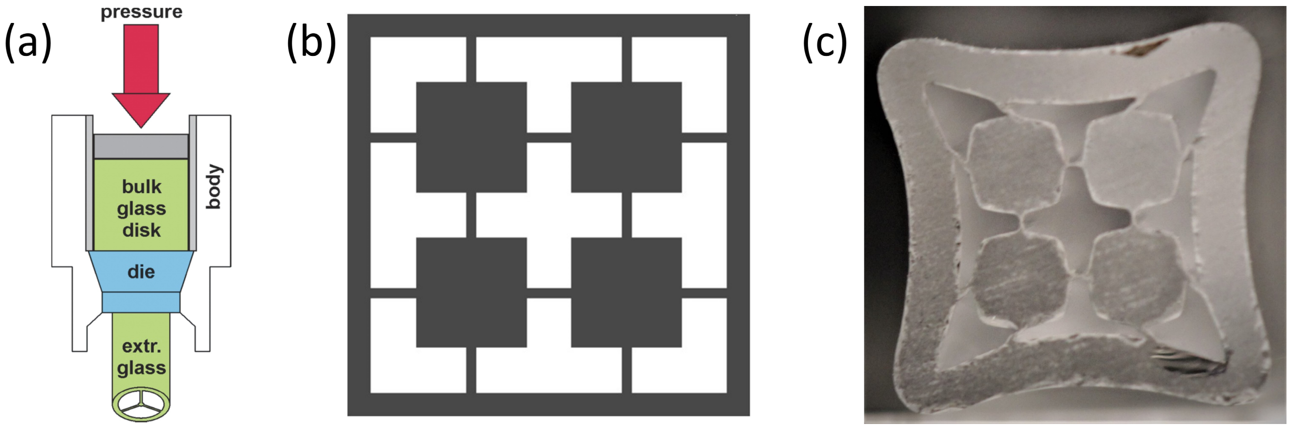

Figure 1. (a) Schematic diagram of the glass extrusion process. (b) Cross section of the die exit used to fabricate the four-core preform where grey refers to the glass exit. (c) Cross section of the extruded four-core preform, diameter approximately 8 mm.

2.2 Fiber drawing

The extruded preform shown in Fig. 1(c) was caned to 1 mm diameter using a fiber draw tower and then stacked in a 5x5 rectangular arrangement. The stacked array was then inserted into an extruded lead-silicate tube with 12 mm round outer diameter and 6 mm diameter square inner. The stacked assembly was then drawn into optical fiber, with the resulting cross-section shown in Fig. 2.

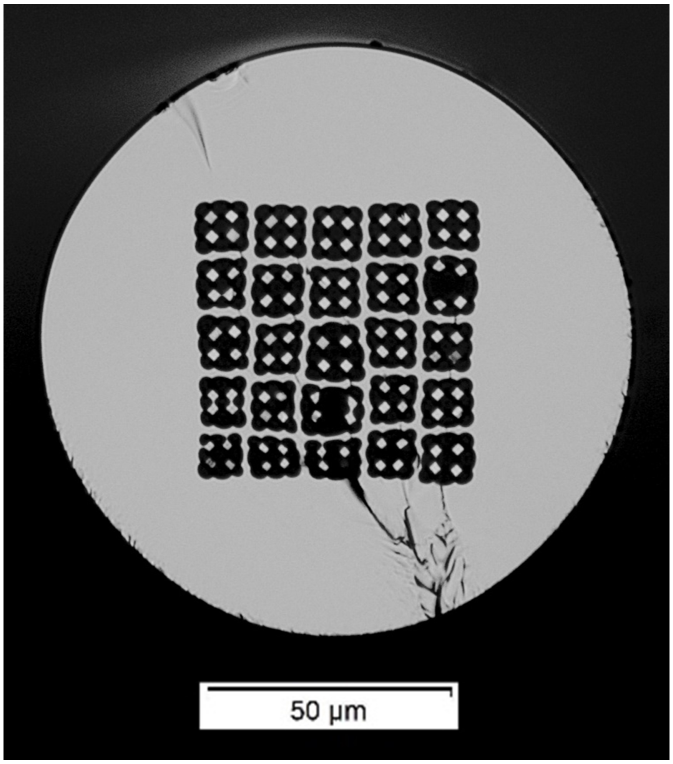

Figure 2. Transmission microscope image of the imaging microstructured optical fiber. Fiber diameter is approximately 160 µm.

3. OPTICAL TRANSMISSION

Optical experiments confirm that the 100 cores independently guide light. The experimental setup is shown in Fig. 3(a), where light from a 532 nm laser was coupled separately into the cores of the imaging MOF. The output of the imaging MOF was then imaged onto a CCD camera to determine if coupling occurred to adjacent cores. Two regions of the imaging MOF are shown as examples, as indicated in Fig. 3(b). For the majority of cores the light was guided within the single pixel, such as shown in Fig. 3(c-e). In a small number of cases where an adjacent strut was sufficiently thick, coupling to the corresponding adjacent core could be observed as seen in Fig. 3(f).

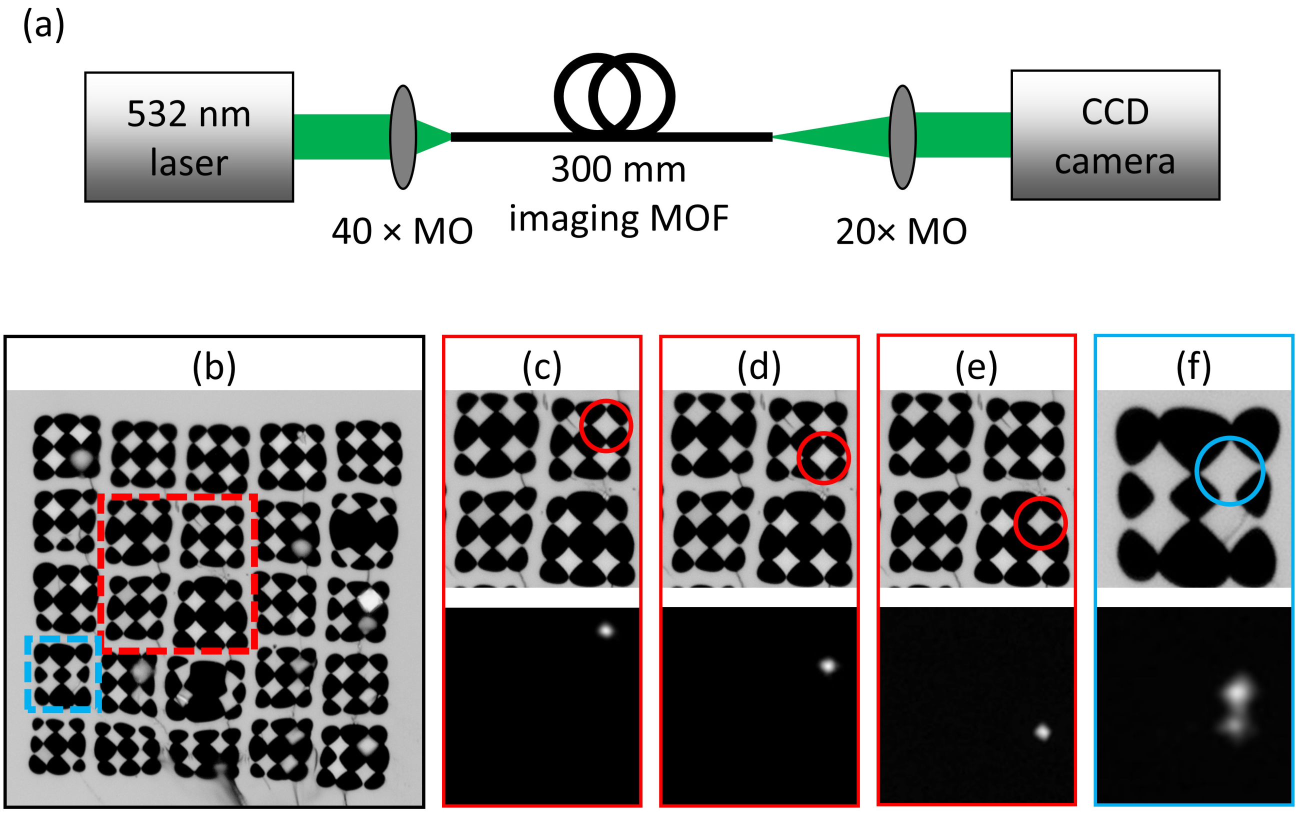

Figure 3. (a) Experimental setup used to demonstrate that individual cores independently guide light. (b) Reflection microscope image from the imaging MOF. (c-e) Light coupled into individual cores where the surrounding struts prevent cross-coupling to neighboring cores. (f) Light coupled into a core where an adjacent strut is sufficiently large to allow coupling to an adjacent core. Reprinted from [10].

4. THEORY

A key requirement for an imaging fiber is that coupling between adjacent cores is minimized. We have numerically modelled this coupling using a simplified model of two square cores with a width and height ("core diameter") of D, and a separation of S and solved using the finite element method (COMSOL v5.2). When the two cores are identical there exists even and odd nondegenerate mode solutions for each polarization [Fig. 4(a)]. The core widths and separation were varied to determine the coupling length, L_c, for coupling between the even and odd modes, where the coupling length is given by [11]:

$$L_c = \frac{\lambda}{2(n^e_{eff} - n^o_{eff})} \tag{1}$$

where λ is the free space wavelength and n_{eff} is the effective index of the even (e) and odd (o) modes.

Figure 4(b) shows the values for core diameter and core separation for three values of coherence length (0.1 m, 1.0 m and 10 m), considering the x-polarization as defined in Fig. 4(a). The dashed lines show values for various fill factors (fraction of glass versus total cross-sectional area). For example, if a core diameter of 1.2 µm is used then the cores must be separated by 0.60 µm to have a coherence length of 1.0 m, in which case the fill factor is just below 50%. This corresponds to approximately 3,800 pixels in a 125 µm fiber or 15,000 pixels in a 250 µm fiber.

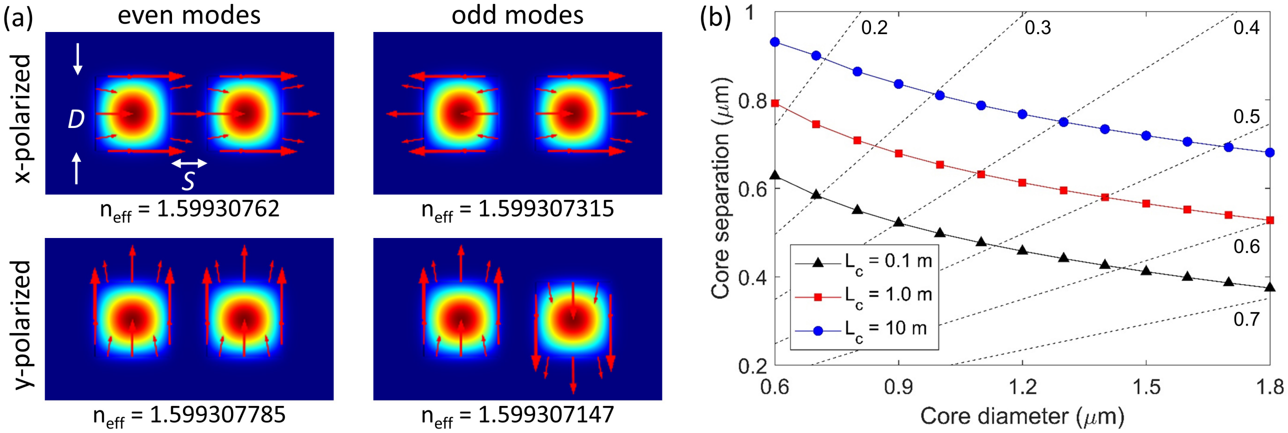

Figure 4. (a). Nondegenerate mode solutions for a waveguide with two identical adjacent cores. The square cores are glass (n = 1.62), surrounded by air (n = 1.00). Wavelength is 532 nm. (b) The calculated coupling length for different values of core diameter, *D*, and separation, *S*. Reprinted from [10].

5. DISCUSSION AND CONCLUSIONS

We have demonstrated the fabrication of a soft-glass imaging microstructured optical fiber. The optical fiber preform was fabricated by extruding lead-silicate glass through a titanium 3D printed die. The preform was then caned, stacked and redrawn into a 100 core fiber. The combination of extrusion and 3D printing with stacking allowed for unprecedented control of the preform and fiber geometry, such as the rectangular features in this work.

Optical experiments confirm that the cores independently guide light. Numerical modelling shows that the number of cores can be increased to up to 15,000 in a 250 µm diameter fiber. Our future work will focus on increasing the uniformity and number of cores in the imaging fiber, and applying spectroscopy techniques for in-vivo imaging.

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