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Prospects for "green" microstuctured optical fibers

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Abstract: A powder-filling technique was used to fabricate a variety of biodegradable microstructured polymer optical fibers using poly(ϵ-caprolactone) and cellulose derivatives. These fibers hold potential for light delivery and sensing.
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OCIS codes: 060.2280 Fiber design and fabrication; 060.2270 Fiber characterization

Biomaterials, or synthetic biodegradable polymers, have proven to be extremely useful for a wide range of health applications such as medical products, scaffolds for tissue engineering, and formulations for controlled drug-release therapies [1]. Independently, the field of microstructured polymer optical fibers (MPOFs) has grown tremendously in the past few years [2, 3, 4]. Polymer optical fibers offer many unique advantages such as low cost and the possibility of tailoring fiber optical properties through doping, polymer functionalization, and fiber geometry manipulation. This versatility has lead to a wide variety of new fiber geometries, allowing integration of several functionalities into the same fiber beyond simple optical guidance. We believe that the marriage of biomaterials and microstructured optical fibers (green fiber optics) opens a new venue for the application of optical fibers in medicine, notably in-vivo sensing and imaging, controlled drug delivery, and power delivery for laser surgery.

In this paper, we report on the fabrication of biodegradable-polymer optical fibers guiding by total internal reflection that were obtained using a powder-filling technique. Schematics of the preform geometries and cross-section images of the drawn fibers are presented in Figure 1.A-C. Furthermore, a supercontinuum white-light source was coupled into the fibers and Figure 1.D-F reports the normalized transmission spectra of the studied fibers for the light launched either in the fiber core or cladding. In the insets, the photos of the intensity distribution in the fiber cross-sections are shown for the two launch conditions.

The first fiber we describe consists of cellulose burtyrate (CB) tubes, bought from McMaster-CARR, that were drawn into capillaries of 393 μm diameter at a temperature of 178 °C. Interestingly, over the distances of several centimeters, such capillaries can guide light in their hollow cores, as seen in Figure 1.D, with an estimated loss of $\sim$1 dB/cm. Further measurement of the light guidance in a CB cladding of a 6.95 cm long capillary lead to a 2.2 dB/cm fiber loss estimate at $\lambda = 633$ nm. CB appears to be the most transparent of the biodegradable polymers studied. In another experiment (not shown here) a poly(L-lactic acid) and cellulose acetate (CA) fiber was fabricated. The transmission losses in the CA region fiber were estimated to be 9.8 dB/cm at $\lambda = 633$nm.

The second and third types of fibers presented are multiple-cladding fibers (Figures 1.B-1.C) that were fabricated by filling the interstitial region between two CB tubes ($n_{\mathrm{CB}} = 1.48$) with an optically different material. CB was chosen as a tube material mainly because of its commercially availability. As filling materials for the interstitial region, higher refractive index poly(ϵ-caprolactone) (PCL, $n_{\mathrm{PCL}} = 1.52$) and lower refractive index hydroxypropyl cellulose (HPC, $n_{\mathrm{HPC}} = 1.34$) were used. Both polymers were purchased as powders from Sigma-Aldrich. Potential application of multiple-cladding fibers include enhanced in-vivo sensing where high intensity light is launched through a smaller core, while reflected light is collected efficiently through an intermediate cladding acting as a larger core [5].

In the first case, a PCL/CB multiple-cladding fiber was fabricated by inserting a small CB tube, having inner and outer diameters of 1/8 and 1/4 inch, into a larger CB tube, having inner and outer diameters of 3/8 and 5/8 inch, respectively. The PCL powder was then tightly compacted in the interstice between the two tubes, thus forming two concentric PCL fiber "cores". The consolidated preform was then drawn at 178 °C into a 410 μm diameter fiber. It was difficult to prevent the formation of trapped air bubbles in the preform. An air hole defect can clearly be seen in the resulting fiber (Figure 1.B) and Figure 1.E shows its transmission spectrum. Whereas the air defect can guide some light, the PCL regions appear to be optically opaque and

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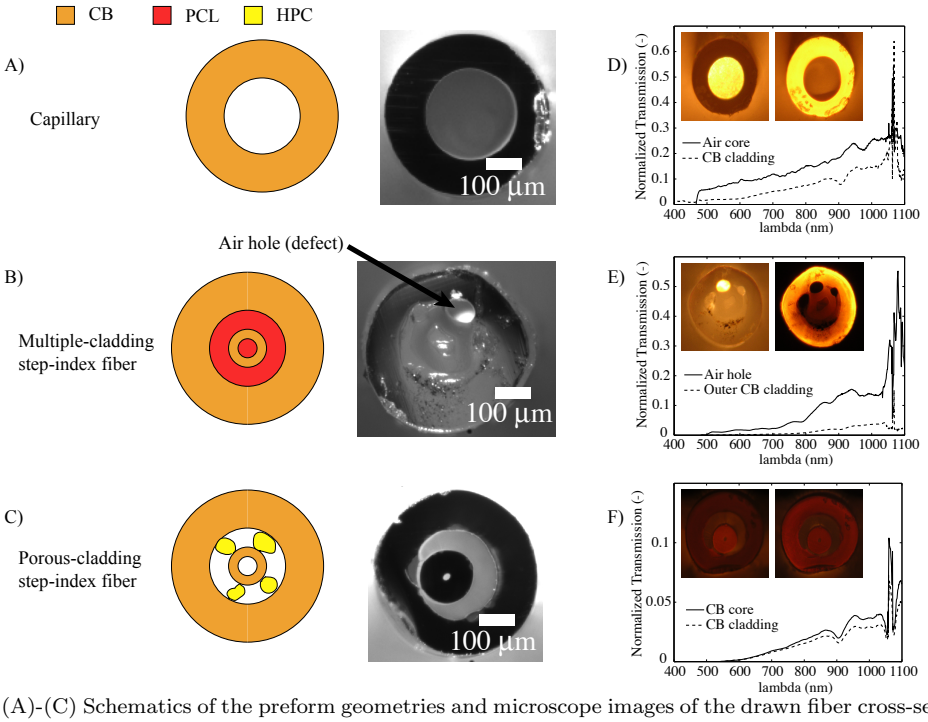

Fig. 1. (A)-(C) Schematics of the preform geometries and microscope images of the drawn fiber cross-sections using various fabrication strategies. (D)-(F) Transmission spectra of the biodegradable optical fibers with images of the transmitted light as insets. The lengths of the measured segments are 6.95, 3.25, and 8.05 cm respectively.

true guidance can only be observed by coupling into the CB regions. We ascribe non transparency of a PCL fiber core to the high degree of crystallinity in this material after perform consolidation, which can be also confirmed as a milky color of the resulting fibers. The loss in the outer CB cladding of this multiple-cladding fiber of length 3.25 cm was estimated to be 8.3 dB/cm at $\lambda = 633$ nm.

For the second multiple-cladding design, a small CB tube is suspended in air within a larger CB tube with the aid of network of distributed lower-index powder particles (Figure 1.C). The chosen lower index material is hydroxypropyl cellulose (HPC), which is a water-soluble derivative of cellulose commonly used in ophthalmology. Interestingly, HPC has higher glass transition temperature than CB and the powder particles remain intact during the drawing process. The details of the fabrication process are presented elsewhere [4]. The transmission spectrum of this porous fiber is presented in figure 1.F. We note that losses through the inner and outer cores are similar, with an estimated loss of 3.1 dB/cm at $\lambda = 633$ nm as measured using an 8.05 cm fiber. These losses are mostly attributable to the HPC particles forming a network of scatterers lining the inner fiber core. A potential application of these fibers is monitored drug release is aqueous environments.

In summary, we have presented different biodegradable microstructured plastic optical fibers fabricated with a powder-filling technique. Furthermore, we have demonstrated that the industrially rugged process of fiber drawing from solid preforms can be applied to the mass production of such fibers. These fibers hold potential for applications in in-vivo sensing, imaging, controlled drug delivery, and high power delivery.

3. References

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