Biodegradable, double-core, porous optical fiber for sensing applications.

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Abstract: Microstructured biodegradable optical fiber is fabricated featuring 1.1 dB/cm loss. Two cellulose butyrate tubes separated with hydroxypropyl cellulose powder were co-drawn into a porous double-core fiber offering integration of optical, microfluidic and potentially, drug release functionalities.

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1. Introduction

We present design and fabrication of a first, to our knowledge, biodegradable polymer optical fiber that simultaneously embodies optical, microfluidic, and drug release functionalities. Double-core porous fiber structure presents a small inner core suspended in air by the low refractive index particles separating it from the larger outer core (Fig. 1(a)). Double core structure enables laser power delivery as well as improved collection of the reflected light for passive sensing, cladding porosity enables microfluidics and active biological sensing, while biodegradable material combination offers a possibility of controllable drug delivery.

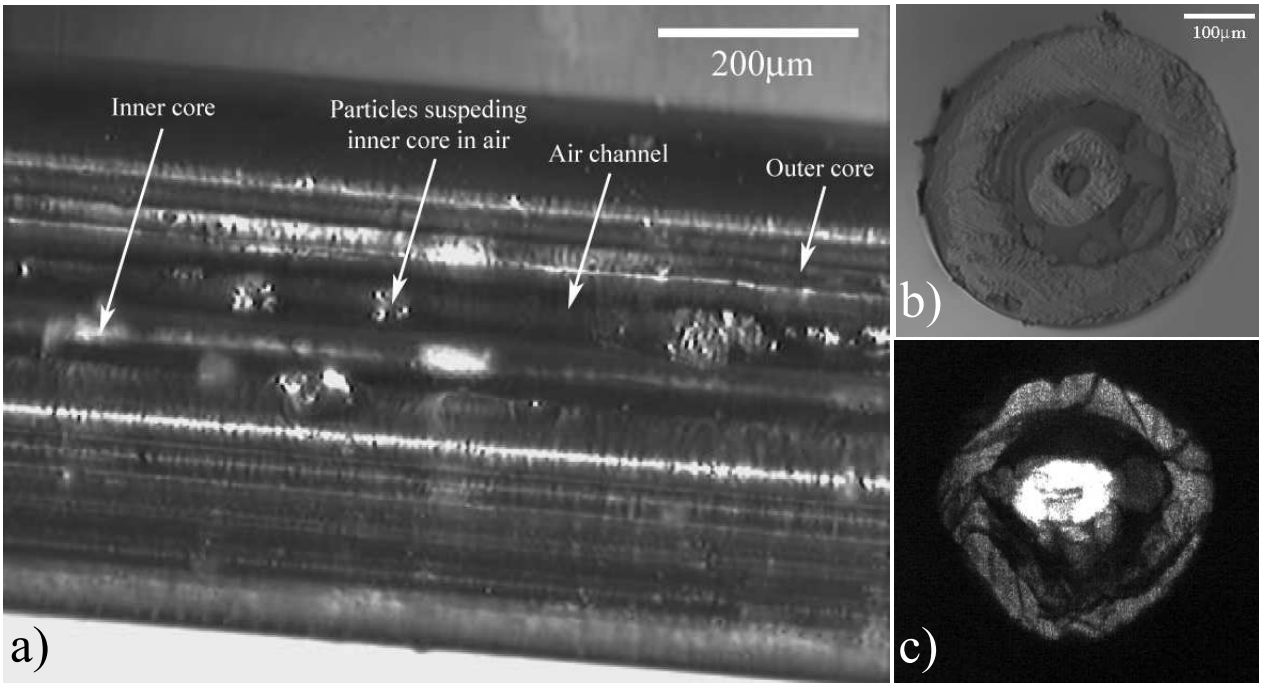

Fig. 1. a) Double core biodegradable microstructured fiber. The inner fiber is suspended in air by the powder particles. b) Fiber crossection. c) Power distribution in the fiber crossection after 3cm of propagation.

Due to their bio-friendly material composition and low cost of fabrication, microstructured polymer optical fibers have recently received much attention in a view of numerous bio-medical applications. Particularly, polymer microstructured optical fibers having porous structure offer a tremendous potential for simultaneous in-vivo medical sensing and laser power delivery, thus offering an integration platform for design of a complete

diagnostic/laser treatment system in a single fiber. Moreover, if made of biodegradable materials such fibers can be impregnated with active pharmaceuticals such as anaesthetics or antibiotics enabling controllable release of chemical therapeuticals during treatment. In a diagnostic mode, a sample to be analyzed can be pumped through the interstices of a porous fiber, while the light guiding through the fiber core can be used for detection. For example, Jensen et al. [1] have demonstrated fluorescence detection of selectively captured antibodies that were labelled with fluorescent markers. They also found that deposition of a sensing bio-layer is considerably easier if done on a polymer surface than on a glass surface, making polymer fibers better suited for bio-sensing than the glass ones. Recently, the use of dual-cladding optical fibers [2, 3] has attracted a lot of interest in the field of fluorescence microscopy as such structure permits single-mode delivery of the excitation pulse through a smaller core, and efficient multi-mode collection of the signal (fluorescent light) by the larger core of higher numerical aperture [2, 3, 4, 5]. In a laser delivery mode, hollow core microstructured fibers have been demonstrated to deliver tens of watts of laser power almost anywhere in the visible and IR, enabling flexible delivery of power from the medically important $Nd:Yag$, $Er:Yag$ and CO_2 lasers [6].

Fig. 2. Photographs of the biodegradable, double core, porous fiber preform, and its crossection.

2. Fabrication and Characterization of the Fiber

Fiber preform (Fig. 2) was prepared using commercially available cellulose butyrate tubes of different diameters that have refractive index of 1.475. The smaller tube has inner and outer diameters of 1/8 and 1/4 inch, respectively, whereas the larger tube has inner and outer diameters of 3/8 and 5/8 inch, respectively. The smaller diameter tube, which forms the inner of the two fiber cores, was sealed at both ends with Teflon tape and placed in the middle of the larger tube that formed the outer core. In the final fiber structure the air hole of the inner tube could be collapsed or left open depending upon application. The space between the tubes was then filled with a polydisperse hydroxypropyl cellulose powder having refractive index of 1.337, in order to obtain a lower index inner cladding. The glass transition temperatures of cellulose butyrate and hydroxypropyl cellulose are estimated to be 95^oC and 120^oC, respectively. As the powder has significantly higher melting temperature than the tubes, it remains in a power state during the drawing process. The preform was preheated in the furnace of the drawing tower at a temperature of 150^oC for one hour and the fiber was subsequently drawn around 180^oC.

The biodegradable fiber was drawn down to a diameter of 450 μm, and a standard cutback measurement was performed to give fiber transmission loss of 1.1 dB/cm at $\lambda = 630$ nm. Distribution of power in the fiber crossection Fig. 1(b) after 3cm of propagation is shown in Fig. 1(c), where nonuniformity in the power distribution is mostly due to the fiber end distortion caused by cutting. In Fig. 1(a) three light sources were used to visualize the particles in the cladding. Powder particles that remained intact during the drawing process are clearly seen to be supporting the inner core. It is difficult to estimate the air fraction of the inner cladding but the resulting structure is very porous. The effective index of refraction of the inner cladding is thus very close to that of air. It is worth mentioning that Kominsky et al. [7] have attempted a similar structure in silica. The marked difference is that they packed silica powder between two silica tubes and the resulting fiber had a random pattern of holes. Since the powder was of the same material as the tubes, those holes had randomly collapsed leaving longitudinal bubbles of random length within the inner cladding.

3. Microfluidics. Time variation of power transmission through the fiber submerged in water

Finally, we report preliminary results on variations in optical power transmitted through the double core microstructured fiber operated suspended in a deionized water. When water with refractive index $n_w \simeq 1.32$ fills an empty space between the two cores $n_c = 1.475$, fiber scattering loss should decrease compared to the air-filled fiber due to a reduced core-clad index-contrast. Thus, after submerging the fiber into water one should observe a considerable increase in the optical power transmission. However, as the hydroxypropyl cellulose powder separating the two cores is dissolvable in water, one would expect that fiber optical properties should eventually degrade when exposed to water for a long enough time. In a typical measurement of a transmitted power through a 2cm fiber piece suspended in a deionized water (Fig. 3), transmitted power would first increase dramatically in the first hour of water exposure, followed by decrease in the transmission loss from $1.1dB/cm$ to $0.46dB/cm$. Transmitted power would then stabilize for approximately 5 hours. After long enough time (typically 5-10 hours) fiber transmission typically goes down, probably due to the failure of a network of particles separating the two cores, causing increase in scattering losses. More experiments on microfluidic properties of such fibers are currently underway.

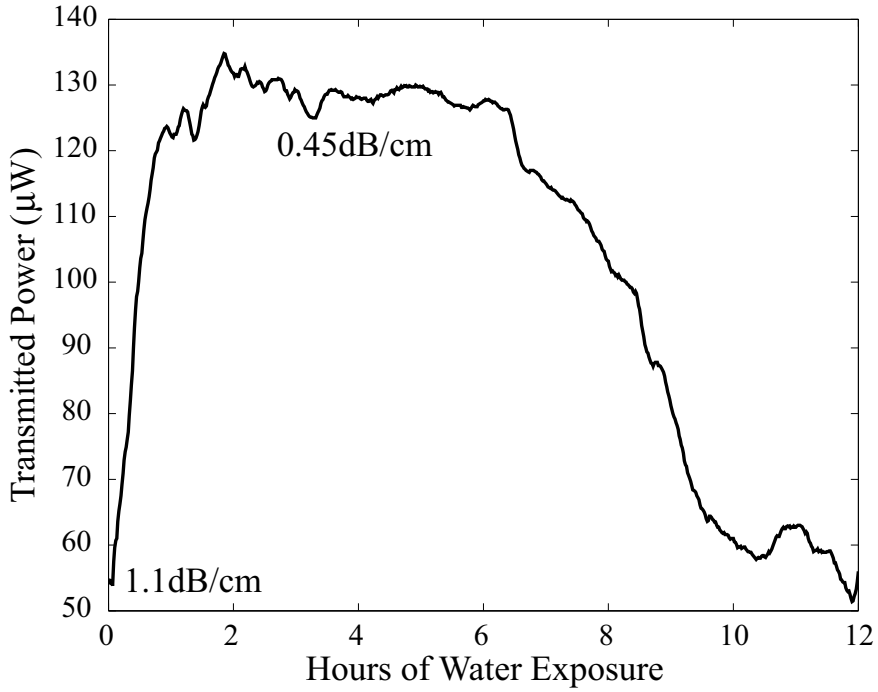

Fig. 3. Transmitted power through a 2cm fiber piece suspended in a deionized water. In the first hour when water penetrates the inter-core space, transmitted power increases dramatically, followed by the decrease in the fiber transmission loss from $1.1dB/m$ to $0.46dB/m$. In the next 5 hours power is stabilized. After 5 hours power transmission slowly goes down, probably due to the failure of the water dissolvable hydroxypropyl cellulose particle network separating the two cores, thus causing additional scattering loss.

4. References

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