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Optofluidic microchannels in aerogel

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We report optofluidic waveguides made by filling microchannels in aerogel with water. The aerogel cladding is a nanoporous material with an extremely low refractive index of ~ 1.05 , giving a large index step from the water core. Channels were formed by removing embedded optical fibers, which could be nonuniform or multiple. The porosity of the aerogel allowed air to be displaced from the channel, preventing the trapping of bubbles. The attenuation of red light in the highly multimode water core waveguide was no greater than 1.5 dB/cm. © 2011 Optical Society of America

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Optofluidics exploits the interaction of fluids and light at the microscale and has attracted much interest in recent years. For example, manipulating the fluid gives optical devices tunability and adaptability, while strong confinement of light aids applications such as fluorescence spectroscopy, biochemical sensing, Raman spectroscopy, and microfluidic dye lasers [1–4].

An optofluidic waveguide is formed from a fluid core filling a channel in a substrate. The material on the channel's surface acts as the waveguide cladding, and so should be transparent with appropriate refractive properties. Reported examples include antiresonant reflecting optical waveguides [5], slot waveguides [6], and total-internal-reflection waveguides with a low-index cladding [3].

Teflon coatings are one choice of cladding material for aqueous core waveguides, though the relatively low refractive index contrast of 0.04 between Teflon and water limits its performance. In contrast, nanoporous porogen film with an index of 1.15 has been used to efficiently collect and transmit fluorescence, demonstrating an advantage of cladding materials with lower indices and higher numerical apertures [3].

In this Letter, we report optofluidic waveguides in hydrophobic silica aerogel. The highly nanoporous aerogel behaves optically like “solid air,” in that it is a rigid transparent material with a refractive index of 1.05 or so. A water-filled microchannel in the aerogel therefore acts as a waveguide with a numerical aperture >0.8 . (These channels were ~ 3 orders of magnitude wider than the aerogel's natural pores, which were ~ 50 nm in scale.)

Figure 1 illustrates how the waveguides were made. An optical fiber with the cross section of the desired waveguide was held in a watertight container. Aerogel was formed around the fiber by pouring a sol into the container and converting it *in situ* into hydrophobic aerogel as described in [7,8]. Cylindrical microchannels were left in the aerogel block by carefully pulling the fiber out. The microchannels were filled with water by injection through an inserted fiber-sized capillary. Light was coupled into the resulting optofluidic waveguide via an optical fiber, again inserted into the microchannel after the capillary was removed.

The initial fiber was tightly embedded in the aerogel so its withdrawal required some force and was accompa-

nied by friction-induced sound. Nevertheless, except for some debris, the smooth surface of the fiber was replicated by the channel surface (Fig. 2) down to the ~ 50 nm scale of the aerogel's pores. This contrasts with the rough surfaces of holes drilled into aerogels by ultrafast lasers [9] and permits channels of indefinite length.

Channels narrower than standard fibers (with diameters down to less than $4\ \mu\text{m}$) were made by tapering the fiber before embedding it [7,8]. This also enabled tapered microchannels (Fig. 3(a)) and could give adiabatic taper transitions in the final optofluidic waveguide. Tapers allow low-loss coupling of light to narrow optofluidic waveguides and give control over dispersion and nonlinearity [10]. Obviously, a tapered fiber cannot be withdrawn in one piece from a constricted channel, but it was easy to break the fiber first at its thinnest point by pulling one end while holding the other (Fig. 3(b)).

Hydrophobic treatment of the aerogel was necessary to prevent it degrading in the presence of water [8], but it meant that the microchannels could not be filled simply by immersion. We therefore injected water into

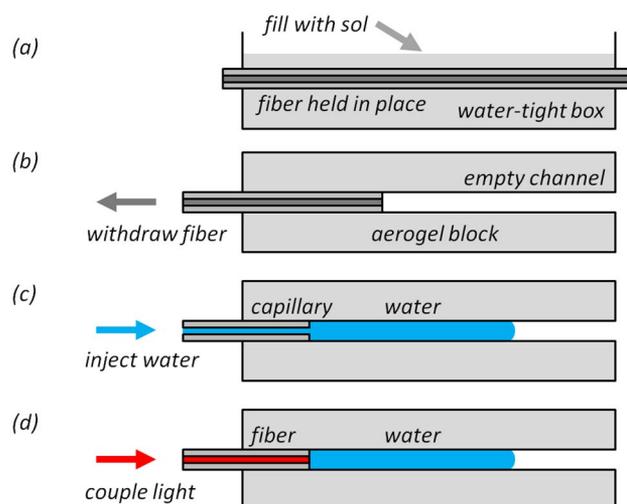


Fig. 1. (Color online) Formation of optofluidic waveguides in aerogel. (a) The precursor sol is poured over a fiber held in a box, allowed to gel, then processed into aerogel. (b) The fiber is pulled out of the aerogel block to leave a microchannel. (c) Water is pumped into the microchannel through a capillary. (d) Light is coupled into the water column via a reinserted fiber.

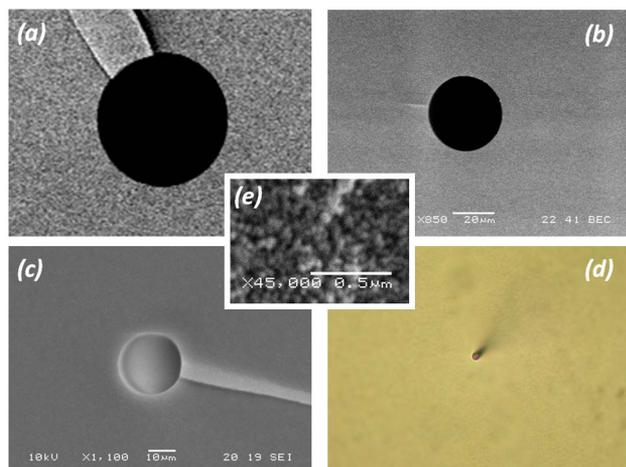


Fig. 2. (Color online) Cleaved cross-sections of microchannels with diameters (a) 100, (b) 35, (c) 23, and (d) $4\ \mu\text{m}$. The first three images are scanning electron micrographs (SEMs) while the last is an optical micrograph. (e) SEM of the aerogel surface; the scale bar is $0.5\ \mu\text{m}$ long.

the channels using a syringe connected to a fiber-sized silica capillary, which was carefully inserted into one end of the channel. A convex meniscus was seen at the end of the water column inside the channel, and a spherical droplet formed when it emerged from the end of the channel (Figs. 4(a) and 4(b)). There was no evidence of penetration of the aerogel's pores by liquid water.

Figures 4(c)–4(e) show the filling of two channels that merge together, a structure formed by embedding a twisted pair of fibers in the aerogel. This could allow the merging of two separate fluids and the combination or splitting of two light waves, which may be important for chemical processes [1]. Curved channels can be formed: indeed, it was possible to pull a millimeter-scale circular loop of tapered fiber out from an aerogel block, though we did not attempt to fill the resulting channel with water afterwards.

Also relevant to chemical applications is the fact that the porous aerogel readily allows gases to pass between the microchannel and the surroundings [8], allowing rapid solution or dissolution. Another consequence is that air bubbles between two separate water columns, or between one water column and a fiber, are not trapped in the channel but can diffuse out through the nanometer-scale pores in the aerogel. Such bubbles are undesirable for microfluid flow [11] and cause huge optical loss from

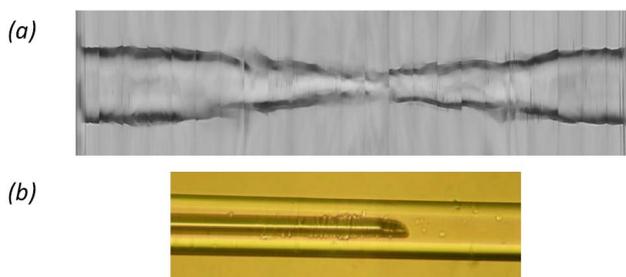


Fig. 3. (Color online) Side views of a $\sim 6\ \text{cm}$ long tapered microchannel in aerogel, $125\ \mu\text{m}$ in diameter at its widest. (a) A montage of images, $55\times$ compressed horizontally. (b) The broken tapered fiber being removed, as seen at a wider part of the channel.

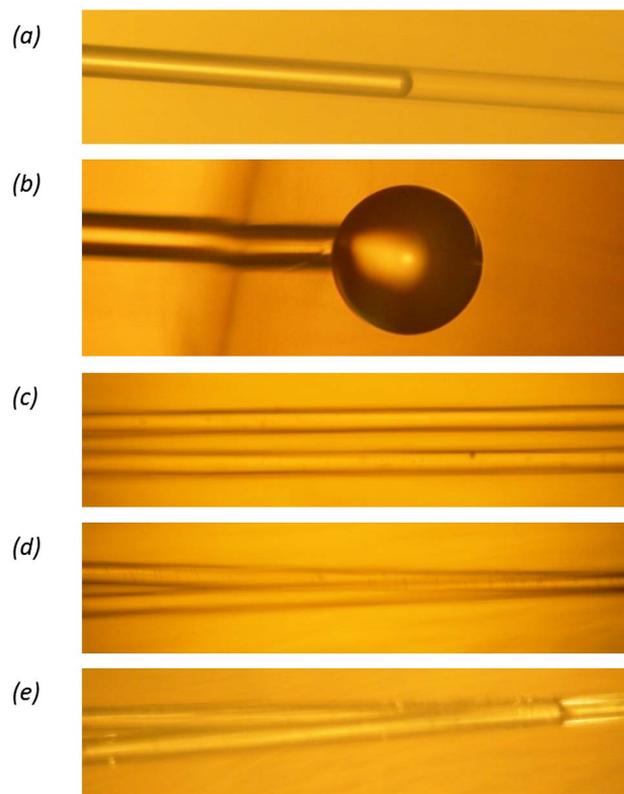


Fig. 4. (Color online) Water in $125\ \mu\text{m}$ diameter microchannels in aerogel. (a) A water column (injected from the left) partly filling a microchannel. (b) The spherical droplet at the end of a completely filled microchannel. (c) Two parallel air-filled microchannels (d) combining at a Y junction. (e) Two separate water columns merging at the Y junction shown in (d).

scattering and the failure of total internal reflection, a problem that is hard to avoid in conventional impermeable microchannels. In contrast, in the aerogel, we simply have to push one element (water column or fiber) towards the other and the air in between quickly escapes sideways, leaving a continuous bubble-free path (Fig. 5).

To demonstrate wave-guiding and measure optical attenuation, a fiber was inserted into a $125\ \mu\text{m}$ diameter microchannel containing a short water column. The air gap between the end of the fiber and the water column was eliminated as described above. Laser light with a wavelength of $635\ \text{nm}$ was injected into the other end of the fiber, which was single-mode at that wavelength. Figures 6(a) and 6(b) show water columns illuminated by the red light. In both cases, the bright scatter spot to the left lay at the end of the fiber, where there was an index mismatch with the water. The fainter scatter spot further

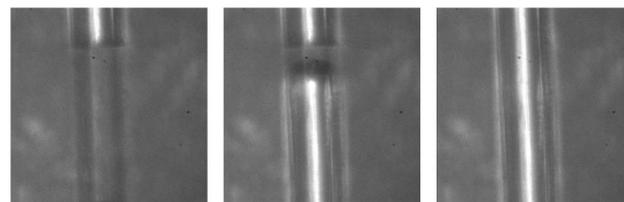


Fig. 5. Elimination of the air gap between two $125\ \mu\text{m}$ diameter water columns, as (left to right) the lower column is pushed towards the static upper column and joins it. (The contrast in these images has been digitally enhanced.)

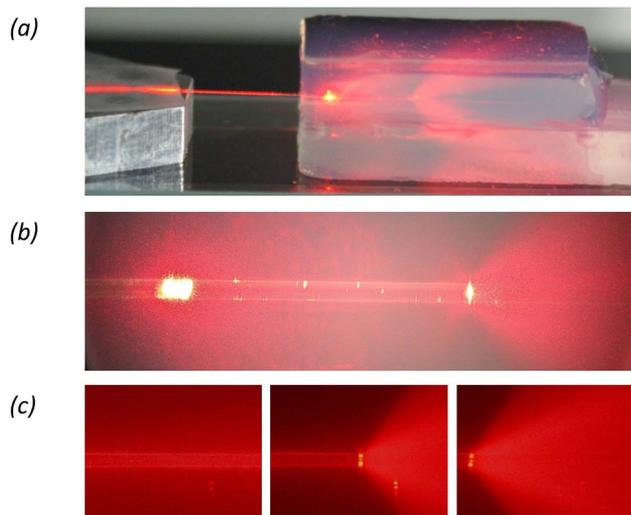


Fig. 6. (Color online) (a), (b) Guidance of 635 nm laser light in water columns of different lengths in a $125\ \mu\text{m}$ diameter aerogel microchannel. The light is incident from the left in a fiber, and emerges from the end of the water column toward the right. The fiber ends at the bright scatter point about 2 mm inside the 10 mm high aerogel block. (c) (left to right) Images taken at 40 s intervals at the end of a water column, as the water evaporates.

to the right was at the far end of the water column, beyond which the microchannel was air-filled and so not a waveguide. The cone of unguided light beyond this point was visible because of Rayleigh-like scattering in the aerogel. The cone half-angle was comparable to the 55° acceptance angle expected for a filled highly multimode waveguide with core and cladding refractive indices of 1.33 and 1.05, respectively, though the meniscus at the end would have caused some lensing. Indeed, we expect that the power of the lens at the end of a full microchannel [Fig. 4(b)] could be varied by manipulating the input fiber to piston the water column in or out, and thereby change the curvature of the meniscus.

The light was well-guided along the water column. The waveguide loss was measured for a 16 mm long water column filling the whole microchannel beyond the input fiber. That is, the waveguide did not terminate within the aerogel block as shown in Fig. 6, but guided the light all the way to the far end of the block. The total loss, including input and output coupling losses, was 2.4 dB, corresponding to a waveguide attenuation no greater than 1.5 dB/cm.

In these optical experiments, we observed another consequence of the porosity of the aerogel: water was

able to evaporate through the pores into the dry lab air. As a result, the water column shortened appreciably over a time scale of minutes. The three micrographs in Fig. 6(c) were taken 40 s apart, showing the end of the water waveguide retreating from right to left. This could be prevented by housing the aerogel in a package with a humid atmosphere, or exploited as a humidity sensor. The large internal surface area of porous substrates has also been proposed as a way of increasing the density of binding sensor probes for biosensor applications [12].

In conclusion, we have demonstrated a simple method to fabricate fluidic microchannels in hydrophobic aerogel, with much better surface quality and lower loss than achieved by ultrafast laser machining. The porosity of the aerogel makes it easy to eliminate air bubbles, since “trapped” air can simply escape through the pores. First measurements of optical attenuation yield an upper bound of 1.5 dB/cm.

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