Sol-gel Derived Microstructured Fiber: Fabrication and Characterization

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Abstract: We discuss a sol-gel casting technique for fabricating microstructured optical fiber. Both the advantages and challenges associated with this fabrication method are outlined.

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1. Introduction

Microstructured fibers possess an array of air columns embedded within a silica matrix, which extend along the z-axis of fiber. The large index contrast between air and silica yields a number of exciting waveguiding properties such as photonic band gap guidance,[1] supercontinuum generation,[2] high birefringence,[3] endlessly single moded behavior,[4] and low bend-loss.[5] Recent improvements in fabrication have led to rapid reductions in the attenuations of microstructured fibers with values as low as 0.28 dB/km for index-guided structures and 1.7 dB/km for hollow core photonic band gap fibers. The reduced attenuations have made microstructured fibers more attractive as alternatives to conventional silica core fibers. Several methods have been developed for the fabrication of microstructured fibers including the stack and draw of glass capillaries, sol-gel casting, prefrom drilling, extrusion, and even outgassing of a porous preform during draw. All of the aforementioned methods have various advantages and tradeoffs in terms of ease of fabrication, cost, design flexibility, material contamination, and precision. Here, we describe our implementation of sol-gel casting technology towards the fabrication of microstructured optical fibers. The large design freedom, low-cost starting materials, dimensional precision, low material contamination and the ability to scale up to large preforms (> 10 km of fiber) makes this fabrication method an attractive approach towards high performance, low-cost microstructured fiber.

II. Fabrication

The sol-gel casting technique was originally developed for the production of large jacket tubes for optical fiber preforms[6] and has been modified for the fabrication of microstructured fiber.[7] A mold containing an array of mandrel elements is assembled and then filled with colloidal silica dispersed at high pH with an average particle size of 40nanometers. The pH is lowered causing the sol to gel. At the wet gel stage, the mandrel elements are removed, leaving air columns within the gel body. The gel body is then treated thermochemically to remove water, organic and transition metal contaminants. The dried porous gel body is then sintered near 1600 C into viscous glass and subsequently drawn into fiber. The air holes are pressurized during draw to obtain the desired size and air-fill fraction. To maintain uniformity along the length of the preform, the mandrels are individually tensioned and the positioning and spacing is inspected and recorded with a digital camera. A number of microstructured fibers fabricated using the sol-gel casting method are shown in figure 1. As a casting method, the sol-gel technique can fabricate any structure, which can be assembled into a mold. The hole size, shape and spacing may all be adjusted independently. By comparison, stack and draw methods are limited to closest-packed geometries such as triangular or honeycomb lattices and cannot easily generate circular patterns such as the one shown in figure 1d. Drilling methods allow adjustment of both the hole size and spacing, but are generally limited to a small number of holes and restricted to circular shapes. Furthermore, drilling of preforms leads to roughened surfaces along the air hole so that extra steps of etching and polishing of the inner surfaces are desired. Extrusion techniques provide design freedom, but are typically limited to soft glasses for which the material loss values are exceedingly high.[8] Several designs such as fibers for low-bend loss,[9] dispersion flattened designs[10] or birefringent fibers[11] require independent spacing, hole size or even noncircular holes. The sol-gel casting method provides additional design flexibility that will be necessary for such fibers.

Sol-gel casting is not without its own set of challenges. The mandrel elements are removed during the wet gel stage, while the gel body is still fragile. Removal of the mandrels at this stage places strain on the gel and for gel bodies with air-fill fractions >25%, cracking of the gel body is common and lowers the overall yield. Numerous

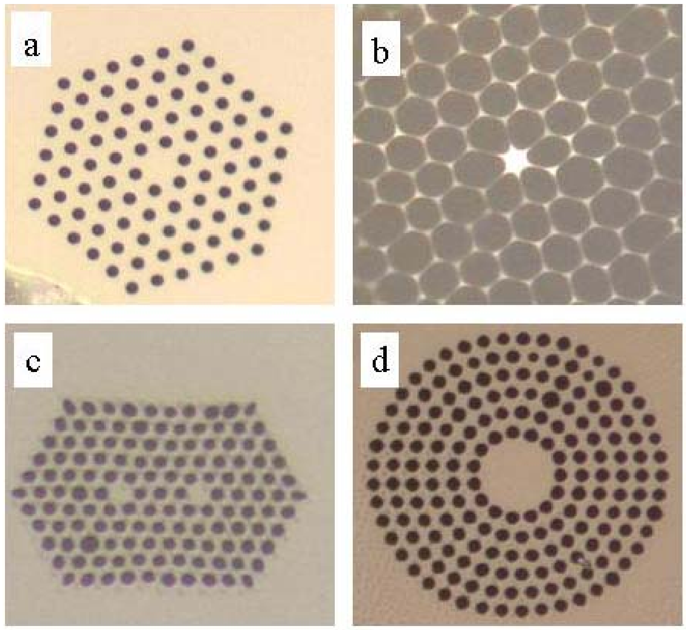

Fig. 1. Cross-sectional images of sol-gel derived microstructured fibers. The dark regions correspond to air columns while the bright regions are silica. a) endlessly single-moded design, b) high delta, highly nonlinear fiber, c) dual core structure and d) circular core microstructured fiber.

microstructured fiber designs such as hollow core photonic band gap fibers or highly nonlinear fibers require air-fill fractions near 90%. To fabricate fibers with high air-fill fractions, the low air-fill fraction glass preforms are etched with HF uniformly along the length of the preform. An example of using HF etching to increase the air fill-fraction of a preform is shown in Figure 2. Additionally, the air-fill fraction may be increased by pressurizing the air holes during draw. Figure 1b shows the resulting fiber with an air-fill fraction of 87% obtained from the pressurized draw a preform with only a 25% air-fill fraction.

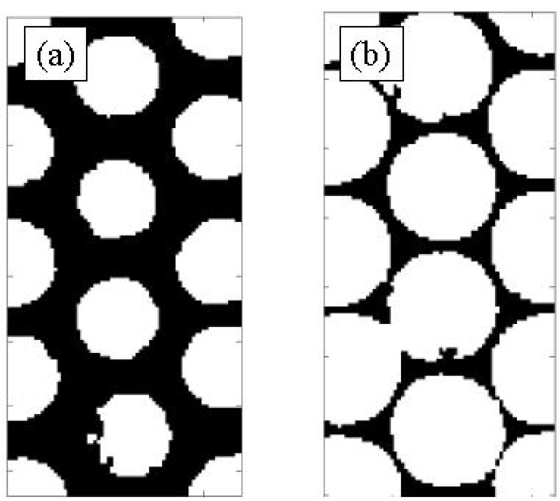

Figure 2. Cross sectional images of a sol-gel derived microstructured prefrom before (a) and after (b) HF etching. The air-fill fraction in the cladding was increased from 46% up to 78%

III. Optical properties

Several kilometer lengths of microstructured fiber have been fabricated using the sol-gel casting technique showing a variation in hole size less than 3% over 2 km spans and a deviation in hole size of less than 1% within a given fiber cross-section. The attenuation spectrum of the fiber in figure 1a is shown in Figure 3. The loss is 2 dB/km at 1550 nm and 7 dB/km at 1384 nm due to absorption of OH^-. The overall loss at 1550 nm, is significantly higher than fibers recently fabricated by stack-and-draw of VAD glass capillaries which polished inner surfaces, with fiber loss values of 0.58 dB/km and 0.28 dB/km by Farr *et al*.[12] and Tajima *et al.*[13] respectively. The leading source of loss for the sol-gel fiber is scattering loss with a Rayleigh scattering value of nearly 4.2 dB/km/μm^{-4}, nearly four times as large as that of Tajima *et al.* Surface roughness of the air hole surfaces is most likely responsible for the large scattering value. Chemical and mechanical polishing of mandrels used to make the air holes in the glass preform should yield lower loss values.

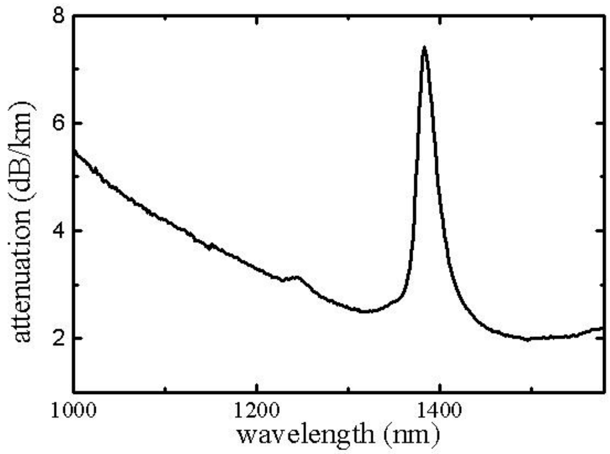

Fig. 3. Attenuation spectrum of the single-moded fiber displayed in Figure 1a.

IV) Conclusions

The sol-gel casting method has been used to successfully fabricate a number of microstructured fiber designs ranging from photonic band gap fibers to highly nonlinear fibers to sensors and devices. The casting technique affords a wide range of design flexibility, which is required for dispersion compensation designs as well as low-bend loss fiber. Furthermore, the casting method may be adapted for large scale manufacturing. Mold assemblies may be reused to cast multiple preforms and the process may be easily scaled to larger preform sizes leading to a cost-effective means of producing long lengths of uniform microstructured fiber.

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