Reducing spectral attenuation in solid-core photonic crystal fibers

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Abstract: We describe the effects of fabrication process timing and preform exposure to atmospheric air on spectral attenuation in photonic crystal fibers. The lowest attenuation is achieved by rapid processing.

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1. Introduction

Solid-core photonic crystal fibers that guide light by total internal reflection [1] have been a subject of wide interest over the past few years. The fibers reported have been fabricated under a range of different conditions, and have widely varying properties. Commonly, a multi-stage stack-and-draw fabrication process is used to create the required cross-section in the final fiber, using low-OH synthetic silica starting material and with no additional halogen-based processing. In this paper we demonstrate that the details of such a fabrication process, in particular the amount of time between the different drawing stages and the material exposure to atmospheric contamination in the interim, are critical in setting the final level of attenuation in the fiber and the spectral features present. We demonstrate that the absorption bands associated with the presence of OH^- ions [2], a broad spectral attenuation centered at 900nm [3], the draw band at 630nm [3] and extrinsic attenuation at shorter wavelengths can all be decreased or eliminated by rapid processing.

2. Design and fabrication

Our work was performed using a simple guiding structure to facilitate the different processing options required. The design consists of a single ring of air holes surrounding a solid core as shown in Fig. 1. The material used throughout our experiments was Suprasil F300 synthetic silica from Heraeus.

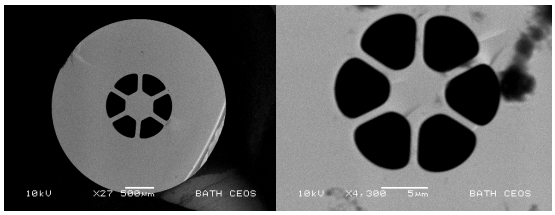

Fig.1. Left: 3mm preform cane. Right: 5µm core PCF as used in the experiments.

Our fabrication process consisted of drawing capillaries and a solid core rod from stock rods and tubes. A stack of six capillaries and one core rod was formed inside a jacketing tube with an outer diameter of 10mm and inner diameter of 4.3mm. This jacketed stack was drawn down to form preform canes, as illustrated in figure 1. The time taken from the start of the process to drawing the preform canes was approximately two hours.

The preform canes were stored immediately after being drawn. Canes were stored in clean room atmospheric conditions (humidity approximately 35%, at 20°C). For fiber drawing, a single preform cane was placed inside a second jacketing tube and pressurized from the top to control the final structure of the fiber during the drawing process. A simultaneously-applied vacuum collapsed the jacket onto the cane during drawing. The final fiber diameter is 125µm with a core diameter of 5µm in all of the fibers.

3. Experiment

The first set of results reported here was obtained using fibers drawn from preform canes derived from the same stack. Fiber A was drawn 90 minutes after the preform canes were drawn. During this 90 minute period the preform cane was stored open to the atmospheric conditions in our fabrication facility. Fiber B was drawn from an otherwise identical preform cane which had been stored for 8 days in atmospheric conditions. The change in the measured

spectral attenuation is dramatic. Fiber A has a 1384nm absorption peak of 18dB/km corresponding to ~0.3ppm OH^- [2]. In Fiber B the OH^- peak in the drawn fiber has increased to 60dB/km, indicating far higher concentration of OH^- ions within the core. There is a similar growth of the smaller OH peak at 900 nm [2]. The 1384nm attenuation for preforms drawn to fiber, for varying times of storage in atmosphere, is shown in figure 2(a) (inset), demonstrating that delays of just a few hours has caused a significant increase at 1384nm. There are several other changes in the attenuation spectra. A peak at 630nm (associated with drawing induced network defects [3]) has appeared following the delay in fiber drawing. There is also substantial increase in attenuation at wavelengths below 600nm (see figures 2 and 3), along with a feature that has altered the attenuation in the spectral region between 700 and 1200nm.

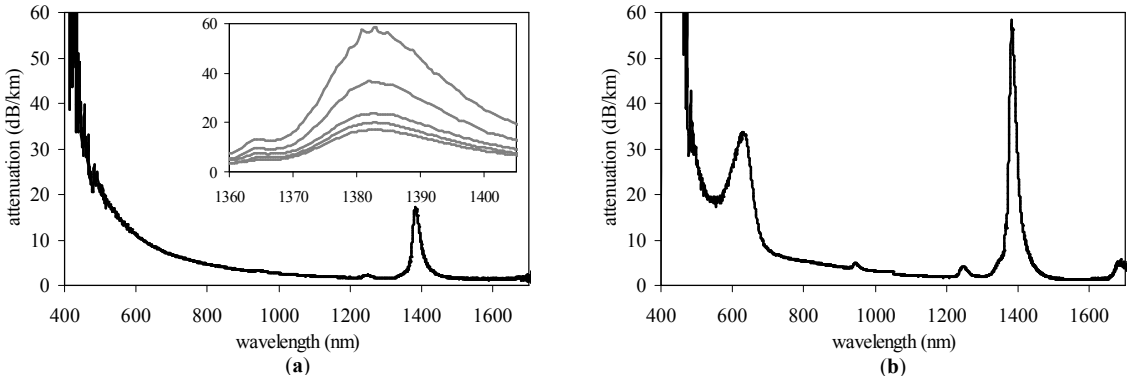

Fig. 2. Spectral attenuation data for two fibers drawn from perform canes kept in atmospheric conditions for different amounts of time. Attenuation increases at 630nm and 1384nm when the amount of time the draw material is exposed to air increases. **a**) Fiber A 1.5 hours; **b**) Fiber B 8 days. **Inset**: attenuation at 1384nm shows time dependence going up from 1.5 hours, 3 hours, 4 hours, 9 hours and 8 days. We measured the spectral attenuation of the fibres using a halogen lamp and an optical spectrum analyzer (OSA). The cutback method was used with the fiber cut back to 50m from 300m. The resolution of the OSA was set to 2 nm..

Figure 3 shows the attenuation from a separately drawn preform, illustrating both the rapid nature of the degradation and the broad attenuating feature at 900nm more clearly. The 900nm peak has been variously attributed to contamination either in the bulk material or during fiber fabrication [3] but in our work it can be conclusively identified as being associated with delays in the fabrication process. Based on spectral fitting of the attenuation data [4] we believe that the increased attenuation at short wavelengths below 600nm is not due to increased bulk Rayleigh or surface scattering. Instead, we consider that there is increased attenuation at the shorter wavelengths which is associated with damage to the silica matrix, and appears whenever the broad 900nm peak is observed.

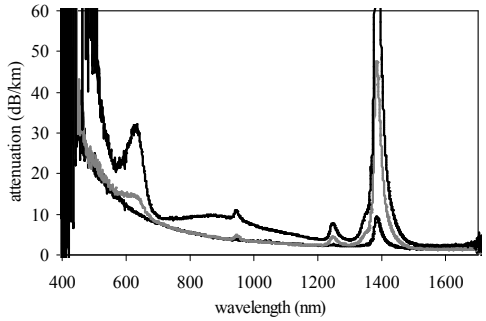

Fig. 3. Spectral attenuation for three different fibers. Attenuation increases at the shortest wavelengths (<600nm), 630nm, 1384nm, and a broadband peak at 900nm [4] for longer exposure of the drawn material to air. Top to bottom: 7 days, 18 hours (gray line) and 3 hours.

In order to determine whether there are changes that take place after the fiber has been drawn, we repeated an attenuation measurement on a specific fiber that had been stored in normal laboratory conditions for a period for one month. The results are shown in figure 4. A feature associated with adsorbed OH^- on the silica surface at 1365nm grows with time after the fiber has been fabricated.

In a further experiment we measured the response of the spectral attenuation with exposure to high temperature. A 10m length of fiber exhibiting all of the above spectral features was heated to >250°C on a hot plate. The spectral transmission through the fiber was monitored while raising the temperature and for a period of one hour. There was

a rapid increase in the first 10 minutes by an order of magnitude in the attenuation peak at 900nm which continued to increase at a slower rate. The same experiment performed with a different sample that did not have the absorption band at 900nm showed no increase in attenuation when heated for an hour.

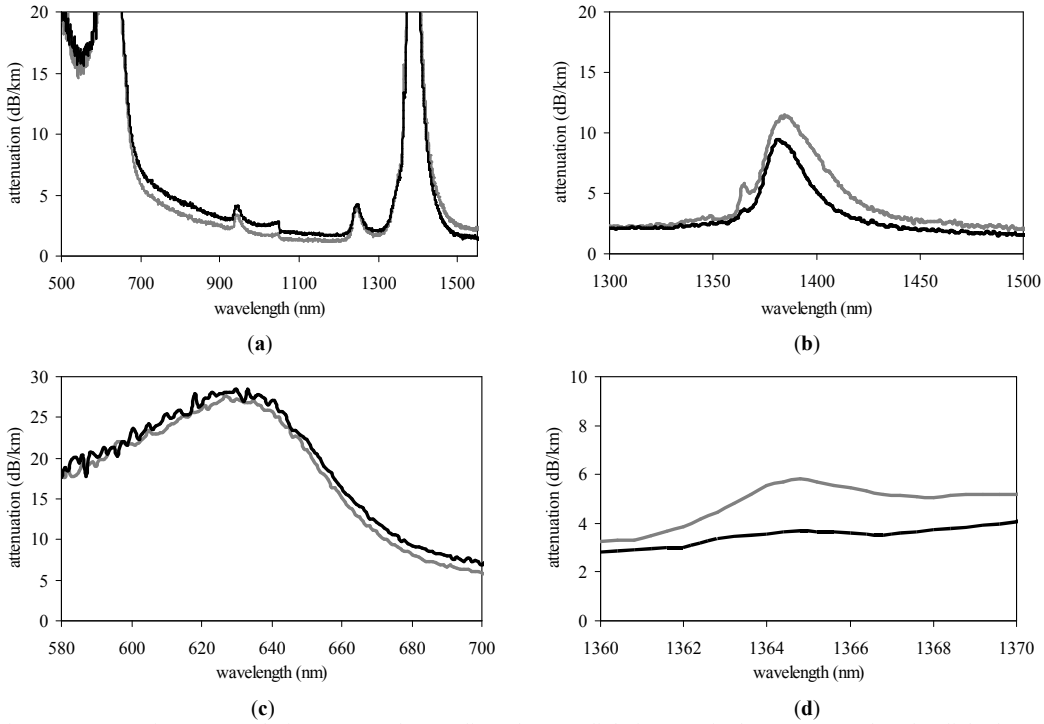

Fig. 4. **a**) Attenuation measured after one month (gray line) shows a slight increase in the 1384nm peak and a slight decrease in the 900nm peak [4]. The discontinuity at 1050nm is an artifact of our OSA. **b)** Different fiber sample shows 1384nm attenuation growth after 1 month. **c**) The peak at 630nm is virtually unchanged after one month. **d**) Surface OH increases after one month.

Conclusions

We have demonstrated that the timing of the multi-stage fabrication process for photonic crystal fibers is critical to obtain low spectral attenuation in the final fiber. The lowest attenuation is associated with the fastest turn-around of the fabrication process. The attenuation band at 630nm which is associated with drawing-induced damage appears if there is a delay between the two drawing stages of more than a few hours, and increases up to approximately 30dB/km. The broad peak centered at 900nm, and the short-wavelength attenuation which appears to be associated with this peak also increases with a delay in the fabrication process. Finally, keeping the fiber for a period of one month after it has been drawn has only a modest effect on these three absorption bands, but causes an increase in the narrow absorption peak at 1365nm, associated with the surface hydroxyls.

We conclude that to fabricate low loss PCF without the use of halogen-based processes and starting from commercially-available low-OH^- silica, it is essential to reduce the time in storage between each step of the process. Delays in fabrication of even a few hours can cause a measurable or even dramatic degradation of the ultimate fiber performance.

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