Retaining and characterising nano-structure within tapered air-silica structured optical fibers

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Abstract: Air-silica fiber 125µm in diameter has been tapered down to ~15µm. At this diameter, it is commonly assumed that the nanostructured fiber holes have collapsed. Using an Atomic Force Microscope, we show this assumption to be in error, and demonstrate for the first time that structures several hundred nanometers in diameter are present, and that hole array structures are maintained. The use of Atomic Force Microscopy is shown to be an efficient way of characterising these structures.

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Introduction

During the past decade, Atomic Force Microscopy (AFM) has been used extensively to characterize a range of optical fibers and photonic devices [1,2]. In general, AFM is used in combination with selective chemical etching [3] to determine the location and concentration of dopants in the silica. Fiber size and complexity are of little consequence to this technique due to the use of nanometer-sized tips for imaging. Fiber core sizes <<1μm can be readily examined, in addition to structures such as tapered fiber couplers with outer diameters of ~10-20μm [4]. In this paper, we investigate the use of AFM to accurately map the complex air-silica structure of tapered air-silica fibers sometimes referred to as photonic crystal fibers [5] or more generically Fresnel fibers [6]. This extends significantly the use of these techniques in characterising complex fiber geometries, offering in some circumstances the only practical alternative characterization means on a reasonable time scale. Previous work focused on demonstrating feasible characterisation with untapered structures as first suggested by Huntington [7] and later reported by Hillman et. al. [8]. Some work has been done in characterising single capillaries used to manufacture tapers for Scanning Near-Field Optical Microscopy (SNOM) tips [9] but to our knowledge this is the first report of the techniques being applied to tapers with multiple hole structures of varying complexity. In optical fiber fabrication generally, the technique has yet to be incorporated routinely.

Standard air-silica fibers are pure silica optical fibers that have air regions or "holes" [5,6] running along their length. Guiding in this type of fiber has been described by one of two extreme mechanisms [5]. In the first mechanism, guiding comes about due to the difference in the effective refractive index difference between the solid silica core and the holey cladding. The second mechanism refers to fibers with distinct periodic hole structure which leads to photonic band gap effects and confinement due to an effective cylindrical Bragg grating in the cross-section. In practice, the first mechanism is only a valid approximation when the hole separation is significantly less than the wavelength of propagating light. This has rarely been the case and consequently propagation is a complex phenomenon dependent largely on coherent scattering from the air-silica interfaces in combination with resonant scattering within the air-holes akin to Mie scattering associated with dielectric low index spheres. The term Fresnel fiber was coined to accommodate these contributions [6]. Air-silica fibers can be readily examined using either optical microscopy or SEM, although both are inadequate for efficient accurate profiling. Optical microscopy clearly runs into resolution issues when the hole dimensions are commensurate or less than the wavelength of light. This may be improved with limited success by analyzing the optical phase of scattered light. In the case of SEM, whilst the resolution is certainly suitable, fiber sample preparation is time consuming, severely limiting this technique as a practical tool to incorporate in a standard fiber laboratory. AFM offers a viable high resolution and reasonably fast turnaround measurement technique that can be incorporated in standard commercial environment for routine characterisation and feedback. Further, the removal of standard polishing and chemical preparation of SEM removes the spurious contributions to the results that these additional laborious steps can generate. The fiber sample is measured immediately upon cleaving inside an AFM and hence can provide almost real time feedback.

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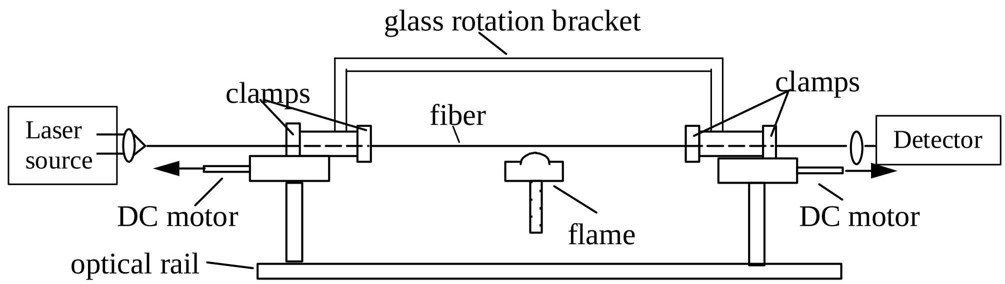

Fig. 1. Schematic of optical fiber tapering rig.

Tapered holey fibers [10,11] are of specific interest for a number of reasons. Firstly, output spot sizes can be increased or decreased by up and down tapering respectively, although the effect is not as dramatic as in a standard single-mode, matched-cladding fiber taper [12]. The fiber numerical aperture can also be modified in a similar way. The commensurate rise in optical intensity possible in a tapered fiber leads to greater efficiency in the nonlinear processes typically associated with super continuum generation [13], for example. Tapering also allows for the fabrication of elaborate and compact band gap structures within relatively small fiber structures, approaching a first-order photonic bandgap structure that has not yet been demonstrated.

Characterisation of these sub-micron periods is therefore of critical interest. The tapered fibers presented in this paper have had their outer diameters reduced from 125µm to 15µm using conventional tapering technology refined for superior control over temperature and velocity of the scanned heat source. Ordinarily, conventional tapering of a complex holey structure is thought to result in collapse of the hole structure – the heat differential problem [14,15] is significantly different to single capillary drawing where sub-micron hole sizes are possible, a technique used to make Scanning Near-Field Optical Microscopy (SNOM) tips [9]. In contrast, similar success for multiple hole capillary tapering of a dielectric has not been reported to our knowledge. The application of AFM to imaging these structures enables us to demonstrate this for the first time.

Fiber Tapers

The fiber tapers examined in this paper are drawn from air-silica fiber using the flame elongation method [11]. Figure 1 shows the tapering rig used. The rig consists primarily of two DC motors connected to horizontal translation stages and a glass rotation bracket. The motors are driven by an electronic circuit which allows for a constant pull rate. The glass rotation bracket allows the sample to be rotated during the drawing process. The flame head uses a methane/oxygen mixture and provides a flame 2-3mm in height. For the tapers presented in this report, a flame temperature of approximately 900ºC was used. The flame temperature can be controlled by adjusting the gas mixture. Typically, optimized pulling speeds for this fiber are ~50 - 80µm/s. The optical output of the fiber is also monitored during the pulling process for adiabaticity using a detector and a computer based data acquisition system. It should also be noted that tapering of standard optical fiber does not produce any of the complex structure observed when air-silica fibers are used.

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Characterisation and Discussion

After drawing, the fiber tapers were cleaved under tension by creating a small structural flaw on one side of the taper, followed by the application of controlled pressure perpendicular to the propagation axis and on the opposite side of the fiber to the flaw. The tapers were then mounted vertically and examined using a commercial AFM operated in contact mode. Untapered fiber samples were also imaged for comparison. Figure 2 shows an example of an AFM scan of the full size (125µm) fiber. This image clearly shows the hole structure in the standard fiber. The holes in this case are ordered, with the absence of a hole in the fiber

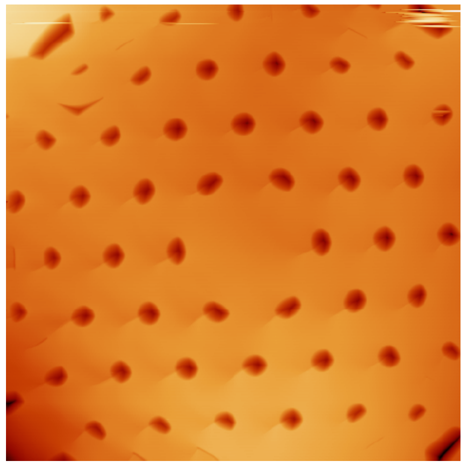

Fig. 2. AFM contact mode image of a 125µm air-silica structured fiber. Scan size = 60µm

center, and slightly larger elongated holes towards the outer edge (visible in the corners of the image). From each hole, a structural flaw extends towards the lower left hand corner of the image. These flaws propagate in the exact same direction as the direction of mechanical cleaving, and extend deeply into each hole. Such a feature is not observed in SEM techniques where the preparation method removes the flaws, thus hiding a potentially problematic issue thus far not recognized in mechanical cleaving of air-silica fibers.

It is observed that each hole seems to display four distinct quadrants. This feature is a well known artifact of the AFM imaging process – such artifacts need to be well understood if the full potential of the AFM technique is to be extracted. The tip itself is at the apex of a square-based pyramid and when imaging deep or steep structures, the pyramid edges slide/interact with the structure. Thus the tip itself in this case is not doing the imaging, rather the square walls that hold the tip are. The end result is that the square geometry is visible in the image. This problem occurs whenever the aspect ratio of the tip is exceeded by the aspect ratio of the object being examined.

To illustrate the resulting tip and hole convolution more clearly, we imaged a sharp narrow spike (aspect ratio spike >> aspect ration tip), with dimensions far smaller than the pyramid. In this case a self-image of the pyramid is obtained. This image is shown in Figure 3. The tilted pyramid shown in this figure is identical to the structure seen within the fiber holes. It is important to note the tip precisely images the edge of each hole. Hence, information on hole size and shape can be confidently obtained with a high degree of accuracy.

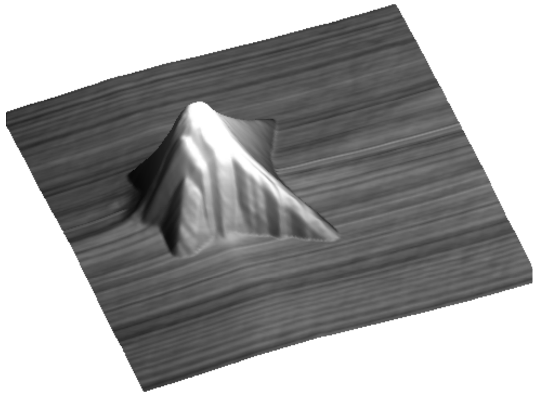

Fig. 3. AFM contact mode image of a nano-size spike clearly showing the self-imaging of the pyramidal tip. Scan size = 1.5µm

The holes shown in Fig. 2 are in hexagonal arrangements. Measurements taken along hexagonal lines as shown in Fig. 4, indicate a hole spacing of (9.0 ± 0.5) µm. The error quoted is a result of inconsistencies in the fiber itself, not the imaging resolution. The hole size for the outer hexagon is measured to be (3.3 ± 0.2) µm.

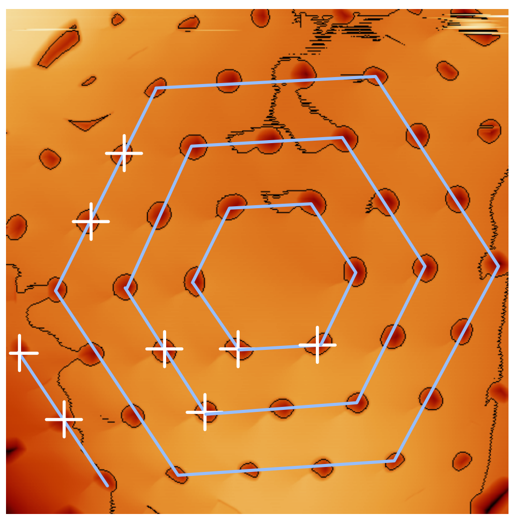

Fig. 4. Hexagonal overlay showing fiber hole arrangement and distances used for inter-hole spacing measurements.

Figure 5 shows an AFM image of the end face of a tapered air-silica fiber (outer diameter ~ 15µm), with a corresponding grid of the hexagon array in Fig. 6. The holes are clearly visible in this image and are in the same arrangement as in the untapered fiber. It should be noted that as the fibers became smaller, difficulties were encountered when cleaving. Figure 5 therefore only shows one quadrant of the fiber enface. Just as different cleaving tensions are require for holey fibers and standard solid fibers, we expect tapered holey fibers will require specific tensions for accurate cleaving. This will be the subject of further investigation. Figure

6 shows three hexagons, a single hole of the 4th hexagon is just visible at the top right of the image. As with the untapered fiber no hole was observed at the fiber center.

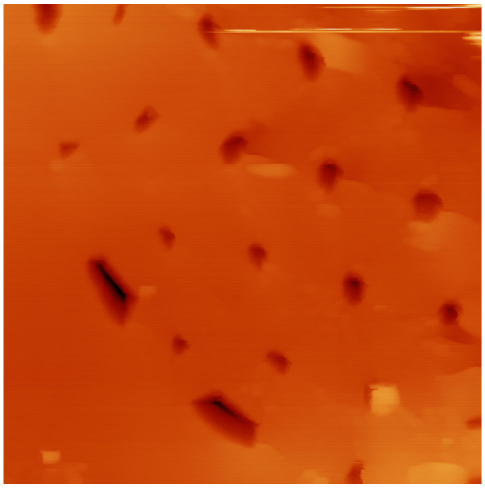

Fig. 5. AFM contact mode image of a cleaved tapered air-silica structured fiber. Scan size = 5µm

The inter hole spacing along each hexagon has been reduced to (1.1 ± 0.1) µm. The holes spacing has therefore been scaled down by a factor of 8.2, which is in agreement with the outer fiber diameter scaling of 8.3. The hole size in the tapered fiber is measured to be (0.35 ± 0.30) µm, leading to a scaling ratio of 9.4 for hole diameter. This indicates that the holes are ~10% smaller than predicted by the fiber diameter and hole spacing scaling factors.

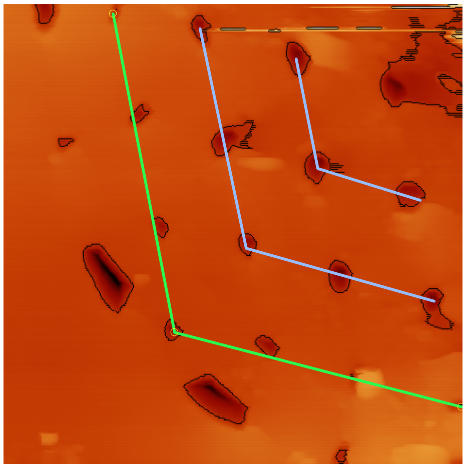

Fig. 6. Hexagonal overlay showing fiber taper hole arrangement and distances used for inter-hole spacing measurements.

Conclusions

We conclude that the hole structure in standard air-silica fibers can be maintained even when the fiber is drawn down to outer diameters of ~15µm, using conventional tapering techniques usually applied to standard fibers. This has been confirmed with accurate measurements based on AFM. Such a technique offers the potential for routine characterisation of air-silica fiber fabrication, both tapered and untapered, prior to installation in a device. For example, the method allowed us to detect micro-structural flaws arising form mechanical cleaving using standard techniques. The high resolution permits sub-micron features to be characterised quickly and virtually “on-line”. Further, to our knowledge no such nano-sized structures have been confirmed to exist within tapered air-silica fibers to date. The ability to measure nanostructure will help to accelerate the development of a new range of technologies, including the more obvious fabrication of true first-order photonic bandgap fiber and optimised tapers for interconnects to planar photonic crystals for example.

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