# Advances and limitations in the modeling of fabricated photonic bandgap fibers

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**Abstract:** We model fabricated silica photonic bandgap fibers and achieve good agreement between simulated and measured properties. We identify the size of the SEM bitmap image as the ultimate limit to the accurate calculation of surfaces modes within the bandgap.

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## 1. Introduction

Modeling the optical properties of fabricated optical fibers is useful to complement measurement results, evaluate properties that are otherwise difficult to measure, or to predict the effect of small changes in the design parameters through perturbation analysis. Obtaining reliable modeling results for silica hollow core Photonic Bandgap Fibers (PBGF) is particularly challenging since the optical properties of these fibers depend critically on both large scale features of the fiber (i.e. the distribution of the air holes within the extended periodic cladding) and on much smaller scale features (i.e. the width of the thin silica struts which are typically of order a few 10s of nanometers). While two simulation approaches have been so far proposed, modeling either an idealized fiber's cross-section [1] or one which is directly obtained from an SEM image [2], no emphasis has been given to the achievable precision and reliability of the two methods.

We routinely model fabricated PBGF to support our fabrication and characterization activities, and in this paper we explore the potential of both simulation approaches and identify the size of the source SEM image as the primary factor limiting the accuracy of the results. We highlight the extreme sensitivity of the photonic bandgap (BG) to small scale features, demonstrate a good agreement between simulated and measured parameters, and suggest that in order to precisely estimate also the position of Surface Modes (SM) inside the BG, the resolution of the images currently obtained must be increase by a factor of five or more.

## 2. Simulation of "idealized" fibers

Fig.1(a) shows an SEM of a typical PBGF, which will be used as an example throughout the paper. For all modal analysis presented herein we employ a full vector finite element tool which allows full control of the mesh density and is therefore particularly suited to simulate small or irregular structural features.

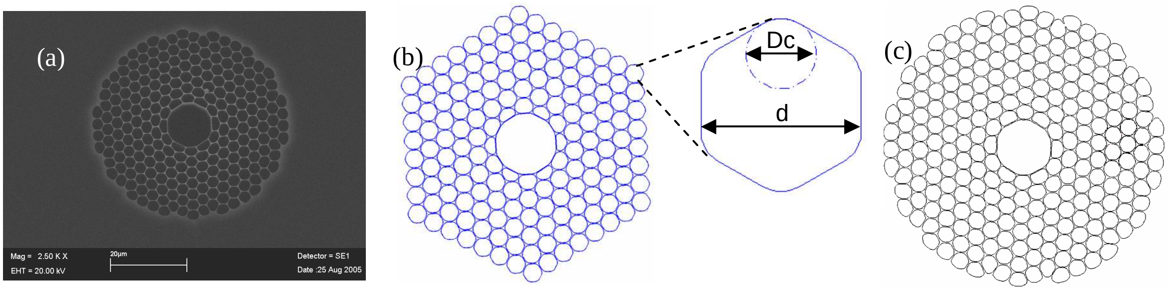


Fig.1. (a) SEM of a PBGF for near IR transmission; (b) idealized representation with $\Lambda$=3.12 µm, d/$\Lambda$ = 0.96, Dc=0.64$\Lambda$ and with a core expanded by 110%; (c) geometry directly obtained from the SEM.

In order to calculate many of the optical properties of a fabricated PBGF it is often adequate to model an idealized version of the fiber cross-section obtained from an SEM image, as in Fig.1(b). Using this approach, structural imperfections (which are irrelevant to a first approximation for many fiber properties) are neglected, resulting in smaller meshes and shorter simulation times. Properties such as the BG position and width, percentage of power in the air and glass, input coupling efficiency, group velocity dispersion and an estimate of the scattering loss can all be obtained for the guided modes in this way. For this idealized approach we have found that 5 parameters generally provide an adequate description of the fiber cross section. The fabrication process used to achieve the high air-filling fraction needed to open a BG for out-of-plane propagation typically results in fibers with hexagonal air holes with rounded corners. Their defining parameters are well described by the hole-to-hole distance $\mathbf{\Lambda}$, the hole diameter **d** and the diameter of the 6 circles rounding the corners **Dc**, where Dc = 0 corresponds to perfect hexagons and Dc = $\Lambda$

to circles [3]. The core expansion or compression factor, and the width of its boundary layer are the two remaining free parameters in the model, which need to be fitted from SEMs of the real structure. The average measure of **Λ** can be obtained from a Fourier analysis of the periodic cladding, while the expansion or compression factor of the core can be directly measured from the SEM. Less accurately determined are the values obtained from the SEM for Dc and for the thickness of the struts in the cladding and around the core. The limited size of the bitmap obtained from a typical SEM (1024x768 pixels) is the main obstacle, as even on highly magnified images (containing a sufficient number of periodic holes to average over their properties) each strut is defined by only a few pixels. Charging effects, sample tilt and the additional thickness of the coating layer represent additional uncertainties.

On the other hand, the BG position and width are strongly dependent on the air filling fraction of the cladding, which is determined by Dc and d/Λ [3]. For example, the BG shift caused by changing the shape of the cladding holes between Dc = 0 and Dc = Λ is shown in Fig.2 for a typical PBGF. The normalized center wavelength of the BG is seen to change between 0.44 and 0.57. A similar effect also results from a small variation in d/Λ. Fig.3 shows the BG shift of the best fitting ideal structures for the fiber in Fig.1(a), with values of d/Λ from 0.95 to 0.96, together with the measured transmission spectrum for this fiber. The difference between d/Λ = 0.95 and 0.96, even on a high magnification image of the cladding, is only ~1 pixel. Analyzing a range of different fibers we found that the BG shift for a change of 1% in d/Λ (corresponding to ±1 or 2 pixels on our images) can be as large as 0.02Λ to 0.03Λ (80 to 120nm for a typical pitch of 4 μm). For this reason we have never been able to reliably predict the BG size and position of a fiber from its SEM image using this approach. However, we believe that in addition to being a valuable tool for designing the fibers, this idealized model can also provide a good estimate of many of the fabricated fiber's properties, if the most critical structural parameters are first determined by fitting the simulated BG properties to the measured data, rather than estimating them from an image.

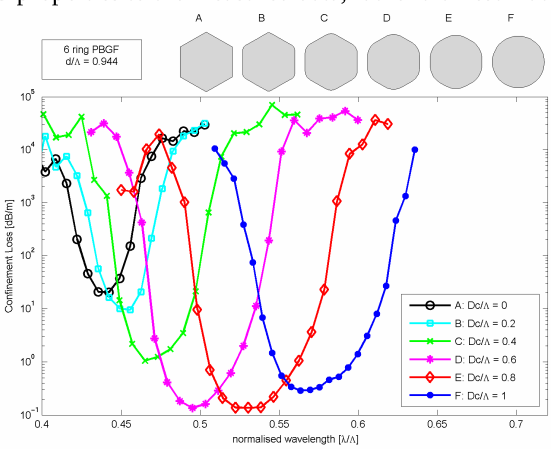


Fig.2. The effect of modifying the Dc parameter representing the hole roundedness from 0 (A) to Λ (F) for an idealised PBGF with d/Λ = 0.944.

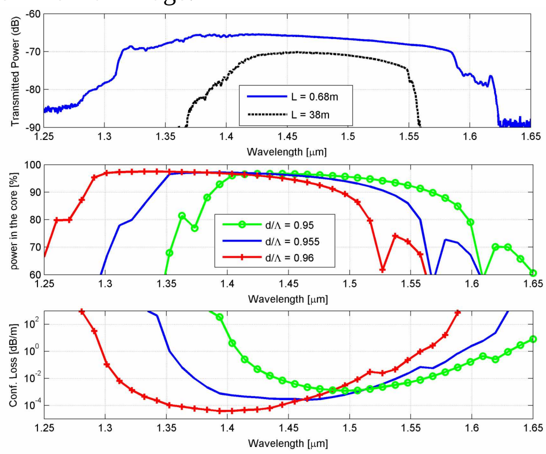


Fig.3. (Top) Measured TX spectrum of the fiber in Fig.1(a) after 68cm and 38m; (Bottom) Simulated percentage of power in the core and confinement loss for 3 close values of d/Λ for the ideal fiber in Fig. 1(b).

### .3. Simulation of "real" fiber structures

Although an idealized fiber structure provides a simple way for estimating the majority of fiber properties, it cannot determine those properties, such as birefringence, that result from structural asymmetries. Neither can it predict the exact location of surface modes inside the BG, which are extremely sensitive to very fine details of the ring surrounding the core in which they are localized [4]. For these purposes it is necessary to model the fiber cross-section obtained directly from the SEM. The process generally involves multiple image-processing stages to eliminate noise, charging effects and to obtain a two-level bitmap, which is then approximated with splines, and finally meshed. Attempts at simulating the full structure [Fig.1(c)] predicted a BG at much longer wavelengths than actually measured. We attribute this to the limited image size. The 19 periods (Λ) along the diameter are represented by ~700 pixels (vertical resolution), which limits the resolution of each individual strut to between 1 and 2 pixels.

However, we have verified that by increasing the magnification by 2-3 times (as in Fig.4) it is possible to determine the hole shapes and positions with sufficient accuracy. Although this approach means that information about the fiber's confinement loss is lost (only part of the fiber is represented), we have confirmed that the principal modal properties are not significantly affected by neglecting the outer rings of holes. For example the BG can still be accurately estimated through the percentage of power in the core ($P_{core}$) of the guided modes. In Figure 5(left) we plot the calculated $P_{core}$ and effective index of the fiber shown in Fig.4. The BG extends from nearly 1.3 to 1.6 μm. A number of SMs, which are different for the two polarizations and are identifiable as dips in the plot, appear at the edges of the BG, while only the fundamental and the higher order modes (not shown) are guided within its central region. This in good agreement with the measured spectrum for this fiber [Fig.3(top)]. However, due to the nature and localization of the SM, their exact position in the BG is extremely dependant upon the thickness of the interface between the core and the photonic crystal [4]. This dependence is demonstrated in Fig.5(right) where we plot the results of a simulation for a similar fiber, in which the thickness of the core boundary has been expanded by just 1 pixel all around (which is within resolution error from our SEM measurements). As a result, the SMs around 1.55 μm shift to longer wavelengths and disappear into the continuum of cladding modes, while other SMs emerge from the short wavelength edge and move towards the center of the BG.

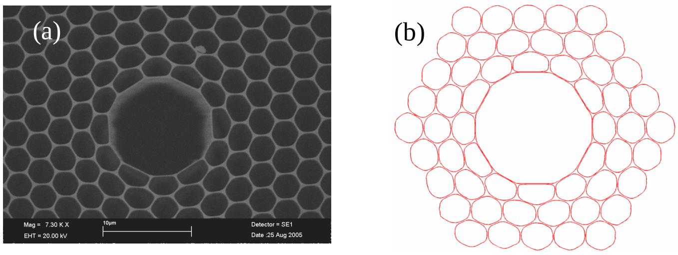


Fig.4. (a) Zoomed in SEM for improved definition of the thin silica struts; (b) geometry derived from it.

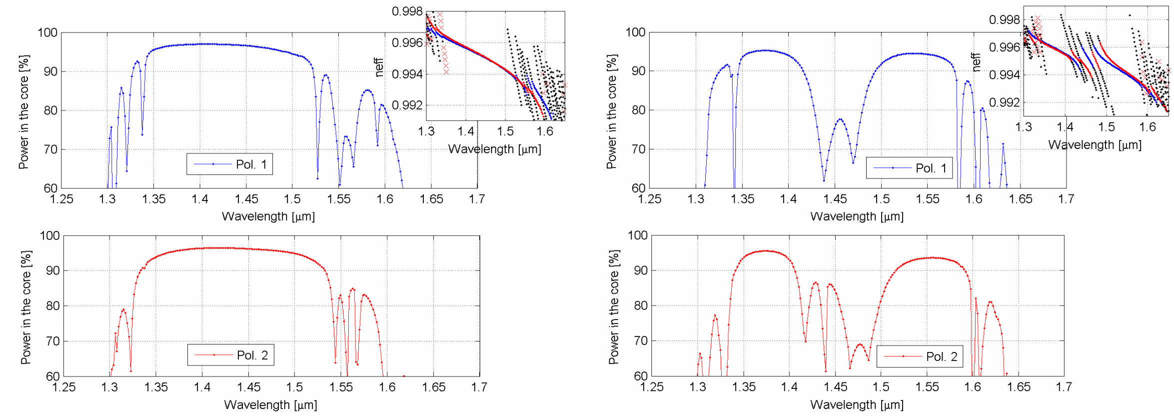


Fig.5. (Left) Simulated $P_{core}$ and (in the inset) effective index plot for the 2 linearly polarized fundamental modes of the structure in Fig.4. (Right) Simulation of the same structure, in which the core boundary has been thickened by one pixel all around.

This example (and similar work on other fabricated fibers) leads us to conclude that by using an SEM image with a strut resolution of at least 3-5 pixels it is possible to accurately predict the width and position of the BG without having to determine the structural parameters via comparison with experimental data. However, we have found that a significantly higher image resolution (estimated factor of 5 increase) would be required in order to accurately estimate also the position of SM within the BG.

## 4. Conclusions and future work

We have underlined the usefulness of modeling real fabricated PBGFs and have reviewed its current applicability and limitations. Ideal, parameterized fibers can be employed to model the fairly regular structures produced with the current technology, although an initial fitting of some structural parameters is recommended through comparison with the measured transmission spectrum. In order to estimate the polarization properties of the fiber, images directly extracted from the SEM can be modeled. In this case we also obtain good agreement with the measured data. We have identified the size of the SEM bitmap as the limiting factor in obtaining reliable information about the exact SM position. Ongoing work focuses on the comparison between measured and modeled optical properties, and on the evaluation of other image acquisition methods or devices which may provide enhanced resolution.

## References

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