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Multi-mode capacity enhancement with PBG fibre

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1. Introduction

The objectives of this part of the Modegap project are:

- To understand how the loss in large core HC-BPGFs scales with wavelength and the region of minimum loss;
- To understand through accurate modelling of fabricated fibres the role of cross-sectional distortions on the measured losses of HC-PBGFs;
- To develop a fluid dynamics model of the HC-BPGF drawing process that can help with fibre development and further structural refinements.

In section 2 we present the first experimental wavelength scaling in 19-cell core HC-PBGF, indicating that the minimum loss waveband occurs at longer wavelengths than previously predicted. Record low loss (2.5dB/km) fibers operating around 2µm and gas-purging experiments are also reported. In Section 3 we present a method to reconstruct the cross-sectional profile of fabricated hollow-core photonic bandgap fibers from SEM images. For the first time, numerical simulations show a good agreement with measured loss and surface mode position. In Section 4 a method to track the evolution of a microstructured fibre, from initial preform to final fibre geometry, is presented. With this model we can now explore effectively new structure development, the effect of various material and drawing parameters on the quality of the final draw and how to upscale the fabrication process to achieve longer fibre lengths.
2. Understanding Wavelength Scaling in 19-Cell Core Hollow-Core Photonic Bandgap Fibers

2.1. Introduction

Hollow-core photonic bandgap fibers (HC-PBGFs) have demonstrated potential to address some of the intrinsic capacity limitations of standard transmission fibers while providing a substantial reduction in signal latency [1]. Scattering from thermodynamically generated surface roughness has been identified as the underlying source of loss for these fibers and a number of theoretical studies [2,3] predict a $\sim \lambda^{-3}$ wavelength dependence and identify the waveband at $\sim 1.9\mu m$ as the region beyond which material absorption becomes the dominant loss mechanism. The wavelength of minimum predicted loss is thus determined by the amount of fractional overlap of the guided mode with the fiber structure, which affects both loss mechanisms [2]. Experimental support for these predictions has been provided by loss studies on 7 cell HC-PBGFs [2,4], however no detailed investigation has been reported for larger core, 19 cell HC-PBGFs, which can achieve lower loss and thus have more practical value for telecoms applications. Moreover it is important to identify what drawing parameters contribute to determine the wavelength of minimum loss in real fibers and verify how effective is wavelength scaling to reduce the loss of these fibers.

Here we report to the best of our knowledge the first experimental wavelength scaling study in 19 cell HC-PBGFs. By measuring the transmission of several homothetically scaled fibers we confirm the validity of the $\sim \lambda^{-3}$ dependence of the scattering loss, and demonstrate that the wavelength of minimum loss occurs at longer wavelengths (around $2.1\mu m$) than previously predicted [2]. A $\sim 2.5x$ loss reduction is achieved by shifting the operating wavelength from $1.5\mu m$ to $2.1\mu m$. Our measurements also seem to indicate that the wavelength of minimum loss is influenced by material properties in addition to mode field overlap. Finally, we demonstrate that undesired gas absorptions can be removed by purging fabricated fibers even in multi-hundred meter lengths.

2.2. Fiber fabrication and results

The fibers utilized in this study had a 19 cell core and were fabricated using a two-step stack and draw technique. The primary stack had $7\frac{1}{2}$ rings of capillaries constituting the cladding region and a core formed by omitting a central element and two surrounding rings of capillaries, and replacing them with a very thin-walled core tube. While the core tube approach is known to introduce additional surface mode loss resonances in the transmission [5], it provides for an increased yield, particularly useful in this study, and an easier control over the core shape during fiber drawing. The stack was used to produce a batch of structurally consistent canes from which nine fibers were produced having almost identical structure but increasing scale factor. The cladding pitch varies from 3.6$\mu m$ to 7.1$\mu m$ while the relative hole size, $d/A$, was kept nearly constant at about 0.98±0.005 for all fibers. The spectral attenuation of all samples was measured by using a broadband source and a standard cutback technique, where however special care was taken to excite the fundamental mode by using mode field matched launch fibers. As expected, loss peaks due to resonant coupling to surface modes were observed for all fibers, resulting in a segmentation of the photonic bandgap in two main low loss windows. In Fig. 1(a), fibers A to I, the respective regions of lowest loss (spanning from 1 to 2.3$\mu m$) are plotted. The minimum loss of each fiber is found to follow very closely the $\lambda^{-3}$ dependence, indicating that the loss is dominated by surface scattering. The overall minimum loss (2.5 dB/km) was measured in fibers F and G operating at $\sim 2.1\mu m$, with a $\sim 2.5x$ loss reduction as compared to fibers C and D that guide at 1.5$\mu m$. Measured losses were consistent with values obtained from an accurate loss model utilizing high resolution scanning electron microscope images to calculate the fiber properties [6].

Fibers H and I have minimum loss falling beyond $2.1\mu m$ and seem to indicate an increase in the measured loss. In order to understand this, we plot the attenuation curves of two different grades -“wet” and “dry”- of silica glass (which correspond to the different hydroxyl contents contained in F100 and F300 types of synthetic silica from Heraeus [7], respectively). To provide a calibration for the infrared absorption curves we also plot in Fig. 1(a) the transmission of fiber J, designed to operate at wavelengths around $3.4\mu m$ and characterized by a very similar mode field overlap as fibers A-I, despite having a slightly different structure [8]. Both simulations and experiments indicate that $\sim 0.2\%$ power propagates in the glass for all fibers.
The figure shows that for a perfectly “dry” fiber the minimum absolute loss waveband would be expected to lie at wavelengths around 2.4 μm, much longer than the 2.1 μm we measured in this experiment or the 1.9 μm previously predicted [2]. This seems to suggest that although our fibers were fabricated from F300 tubes, a small but non negligible amount of hydroxyl ions might have been incorporated in the glass as a consequence of multiple fiber preparation processes at high temperature. Therefore, we believe that there is scope to achieve even lower attenuation values by reducing the OH content in the fibers and thus shifting the lowest loss region to even longer wavelengths. In addition, by using a 37 cell [9] rather than a 19 cell design would also reduce the mode field overlap with the glass to around 0.1% or lower and therefore produce a further loss reduction effect. The full attenuation spectra of fibers F, G, H, and I are plotted in Fig. 2. Despite the presence of surface modes in the middle of the bandgap, 3dB bandwidths in excess of 90nm were obtained in all fibers, with that of fiber F as wide as ~120nm. The lowest measured loss of 2.5dB/km at 2035nm represents a new lowest value for HC-PBGF in this waveband and an x2 improvement as compared to our previous results [10]. More importantly, the attenuation values were measured over long length of bands. For example, the length of fiber G is ~1.1km.

Fig. 1:(a) Scaling of minimum loss vs. wavelengths in 19 cell HC-PBGFs: different traces (labelled A to J) show the lowest loss region of ten fibers with identical structure (except for fiber J) but varying scale factor. Below ~2.1μm the minimum loss follows the $\lambda^{-3}$ dependence (red curve) predicted for surface scattering loss. In order to account for the loss at longer wavelengths, which is determined by the infrared absorption of silica glass, the attenuation of “wet” and “dry” silica [7] weighed by the estimated overlap factor (0.2%) of our fibers is plotted. To provide calibration for these curves a HC-PBGF designed for operation at 3.4μm [8] is also shown (Fiber J). (b) The scanning electron microscope (SEM) image of fiber F.
We observed substantial absorption from CO$_2$, H$_2$O and HCl as previously reported [4, 11]. In an effort to remove such absorptions, we have utilized a purging method similar to the one described in [11], using ultra-dry Argon in this instance. Fig. 3 shows the attenuation of Fiber F (~500m in length) measured with an optical spectrum analyzer (OSA) with a nominal resolution of 50pm, before and after purging for 7 days at 6 bars pressure. The three bands of CO$_2$ at 1.95–2.1 µm were completely eliminated, providing an absorption-free low loss window. The amount of HCl and H$_2$O was also very substantially decreased. Although it is preferable to remove these species during the fabrication process, it appears wholly feasible to remove absorbing gas species on fiber lengths of km scale.

2.3. Conclusions

We have presented for the first time the wavelength scaling of loss in 19 cell HC-PBGFs. For wavelengths shorter than ~2.1 µm, the minimum loss is in excellent agreement with the $\lambda^{-3}$ scaling law predicted for surface scattering loss, suggesting that loss in our fibers is indeed limited by this mechanism. For longer wavelengths the loss becomes dominated by material absorption and we have identified the role of hydroxyl content in determining the precise value and wavelength of the minimum loss. Although the minimum loss region is very
sensitive to the detailed fiber design, it can be deduced that this region will move to longer wavelength by reducing the overlap with silica glass and the hydroxyl content in the glass. As a part of this study, we also produced a number of HC-PBGFs with losses around 2.5–2.7dB/km at 2.03–2.14μm, which represent a new record in this wavelength region. In addition, we have demonstrated that impact of absorbing gas species can be greatly alleviated by purging the fibers with dry gas and this approach is viable for lengths up to 500m, and can likely be extended to lengths of km scale.

2.4. References

3. Accurate Loss and Surface Mode Modeling in Fabricated Hollow-Core Photonic Bandgap Fibers

3.1. Introduction

The loss in HC-PBGFs is well known to be fundamentally limited by scattering from surface roughness, which is critically affected by fine structural details in the microstructured cladding, especially by those on the boundary between core and cladding. The accurate numerical modeling and assessment of the properties of fabricated samples, an important process in the design of low-loss HC-PBGFs, has so far proved challenging. This crucial verification step is important to confirm whether or not a designed fiber operates as intended, to understand the effect of small structural imperfections and to provide feedback to the initial design. Traditionally, it has been carried out by modeling geometries obtained from scanning electron micrographs (SEM) of the fiber cross sections. The standard procedure consists of converting the grayscale SEM image into a two-level one and using edge detection routines to turn the boundaries of the air holes into smooth curves, usually splines [2, 3]. The challenge arises because the limited resolution of the SEM images prevents one to simultaneously resolve the entire microstructured cross-section (∼100µm) and at the same time the smallest features such as the thin silica struts in the cladding (typically ≤200nm). Furthermore, the metallic coating required to prevent charging effects and the hard to control tilt of samples during the SEM acquisition contribute to exaggerating the value of the strut thickness, resulting in the images always showing a lower air-filling fraction (and therefore a photonic bandgap centered at longer wavelengths) than in practice [3]. Reported attempts to circumvent this problem have mainly consisted in increasing the magnification of the SEM images, thereby limiting the field of view to the core and to the first few rings surrounding it [3, 4]. Although modal properties such as dispersion and birefringence can be reproduced, any reasonable comparison of measured and modeled loss values is foregone as only a portion of the fiber is simulated.

Here we propose a novel, fast and efficient method to faithfully reproduce HC-PBGF structures from SEM images. Because our method offers full control over the thickness of individual silica struts within the fiber cross-section, the resolution challenge is easily overcome. For the first time, simulations on the geometries of real HC-PBGFs show a good agreement with measured fiber loss and surface modes position within the bandgap.

3.2. Reconstructing structural profile from SEMs

The procedure we use to reproduce the geometry profiles of HC-PBGFs from their SEM images is shown in Fig. 4.

![Fig. 4: Procedure to reconstruct the fiber geometry from an SEMs (left). The central position of all holes and nodes is automatically detected (center) and used to recreate the fiber structure (right) using two free parameters, t and Dc.](image)

First we filter and convert the grayscale image into a binary black and white one. At this stage, each air hole can be identified and its center of mass accurately located by using simple image processing routines (e.g. in MATLAB). We then apply a dilation to each air hole with a structural element appropriately chosen so that all the air holes are merged together. This leaves the interstitials nodes as isolated objects, the center of mass of which can be also accurately located. Once the position of the center of each air hole and interstitial node is found, a hexagon (or pentagon) is built around each air hole by finding the six (or five) closest nodes to its center. Each edge of the hexagon (pentagon) is then moved closer to the hole’s center by a distance corresponding to half the desired strut thickness t, which in this model is a free parameter. The second free parameter is Dc the fillet diameter used to round the corners of the resulting hole (Fig.1). A good estimate of these two parameters can be obtained from averaging measurements on highly magnified portions of the cross section, adjusted by the estimated coating thickness. Alternatively a mass-conservation model predicting the
evolution of second-stage preforms into fibers can be used [5]. The freedom to create struts of arbitrary thickness allows one to generate geometries better matching the actual fiber, avoiding the limitation posed by the finite SEM resolution. Note that since no nodes lay beyond the outermost ring of air holes, this final ring is not reproduced in the final geometry. Nonetheless, its omission has very little effect on the fiber’s confinement loss which remains negligible, while scattering and absorption loss are largely unaffected. To make the generated structure even more similar to that of the real fiber, we apply mass conservation to each silica strut. Struts with lengths corresponding to the average strut length are made of thickness t, while longer and shorter are made thinner and thicker, respectively, by imposing their thickness to be inversely proportional to their length. This is particularly important for the struts on the core boundary, the thickness of which determines whether or not surface modes are supported within the photonic bandgap [6].

3.3. Results and discussion

We have used the method described above to model the optical properties of several fabricated fiber samples. Figure 5 shows simulation results for two fibers drawn from similar preforms, but scaled to operate around 1.55μm and 2.0μm respectively.

![Image](image.png)

**Fig. 5:** Comparison between simulation results and measurements for a fiber operating: (A) around 1.55μm and (B) near 2μm. The inset in the central figures is a modal effective index map showing the multiple surface modes crossing the air guide mode (red curve). The simulated loss in the figures on the right is calculated as the sum of scattering and confinement loss contributions.

Fiber A, drawn to operate near 1.55μm, has average hole-to-hole spacing, strut thickness and average fillet diameter of \( \Lambda = 4.02\mu m \), \( t = 100nm \) and \( D_c = 0.5\Lambda \), respectively. Fiber B made to operate around 2μm has average parameters \( \Lambda = 5.5\mu m \), \( t = 120nm \) and \( D_c = 0.45\Lambda \). As can be observed from the plots of Fig 2, the simulated and measured photonic bandgaps are in good agreement. More importantly, the surface modes positions within the bandgap match pretty accurately the measurements, with a large group of them guided at center bandgap. This arises from the fact that the preforms employed had a thin core tube, thus making the strut edge on the core boundary thicker than those in the cladding [6]. The wider surface mode affected region observed in real fibers could arise from small longitudinal variations of the structure.

At these wavelengths the loss is dominated by scattering from surface roughness, since the incorporation of seven rings of air holes outside the core limits leakage loss to negligible values [7]. Simulations on numerous fibers revealed that the scattering loss can be inferred with excellent fidelity from the simulated normalized interface field intensity, given by:

\[
F = \left( \frac{\varepsilon_0}{\mu_0} \right)^{1/2} \int_{\text{hole perimeters}} |E|^2 ds \int_{\text{cross-section}} E \times H^* dA
\]

where, \( E \) and \( H \) are the electric and magnetic fields respectively. For our fibers, we found that \( F = 0.0116\mu m^{-1} \) around 1.5μm corresponds to a loss value of 3.5dB/km. Additionally, scattering loss for fibers operating at different wavelengths follows the well-known \( \lambda^{-3} \) wavelength dependence [7]. Using this simple scaling, the simulated minimum loss obtained for several samples with photonic bandgaps centered at different wavelengths has shown remarkable agreement with cutback measurements, as can be seen in Fig. 2. This is to the best of our knowledge the first time simulated loss values for fabricated fibers have shown good agreement with measurements. The small discrepancies in bandwidth and loss between simulations and experiment could
indicate some residual inaccuracies when generating the profile, or they may result from longitudinal variations along the fiber.

We also performed finite element calculations for the fiber in Fig 1, which was drawn from a preform stacked without a core tube and designed to operate in the mid-infrared near 3.4μm (with λ = 9.3μm, t ≈ 300nm and D_c = 0.45)[8]. Here, material absorption rather than scattering dominates the loss, as shown in Fig. 6.

![Fig. 6: Transmission and loss measurement versus simulated power in the core and loss for a fabricated mid-IR HC-PBGF. Simulations with and without the glass absorption clearly indicate the dominant source of loss at these wavelengths.](image)

Our simulation used the wavelength dependent absorption of dry silica (Suprasil F300) extracted from the data of Humbach et al. [9]. Even in this case the simulated loss agrees well with the experimental data, particularly at longer wavelengths, confirming that despite the low modal overlap with glass (<0.2%) the loss in this region is dominated by the glass absorption [8]. We note that as a result of the thin core surround no surface modes appear near the center of the photonic bandgap, neither in the simulation nor in the real fiber. The oscillations seen in the loss curve are due to modal beating (3100-3300nm) and gas absorption (3300-3600nm) [8].

### 3.4. Conclusion

We have presented a novel, accurate method to reproduce the structural profiles of HC-PBGFs from SEM images of their cross-section. Our method overcomes the previous issue of insufficient image resolution. Finite element method simulations performed on various fabricated fibers show for the first time that the loss and surface mode positions in fabricated HC-PBGFs can be accurately modeled. Our simulations indicate that distortions near the core play an important role in determining the scattering loss of the fiber. The method outlined here shall therefore serve as a valuable verification tool in HC-PBGF design, and can allow the study of how small structural changes around the core impact the loss and bandwidth of these fibers.

### 3.5. References

[6] Poletti et al, ECOC 2013 London 22-26 Sep 2013 Tu.3A.4
4. Novel Fluid Dynamics Model to Predict the Draw of Hollow Core Photonic Band-Gap Fibres

4.1. Introduction
Efforts within the Mode-Gap project, some of which have been reported in the previous sections, have established that in order to achieve the correct band-gap the HC-PBGFs their structure must be delicately controlled. Efforts to reduce the loss in these fibers demand increasing precision of node position and strut thickness. Practically, these HC-PBGFs are drawn and designed using experience and trial and error; a process that is both expensive and time consuming. When specific and unconventional structures need to be targeted then a predictive tool would rapidly speed up the development cycle and reduce the number of iterations required.

Current simulation methods, applying conventional computational fluid dynamics approaches of microstructure fibres, are in development but still limited to a small number of holes [1,2]. The limitations are intrinsic in the nature of the method, finite volume or difference methods require a high mesh density to resolve boundaries effectively and high aspect ratio volumes need to be avoided. Even for a 2D holey fibre the mesh size required is high. For an HC-PBGF where the struts are thin, with an aspect ratio >20, the mesh density required for the full structure is prohibitively high.

A computational method has many applications such as considering how different materials might behave, novel structures evolve and industrial length up-scaling. As these simulations are relatively cheap, one can search the design space by casting a wide net of parameter combinations. The migration from research scale fabrication to industrial scale fabrication requires preforms to become significantly larger, draw speeds of the order of km/min and consequently hotter furnaces. This model can help understand the changes in draw parameters required for volume up-scaling. The kernel of the method currently sets up hexagonal lattice geometries but could easily be adapted to solve any lattice based microstructure, such as anti-resonance or suspended-core microstructure fibres.

In this section we present a simple and flexible method to model the structure of a hollow core microstructured fibre. First, the method structure and governing equations are outlined; we follow this with a simple set of results and compare them with Scanning Electron Micrographs (SEMs) of real HCPBGFs. Finally we comment on the capabilities of this model.

4.2. Method
To simulate the evolution of the microstructure during the draw we split the simulation process into two parts: the external jacket glass is modelled like a simple drawn capillary using the model of Fitt et al.[3]. The Fitt model predicts the inner and outer diameters of a drawn capillary for a non-isothermal draw with applied pressure and surface tension. The internal microstructure, Fig. 7, uses that capillary as a boundary while solving physical equations that govern its motion.

Fig. 7: Our representation of a fibre preform microstructure, the jacket glass is 3mm thick.
Fig. 8 shows the neck down generated using the Fitt model. The simulation starts with a 2D preform geometry, Fig. 7, and marches in the z-direction - the direction of fibre draw.

The Fitt model governs the boundary motion, while the forces of pressure, viscosity and surface tension are applied to the microstructure which evolves accordingly. Consider the most typical HC-PBGF preform; it is a triangular lattice of capillaries. We replace this with a honeycomb like structure of rectangular struts within a boundary defined by the jacket glass, Fig. 7 shows our representation of the structure. Each strut connects 2 nodes, and each node is a junction of 3 struts. We now consider each of these struts to be a 1D control volume of fluid upon which we apply forces of viscosity due to strut extension rate (Eq. 1), gas pressure (Eq. 2) and surface tension from curvature at the junction between struts (Eq. 3).

\[ F_v = 2\mu \frac{d\bar{u}}{ds} wD\hat{s} \]  
\[ F_p = (P_A - P_B)Dl\hat{n} \]  
\[ F_s = \gamma R_c A_c \hat{c} \]

where \( \mu \) is the glass viscosity, \( \frac{d\bar{u}}{ds} \) is the rate of change of extension in the direction of the strut, \( w, D \) and \( \hat{s} \) are the width, depth and unit vector along the length of the strut.

Self-pressurised draws can be simulated by using a gas volume conservation relationship to change cell pressure, \( p_1 \), as a function of gas volume on a cell by cell basis by comparing the new volume, \( V_1 \), with the original volume, \( V_0 \), and ambient pressure, \( p_0 \), using \( p_0V_0 = p_1V_1 \), no other pressure is applied. The mass of each strut is conserved, i.e. if struts are stretched they become thinner. The forces on each of the struts are resolved to the node and a numerical scheme finds the velocities and positions in time and \( z \). The simulation finishes when the slice exits the furnace.

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This computational model gives us access to the in-furnace dynamics – we can see the evolution of the microstructure in the hot zone. The dynamics in the furnace are governed by a delicate balance between the
forces of surface tension and pressure and viscosity. In this manner the model can help us understand the physical effects occurring throughout the furnace rather than just the final fibre shape.

4.3. Results
Here we demonstrate that this model can simulate fibre draws from preform to fibre and produce realistic fibre structures based on physical forces. A 19 cell 7 ring cane, 3mm in diameter, was placed in a jacket tube with inner and outer diameter of 3.5 and 10.0 mm. In total 3 fibers were drawn, with a nominal expansion ratios $e \sim 50\%$ (defined as the microstructure to outer diameter ratio), each with 3 different core pressure values but constant cladding pressure. The pressure of importance in this study is the difference between the cladding and the core pressure, $\Delta P_{\text{core}}$. The pressure of Fiber A was chosen to produce a typical sized core, this became the baseline pressure. The pressures of the following 2 fibers were 4KPa and 8KPa above such baseline. The simulated preform was drawn to fibres with OD of 200 micron using the Fitt model and the same parameters as in the experimental study. Fig. 10 (bottom row) shows the simulated fibre microstructures for the 3 different core pressures. It is clearly evident that the jacket glass and struts become thinner with higher expansion ratios as we would expect. The cells surrounding the core become increasingly elliptical and the corner holes show increasing node spacing as the fibre is expanded.

![Fig. 10. Comparison of optical micrographs of Experimental fibers A, B & C (left) with Simulated fibers 1, 2 & 3 (right).](image)

Compare these simulated structures with the optical microscope images of fibres fabricated with the same parameters, shown in the top row of Fig. 10. The honeycomb-lattice is regular and balanced in both experiment and simulations. The distance between the corner nodes in the core increases as the fibre expands, this feature is accurately portrayed by the simulation. Now consider the core size; both experiments and simulations follow the trend of expanding core size with increasing core pressure. The general cladding structure is reasonably uniform in shape and size when the core is small, but as the core is expanded the cells in the surrounding structure begin to compress. The compression is felt strongest in the ring nearest to the core while the cells near the jacket glass show the least (but still notable amounts of) deformation. Finally examine the first ring nearest to the core, the corner cells are larger and a different shape to the side holes in between them. As the core expands the corner holes stretch until, in the final case, the membranes are so thin they are unobservable with an optical microscope. All of the effects seen in the experimental micrographs are recreated in the simulation with apparently equal magnitude.

4.4. Capability
The model presented here is a powerful tool for accurately predicting the microstructure of a HC-PBGF drawn from a cane with a hexagonal lattice structure which has been used to draw low loss HC-PBGFs [5]. The model offers the potential scope for rapid optimisation of fibre fabrication parameters by predicting the necessary
drawing conditions \textit{a priori}. This potential can then be harnessed to up-scale the lengths of HC-PBGF which can feasibly be drawn from a single preform therefore maximising the potential yield. Combining this model with a finite element model that can predict the optical properties of the fibre allows for the virtual draw and characterisation of fibres. The proposed system is then tasked to rapidly search and optimise preform designs and draw parameters to produce low loss fibres for a specified wavelength.

4.5. References