Combined Structural and Optical Modelling tool to Optimise Design and Fabrication of Hollow Core Photonic Band Gap Fibres

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Abstract *Two powerful simulation tools are combined to predict geometry and optical properties of Hollow Core Photonic Band Gap fibres from their preform structure and draw parameters. Broad parameter space scans allow identifying structures for optimal optical performance.*

Introduction

Hollow Core Photonic Band Gap Fibres (HC-PBGF) possess some exciting properties such as extremely low nonlinearity, low latency and potential for low loss[1]. Optimising their design and fabrication process, however, is a difficult, cumbersome and expensive task based on empirical trial and error which severely limits the possibility to optimise the design and drawing parameter space to achieve the best possible structures. Optical modelling of HC-PBGF has developed over the years. However, most of the work performed on these structures has focused on the study of either "idealized" geometries or on the post-fabrication analysis of their properties from scanning electron micrographs (SEM)[2], with no attempt to help optimising the drawing process.

In this paper we present a modelling tool that combines a recently developed fluid dynamics model that can predict the geometry of fibres from their preform for any arbitrary draw parameter[3], with electromagnetics simulations to predict their final optical properties. The toolset is validated by comparing its results with an older experimental draw[4]. We virtually draw a broad range of fibre structures recreating with good agreement not only the experimental structure but also its optical properties. The toolset is then used to speculate the performance that the same fibre would have if drawn to a higher expansion, showing that improvements to both bandwidth and attenuation are possible.

Drawing HC-PBGF

HC-PBGFs are made with a 2 stage stack and draw process; ~1mm glass capillaries are stacked inside a larger tube (~25mm) with a central core made by omitting capillaries (19 in this work). The assembled stack is drawn in a vertical furnace down to canes (~3-5mm OD), which are placed inside thick jacket tubes (~10mm OD, ~3mm ID) and then drawn to fibre (~150µm). During the second stage draw 2 gas pressures are applied: to the cladding, to prevent the holes from collapsing, and the core to control its size. In this work we will concentrate on modelling the second stage draw, concerning ourselves with the two most important control parameters: relative core pressure and draw tension[5].

The models

Two models are used in this work: the MSEM - a fluid dynamics model that predicts the microstructure evolution through the draw from a given starting cane[3], and a full vector FEM-based electromagnetics model that calculates the optical properties of each virtually simulated fibre[6]. The structure used by the FEM stage is interpreted from the MSEM output using mass conservation routines to distribute glass to the nodes, fillets and struts appropriately.

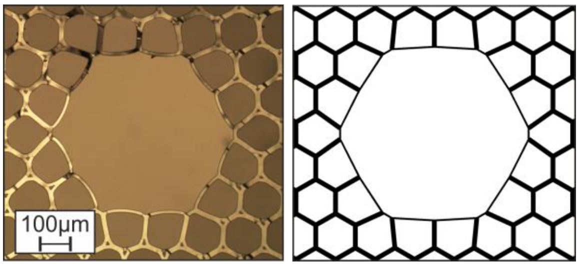

Fig. 1: Core of experimental 2nd stage preform (left) and initial geometry for structural simulation (right).

The modelling process

To illustrate how the process works we model a 3.5dB/km 19 cell HC-PBGF fibre already extensively characterised[4]. First we carefully measured the preform and accurately recreate its geometry, Fig.1. Then we launched MSEM simulations replicating the experimental draw parameters and targeting a fibre with the same outer diameter (OD) of 160µm and expansion (ID/OD) of 45%. We used draw tension and applied pressure differential between core and cladding, ΔP_{core}, as free parameters for a broad parameter sweep around the experimental draw parameters.

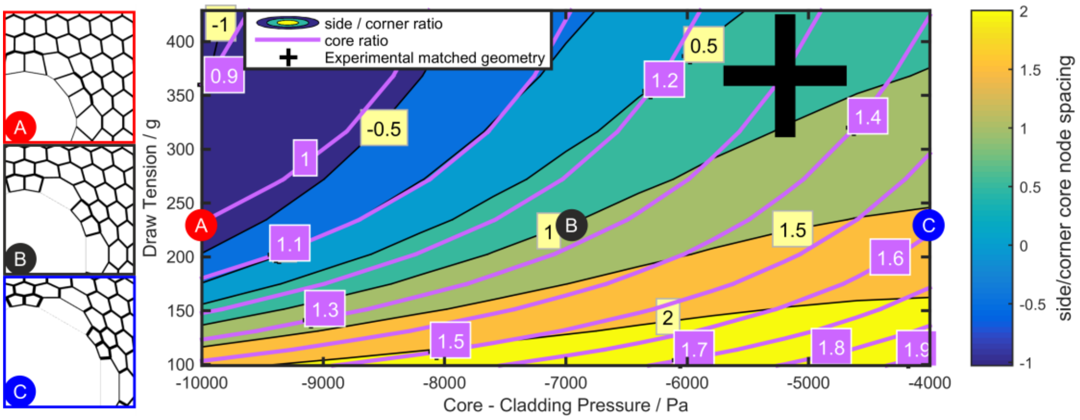

Fig. 2: Summary of 121 virtual fibre draws using the core size and core node spacing metrics, 3 structures are spotlighted to show how metric values relate to the fibre structures. The geometry that matches the experimental fibre is indicated with +.

Results

To help summarise the salient features of the resulting geometry of all the virtual fibre draws (121 in this case, on an 11x11 fibre grid) we define two metrics that describe key parts of the fibre structure: core size as a ratio of fibre core diameter to ideal core diameter $\phi_c = r_{core}/(5/17)$ (based on the stack), and core node uniformity defined as $\phi_n = l_{corner}\text{-}l_{side}/\mathrm{mean}(l)$ where l is the distance between neighbouring nodes around the core. With these metrics Fig. 2 summarises the most distinctive characteristics of each fibre structure and presents all the fibre geometries as a function of ΔP_{core} and draw tension.

From Fig. 2 we can see that the geometry is affected by both ΔP_{core} and tension in different ways, but with similar trends. The core size is a function of ΔP_{core} as expected, while increasing the draw tension promotes a smaller core. Equal node spacing on the core surround, $\phi_n = 0$, has been associated with lower attenuation, but so has the effect of a larger core size[6]; in our virtual draw these two attributes appear to trade-off each other, Fig. 2(a-c).

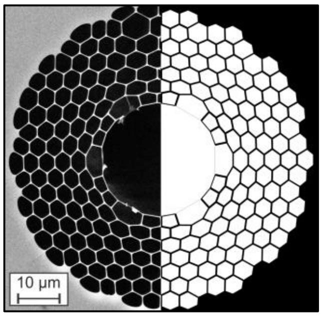

Fig. 3: SEM of an experimental fibre (left), simulated fibre with same geometry metrics (right).

Now let us consider the experimental fibre that has been drawn from this cane[4]; an SEM of which is shown in Fig. 3. From this SEM we can measure its ϕ_n and ϕ_c and position it in the parameter space of Fig. 2. The simulated fibre corresponding to that point is also shown for comparison in Fig. 3. The very good structural match confirms that the two metrics identified are an effective way of describing the whole microstructure. A discrepency in pressure values between experimental (-7.4kPa) and simulated (-5.2kPa) draws was encountered; this was already obserrved previously and appears to be systematic in the MSEM[3].

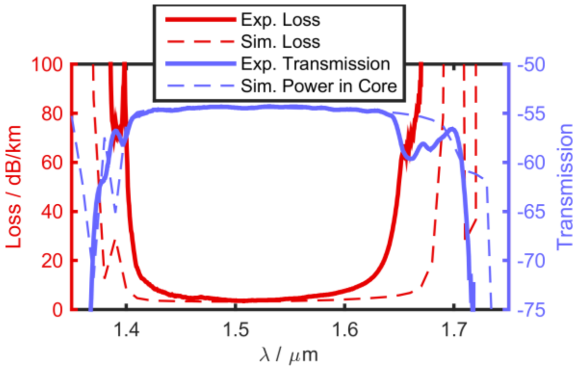

Fig. 4: Transmission and loss of fibres from Fig. 3, experimental and simulated.

The optical properties of the virtually drawn fibre are now compared with the experimental measurements. The results, shown in Fig. 4, compare extremely well in terms of loss (3.2 vs 3.5 dB/km – sim. vs exp.) and central wavelength (1530 vs 1510 nm), considering that no free-parameters were used in the model.

The optical results of each structure can be approximately summarized with two metrics: lowest loss and 3dB bandwidth. These can once again be summarised in a single map for all the fibres in the parameter sweep (the central wavelength of all structures is the same). The optical map is shown in Fig. 5, also indicating the position of the experimental fibre. The map clearly shows that the experimental fibre has a loss close to the minimum possible for this particular operational wavelength and cladding expansion. This is not surprising, given that a considerable effort and many empirical trials had been done to minimise the loss of fibres drawn

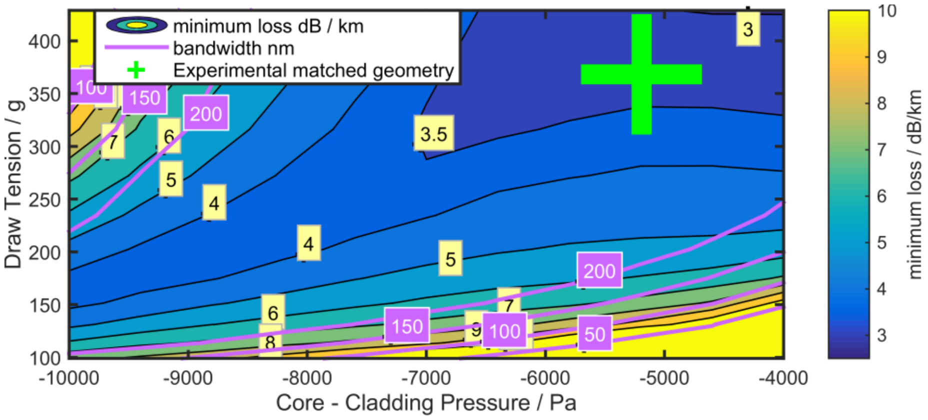

Fig. 5: Summary of the simulated optical results of 121 simulated fibre geometries. Matched experimental structure marked with '+', the complete optical result of this case is given in Fig. 4.

from this preform. We can also see that fibres with equally good optical properties are available for a large range of ΔP_{core} values and tension values > 250g, for this preform.

For fibres with the same OD and expansion ratio in this simulation sweep we found a minimum loss of 3 dB/km with a bandwidth of >240nm. We then studied the optical properties of the same parameter sweep but with increased expansion ratio from 45% to 55%. The thinner struts in the cladding and higher air-filling fraction is predicted to lead to lower loss.[1] Simulations indicated that the lowest loss decreased to 2.6dB/km with a 3dB bandwidth of >340nm, Fig. 6. This demonstrates the power of this toolset: a simple exploration of a broad parameter space can point to viable routes to improve the optical attenuation.

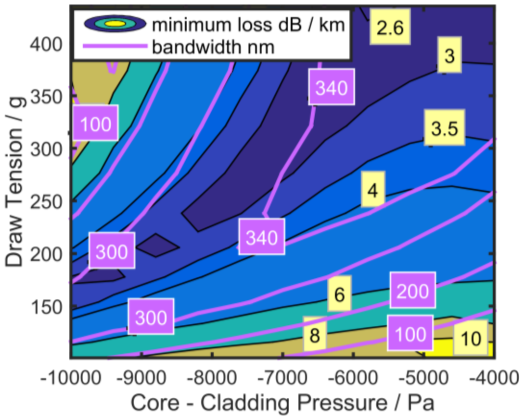

Fig. 6: Summary of the simulated optical results of with expansion ratio increased to 55%. Significant broadening of the bandgap and a small loss reduction result.

Conclusions

We have presented a novel numerical tool to guide the design and drawing process of hollow core photonic band gap fibres. The system combines two numerical models and allows the accurate prediction of fibre structures originating from arbitrary drawing parameters, and also the optical properties of each of these structures. The tool was validated through the accurate recreation of an experimental result, for which it showed that the drawing parameters of the HC-PBGF under examination had been already optimised empirically. We have also shown with one simple example that the tool can represent a fast and powerful alternative to expensive empirical trial and error approaches to guide design and optimise fibre drawing of lower loss HC-PBGFs. By processing each fibre concurrently on a compute cluster we can obtain a large sweep of structural results in a few minutes and of optical results in just a few hours, as compared with the several weeks that would be necessary to scan the same parameter space experimentally.

Acknowledgements

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