Predicting Structural and Optical Properties of Hollow-Core Photonic Bandgap Fibers from Cane Structural Information

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Abstract: We propose a simple theory based on mass conservation that allows accurate prediction of guidance properties in hollow-core photonic bandgap fibers (HC-PBGF) from knowledge of the second stage preforms from which the fibers are drawn.
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1. Introduction

By confining and guiding light within an air core, hollow-core photonic bandgap fibers (HC-PBGFs) offer the prospect of low latency, nonlinearity-free and potentially ultralow loss data transmission media [ref]. Reducing fiber loss and improving yield and longitudinal consistency requires considerable improvements in current fabrication techniques, conventionally based on a *two-step stack and draw* procedure [1].

In this procedure, meter-long hollow silica tubes of millimeter diameter size are initially *stacked* to form a primary preform, which is fused together and drawn into canes of, again, millimeter transversal size. In a second step the cane is inserted in a jacketing tube and the assembly drawn into fibers. During this step, the control of pressure inside hollow regions is key to counterbalance the effect of surface tension, which would otherwise tend to collapse the holey structure. As a result of a complex thermodynamic viscous flow process in this stage, the fiber structure typically differs substantially from the initial cane and it has been so far impossible to predict its structural and optical properties during the fiber draw without performing cumbersome measurements.

In this work we propose a simple model that allows prediction of the average geometrical parameters of the microstructured cladding in the final fiber (see Fig.1) and hence of the position and width of its photonic bandgap. Our model only requires knowledge of (i) structural parameters in the cane and (ii) two parameters that are easily measurable during fiber draw: the outer fiber diameter (OD) and the expansion ratio $e = ID/OD$, where ID is the average diameter of the microstructured region. The model is based on the principle of mass conservation and does not require any information on drawing or physical parameters such as temperature, drawing speed, surface tension, pressure, viscosity, etc. We show that despite its simplicity, this model can predict the guidance properties of fabricated HC-PBGFs and could therefore prove a useful tool for fiber fabricators.

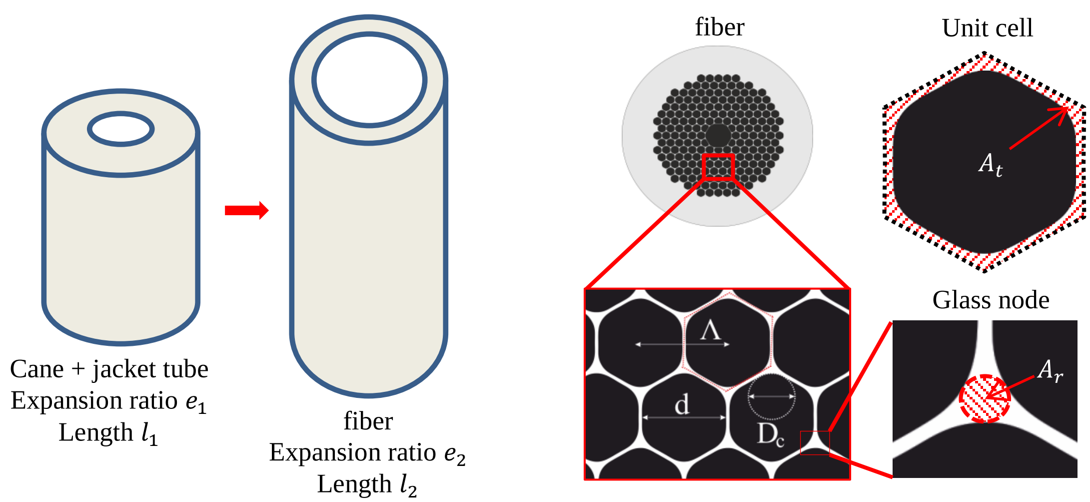

Figure 1: (a) A cane and jacket tube with expansion e_1 is drawn into a fiber with much smaller diameter but larger expansion e_2. (b) Definition of cladding parameters and separate areas of material that redistribute along the fiber length to achieve mass conservation.

2. Model derivation

Figure 1 illustrates a portion of the cladding of an ideal HC-PBGF, which can be accurately modeled as a triangular lattice of rounded hexagonal air holes of diameter d and period Λ, with corners filleted with a circle of diameter D_c [2]. Together with the glass refractive index, the three parameters $(\Lambda, d/\Lambda, D_c/d)$ completely define the position and width of the photonic bandgap. In this work we therefore aim to predict the values these parameters will assume in the drawn fibers as a function of the fiber's outer diameter and expansion ratio.

The model applies the principle of mass conservation, based on a number of reasonable assumptions: first we assume that during the fiber draw no amount of glass flows between the solid outer jacket and the inner microstructured region. Second, we also assume that since all air holes are subject to an isotropic expansion, no glass flow occurs between the glass nodes (A_r) highlighted in Figure 1 and their neighboring thin glass struts. As a result, the glass is therefore predominantly redistributed along the length of the fiber.

Under the first assumption, if the same cane is drawn into two different fibers 1 and 2 with the same outer diameter ϕ but different expansion ratios e_1 and e_2, the glass in the outer jacket will be redistributed so that:

$$\frac{\pi\phi^2}{4}(1-e_1^2)l_1 = \frac{\pi\phi^2}{4}(1-e_2^2)l_2 \;\Rightarrow l_2 = \frac{1-e_1^2}{1-e_2^2}l_1 \tag{1}$$

This implies that higher expansion ratios result in longer fibers. Besides, additional longitudinal elongation will also affect the inner microstructured region by thinning struts and nodes. As all the holes are equally enlarged, it follows that the pitches in the two fibers must satisfy $\Lambda_2 = e_2 \cdot \Lambda_1/e_1$. The second assumption leads to glass redistribution within the microstructured region such that the total volume in the nodes and in the struts is conserved. The fiber nodes can be approximated by circular area highlighted in Fig.1 as A_r:

$$A_r = \pi\left(\frac{D_c}{2d}\frac{d}{\Lambda} + \frac{(1-d/\Lambda)}{\sqrt{3}}\right)^2 \Lambda^2 \tag{2}$$

While the total area occupied by glass in a unit cell is:

$$A_t = 3\frac{(1-D_c/d)}{\sqrt{3}}\frac{d}{\Lambda}\left(1-\frac{d}{\Lambda}\right)\Lambda^2 + 2\left[\left(\sqrt{3}-\frac{\pi}{2}\right)\left(\frac{D_c}{2d}\right)^2\left(\frac{d}{\Lambda}\right)^2\Lambda^2 + \sqrt{3}\frac{D_c}{2d}\left(1-\frac{d}{\Lambda}\right)\Lambda^2 + \frac{\sqrt{3}}{4}\left(1-\frac{d}{\Lambda}\right)^2\Lambda^2\right]. \tag{3}$$

From mass conservation, for two fibers drawn from the same structure and having the same diameter:

$$A_{r2}l_2 = A_{r1}l_1 \tag{4}$$

$$(A_{t2} - 2A_{r2})l_2 = (A_{t1} - 2A_{r1})l_1 \tag{5}$$

If the cladding parameters $(\Lambda, d/\Lambda, D_c/d)$ are known in the cane, Eq. 4 and 5 can be solved to find their values in the fibers with the only required inputs being the final expansion ratios and ODs of the fibers. Fiber 1 is taken as the cane isotropically scaled down to the desired OD while keeping its expansion ratio (e_1) and geometrical parameters $(d/\Lambda, D_c/d)$ and fiber 2 is the targeted fiber with expansion e_2.

3. Results and discussion

Figure 2 shows an optical microscope image of a cane we recently produced and drew into fiber. By analyzing the optical microscope image we found that in this cane $\Lambda = 80.9\mu m$, $d/\Lambda = 0.87$ and the air holes are nearly circular, giving an estimate of $D_c/d = 0.49$. Additionally, the cane had an OD of $1.76mm$ and as it was drawn into fiber, it was surrounded in a jacketing tube of outer diameter $10mm$ and inner diameter $4.8mm$.

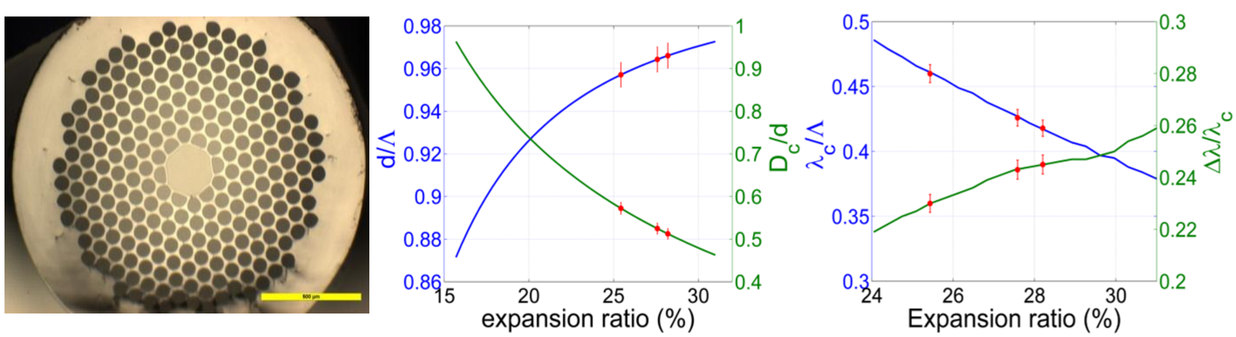

Figure 2: (a) Optical microscope image of the cane to draw into fiber. (b) Predicted cladding parameters as a function of expansion ratio during fiber draw. (c) Corresponding central wavelength and bandwidth as a function of expansion.

With these cane parameters, we solved eq. (4) and (5) for $(d/\Lambda, D_c/d)$ in the possible resulting fibers as a function of expansion and plot the results in Figure 2(b). As expected, more expansion leads to thinner glass struts and to air holes with more hexagonal shape. These parameters were used as input to a fully vectorial finite element method solver to find the normalized central wavelengths and bandwidths for the plausible fibers with expansion ratios between 24 and 30% plotted in Fig.2(c). Three fibers A, B and C were drawn from the cane with expansion ratios $0.254, 0.276$ and 0.282 and ODs $206.3, 214.3$ and $218\mu m$, respectively. The data points highlighted in Figs 2(b) and 2(c) correspond to these fibers respectively. We simulated 7c fibers with the cladding parameters ($\Lambda, d/\Lambda, D_c/d$) predicted for fibers A, B and C and plot in Figure 3 the calculated fraction of guided power in the core, which we have superposed to the measured short transmission over a short fiber length. Table 1 shows a comparison between simulated and measured parameters.

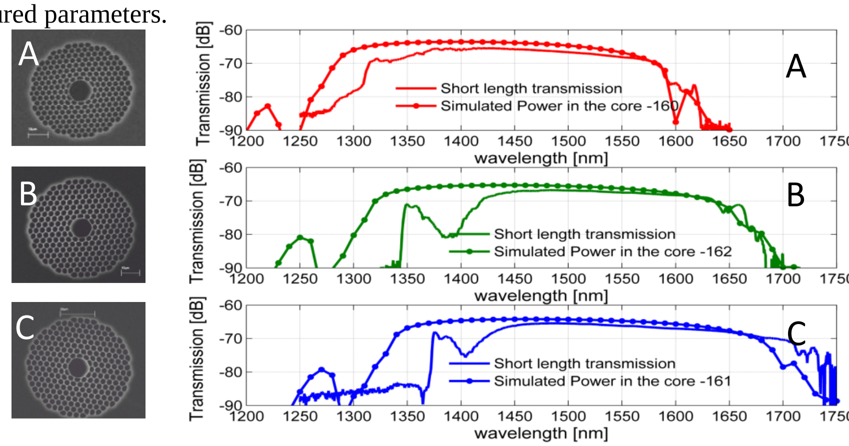

Figure 3: SEM images and short length transmission measurements of the three fibers that were drawn. The transmission curves are superposed with the simulated percentage of power in the core adjusted so that both data lie in the same range.

Table 1: Predicted and measured cladding parameters for fibers A, B and C.

Fiber	$\Lambda(\mu m)$	d/Λ	D_c/d	Measured λ_c/Λ	Predicted λ_c/Λ	Relative error on λ_c/Λ (%)	Measured $\Delta\lambda/\lambda_c$	Predicted $\Delta\lambda/\lambda_c$	Relative error on $\Delta\lambda/\lambda_c$(%)
A	3.1	0.957	0.592	0.475	0.460	3.1	0.212	0.230	7.8
B	3.47	0.964	0.545	0.434	0.426	2.8	0.225	0.243	7.4
C	3.62	0.966	0.533	0.428	0.418	2.3	0.232	0.245	5.3

As can be seen, the agreement between our simple model and the measured transmission is good. Our predicted pitch values are within $0.1\mu m$ of the average ones measured in all the six directions on the SEM images.

Our assumptions in the previous section can be seen to result in general in a bandgap centered at a slightly shorter wavelength than measured, but also to a slightly broader photonic bandgap as well. These small departures are well within acceptable errors, considering the fact that the parameters in the cane are only measured approximately but also that the fiber cladding always possess some non-uniformities and is not ideal. The good agreement between measurement and modeling, as well as the accurate response of our model to small changes in fiber expansion and OD show that our theory can reliably be used to predict fiber properties before they are drawn from canes.

5. Conclusion

We have derived a simple model based on the principle of mass conservation that allows predicting HC-PBGFs geometrical parameters and optical properties from those of the originating canes. Our model can predict photonic bandgap position and width in fibers with reasonable accuracy and without the need for additional measurements during the fiber draw. This simple model can be used to improve preforms and canes in order to target HC-PBGFs with desired properties and potentially provide guidance for future upscaling of HC-PBGFs production volumes.

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