Hollow Core Fiber Technology for Data Transmission

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Abstract: We review our recent progress in developing hollow core photonic bandgap fibers for high capacity data transmission. Novel numerical and characterization tools developed to improve fiber performance and yield will be discussed.
OCIS codes: (060.4005) Microstructured fibers; (060.2280) Fiber design and fabrication; (060.2270) Fiber characterization.

1. Introduction

Hollow core photonics bandgap fibers (HC-PBGFs) open unprecedented application opportunities in areas that include data transmission with low latency, ultralow nonlinearity and improved robustness to ionizing radiation, mid-IR gas spectroscopy and high power laser delivery [1]. Owing to their low nonlinearity, ultimate-low signal latency, an ideal match to thulium-doped fiber amplifiers, and the potential to deliver ultralow loss, potentially comparable or even below the level of state-of-the-art single mode fibers, they are emerging as contenders in the race to identify the best solution for next-generation high capacity transmission systems.

Recently, we have reported substantial progress in the development of HC-PBGFs: by exploiting both polarizations, and spectrally efficient coherent modulation formats we have demonstrated up to 30.7 Tbit/s using 32QAM (2x96x160 Gbit/s/channel/polarization) [2]. We have achieved further capacity expansion through a MIMO-aided SDM scheme: using the 3 lower spatial modes (in both polarizations) and 96 DWDM channels modulated with a 16 QAM format, we have demonstrated a total data rate of 73.7 Tb/s over 310m of a HC-PBGF, which currently stands as the highest data rate ever transmitted through a PBGF [3]. We have also demonstrated data transmission at wavelengths around 2µm, the minimum predicted loss region for these fibers, using commercially available and custom built transmission components [4].

However, for these fibers to stand a realistic chance of competing with solid transmission fibers, significant efforts to further reduce their loss and improve the fabrication yield need to be put in place. In this work we review our recent work in this direction, which includes the formulation of a fluid dynamics model of the HC-PBGF fabrication process and the development of a modelling scheme that allows accurate simulations of the properties of fabricated fibers. Finally, we also report our work on the investigation of longitudinal uniformities in HC-PBGFs and present a systematic study of defect observed in these fibers – a first step towards their removal and thus towards the demonstration of multi-kilometer lengths of defect free fibers.

2. Modelling the fluid dynamics of the fiber drawing process

To produce HC-PBGFs with optimum properties the fiber microstructure must be delicately controlled; efforts to reduce loss demand increasing precision of node position and strut thickness. Practically, these fibers 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, a predictive tool would rapidly speed up the development cycle and reduce the number of iterations required. We have recently developed a simple and flexible method to model the structure of a hollow core microstructured fiber [5]. 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. [6]. 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. 1(a), uses that capillary as a boundary while solving physical equations that govern its motion. For each strut and at each node in the microstructure the forces of pressure, viscosity and surface tension are solved for at each longitudinal position down the furnace. The overall structure is then evolved using an appropriate numerical scheme. The model we have developed is a powerful tool for accurately predicting the microstructure of HC-PBGFs, see Fig.2(b) and Fig.2(c). The model offers the potential scope for rapid optimization of fiber fabrication parameters by predicting the necessary drawing conditions *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 maximizing the potential yield.

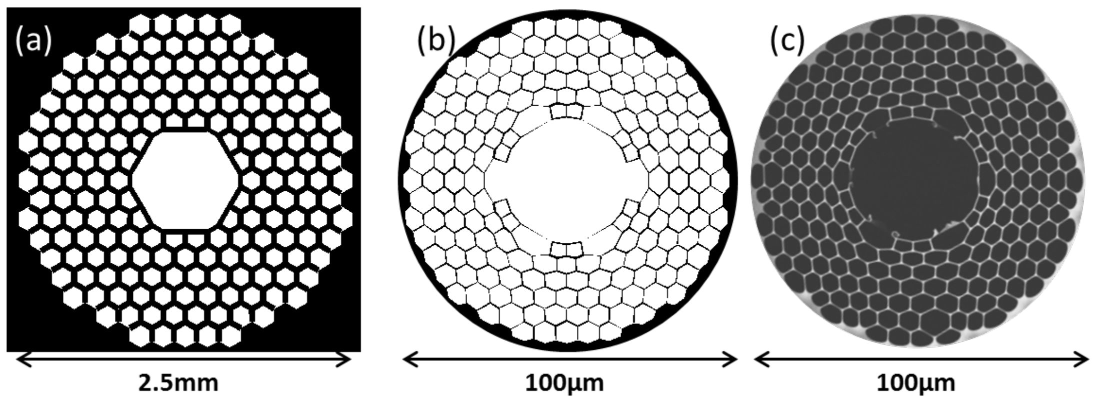

Fig. 1: (a) Microstructured preform of a 19c HC-PBGF; (b) final simulated fiber; (c) comparison with a fabricated fiber.

3. Modelling fabricated fibers

To improve the optical performance of HC-PBGFs further (e.g. reduce their loss, widen their transmission bandwidth, control their dispersive and modal properties), it is critical to be able to understand and control the effect of various types of small scale distortions that are often present in their cross section. Conventional structural reconstruction methods based on edge-detection routines are unable to capture the finest details with the accuracy required for this task [7]. Recently we have proposed a novel method to capture the structural irregularities of fabricated fibers with the nanometer scale accuracy required [8]. Using image processing tools we automatically detect the hole and rod positions, which are then used to build a reconstructed fiber cross section using information on average membrane thickness and rod sizes and imposing mass conservation arguments. Using this new method we have studied several fabricated HC-PBGFs and we have demonstrated that for the first time it is possible to simulate with high accuracy and with no free parameters not only the scattering and absorption loss of these fibers, but also their optical bandwidth and, even more strikingly, to accurately match the presence or absence of surface modes (Fig.2A). The accurate reproduction of fabricated HC-PBGF cross-sections allows us to study the dispersive properties of all their guided modes (Fig.2B), their differential loss, and more in general to understand which structural features are responsible for the guidance of surface modes and/or for an excess loss in the fibers. We believe that using this understanding it will be possible to improve fabrication processes to realize HC-PBGFs with greatly improved performance.

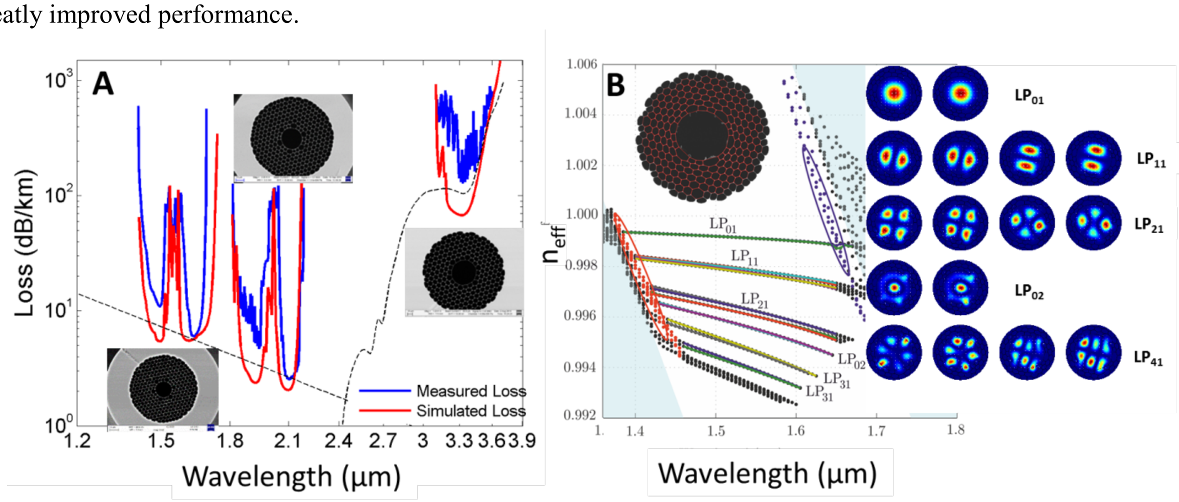

Fig. 2: (A) Simulated and measured loss of 3 HC-PBGFs guiding at 1550, 2000 nm (surface scattering loss dominated) and at 3300 nm (glass absorption dominated). (B) simulated modal dispersion and modal intensities for a fabricated wide bandwidth HC-PBGF.

3. Analysis of structural longitudinal defects in long lengths of HC-PBGFs.

A major challenge yet to be fully addressed for HC-PBGFs is the requirement to produce long fiber lengths (tens to hundreds of km). This involves the scaling up of fiber preforms (current preform sizes typically produce a few kilometers of fiber), but also, more critically, the ability to identify and avoid the occurrence of longitudinal defects that might otherwise impair the transmission properties, e.g. by introducing additional loss and coupling between different modes. Although such defects are well known, particularly amongst fiber fabricators, to occur in practical draws, they have seldom been reported in the literature and indeed very little is known about their origin, formation, and evolution during the fiber draw, and even techniques to allow for their detection have not yet been investigated in detail. The most straightforward inspection methods rely of the fact that any longitudinal inhomogeneity will cause a fraction of the light guided in the core to be scattered to other modes, either guided or radiative. To improve the spatial resolution provided by standard OTDR techniques, we study side scattering from the fiber using a direct imaging approach with a high sensitivity InGaAs camera. This technique provides sub-mm resolution and is able to identify some specific scattering points in the fiber which result in no appreciable feature in the OTDR traces [9].

By using the side imaging technique, a large number of defect points in HC-PBGFs was examined, aimed at investigating their morphology and longitudinal characteristics. A technique to precisely cleave the fibers at the exact position of the onset of the defect and subsequently at distances of 3-5mm apart was devised, which allowed us to track the evolution of each defect along the fiber length. Three main defect types were identified, as shown in Fig 3(a): “collapsed core”, “enlarged corner hole” and “over-expanded core”. In all these instances no appreciable variation of the fiber draw parameters, and in particular core and cladding pressure and fiber diameter, was detected.

The evolution length scale of all defects was found to be of the order of a few tens of cm. The sequence of images in Fig. 3(b) corresponds to samples taken at increasing distance from the onset point and shows the evolution of a “corner hole” type defect from its inception to its regression to the unperturbed steady state, which in this case was found to be approximately 230mm; at the typical drawing speed this lengths corresponds to about 1.3 seconds, indicating that draw instabilities are unlikely to play a direct role (as they would have a longer characteristic time). On the other hand, accounting for the draw down ratio, the defective fiber length corresponds to a length of just ~54μm in the preform from which the fiber is drawn, which strongly hints at the possibility of discrete, small scale glass inhomogeneities.

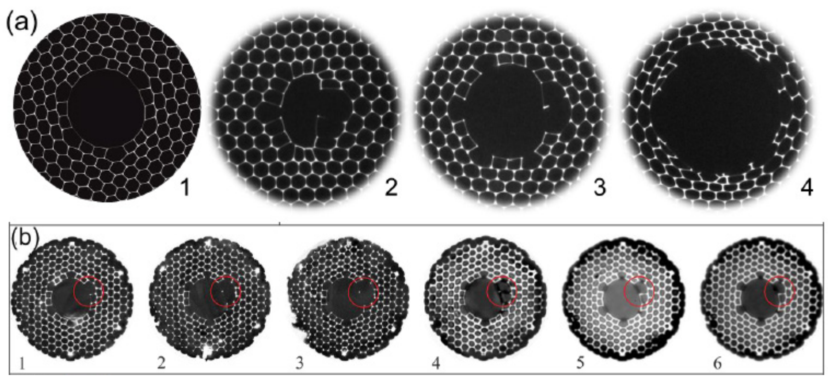

Fig. 3: Analysis of longitudinal defects in HC-PBGFs: (a) unperturbed fiber structure (1) and typologies of observed defects: (2) collapsed core; (3) enlarged corner hole; (4) over-expanded core. (b) Evolution over length of the “corner hole” defect.

4. Conclusion

We have reviewed our recent progress in the development of HC-PBGFs suitable for high capacity data transmission. The combination of fluid dynamics models that reproduce the fabrication process and predict realistically achievable fibers, with electromagnetic models that enable the study of the optical performances of such fibers represent an essential suite of tools to progress the development of low–loss HC-PBGF technology. The study of longitudinal defects and their causes is a first step towards the production of ultra-long lengths of such fibers.

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5. References

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