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Photonic Bandgap Fiber with Multiple Hollow Cores

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Abstract—**We report the fabrication and characterization of the first photonic bandgap fiber with multiple hollow waveguiding cores. Perspectives for scaling to highly multi-core designs are discussed.**

Index Terms—**Hollow Core, Multicore, Photonic crystal fiber, pulse delivery**

I. Introduction

HOLLOW core photonic bandgap fibers [HCPBGF] were first demonstrated over ten years ago [1] and since then worldwide interest has driven significant improvements in their optical properties. Currently, efforts are directed towards optimizing fiber designs for specific application areas, such as manipulation and delivery of ultrashort optical pulses [2], gas sensing and measurement [3] and laser/matter interactions [4]. A HCPBGF is unique in that light is confined to a low index core by a two-dimensional bandgap for light created using a photonic crystal cladding. The photonic crystal cladding is formed by a triangular array of holes in pure silica, which runs down the entire fiber length. The individual air holes have a six-fold symmetry and are surrounded by thin, straight, silica bridges (struts) which span between triangular islands of silica (nodes) [5]. Specific combinations of node and strut sizes can lead to formation of a two-dimensional photonic band gap spanning a range of non-zero propagation constants. By optimizing the fiber design and improving fabrication capability there have been significant steps to reduce the attenuation [6, 7], with the lowest recorded attenuation to date being 1.2 dB/km at 1620nm. To achieve such a low attenuation requires a very high air-filling fraction in the cladding (typically around 93%). The attenuation rises rapidly at shorter wavelengths because of increased scattering [7].

Careful construction of the wall of silica surrounding the core can yield large birefringence [8], wider band gaps and flatter dispersion [9]. Hollow core fibers have unique transmission and dispersion properties: they guide light only over a narrow range of frequencies determined by the photonic bandgap, and they typically have both normal and anomalous dispersion within their transmission window. The fibers can simply be scaled to guide at any wavelength. Their dispersion is important for short pulse compression and delivery [2]. The motivation for the work here is to investigate the possibility of these fibers for delivering pump pulses suitable for nonlinear optical endoscopy. Conventional fibers have severe drawbacks for this application: the group-velocity dispersion and the nonlinear response of a solid glass core will stretch the pulse in time, reducing the peak power, while creating new spectra components which will interfere with the desired signal. A hollow core fiber provides an ideal means to deliver the picoseond or sub-picosecond pulses that are required, with very low nonlinearity and engineerable dispersion. Multiple cores in a semi-regular array are most commonly used in endoscopic imaging. Our intention in this work is to expand the technical capability to include multiple cores in silica HCPBGF. A two-hollow-core photonic crystal fiber has been demonstrate [10], but the performance of that fiber was intrinsically limited because it did not guide light using a photonic bandgap. Other similar-looking structures developed for imaging applications are likewise fundamentally different from the fiber reported here. We report on the first all silica HCPBGF with more than one intentional core.

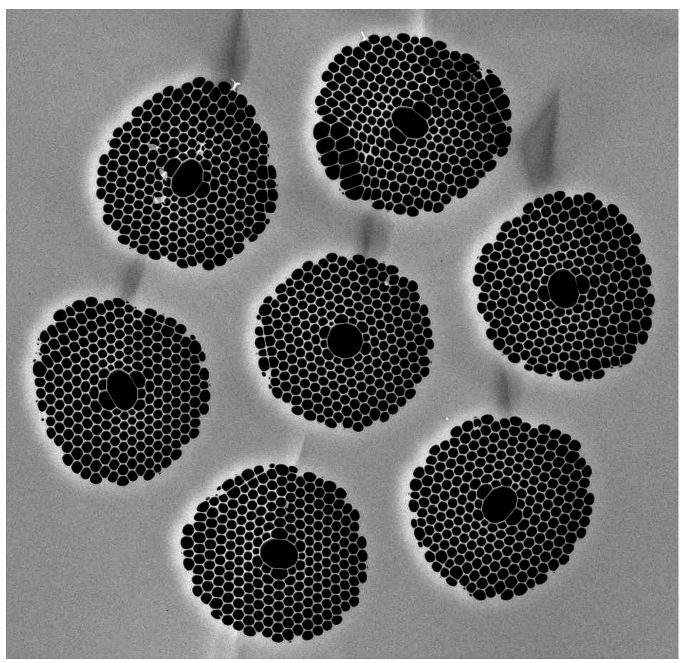

Figure 1. A scanning electron micrograph of the multicore hollow core photonic crystal fiber. Six hollow core waveguides surround a seventh structure at the center of the fiber.

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II. Fabrication and Fiber Structure

A. Fabrication

The multicore HCPBGF was fabricated using the stack and draw process described previously. There are two reported techniques to fabricate hollow core bandgap fibers. The final fiber structure resulting from the two methods is usually very similar. The difference is in the preform, a silica cane several millimeters in diameter and up to 1m long, with a micro structured cross section similar in design to the final fiber. In one method the canes have a high air filling fraction (approximately 90%) with significantly more silica at the apexes where the thin silica struts in the cladding meet to provide a distinct region of silica[6,7]. This cane design is closer to the final fiber structure required but significantly more time is required to fabricate the preform. The second method uses a lower air filling fraction cane [1, 9], fabricated using silica capillaries with a lower air filling fraction of approximately 75%. The air filling fraction is then increased by inflation during the final fiber drawing process. A major difference between the two approaches is that with the second method, the ring of silica surrounding the central waveguiding core – the “core wall” – is significantly thinner. Using the thinner core wall has been reported in [9] to reduce the impact of surface modes and increase the spectral transmission band of the fiber. The inflation of the air holes redistributes the silica in the fiber cladding structure to create the thin struts in the cladding and significant silica mass at the apexes. It is the second method with greater inflation that was used to fabricate fibers presented here.

The canes were originally fabricated in order to draw single-core fibers. They have a hole-to-hole spacing (pitch) of 80um and wall thickness of 9µm, with seven rings of holes around the core. Seven periods of the lattice are omitted at the centre of the fiber to form the hollow core. For structural integrity a solid silica jacket surrounds the entire holey region.

Six such canes were chosen to surround a seventh cane at the centre of the “superstack” of perform canes. Seven canes are the simplest option to stack in a stable pattern, and provide a near-circular outer perimeter which can conveniently be jacketed with a further silica tube. The seven canes were drawn from the same original single-core stack so that they were similar to each other. The canes were assembled inside a tube which forms an outer (non-optical) cladding of the fiber. Silica rods were placed at the interstitial sites between the canes to reduce any deformation that might otherwise have occurred during the draw when the vacuum was applied. A sealant was used at the top of the assembled canes to ensure that the vacuum that was applied between the canes was not affected by the positive pressure that was simultaneously applied to the cladding holes at the top of the canes. The seven cores were isolated from the cladding by silica capillary inserts so that they could be pressurized independently. All the cladding holes were pressurized from a common pressure source so that they were subject to the same pressure. The seven cores were also pressurized together to a single common pressure.

TABLE I
Structural Parameters of the Waveguides

	Pitch \ µm	Core Diameter \ µm	Core ellipticity	PCF Region \ µm
Central Waveguide	1.4 – 1.5	4.9	1.0	24.9
Outer Waveguide	1.3 – 1.7	4.9	1.5	25.6

B. Fiber structure

A scanning electron micrograph (SEM) of the multicore HCPBGF is shown in Figure 1. The waveguides are arranged in a triangular pattern with six waveguides surrounding a waveguide at the centre of the fiber. The diameter of the fiber is 151 µm and the core to core spacing is on average 30 µm. The air filling fraction as calculated from the draw down ratio and the diameter of the waveguide is approximately 95% in this fiber. Table I shows the most relevant fiber parameters. The PCF region and core diameter given are the average of three measurements along each axis and the ellipticity is the ratio of the maximum to the minimum measurement.

The outer waveguides have some distortion in their cladding compared to the central waveguide. The central waveguide is symmetrically surrounded by the outer waveguides. This has resulted in the core being very symmetric. The outer waveguides are in a less symmetric environment and it can be seen in the SEM that these waveguides have not inflated symmetrically, with the holes furthest away from the centre expanding significantly more than the holes nearer the centre. This has had an effect on the core, making them elliptical. Due to this ellipticity, the cores were inflated to a greater extent than the usual 3-period diameter. For smaller cores the ellipticity was significantly higher and it was likely that attenuation would be far higher. We anticipate that this effect will be reduced when the size of the array is scaled up to include more waveguides.

The cladding of the waveguide in the top right of the picture is significantly more distorted than the others. This is due to some of the sealant between the canes running into the holes, and it is not expected that this would be a problem in future iterations.

III. Optical Characterization

Light generated from a supercontinuum source was used to characterize the fibers. An endlessly single mode PCF with a core diameter of 5um was pumped with a 1064 Q-switched nanopulse laser [11]. A spectrum from 450nm to greater than 1750nm was generated. All precautions were taken to make sure that the source was stable before any measurements were taken.

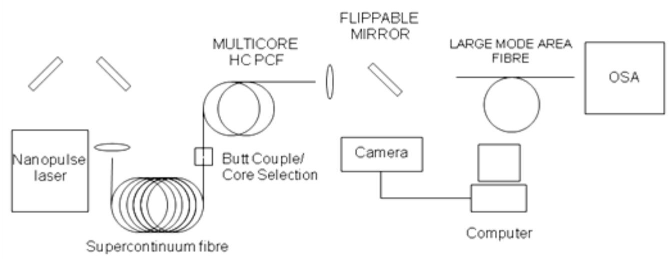

Figure 2. A schematic of the setup used for the optical characterization of the multicore HCPBGF. Light is generated using a supercontinuum (SC) light source. The SC fiber is butt coupled to the HCPBGF. Due to the similar core sizes this configuration enables clean excitation of single core in the multi-core fiber. A CCD camera is used for identifying the cores, and a large mode area fiber in the image plane of the near field is used to spatially filter the output from each core. The spectrum is measured using an Ando AQ-6315B Optical Spectrum Analyzer.

A. Transmission Measurements

The experimental setup for the transmission measurements is shown in Figure 2. The supercontinuum fiber is butt coupled to 20 meters of multicore HCPBGF. The core diameter of both fibers is very similar so efficient coupling is possible without obvious excitement of modes other than the fundamental core mode in each waveguide. The nearfield of the multicore HCPBGF is imaged onto a CCD camera, using a 10X objective lens and a mirror, so that coupling of light into each core can be optimized. The mirror is removed and a large mode area (LMA) fiber, positioned the same distance from the mirror as the CCD camera, spatially filters the light from each core in the image plane of the near field. The spectrum of the light in the large mode area fiber is then measured using an ANDO AQ-6315B optical spectrum analyzer (OSA).

The transmission spectra of six of the cores are shown in Fig 3. The resolution of the OSA was set to 5nm. The seventh core - one of the outer waveguides - did not guide any light through the 20 meters of fiber that was investigated. It is suspected that this is the waveguide with expanded holes along one side. Apart from this all the cores guided light over a similar broad spectral range. Given the deformations in the different waveguides this is very encouraging both for the work presented here and for more complicated designs in the future. The bandwidth of the fiber is approximately 80nm. This is relatively low for a hollow core fiber of this design at this wavelength. Usually at 800nm wavelength a bandwidth of 120nm or more can be expected. The fiber was drawn with a relatively low air filling fraction to reduce the deformations of the outer waveguides, and a higher air filling fraction would have given a larger bandwidth.

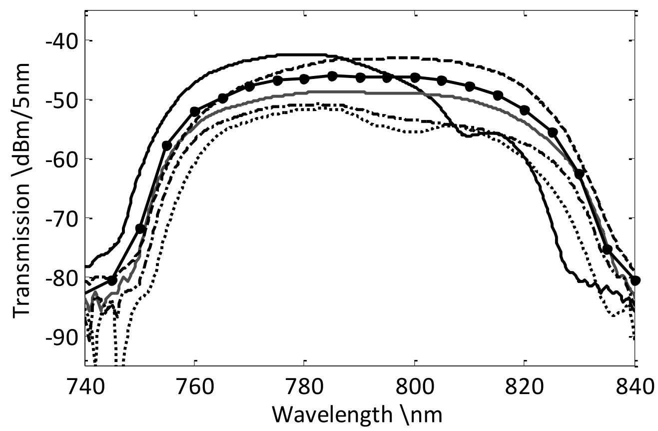

Figure 3: The transmission spectrum of six of the hollow core waveguides in the multicore HCPBGF. The central core is plotted with a solid black line, and differs most from the others, as might be expected from looking at the micrograph shown in Fig. 1. The other lines are the surrounding outer waveguides.

B. Intra-core coupling

An important part of this work is to demonstrate that the cores are independent of each other, or more specifically that light in one core does not couple into any of the neighboring cores. Light can either couple via the evanescent tail of the mode or by scattering. To measure this using our setup in Figure 2, light was coupled into one of the outer cores and the output of the core was collected using the LMA fiber. The spectrum was measured using the OSA and shown in Fig 4. To remove any ambiguity in the measurement the LMA fiber remained in this position so that only light in this core would be measured. The mirror was used to redirect the near field image to the CCD camera so that the light could be coupled into the three cores surrounding this core. Light was launched into the three cores sequentially with the spectrum of the original core measured each time. After these measurements were performed, the light was then coupled back into the original core and the same spectrum was obtained which confirmed that nothing had changed in the collection of the light whilst the experiment was in progress.

When light was optimized into one core, no signal was detected at the locations of the other cores on the CCD camera, even when the power incident on the CCD camera was heavily saturated for the excited core. The spectra taken in Figure 4 confirm this observation - that any coupling between the cores is less than 40dB (1 part in 10,000). Although no coupling was expected, due to the large number of cladding periods and solid silica cladding between the waveguides, this was a useful measurement to clarify that there were no unexpected problems.

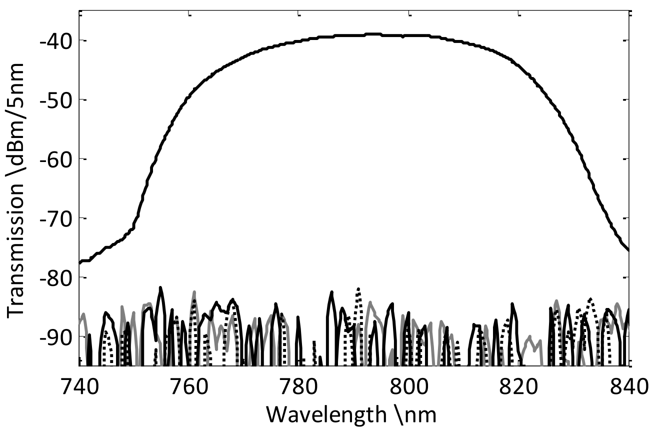

Figure 4. Transmission through one of the outer cores of the fiber with light coupled into the measured core and then the three surrounding cores. Only detector noise can be seen when light is coupled into cores other than the measured core.

C. *Spectral attenuation of the fibre*

Light was launched into one of the outer cores, with no signal observed in any of the other cores, using the setup in figure Figure 2. The multicore fiber was then removed from the setup and plugged directly into the OSA. The fiber spectrum was measured and whilst maintaining exactly the same input coupling the fiber length was reduced from 20 meters to 10 meters and the spectrum of the fiber was measured again (there were three measurements at each length to ensure the repeatability of the cleave). Taking the difference between these two measurements the attenuation spectra was calculated and plotted in figure 5. The lowest attenuation measured 0.38dB/m at 780nm with a 500dB bandwidth of 75nm. As with the transmission bandwidth, this is somewhat degraded compared to the current state-of-the-art for hollow-core fibers at this wavelength. We attribute this degradation to the compromises made to ensure guidance through 6 of the 7 cores.

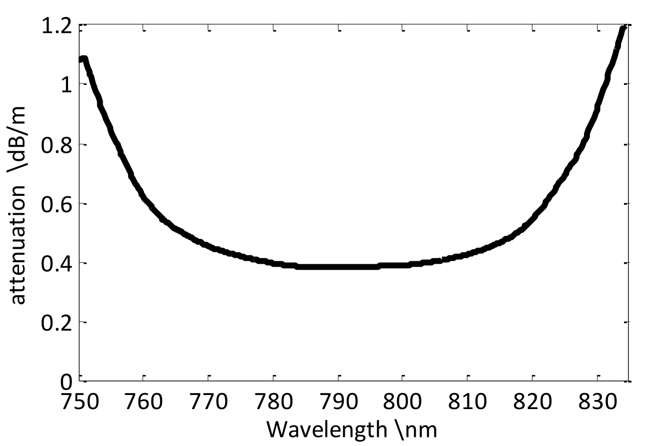

Figure 5: Attenuation Spectrum of one of the outer cores of the multicore HCPBGF.

IV. Conclusion

We have fabricated and demonstrated a hollow-core photonic bandgap fiber which guides light in six independent cores. The fiber was fabricated by stacking together seven independent preform canes and jacketing the stack before drawing it to fiber. The fiber was monolithic, but each guiding core had its own optical cladding as shown in Fig. 1. The results obtained give us confidence to proceed to fabricate a fiber in which multiple cores have a single shared optical cladding. This will enable a much higher packing density of cores (reduced inter-core spacing) and will also enable us to measure cross-talk between the cores.

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