# Modal Analysis of Anti-Resonant Hollow Core Fibers

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**Abstract:** We show the exploration of higher order core mode content in various designs of anti-resonant hollow core fiber using spatially and spectrally resolved imaging.
**OCIS codes:** (060.2280) Fiber design and fabrication; (060.2270) Fiber characterization.

## 1. Introduction

Hollow core fibers based on the anti-resonant effect are quickly gaining attention for their excellent guiding properties, such as low loss and wide transmission windows [1]. Various designs have been investigated in both simulation and experiment in attempt to reduce bending loss, shift the resonance wavelengths, and reduce the overall attenuation [2–5]. While many of these fibers' guidance characteristics have been studied in detail, the higher order mode content has not been looked at in depth experimentally. Understanding the mode content of ARHCFs is crucial for their applications, which include high power delivery, mid IR transmission, and in-fiber gas lasers.

Here we show an analysis on the mode content of several different geometric designs of anti-resonant hollow core fiber (ARHCF). Using spatially and spectrally resolved imaging ($S^2$), the number of guided modes as well as the distribution of power between them can be accurately measured [6]. $S^2$ uses both the spatial and the spectral interference produced by the propagation of multiple modes in a fiber to simultaneously image all of the modes and measure their intensities.

## 2. Results

Several different designs of anti-resonant hollow core fiber have been fabricated and analyzed for their core mode content. Specifically, two ARHCFs are shown here, one with an eight non-touching rings design, and the other, a hexagram design. Both fibers were excited with standard SMF, had a length of 1.6 m, and were interrogated in the spectral region of 1400-1600 nm, far from the resonance wavelengths of both fibers.

Figure 1(a) shows the ARHCF cross-section image with the eight non-touching rings. The core of the fiber is 70 µm, the rings are 19 µm in diameter with a 1 µm silica thickness, and the outer diameter is 150 µm. Below this is the reconstructed near field image from the $S^2$ imaging, showing a non-perfect Gaussian mode. The calculated Fourier spectrum is shown in Fig. 1(c), with three distinct peaks. The mode images associated with the group delay differences (GDD) are inset. This result shows that in addition to the fundamental mode, three higher order modes are present in the core of this ARHCF and each has about 1% of the power, with 97% of the power being in the fundamental mode.

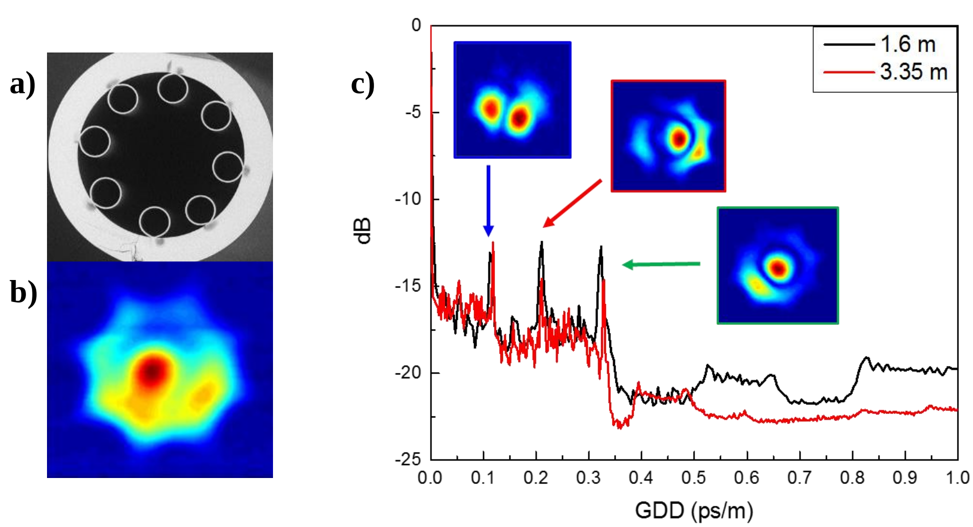


Fig. 1. (a) SEM cross-section of non-touching ring ARHCF. (b) Reconstructed near field. (c) $S^2$ Fourier spectrum with corresponding mode images for two fiber lengths.

A longer length of this fiber, 3.35 m, was also measured. The same three higher order modes were found, but the intensity of the $LP_{02}$ modes dropped to 0.5% each, as shown in Fig. 1(c). This is indicative that the higher order modes have a higher propagation loss than the fundamental mode, as is predicted [7].

Another ARHCF that was fabricated and tested was a hexagram shaped fiber, shown in Fig. 2(a). The core is 50 μm in diameter, the thickness of the silica strands surrounding the core is approximately 250 nm, and the outer diameter is 150 μm. The reconstructed near field, Fig. 2(b), shows a much cleaner, more Gaussian-like mode. The Fourier spectrum shows the presence of only one higher order core mode, with approximately just 0.1% of the power. Single mode operation was predicted for this fiber design, due to the preferential coupling of the fundamental core mode to cladding modes, as opposed to higher order core modes [8].

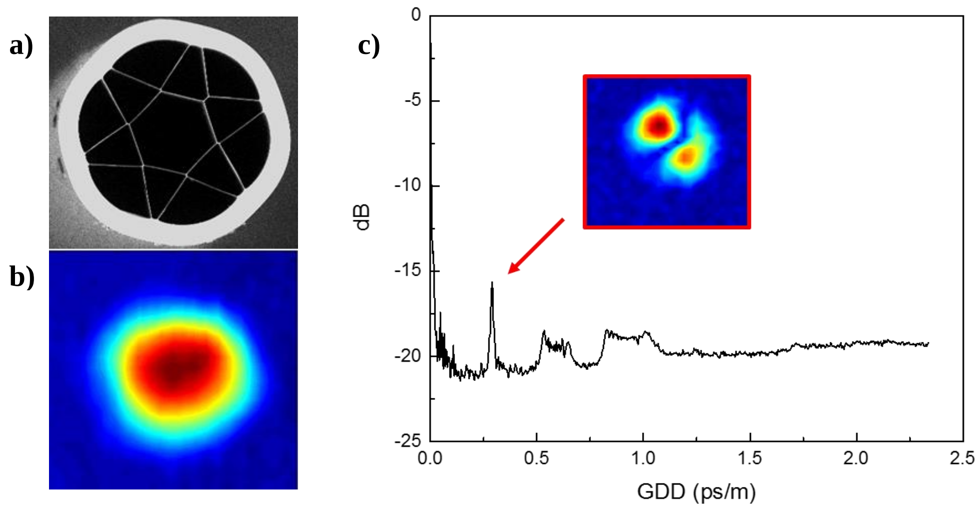


Fig. 2. (a) SEM cross-section of hexagram ARHCF. (b) Reconstructed near field. (c) $S^2$ Fourier spectrum with corresponding mode image.

## 3. Conclusion

We have shown, for the first time, experimental mode analysis of two ARHCF with different geometries. While both fibers contained higher order mode content, the hexagram design proved to be much closer to single mode operation. However, we also saw that longer lengths of non-touching ring HCF produced less higher order mode content due to the higher propagation loss of the $LP_{02}$ mode. The dependence of the core mode content on the fiber design, length, bend radius, and excitation conditions is currently being explored. Further $S^2$ imaging measurements will give better understanding to the guidance properties of these novel hollow core fibers.

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## 4. References

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