S^2 Measurement of Higher Order Mode Content in Low Loss Hypocycloid Kagomé Hollow Core Photonic Crystal Fiber

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Abstract: We present the first detailed investigation of modal properties in hypocycloid Kagomé fibers; even with an optimized input launch, higher order modes propagate over long fiber lengths, indicative that these modes have low attenuation.
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1. Introduction

The development of Kagomé Hollow Core Fibers (KHCFs) with a hypocycloid-shaped core surround has led to a significant loss reduction for this class of anti-resonant microstructured fibers [1]. KHCFs can exhibit an extremely low overlap between the core guided light and the surrounding silica microstructured cladding, and thus offer ultra-low nonlinearity and considerably higher damage thresholds as compared to solid fibers. Furthermore, the anti-resonant guidance mechanism demonstrated by KHCFs enables fabrication of fibers with large core diameters (and correspondingly large mode field diameters (MFDs)), low group velocity dispersion and broad transmission bandwidths; these factors, in combination with this recent loss reduction, make these fibers excellent candidates for high power pulse delivery [1] and frequency standard [2] experiments. Despite 7 and 19 cell KHCF being implemented in experiments which typically require high modal purity, no thorough investigation of the modal content in this class of fibers has yet been reported to date. Here, we present for the first time detailed spatial and spectral (S^2) imaging measurements of the higher order modes (HOM) propagating in 7 and 19 cell KHCF with similar optical and structural properties to the state-of-the-art fibers which have been reported in the literature.

2. Hypocycloid Kagome Hollow Core Photonic Crystal Fiber

The 5 m transmission and loss measurements of the 7 and 19 cell KHCFs used in this work are shown in Fig.1; the measurements were made with an incandescent white light source and an optical spectrum analyzer (OSA). Coupling to the fundamental mode of the fiber was achieved through a butt-coupled launch from endlessly single mode PCF (LMA25) for the 7 cell KHCF and from a graded refractive index fiber (GIF50, selective SM excitation) for the 19 cell KHCF.

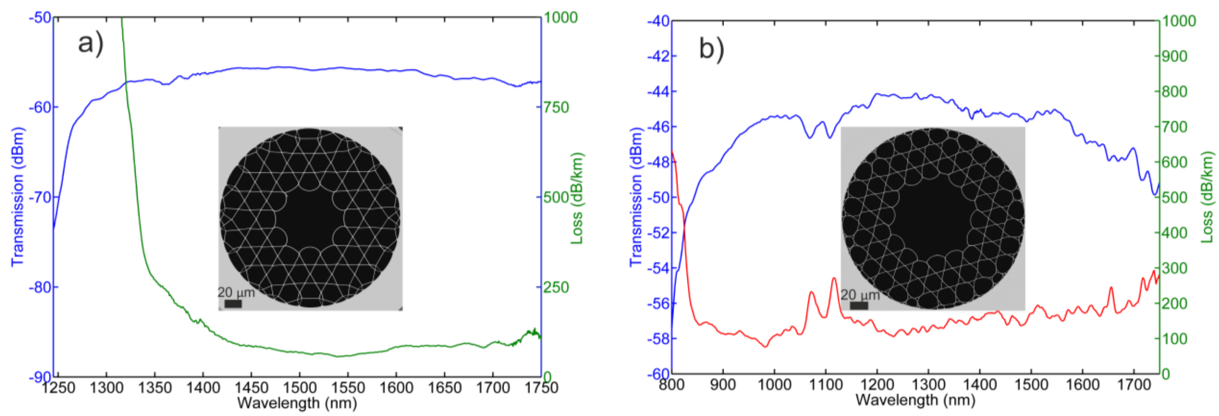

Fig. 1. Transmission (blue, 5m length) and loss spectra (green) of a) 7 cell KHCF (cutback length = 20 m) and b) 19 cell KHCF (cutback length = 30 m). Insets are SEMs of transverse fiber structure.

A scanning electron micrograph (SEM) image showing the 7 cell KHCF microstructure is shown in Fig. 1a (inset); the fiber has a ≈65 µm inner core diameter (corresponding to an estimated MFD ≈ 51 µm), ≈ 650 nm strut thickness and negative curvature parameter, b = 0.59 (as defined in [3]). The 7 cell KHCF guides over a bandwidth of ≈ 350 nm (1400 -1750 nm) with a minimum transmission loss ≈ 58 dB/km at 1541 nm. The 19 cell KHCF (SEM inset Fig 1b) has ≈ 400 nm strut thickness, ≈86 µm inner core diameter (MFD ≈ 68 µm) and b = 0.49. It has broadband guidance spanning ≈ 850 – 1750 nm with minimum loss of ≈ 80 dB/km at 980 nm (160 dB/km at 1550 nm); the loss and transmission properties of our fiber are similar to state of the art for 19cell KHCF as reported in [4].

3. Spatial and Spectral Imaging of Kagome HCF

The S^2 imaging system consists of a tunable laser source (TLS, range 1520 – 1630 nm, minimum step size of 1 pm) and an InGaAs camera [5]. A single mode fiber (SMF) delivers the laser to an aspheric collimating lens with a focal length ≈ 4.5 mm, the collimated beam is then coupled into the fiber under test with a microscope objective with a focused spot size ≈ 58 μm. A telescope collects the light from the fiber under test and directs it to the camera, which is triggered directly from the TLS and controlled by a PC resulting in close to real time acquisition times [6].

Fig. 2 shows the S^2 modal content (multi-path interference, MPI, vs. differential group delay, DGD) curve measured on a 31.5 m of 7 cell KHCF by scanning the TLS output over 20 nm. In Fig 2a six peaks marked A-F can be readily identified, corresponding to four higher order mode groups propagating in this fiber. The reconstructed mode profiles associated with these peaks (assigned to the LP_{11}, $LP_{21,}$ LP_{02} and LP_{31} modes) are shown below the DGD curve. The LP_{11} mode group has a MPI) of-16.2 dB which corresponds to ≈ 2.4 % of the total optical power guided in the fiber.

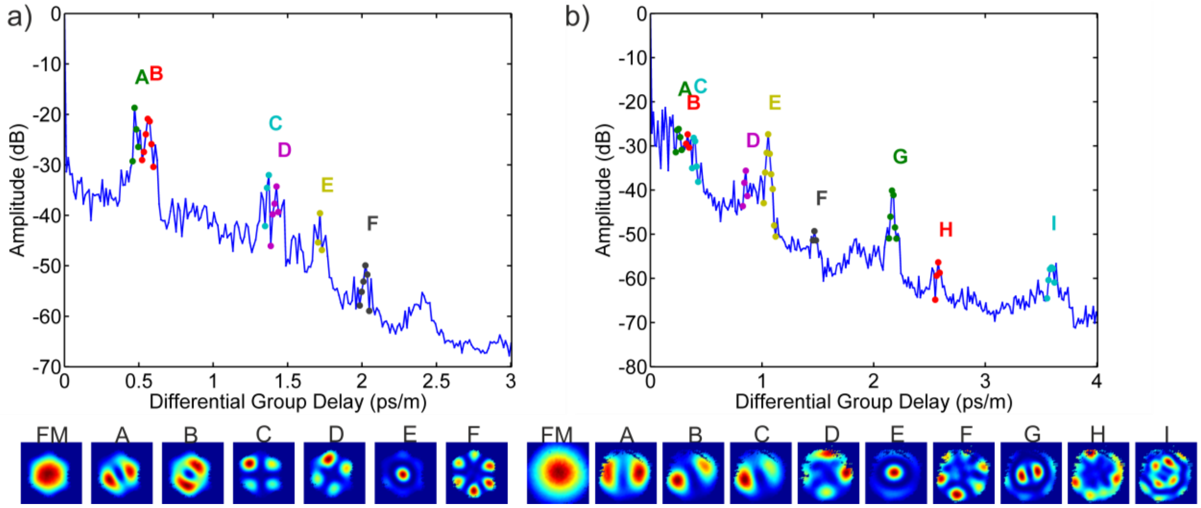

Fig.2. Differential group delay curves of the HOM content propagating in a) 7 cell KHCF and b) 19 cell KHCF. Below are reconstructed mode field profiles corresponding to the peaks in the DGD curve.

Fig. 2b shows the DGD curve for the 19 cell KHCF measured through 30 m; unsurprisingly the larger core 19 cell KHCF supports more HOM groups than the 7 cell KHCF with 7 mode groups detected. These mode groups are identified as LP_{11}, LP_{21}, LP_{02}, LP_{31}, LP_{12}, LP_{41} and LP_{42} (peaks A-I) and the reconstructed mode profiles can be seen in the lower panel of Fig 2b. It is noteworthy that for both types of KHCF, these HOMs are measured through relatively long lengths of fiber, indicating that these modes are not significantly lossier than the fundamental mode.

4. Conclusion

Hypocycloid 7 and 19 cell KHCF have been investigated with the S^2 technique, revealing for the first time that 4 and 7 HOM groups are able to propagate in these fibers respectively over long lengths. KHCF have large MFDs and are inherently hard to mode match; here a free space launch is used to optimize the MFD match, however we still found a small but measurable amount of HOM content in 7 and 19 cell KHCF. The low level of HOM content reported here means that for some applications such as power delivery these fibers can be operated in an effectively single mode regime, however even this level of HOM content can be detrimental to applications such as frequency standards, gyroscopes and gas sensing experiments. Thus, it is paramount to investigate these effects and understand if the HOM content can be suppressed through fiber design.

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