Modal Analysis of Large-Mode-Area Photonic Crystal Fiber for High Power 2µm Fiber Lasers

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Abstract: Modal properties of a new-generation polarizing large-mode-area photonic crystal fiber are studied based on the S^2 imaging technique. Single mode operation in the 2µm spectral range is demonstrated for coiling diameters smaller than 40cm.

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1. Introduction

Interest in coherent light sources emitting in the 2µm wavelength range has dramatically increased in the past years. Efforts for developing such sources are motivated by a large variety of applications, from spectroscopy and component testing applications to atmospheric sensing and eye-safe LIDAR. Rare-earth thulium doped or more recently thulium-holmium co-doped glasses pumped around 800nm are candidates investigated for laser emission in the 2µm range. Amongst possible laser geometries, fiber lasers provide the stability, compactness and robustness that make them very attractive for use in laser systems. Furthermore, many applications in the 2µm wavelength regime require large mode area (LMA) and optical fibers to ensure low loss transmission of the 2µm laser radiation and high-intensity pulses propagation without distortion while providing diffraction-limited beam quality. To reach this goal, a polarizing large mode area photonic crystal fiber (PCF) has been designed by NKT photonics. The cross-section design is similar to previously investigated LMA PCF that has been proven to be single mode at 1µm [1]. In this study, the recently introduced spatially and spectrally resolved imaging technique [2] is used to characterize the modal content of this passive fiber around 2µm wavelength and at a smaller wavelength around 1.3µm to demonstrate the possibility of single mode operation throughout the eye-safe spectral region.

2. Single mode operation at 2µm

A 5.3 meters long piece of double clad LMA PCF with 50µm core diameter, 250µm cladding diameter and 0.22d/Λ is provided by NKT photonics. A microscope image of the fiber cross section is displayed in Figure 1. Two stress rods for polarization control were inserted on both sides of the core. This fiber is aligned inside a S^2 measurement setup as shown on Figure 1 .

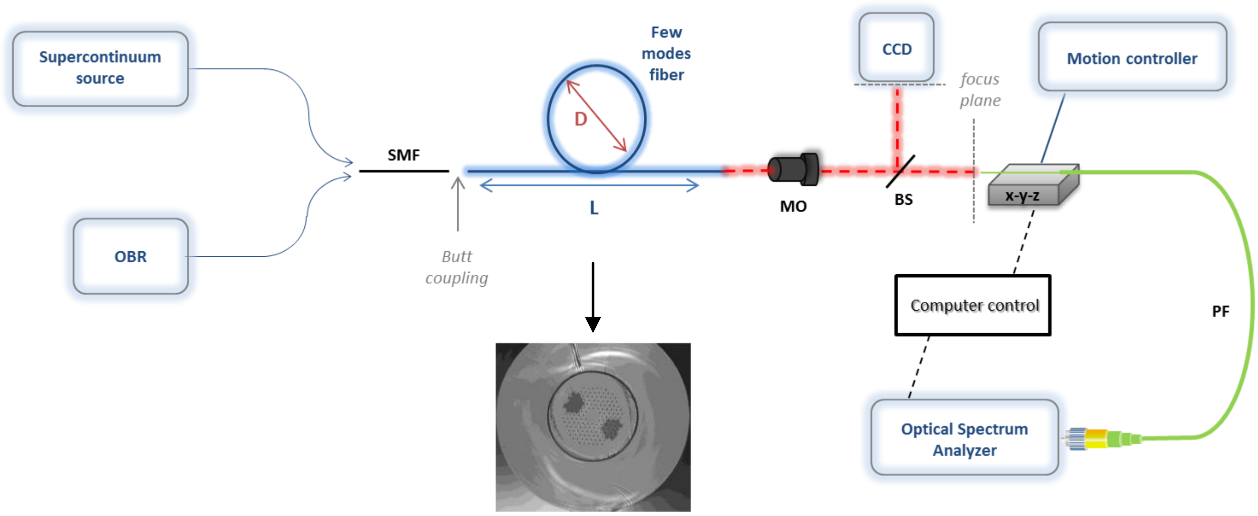

Figure 1 : S^2 experimental setup for mode analysis of few modes fibers**.**
OBR: optical backscatter reflectometer for fiber length mesaurement, SMF: single mode fiber, MO: microscope objective (x4), BS: beam splitter, PF: probe fiber.

A single mode fiber (black) with 4µm core, 125µm cladding and 0.14NA couples light from a broadband source (0.4µm-2.2µm) into the core of the fiber to be tested (blue). The coupling can be realized either by fusion splicing, butt-coupling or free space alignment using a pair of microscope objectives. It was demonstrated [1] that the mode content can depend on the launching conditions. Accordingly, the 400µm outer diameter PCF standing on a three dimensions stage is butt-coupled with the incident SM fiber allowing active control of the launching conditions. It has also been demonstrated [3] that coiling an optical fiber induces higher order modes suppression while shifting the cut-off wavelength towards smaller wavelength. In our experiment, the PCF is coiled down to a diameter (D), which varies during the mode content study. Using a 4x microscope objective, the fiber output facet is imaged onto both a CCD detector to record real-time images of the PCF facet and the plane of the probe fiber tip. The probe fiber (green) transmits the signal of one pixel of the image to an optical Spectrum Analyzer (OSA). The pixel size is determined by the core size of the probe fiber. This fiber is fixed on a computer controlled 3D motorized stage, allowing scanning across the image plane. Both motorized stage and OSA are synchronized resulting in a fully-automated S^2 measurement. A 30x30 pixels array is reasonable measurement size to cover the entire image of the PCF output facet. Experimental results are exported and numerically treated using MATLAB. Following the development of Nicholson *et al.*, a fast Fourier transform algorithm is applied to each of the recorded spectra previously converted into frequency scale. The resulting Fourier spectra are expressed in terms of group delay differences (unit ps/m) and will exhibit features due to multimode interference if higher order modes (HOMs) are propagating through the PCF. From these features, one can numerically reconstruct the total intensity distribution at the image plane as well as the intensity distribution of propagating HOMs. It is also possible to estimate the amount of power carried by individual HOMs, also called mode fractional powers (MFPs) or HOM suppression value. Figure 2 shows the Fourier transform resulting from three S^2 measurement sets of the PCF across a 20nm bandwidth centered at 2µm. For each measurement set, representing different coiling diameters and launching conditions, the reconstructed intensity distribution at GDD=2ps/m is also displayed.

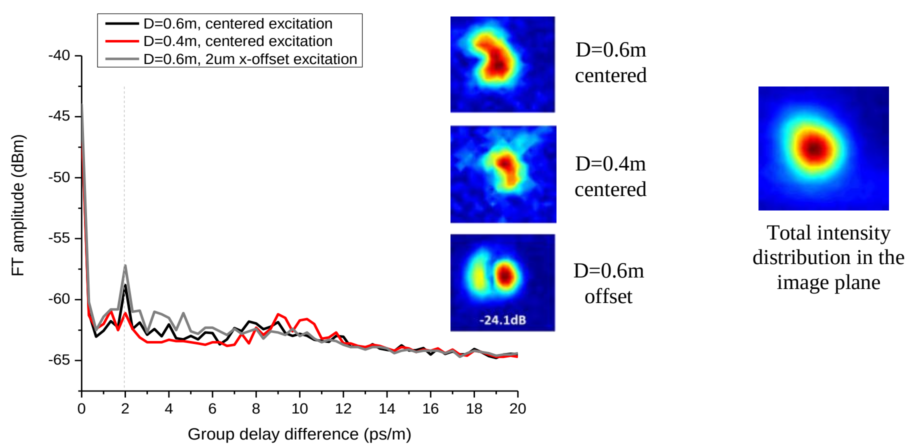

Figure 2 : Effects of different coiling and change in launching conditions on modal content at 2µm**.**
Numerically reconstructed total intensity at focus and HOM intensity distribution are displayed from 29x29 measurement

A circularly centered incident light source should exclusively excite fiber modes (including HOMs) with zero angular momentum, i.e. the LP_{0N} modes. The two measurements at 0.6m coiling diameter show that the HOM LP_{11} is excited carrying less than 1% of the total power when the input fiber is slightly offset compared to the PCF axis. For comparison, even if a small peak appears on the black FT curve, the reconstructed mode intensity shows that only negligible HOMs are excited when the source is centered for the same coiling diameter, which follows expectations. The red curve does not show any feature across the GDD range. Tight coiling diameters result in complete HOM suppression confirming that this PCF supports single mode operation at 2µm for coiling diameters smaller than 40cm.

3. Higher order modes characterization

In order to quantify the effect of coiling and launching conditions on higher order modes, S^2 measurements are performed over a 20nm bandwidth centered at 1.3µm. From experimental results at 2µm we concluded that 0.6m is a reasonable coiling diameter allowing for some HOMs to propagate. For this coiling diameter, the mode content is characterized for varying launching conditions and the data are presented in Figure 3. The darker blue circle represents the PCF core and the light blue area is the cladding. The black dots in the right part indicate different locations of the SM fiber used for changing the launching conditions. These positions for which S^2 measurements were performed correspond to 2µm offsets along the x and y axis, respectively.

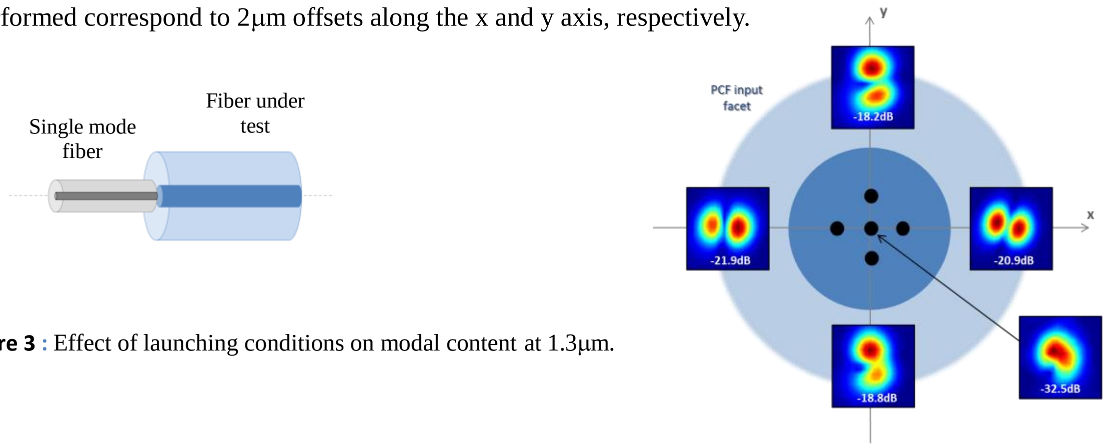

Figure 3 : Effect of launching conditions on modal content at 1.3µm.

When the excitation source and the PCF are close to perfectly aligned, the LP_{11} is not excited as shown in the reconstructed intensity distribution at the GDD of interest (assuming that -30dB corresponds to total HOM suppression). However, offsetting the input fiber either along x or y direction leads to an excited HOM carrying about 1% of the total power. We could observe that the orientation of the lobes of LP_{11} follows the offset. To study the effect of coiling on HOM propagation, the single mode input fiber is deliberately offset by about 2µm. Different coiling diameters were measured and their effect on HOM is quantified in Figure 4.

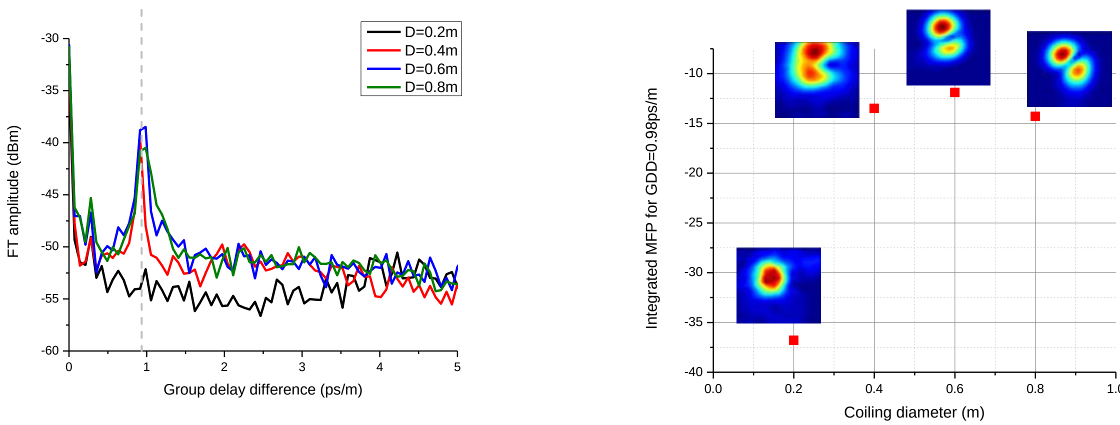

Figure 4 : HOM suppression as a function of coiling diameter at 1.3µm

For diameters larger than 40cm, LP_{11} mode propagates with group delay difference around 1ps/m. The corresponding mode fractional power, i.e., the power carried by the HOM, and intensity profile are plotted on the right as a function of coiling diameter. 20cm coiling very efficiently suppresses HOMs, whereas about 5% of the total power is carried by the LP_{11} mode for coiling diameters larger than 40cm.

4. Conclusion

This specialty fiber has been demonstrated to be single mode for light transmission at 2µm for bending diameters smaller than 40cm. Effects of coiling and launching conditions have been investigated at 1.3µm to show that mode content can be controlled. Recently, an active version of this PCF has been used to generate laser emission at 2µm [4].

References

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