Complementary Analysis of Modal Content and Properties in a 19-cell Hollow Core Photonic Band Gap Fiber using Time-of-Flight and S^2 Techniques

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Abstract *We study the rich multimode content of an ultra-low loss hollow core photonic bandgap fiber using two complementary techniques which allow us to investigate both short and long propagation distances. Several distinct vector modes are clearly identified, with evidence of low intermodal coupling and distributed scattering*.

Introduction

Hollow Core Photonic Band Gap Fibers (HC-PBGFs) show great promise for optical communications[1] due to their ultralow optical nonlinearity, low latency and the potential for low transmission loss. Moreover, these properties make HC-PBGFs interesting for a host of other applications in sensing, gas based nonlinear optics and laser beam delivery, where the device length and loss requirements are often substantially less demanding.

In order to achieve the lowest losses and nonlinearities a large core is required, which is typically obtained by omitting 19 capillaries from a stacked preform – the resulting fibers being referred to as 19-cell HC-PBGFs. The downside of this is that it introduces a large number of core guided modes (indeed more than 40 vector modes are predicted, including all degeneracies)[2]. This fact can significantly limit the usefulness of the fiber in many instances since the great majority of applications require stable transmission in a single spatial mode – ideally the fundamental. To further complicate matters, surface modes can also propagate through HC-PBGFs[3] and their anti-crossings with the air guided modes of all orders increase the sensitivity of the fiber to external perturbations[4] and make stable mode propagation difficult[5]. This even makes optical mode reconstruction, which would otherwise be relatively straightforward through the use of the S^2 or similar imaging techniques, very challenging[6].

Recently we demonstrated a large core, 19-cell HC-PBGF with no surface modes throughout the whole central part of the bandgap[1]. In that work we characterized the multimode content of the fiber (excited under different launch conditions) using a Time of Flight (ToF) technique, which enabled us to obtain a direct measurement of the Differential Group Delay (DGD) between different guided modes as well as an estimate of the amount of power transmitted into individual modes. This technique provides real time information but requires sufficient time delay between modes, hence long propagation lengths. Besides, it cannot provide information on what modes each observed peak corresponds to; this can only be estimated by comparison with simulations.

Here we apply a self interferometric technique (S^2) to measure multimode content over short fiber lengths and simultaneously obtain the modal spatial distribution of intensity[7]. We find good agreement with our earlier ToF measurements as well as the expected evidence of additional high order mode peaks,

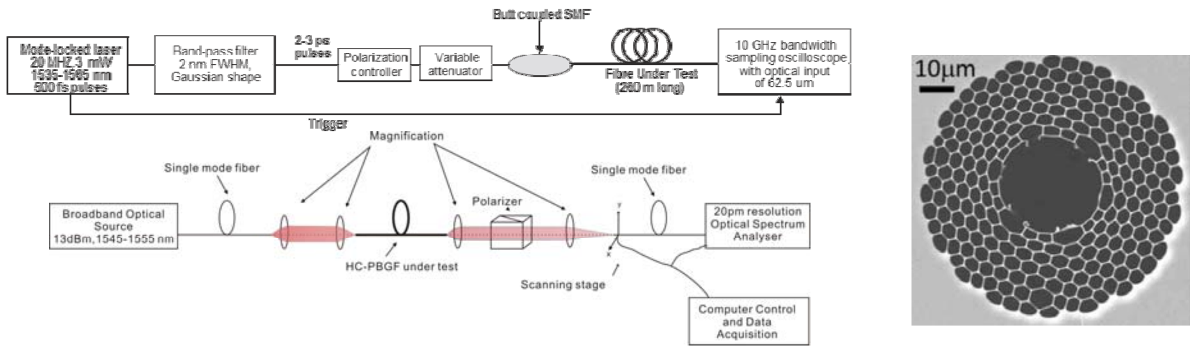

Fig. 1: Set-ups for time-of-flight (top) and S^2 (bottom) measurement, and SEM of the HC-PBGF under test.

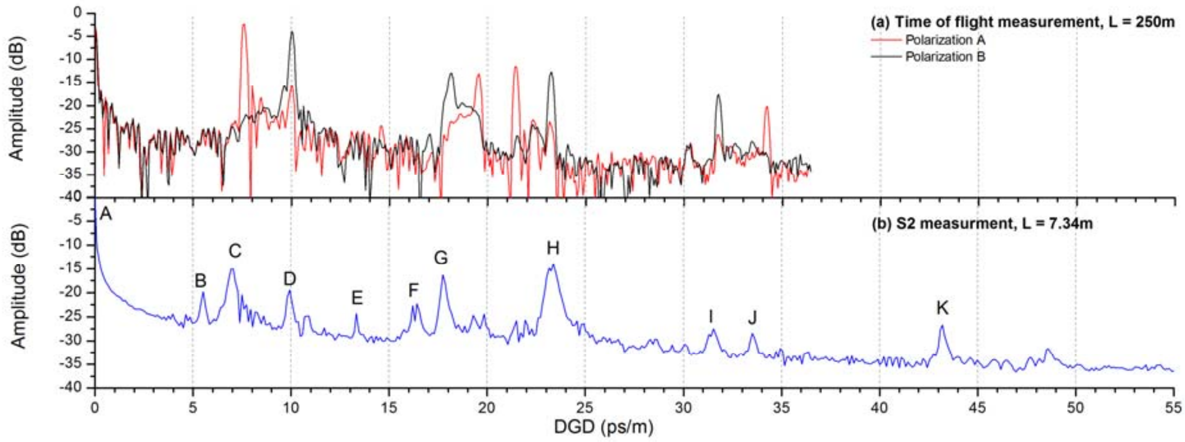

Fig. 2: Differential group delay (DGD) per unit length comparison between (a) ToF measurement over 250m of HC-PBGF; (b) S^2 measurement over 7.34m of the same fiber

which presumably disappear below the noise floor over the longer lengths used in our TOF measurements due to a higher propagation loss.

Time of flight versus S^2 set-ups

Here we focus on the low loss, wide bandwidth HC-PBGF recently presented (see Fig. 1 for an SEM image)[1]. It has 6 ½ rings of cladding holes with an average pitch and relative hole size of 4.4 µm and 0.97 respectively, and a core size of 26 µm. The fiber has a minimum loss of 3.5 dB/km at ~1500 nm and a very wide surface mode free central region of the bandgap with a 3-dB transmission bandwidth of 160 nm.

Fig. 1 shows the two different set-ups used. In the time of flight set-up we launched 2-3 ps pulses emitted at 20 MHz repetition rate from a passively mode-locked fiber laser into a 250 m long fiber and measured the corresponding temporal impulse response using a 10-GHz bandwidth photodiode and fast sampling oscilloscope. The pulses were core-offset launched into the HC-PBGF to ensure efficient coupling to Higher Order Modes (HOMs). (For central coupling a clean fundamental mode was observed at the PBGF with power in the next highest intensity HOM reduced by 17 dB).

In the S^2 set-up a low-coherence broadband Er:ASE source is used in combination with an Optical Spectrum Analyzer (OSA) to collect the spectrally resolved beatings between various modes at different spatial locations of the magnified near-field output of the fiber. A 7.34 m length of the HC-PBGF was used in this instance and the ASE light was free space launched (with a 1:1 imaging lens configuration) from a SMF (with a mode field diameter (MFD) of 9 µm) into the HC-PBGF (MFD~16 µm for the fundamental mode). The total measurement bandwidth was 10 nm (1545-1555 nm) and the minimum nominal OSA 3-dB resolution was 20 pm, providing a maximum theoretical measurable group delay of 200 ps (27.3 ps/m for this fiber length). In practice, we were able to resolve beatings with spectral periods smaller than the OSA 3-dB resolution, enabling us to reconstruct modes with DGD values up to 43 ps/m. Note that a polarizer was placed before the collection fiber in order to simplify the analysis of the results.

Results

In Fig. 2 we compare the results of the two measurements. From the ToF measurements (upper plot) 4 pairs of HOMs sited at around 8, 17, 22 and 33 ps/m can clearly be identified. By modifying the input pulse polarization we were able to selectively excite either one or other of the two (polarization) modes associated with each HOM, or any linear combination of the two. Simulations suggest that the HOMs correspond to the LP_{11}, LP_{21}, LP_{02} and LP_{12} mode families, although there is no simple way to confirm this with this method alone. Other than these strong peaks that sit well above the ~-30 dB noise background there appears to be some evidence of other modes close to the noise floor but it is difficult to clearly resolve them.

The S^2 measurements (lower plot) broadly confirm the main features of the ToF measurement, with several peaks appearing at approximately the same value of DGD. The high intrinsic sensitivity of this interferometric technique and shorter fiber length used make it possible to clearly observe a larger number of peaks, even though no particular effort was made to excite HOMs by offsetting the free space launch. The inferred Multi Path Interference (MPI) is in some cases higher than -50 dB illustrating the excellent dynamic range associated with this technique.

Fig. 3 shows the reconstructed modal

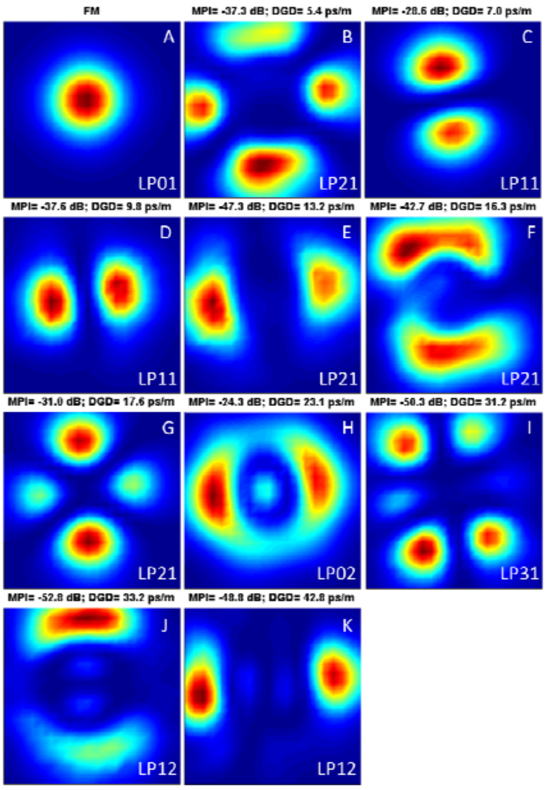

Fig. 3: Reconstructed intensities of the modes at peaks A-K in Fig.2. The respective MPI levels and DGDs are indicated above each figure

profiles of the 10 most prominent peaks in Fig. 2(b). All expected modes up to LP_{12} can be clearly distinguished, with some other interesting observations that can be made. For this particular launch there are 2 main LP_{11} peaks (C and D) each of which is followed by a smaller peak corresponding to a mode in the same spatial orientation but opposite polarization, all in the 7-11 ps/m region, in good agreement with the ToF results. Four distinct peaks corresponding to the 4 different vector modes of the LP_{21} mode group (peaks B, E, F and G), can also be observed although interestingly, mode B seems to travel faster than the LP_{11} group, indicating unusual dispersive properties for this mode – possibly the result of an anti-crossing with a surface mode adjacent to the spectral region investigated here. For the LP_{02} mode (peak H) only one of the two peaks seen with the ToF is observed in this particular measurement. In separate measurements (not shown here) we have however verified that a second peak around 21.5 ps/m can indeed be observed if the launch polarization is adjusted slightly. The peak at 32 ps/m, erroneously attributed to the LP_{12} mode in previous work[1], is actually the LP_{31} mode, while the two different peaks corresponding to orthogonally oriented LP_{12} modes can be seen to have a very broad separation (peaks J and K), again likely evidence of unusual dispersive behavior.

It is important to emphasize that no plateau due to distributed scattering is evident after 7.34 m and the MPI in the region between peaks at around 12 ps/m is as low as -58 dB. Over a longer 250 m length the intermodal cross-talk is certainly below the ~25 dB noise floor due of the photodiode impulse response. Such a low level of intermodal cross-talk and the well behaved modal content is promising for data transmission through reasonable lengths of such a fiber.

Conclusions

We have applied two very different techniques to provide modal analysis of a multimoded HC-PBGF and generally observed good agreement in the results. Our results highlight the relative strengths of the two complementary approaches we have used: ToF measurements provides for *real time* MPI characterization over relatively long fiber lengths (such that the intermodal group delays are larger than ~1 ns in this instance, although improved resolution is clearly possible using shorter pulses and a faster detection system). Although not shown here, the ToF technique also enables to measure the group velocity dispersion of the modes. S^2 is inherently a non-real-time technique (measurements typically take a few minutes) and it can only be used over relatively short fiber lengths as compared to ToF (the maximum total DGD has to be in the range of a few 100s to a few 1000s ps). However, the technique does allow for the simultaneous reconstruction of modal profiles, which in a complex scenario like in a HC-PBGF is extremely helpful. Our results indicate that robust single-mode data transmission should be achievable over at least 250 m of our current fiber (and probably over much longer lengths also when available) and that inter-mode coupling is also quite small illustrating potential for Space Division Multiplexing opportunities.

Acknowledgements

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