Measuring Distributed Mode Scattering in Long, Few-Moded Fibers

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Abstract: We present measurements of higher-order modes in lengths of few-moded fibers up to 0.5 km long using Spatially and Spectrally resolved (S^2) imaging. Both discrete scattering events and mode-mixing due to distributed scattering are measured.
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The exponential increase in traffic on optical communications networks has led to concerns about a coming capacity crunch [1]. One possibility for increasing the capacity of an optical fiber is spatial division multiplexing (SDM) by using multi-core optical fibers to simultaneously carry multiple channels [2]. Another means to increase capacity is mode division multiplexing (MDM) in which few-moded fibers are used and different higher-order modes are used to carry distinct communications channels [3,4,5]. In MDM systems mode mixing due to distributed scattering between modes is an important impairment to consider and techniques for quantifying the mode mixing are necessary. Spatially and Spectrally resolved mode imaging (S^2 imaging) is a recently demonstrated technique for quantifying the mode content when multiple higher-order modes are simultaneously co-propagating in the optical fiber [6]. In prior work it has been used to characterize large-mode-area fibers [7], and photonic bandgap fibers [8]. In this work we measure the mode content in long lengths of few-moded fibers using S^2 imaging. A 500 m length of fiber that supports two modes, and a 400 m length of four moded fiber are measured. Both discrete and distributed scattering events are characterized. This is the first time S^2 imaging has been applied to such long length of fiber designed for MDM systems.

Higher-order modes (HOMs) in optical fibers propagate with different group delays, and therefore multiple HOMs co-propagating in a fiber produce spectral interference whose beat frequency is the inverse of the mode group delay difference. By spatially resolving the spectral interference pattern in the beam output from a few-moded fiber, the number, type and relative power levels of modes in the fiber can be quantified [6]. Because the modes have different group delays and spatial interference patterns multiple co-propagating modes can be distinguished in a single measurement. The original S^2 setup was based on a broadband source propagating through a fiber under test. An SMF probe was raster scanned through the image plane of the output of the fiber under test, and at every (x,y) point the optical spectrum was measured. Fourier transforming the spectra gives a picture of the mode beat versus group delay difference between fundamental mode and the higher order modes. With relatively simple data analysis [7] one obtains the mode image and the relative HOM power levels (also known as multi-path interference, or MPI). Because the maximum group delay that can be measured is inversely proportional to the frequency resolution, and the OSA used had a resolution bandwidth of 0.05 nm, the maximum group delay that could be measured was 80 ps, and consequently the longest fibers measured were a few tens of meters at most.

More recently, a high resolution S^2 setup based on a tunable laser and a CCD camera was demonstrated in which the beam profile as a function of wavelength from the FUT was measured [8]. One advantage of this setup was substantially decreased measurement time. Furthermore the tunable laser used in the experiment had a 0.001 nm step size which translates to a maximum measureable group delay of 4000 ps, allowing for the measurement of long fiber lengths.

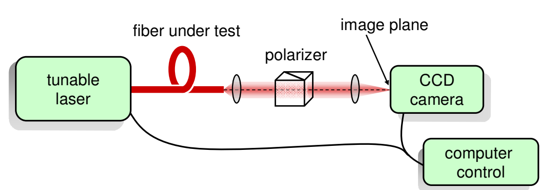

Fig. 1: Schematic of the S2 setup using a tunable laser and CCD camera.

A schematic of the setup is shown in Fig. 1. The camera used in these experiments was an InGaAs array (Ophir-Spiricon model XC-130) with 320x256 pixels. The laser was a Tunics external cavity laser from Photonetics that can tune from 1480 nm to 1600 nm with 0.001 nm step size. The laser power was set to 3 mW. Multiple ND filters were used to attenuate the optical beam to avoid saturating the camera, and a polarizer was included to measure the HOM content for different polarization settings.

Two different few-moded fibers were tested in these experiments. Fiber 1 had a core diameter of 19 µm, an NA of 0.12, and guided LP_{01} and LP_{11}. Fiber 2 had a core diameter of 25 µm, an NA of 0.12, and guides LP_{01}, LP_{11}, LP_{21} and LP_{02}.

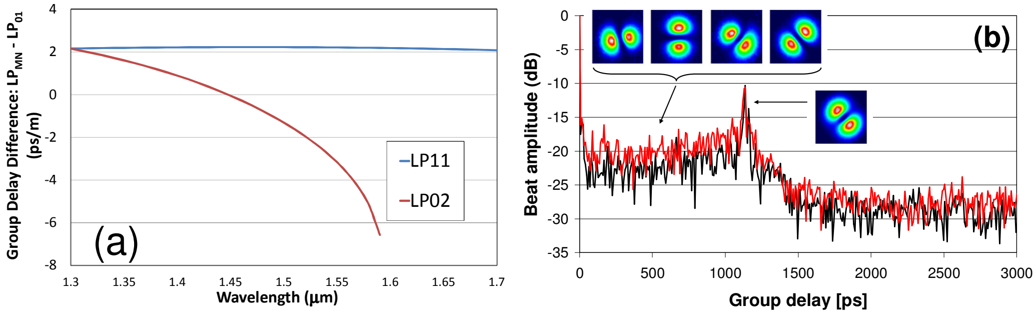

Fig. 2: (a) Calculated group delay difference between HOMs and the fundamental mode for the modes in fiber 1. (b) Mode beat vs. group delay and mode images for a 500 m length of fiber 1.

First, A 500 m length of fiber 1 was measured in the setup. The group delay difference between fundamental and higher modes of fiber 1, calculated from solving the scalar wave equation for the measured index profile, are shown in Fig. 2a. Fig 2b shows the plot of mode-beat vs. group delay obtained from the S^2 measurement. The measurement was made by tuning the laser from 1550 nm to 1551 nm with 0.001 nm step size. The black curve shows the measurement result when the polarizer was oriented for maximum power throughput, and the red curve shows the measurement when the polarizer was rotated 90 degrees from the maximum power setting.

Because S^2 imaging resolves modes with respect to group delay, the distributed and discrete scattering events can be distinguished [7]. Discrete scattering, which occurs at well-defined locations such as splices, appears as a strong, sharp spike, well localized in group delay. Distributed scattering occurs between modes along the length of the fiber on the other hand, and consequently appears as a long plateau. These phenomena can be seen in the plot of mode beat vs. group delay in Figure 2b. The sharp spike at 1140 ps corresponds to the LP_{11} mode which is launched at the input splice. The data analysis shows a clear LP_{11} mode for this spike. The relative power, or MPI, of this mode is -19.6 dB. This agrees well with the expected group delay difference between the LP_{01} and LP_{11} shown in Fig. 2a. In addition a plateau stretching from 0 ps to the discrete scattering event is observable. When the Fourier filter is placed anywhere within this plateau, we obtain an LP_{11} image, with the LP_{11} mode rotating with different group delays. By integrating over this plateau for the two polarization measurements we are able to quantify the mode mixing due to distributed scattering from LP_{01} to LP_{11} in this fiber and obtain an MPI of -18.2 dB.

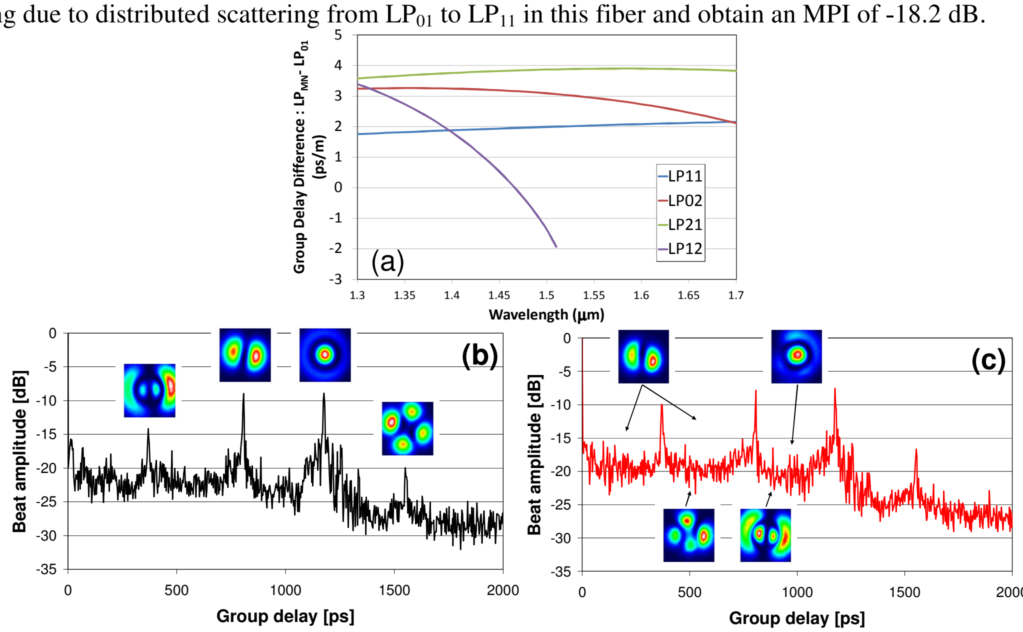

Fig. 3: (a) Calculated group delay difference between HOMs and the fundamental mode for fiber 2. (b) Mode beat vs. group delay from the S^2 imaging measurement of 400m of fiber 2. Modes corresponding to discrete scattering peaks are shown. (c) Mode images obtained in the distributed scattering area, between discrete peaks are shown.

Next, fiber 2 was measured; the calculated group delay between the fundamental mode and the various higher order modes in fiber 2 are shown in Fig. 3a. In order to launch into multiple HOMs the SMF launch fiber was spliced to the 400 m length of fiber 2 with an offset splice. For this measurement the laser was scanned from 1550 nm to 1553 nm in 0.001 nm increments. The mode beat vs. group delay is shown in Fig. 3b along with the mode images obtained at the strong discrete peaks. The group delays of the discrete scattering peaks of the LP_{11}, LP_{02}, and LP_{21} modes agree well with expectations from the calculation in Fig. 3a. According to the calculation from the index profile the LP_{12} was not guided for wavelengths longer than 1510 nm. However a distinct discrete peak corresponding to the LP_{12} was consistently observed in the measurements. Further investigation is required to fully understand the discrepancy.

Because of the larger number of modes in fiber 2, the distributed scattering picture is considerably more complex than in fiber 1. In general, nearest neighbor scattering between modes ($LP_{m,n}$ to $LP_{m\pm1,n}$) is the dominant scattering mechanism [9]. Therefore the LP_{01} scatters to the LP_{11}, and the LP_{02} scatters to the LP_{12}, for example, and depending on at what group delay Fourier filter is placed, different modes are observed in the distributed scattering regions between the discrete peaks. Note that in the distributed scattering region, because a number of different types of modes overlap in group delay, the mode image changes greatly with group delay and is often highly distorted. Nevertheless distinct mode images can be observed in the distributed scattering regions.

Modes observed in the distributed scattering regions between the discrete peaks are shown in Fig. 3c. For example the LP_{11} mode is observed strongly in the region stretching from 0 group delay out to the LP_{11} peak, as expected. We also occasionally observe the LP_{21} mode in this group delay, consistent with LP_{11} to LP_{21} scattering.

In between the LP_{12} discrete peak and the LP_{02} discrete peak, we observe the LP_{12} mode, consistent with LP_{02} to LP_{12} scattering. We also observe the LP_{02} mode in this region, consistent with LP_{12} to LP_{02} scattering.

By integrating the total HOM content, and subtracting off the amount of power obtained from the discrete scattering peaks, we obtain a measurement for MPI due to distributed scattering. Note that because of the complexity of the distributed scattering picture it is difficult in this experiment to assign a distributed scattering rate to an individual mode. Rather what we measure here is the total integrated modal content due to all the distributed scattering events. For this 400 m length of fiber 2, the total amount of power in HOMs due to distributed scattering was – 10 dB. This number was obtained from measurements of both polarizations, as in fiber 1.

In conclusion, for the first time, we have applied S^2 imaging to 0.5 km lengths of few-moded fiber. We have shown that even over such long lengths of fiber we can observe clear signatures of both discrete and mode mixing due to distributed scattering. As the number of modes in the fiber increases, the mode mixing due to distributed scattering events become considerably more complex. In the future, this type of measurement is expected to be critical for optimizing optical fiber for mode-division multiplexing applications.

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