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Measurement of Modal Dispersion and Group Delay in a Large Core Count Few-Mode Multi-Core Fiber

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Abstract *In this work, the impulse response of a 39-core 3-mode fiber is measured and analyzed, finding durations of 0.6 ns–3.0 ns, with total group delay varying by 17 ns between cores and observing largely different modal dispersion and wavelength dependence of propagation delay.*

Introduction

The introduction of space division multiplexing (SDM) has allowed extending the capacity of optical communication systems beyond the limit of conventional single mode fiber (SMF) of around 100 Tbit/s by increasing the number of spatial channels[1–3]. Channel counts above 100 have been demonstrated using few-mode multi-core fibers[2,3] and enabled capacities of 10 Pbit/s in a single fiber[3]. This increase in capacity comes at a price—the use of few mode transmission will require multiple-input multiple-output (MIMO) processing to reverse the mode mixing occurring in the spatial multiplexers, along the fiber etc.[4], while crosstalk between multiple cores may limit achievable data rates and distances or require even more complex inter-core MIMO processing[1].

The complexity of the MIMO processing is determined first by the required dimensions, i.e., the number of spatial channels considered for joint MIMO processing, and second by the maximum length of the combined impulse response of those channels, which determines the required number of taps[2,4]. Optical vector network analysis has been shown to be a powerful tool to easily measure the full complex impulse response of an SDM device, fiber or system, providing all key characteristics such as insertion loss, mode-dependent loss and differential modal group delay (DMD)[5,6].

In this work, optical vector network analysis is used to measure the impulse response of a novel large core count, graded-index 39-core 3-mode fiber with a cladding diameter of 312 μm. The measured impulse responses are analyzed with regards to impulse response duration, DMD and group delay differences between cores. For a 13.6 km span of fiber, the total duration of the in-dividual impulse responses of the cores is found to vary between 0.6 ns and 3.0 ns, while the difference in group delay between cores is as much as 17 ns. These results allow prediction of the required MIMO equalizer complexity and show that, in a—by design—homogeneous FM-MCF, significant differences between cores exist and that small deviations from the design refractive index profile or small manufacturing errors have large impact on the observed impulse response.

Spatially-Diverse Optical Vector Network Analyzer for Few-Mode Fiber Analysis

Optical vector network analysis, based on swept wavelength interferometry, provides an easy and fast way to measure the impulse response $h(t)$ and transfer function $H(\omega)$ of an optical device, fiber or system[5,6]. A spatially diverse optical vector network analyzer (OVNA) with three input and output ports was set up, as shown in Fig. 1, to sequentially measure the full 6×6 transfer matrix of each of the cores of the 39-core 3-mode fiber and analyze their impulse responses and group delay behavior. The setup includes a wavelength swept tunable laser (STL), followed by an interferometric structure, where one arm contains the device under test (DUT) and the other serves as reference. Their combined output is received on a balanced photodiode and the beat signal recoded for extraction of the device response.

To allow polarization diverse measurement, the device arm includes a polarization multiplexer, delaying one polarization by τ_P with respect to the other, and a polarization diverse receiver is employed. Similarly, spatial diversity is achieved by introducing delays $\tau_{\mathrm{in},i}$ and $\tau_{\mathrm{out},j}$ at the input and output ports to the DUT. Careful selection
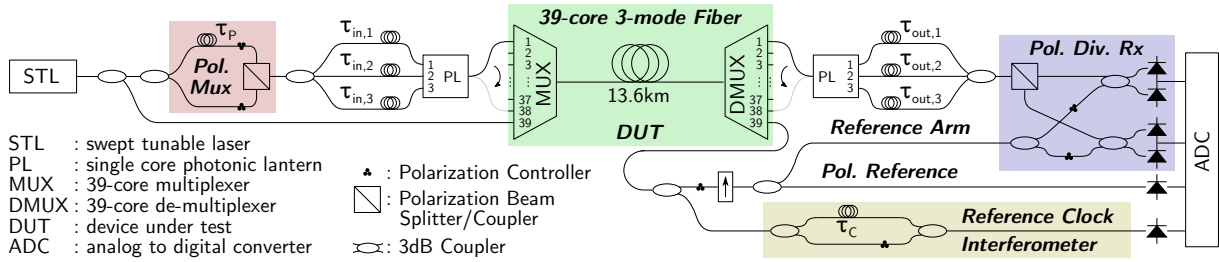
Fig. 1: Spatially-diverse optical vector network analyzer setup for SDM fiber analysis.

of all the delays ensures all resulting combinations are different and their spacing is larger than the maximum duration of the impulse response to measure. The different components $h_{ij}(t)$ of the impulse response, pertaining to different combination of polarization, input- and output port, are then easily separated by temporal windowing of the Fourier transform of the received interferogram[6]. In the presented case, to analyze the 39-core 3-mode fiber, the same two photonic lanterns (PLs) are employed as mode multi- and de-multiplexers for all cores and core 39—which is a single mode (SMF) core—is employed as the reference arm.

Two auxiliary structures allow compensation of experimental impairments: first, an additional reference interferometer allows compensation of sweep frequency non-linearity[6], second, to overcome an observed wavelength dependence of the output state of polarization from the single mode core, the signal of the reference arm is polarized and split, before serving as reference on the polarization diverse receiver. The additional copy of the polarized reference signal is recorded on an additional channel of the analog to digital converter (ADC) and its intensity profile over time is used to normalize the recorded interferogram, successfully compensating for the varying beating efficiency resulting from different states of polarization at different wavelengths.
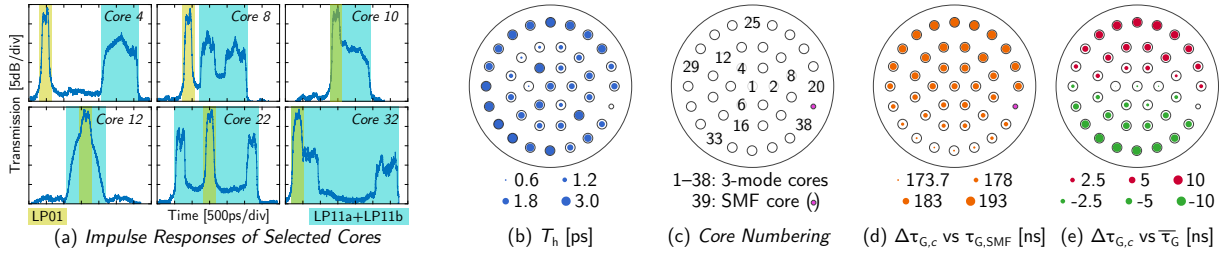
Impulse Response and Group Delays of the 39-Core Few-Mode Multi-Core Fiber

Measurement of the 39-core 3-mode FM-MCF yields a 6×6 complex impulse response matrix for each core, fully describing the transfer function of the fiber. As for analysis of MIMO complexity only the total duration is of interest, and to simplify further analysis, each 6×6 complex impulse response matrix may be reduced by addition of the squared absolutes of the matrix elements, yielding simplified impulse responses—as shown in Fig. 2(a) for a selection of cores—that still allow straight forward analysis of impulse response duration and of modal dispersion.

As can be observed, modal behavior and modal dispersion vary significantly across cores, with some cores showing a compact impulse response with overlapping mode groups (e.g., core 12) or with a slight offset (e.g., core 10), while others show large separation between the mode groups (e.g., core 4) and again others showing the two modes of the LP11 group being separated by different amounts (e.g., cores 8 and 32), potentially with the LP01 group falling in between (e.g., core 22). Comparing the total duration of the impulse response for different cores, durations between 0.6 ns and 3.0 ns are found and plotted across the fiber cross section in Fig. 2(b)—showing a generally larger impulse response duration for the outer ring of cores, but with some of the inner cores exhibiting similarly long impulse responses.

Further analysis of the overall group delay for each core $\tau_{G,c}$ and comparison to the group delay of the SMF core $\tau_{G,SMF}$, as shown in Fig. 2(d), first shows all few-mode cores to have a much larger total group delay than the SMF core and, second, shows a difference of almost 20 ns between the few-mode cores. The duration of the impulse response shows no conclusive dependence on core position. However, the total group delay is clearly smallest on one side of the fiber and largest on the other—as is further illustrated in Fig. 2(e), where the group delays of the cores are compared to the average group delay of all few-mode cores $\overline{\tau_G}$. This tilt is likely caused by the fiber under test being spooled—although on a spool with increased diameter—and hence the cores on the inner side being constantly compressed, while those on the outer side are stretched. Comparing the total impulse response durations and the spread of overall group delays suggests, that core-by-core MIMO for mode recovery (i.e., 38 times 6×6 MIMO) only needs to cover 3 ns, while any MIMO to also remove crosstalk between cores would have to cover as much as 20 ns and hence be of significantly larger

(a) Impulse Responses of Selected Cores   (b) T_{h} [ps]   (c) Core Numbering   (d) $\Delta\tau_{\text{G},c}$ vs $\tau_{\text{G,SMF}}$ [ns]   (e) $\Delta\tau_{\text{G},c}$ vs $\overline{\tau_{\text{G}}}$ [ns]

Fig. 2: Analysis of measured impulse responses and group delays for the different cores, measured with a sweep from 1530 nm to 1570 nm: (a) impulse responses for selected cores, showcasing different levels of modal and chromatic dispersion, (b) total duration T_{h} of impulse response for all cores, (c) core numbering scheme, (d) difference $\Delta\tau_{\text{G},c}$ in group delay between few-mode cores and SMF core ($\tau_{\text{G,SMF}}$), (e) group delay difference $\Delta\tau_{\text{G},c}$ between few mode cores and average group delay of all few mode cores $\overline{\tau_{\text{G}}}$.
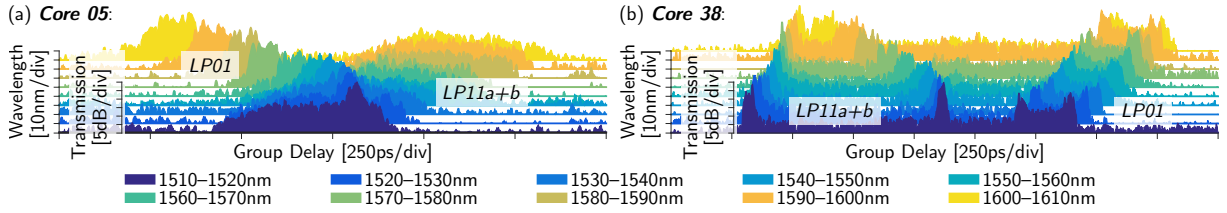
Fig. 3: Evolution of differential group delay with wavelength for (a) a core on the inner ring (core 5) and (b) a core on the outer ring (core 38).

complexity not only due to the large MIMO dimensions, but also due to a much larger number of required taps.

Finally, both modal dispersion and group delay depend on wavelength, as seen in Fig. 3, which shows the development of the impulse response and the mode groups therein over an extended wavelength range from 1510 nm to 1610 nm for cores 5 and 38. The former clearly shows that mode groups may overlap at one wavelength, but have opposite signs on the wavelength dependence of their group delay and thus be clearly separated at another, while the latter shows that if modes within a mode group are separated, this separation may change with wavelength. Furthermore, for core 38 the modal coupling both between the two LP01 polarizations and the LP11 modes can be observed as a pedestal between the corresponding peaks. Finally, these measurements clearly show the impact of chromatic dispersion, with the individual modes becoming more and more spread as wavelength increases and show the amount of dispersion to vary both between modes and cores.

Conclusions

In this work, the impulse response of a 39-core 3-mode FM-MCF was measured and analyzed. The individual impulse responses of the different cores were found to vary in duration between 0.6 ns and 3.0 ns and the overall group delays were found to vary by up to 17 ns between cores for a spooled fiber. Significant differences in group delay dependence on wavelength and relative delay between modes and modal groups are observed for different cores.

These results show, that the behavior of large core count, graded-index FM-MCFs differs significantly from that of single-core few-mode fibers, as even small deviations from the design refractive index profile or small manufacturing errors may have significant impact on the impulse response and modal dispersion. The measurements provide the basis for an estimation of the complexity of MIMO processing required to reverse the mode mixing in such FM-MCFs.

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