Simplified Impulse Response Characterization for Mode Division Multiplexed Systems

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Abstract: We present a single transceiver based modal characterization method for estimating the channel impulse response of MDM systems. Good agreements are found between the measured and simulated DGDs of a RCF supporting 5 mode groups.
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1. Introduction

The channel impulse response is an important parameter when evaluating fiber designs and developing DSP for mode division multiplexing (MDM) systems. In order to fully understand the mode coupling in a MDM system with M channels, an experimental measurement of the M×M channel matrix is required, which includes the effects of discrete crosstalk in the mode MUX/DEMUX and the distributed mode coupling in the fiber. The differential group delays (DGDs) can also be extracted from the channel matrix by measuring the delays between the main impulses in the diagonal elements. However, the implementation of such a measurement requires that all the M channels to be transmitted and received simultaneously using multiple transmitters and receivers [1, 2]. The MDM channel characteristics can also be obtained using a Swept-Wavelength Interferometer system adapted to MDM systems [1], or spatially resolved power measurements using a spatial light modulator (SLM) [2]. The first technique provides the complete impulse response however it requires a specialized setup including M delay lines and a MUX/DEMUX pair to launch into and out of all the spatial modes in the MDM system. The second technique does not require a delay lines or a full MUX/DEMUX but is limited in that it only provides a measurement of the total power coupling between the modes and therefore is not able to measure DGD or show where the crosstalk occurs.

In this paper, we propose a simplified method that only requires a single transmitter and an SLM MUX to selectively launch into each of the fiber modes and a single receiver and an SLM DEMUX to receive each supported mode in a sequential manner. Instead of characterizing only the diagonal elements in the channel matrix [3], the magnitude of each element in the channel matrix of the impulse response is estimated using a known data sequence and a least-square (LS) estimator. We apply this method to characterize a 100 m long graded index RCF, that is designed to support 9 linear polarized (LP) modes in 5 mode groups and minimize the coupling between mode groups [4]. Good agreements are found between the simulation and the measurement which shows that this characterization method can be used to gain understanding of MDM channels with selective mode excitation.

2. Characterization setup

The experimental setup is shown in Fig. 1 (a). A single polarization 28 Gbaud quadrature phase shift keying (QPSK) transmitter feeds the MUX module via an SMF fiber. A 1550 nm beam is first collimated and, after some polarization control, the vertically polarized light is incident on the MUX SLM. This SLM is a phase-only nematic liquid crystal array of 512×512 pixels that works in reflection. The reflected light from the SLM is then modulated in phase after applying the required holographic mask to launch a given LP mode (see Fig. 2 (a)). The LP excitation profile is finally focused on the RCF input facet using an f = 8 mm lens. After propagating through the 100 m RCF, the output is coupled back into an SMF fiber using a DEMUX setup, which is identical to the MUX module.

The MUX/DEMUX alignment procedure is as follows. First, a 2D beam-steering scan is performed at the input of the RCF fiber. At this point, a simple Gaussian beam excitation is chosen for the scan. Afterwards, the steering point with maximum optical coupling into the RCF fiber is chosen to find the optimal focus profile on the SLM. The 2D final scan including the correction for focus is shown in Fig. 1 (c). The optimal launch beam-steering point is then determined as the one aiming at the center of the input RCF. Next, a higher order mode, e.g. LP31 is launched by adding the corresponding phase mask to the optimal beam-steering and focus profiles. The mode mask position on the SLM pixelated plane is optimized by slowly shifting its center by a pixel at a time in both vertical and horizontal

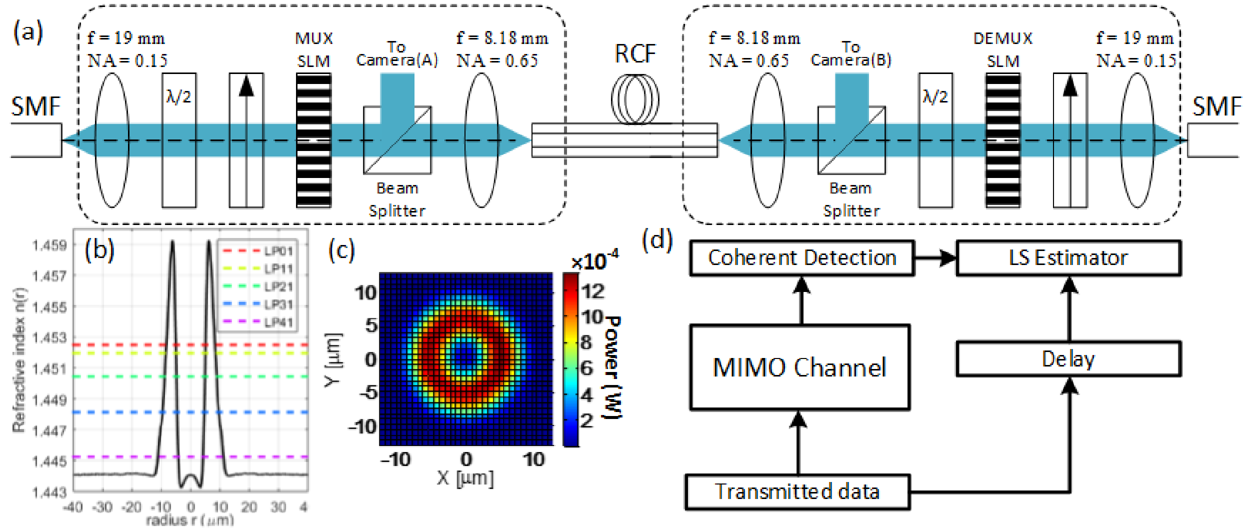

Fig. 1. (a) Experimental setup for the characterization of the RCF. (b) Measured RIP (solid line) and calculated effective refractive index of each mode groups (dotted line). (c) 2D steering scan using a Gaussian excitation beam as the input to the RCF. (d) Algorithms for the channel estimation.

directions to achieve the highest radial symmetry for the LP31 image pattern, which is captured by Camera A in Fig. 1(a). These optimized launched modes are shown in the left column of Fig. 2(a).

The two steps of steering and focus optimization are repeated for the DEMUX module. The best LP31 phase position is then found in the DEMUX SLM plane by maximizing the power coupling into the receiver SMF while minimizing the power coupling to lower order modes such as LP21 and LP12 when their corresponding phase masks are also applied. Further optimization to the phase mask positions in the MUX and DEMUX SLMs planes as well as the optimal beam-steering grating are performed when considering the entire power coupling matrix as shown in Fig. 2(b). The goal of optimizing the MUX/DEMUX is to mitigate the coupling between mode groups for the worst case in the coupling matrix.

When the mode MUX/DEMUX is optimized, a modulated 28 Gbaud QPSK signal is selectively launched into one of the 5 supported modes. After transmission over the 100 m RCF, the signal is then demultiplexed by displaying the phase mask for each of the supported modes sequentially using the SLM and detected by an optical coherent receiver. In order to avoid the effect from the laser phase noise and frequency offset, homodyne detection is used where both the signal and local oscillator are generated from the same laser source. The in-phase and quadrature components of the received signal are captured by a real-time oscilloscope sampling at 80GS/s. The captured M waveforms are used for the estimation of one column of the channel matrix (see Fig. 2(c)). The procedure is then repeated to measure the remaining launch modes. In total M×M waveforms are captured to estimate each of the element in the M×M channel matrix.

The oscilloscope is triggered by the pulse pattern generator, so that the captured waveforms for each launching and receiving mode combination are synchronized. The received waveforms are first downsampled to 2 samples/symbol and then processed as shown in Fig. 1(d). The known transmitted data pattern is then upsampled to match with the sampling rate of the received data pattern. Both data patterns are input to the LS estimator [5, 6] where one element in the channel matrix is estimated. Since two-fold oversampling of the received modulated signal is used in the LS estimator, the time resolution of the estimated channel matrix equals half of the symbol period.

3. Results

The measured 5×5 MIMO channel impulse response of the RCF is plotted in Fig. 2(c). From the magnitudes of the channel impulse response ($|h_{t,r}|^2$), where t and r correspond to the Tx and the Rx mode index, the coupling or crosstalk in the system can be separated and independently analyzed according to the location where the impulses occur. In the absence of crosstalk and coupling, the channel impulse response is represented by a single impulse located in the diagonal element of the channel matrix at a time depending on the DGD of the launched mode (see the colored elements in Fig. 2(c)). To validate the measurement technique, in Fig. 2(d), we compare the measured DGD values extracted from the channel impulse response, shown in Fig. 2(c), with those calculated using the measured fiber refractive index profile shown in Fig. 1(b) and find good agreement between the two.

When other impulses show up in the channel response, this is typically the evidence of crosstalk at the mode MUX/DEMUX. By contrast, a wider plateaued impulse corresponds to distributed coupling along the fiber. As an

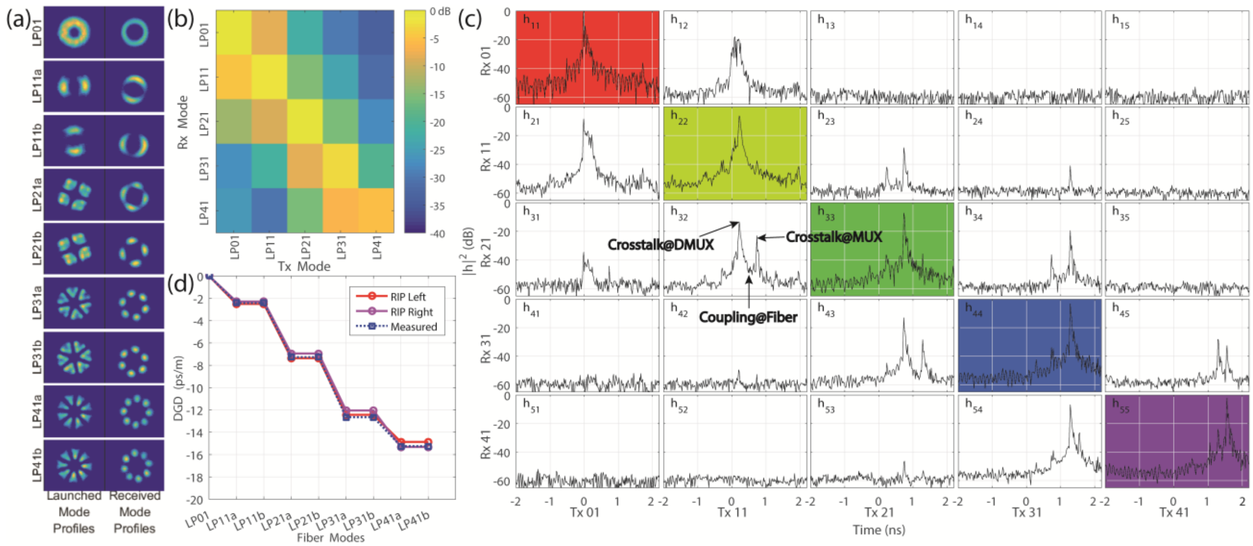

Fig. 2. (a) Intensity profiles of each mode at the input (Left column, Camera A in Fig. 1 (a)) and output (Right Column, Camera B in Fig. 1 (a)) of the RCF. (b) Total coefficients of coupling and crosstalk according to the received power measurement. (c) Measured channel matrix of the 100 m RCF. (d) Measured DGDs of the 100 m RCF (dotted line) and the simulated DGDs from the measured RIP (where left and right refer to the profile measured at either end of the fiber.

example in h_{32} of the channel matrix, the impulse on the left hand side corresponds to the response of launching an impulse into the LP11 mode at the Tx, since it arrives at the same time as the main impulse in h_{22} of the channel matrix, which means that this impulse is perfectly launched into the LP11 mode and then propagates along the fiber with a group velocity corresponding to the LP11 mode. However, this impulse is then received when the LP21 phase mask is applied on the mode DEMUX, which indicates that the coupling from the LP11 mode to the LP21 mode occurs at the mode DEMUX. Analogous to the analysis above, the impulse on the right hand side in h_{32} is due to the crosstalk at the mode MUX, while the plateau between the two impulses is the result of mode coupling between the two mode groups in the fiber during the propagation.

By calculating the energy that is located at different positions in each element of the channel matrix, the mode coupling that has arisen from individual coupling sources is calculated. It is found that the mode coupling occurs predominantly at the mode DEMUX in the tested system, with a maximum crosstalk of -5.6 dB observed while the maximum crosstalk observed at the MUX was -16.3 dB. It should be noted that the coupling between the LP01 and LP11 mode group is 1.1532 /km in the fiber, while the coupling between other mode groups in the fiber is below 0.1259 /km. This is due to the fact that the designed Δn_{eff} between the first two mode groups is relatively lower comparing to that of the higher order mode groups (see Fig. 1 (b)). The small Δn_{eff} can also be demonstrated from the DGD measurement as shown in Fig. 2(d). The lowest DGD is found to be 2.4 ps/m between the LP01 mode and the LP11 mode group.

4. Conclusion

We present a simplified method for characterizing the channel impulse response of MDM system. This technique requires only a single transceiver and selective excitation of the fiber modes. It can provide not only the time information but also the separation of different mode coupling sources along the link. The method is used to characterize a 100 m graded index RCF. Good agreements are shown between the measured and the simulated DGDs. Since there is no limitation on the mode excitation using SLM based mode MUX/DEMUX, this method can be generally used to characterize MDM systems with other types of fibers.

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5. References

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