Transmission at 2x100Gb/s, over Two Modes of 40km-long Prototype Few-Mode Fiber, using LCOS-based Mode Multiplexer and Demultiplexer

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Abstract: We transmit two 100Gb/s PDM-QPSK data streams over two different modes of a 40km-long prototype few-mode fiber. Our experiment is performed with an LCOS-based mode multiplexer/demultiplexer and 4x4 MIMO algorithm in a coherent receiver.

OCIS codes: (060.2330) Fiber optics communications ; (060.1660) Coherent communications

1. Introduction

Increasing the constellation complexity has been the most frequently-reported approach to increase the transmission capacity in the past few years, but it can have a detrimental impact on reach, e.g. a reduction by a factor of five from 100Gb/s Polarisation Division Multiplexed (PDM) Quaternary Phase-Shift Keying (QPSK) to 200Gb/s PDM-16-QAM (Quadrature Amplitude Modulation) [1]. A new and disruptive approach for increasing capacity would be Mode Division Multiplexing (MDM), even though the MDM experiments reported so far have only achieved short distances [2]. The recent introduction of signal processing algorithms in receivers opens tremendous opportunities for the multiple detection of modes. Multiple-input multiple output (MIMO) algorithms have already been used in a coherent receiver [3] in a transmission over a short multi-mode fiber (MMF), with simple single-mode fiber (SMF)-to-MMF couplers as mode selectors.

In this paper, we demonstrate the transmission of two independent modes, which we shall call LP11a and LP11b, in a prototype few-mode fiber (FMF). This FMF has the advantage of exhibiting very large-mode delays and thus low linear [4] and nonlinear [5] crosstalk between modes, with only 0.22dB/km loss. For mode multiplexing and demultiplexing, we designed an integrated spatial mode converter incorporating a Liquid Crystal on Silicon (LCOS) spatial light modulator, being reprogrammable to any desired mode profile [6]. However we could not fully achieve the expected mode rejection ratio. The LCOS is an alternative to the simpler but fixed mode-selective phase masks fabricated in glass [7]. At the receiver side, we use two coherent receivers with joint digital signal processing for the detection of two modes at a time. The two modes are recovered with excellent performance after 20km. Interestingly, only a limited additional penalty is measured when the distance is increased to 40km.

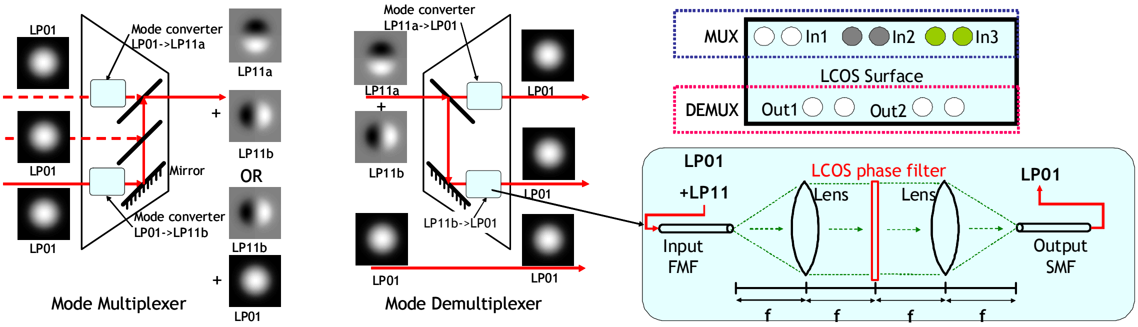

Figure 1: a) Schematic of mode mux and demux (polarisation diversity not depicted) b) Usage of LCOS display surface for creating programmable phase masks c) Mode conversion with LCOS in the Fourier plane of a 4f-configuration

2. Experimental set-up

To perform MDM, we rely on SMF-to-FMF mode conversion using a spatial light modulator, located in the Fourier plane of a 4f-lens configuration, as represented in Fig 1. We devised 3x1 and 1x2 mode converters to be used as mode multiplexer and demultiplexer, respectively. They share a single LCOS of 1920x1080 pixels, operated in reflective mode. The 3x1 converter uses the upper size of the LCOS screen. At each of its three inputs, light from the collimated SMF pigtail is split along two optical paths, one for each polarization, by a polarization splitter, and hit the LCOS onto two of six possible spots. Note that we use only phase modulation, whereas ideal mode conversion would require phase and amplitude masks, at the expense of an excessively complex design. Each spot on the LCOS device counts approximately 80x80 pixels and is programmed with the phase mask corresponding to the desired mode, i.e. according to the profiles in Fig. 2b. Light from all six paths is sent back to three polarization beam combiners, then into a 3x1 free-space combiner and collimated into the FMF. At the receiver end, the 1x2 converter is designed similarly, but with only two SMF-fiber pigtails as output ports (hence 4 spots on the LCOS phase modulator for polarization diversity), the input being the FMF. It uses the lower part of the LCOS device.

In our set-up, depicted in Fig 2a, the light from a laser at 1533.47nm is passed into an integrated transmitter. The transmitter uses a serializer to produce four 28Gb/s electrical pseudo-random signals of length 2^{15}-1, each shifted by 8192 bits, which feed a quad-driver and a polarization-multiplexed nested Mach-Zehnder modulator. It generates a data stream at 112Gb/s PDM-QPSK, including 12% protocol and forward error correction (FEC) overhead. This stream is replicated along two fiber paths decorrelated by several thousands of symbols using a SMF patch-cord, and fed to two optical amplifiers, connected to the three inputs of the mode multiplexer. Another independent PDM-QPSK transmitter at is used for the generation of the fundamental mode LP01, but not more than two transmitters are used at once.

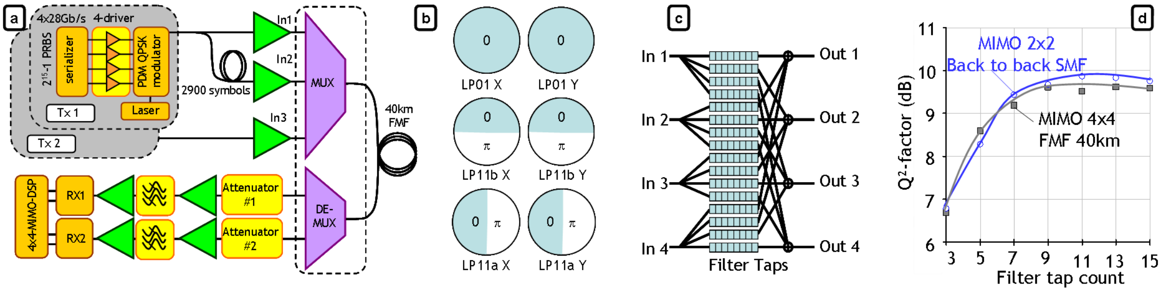

Figure 2: a. Experimental setup; b. phase masks send to the LCOS c. Representation of 4x4 FIR filters for polarization/mode demultiplexing in 4x4 MIMO DSP. d. Q-factor as a function of the number of taps of the FIR filters.

The output of the mode multiplexer is spliced to a prototype FMF supporting up to 4 modes (LP01, two generated LP11 modes a+b, LP02) with low attenuation (0.22dB/km) and large effective area (>120μm^2). The differential mode group delay (DMD) per unit length between LP01 and LP11 is quite large, at 4.35ps/m (4872 symbols after 40km at 28GBaud). Because mode coupling is inversely proportional to this value, a large DMD guarantees a low mode coupling, as in [4]. Note that the fabrication process and most of the propagation properties of FMF are very similar to that of SMF, as required for compatibility with future long-haul transmissions.

With this setup we have investigated several configurations: single mode transmissions (LP01 only) and MDM transmission (LP11a + LP11b or LP01+LP11b). In all configurations, the power into each receiver is varied using dedicated attenuators and the performance is measured. The coherent receivers incorporate optical preamplifiers and four balanced photodiodes in a polarization diversity configuration. Sampling is performed with two real-time oscilloscopes (analog 16GHz bandwidth) all synchronously triggered. LP01 is detected with a constant phase mask and using a single receiver. When the phase masks are set to select LP11a and LP11b, two receivers are used to perform joined signal processing.

The two receivers provide 4 complex signals representing the optical field. To discriminate between the degenerated modes LP11 along the two polarization axes, a 4x4 MIMO equalizer is needed, as opposed to the conventional 2x2 MIMO used for polarization demultiplexing over SMF. The structure of the 4x4 equalizer is depicted in Fig 2c. The 4 complex signals are split into 4, each sent into an FIR filter having up to 15 taps. Each of the 4 outputs is the combination of the 4 inputs, filtered by a dedicated FIR. We vary the FIR tap count in order to estimate the required length of the equalizer. We use 100Gb/s PDM QPSK performance in back-to-back as a reference (MIMO 2x2 over SMF). An almost flat Q^2 factor is measured from 9 taps to 15 taps, both for 100Gb/s PDM-QPSK and 2x100Gb/s MDM after 40km, as shown in Fig 2d. The 4x4 MIMO receiver operates in blind mode, using traditional CMA for FIR update. The complexity of such an architecture is only doubled (per transmitted bit) compared to standard single mode operation, as 16 adaptive filters are required to process 2x100Gb/s (4x4 MIMO) compared to 4 filters for 1x100Gb/s (2x2 MIMO). It should be noted that CMA tends to converge to the more powerful signal tributaries. In particular, in presence of multiple inputs it is necessary to correctly initialize the filter taps for allowing the detection of all the polarization/mode tributaries. Failing to do so would cause different outputs converging to the same input. We employed a 1-tap blind source separation algorithm [8] and we performed identification after detection by comparing the delays of the different tributaries.

4. Experimental results

The first experimental results have been recorded after 20km of FMF fiber. To ease comparisons, we choose to focus on the same received power in all configurations namely -31dBm. In Fig. 3a, the fundamental mode LP01 shows 1.1dB sensitivity penalty after 20km compared to the reference back-to-back. After the same distance, the average Q^2-factor of the LP11a + LP11b modes detected with the 4x4 MIMO receiver is reduced by another 0.6dB with respect to the LP01. After 40km of FMF, the modes LP11a + LP11b are further degraded, but by no more than 1.1dB. The values represented in Fig.3a are averaged over all the received mode/polarization tributaries (2 for the LP01 and 4 for the LP11). Fig. 3b depicts the actual performance of all mode/polarization tributaries of LP11. The Q^2-factors of mode LP11a-polarization X of appear significantly lower (by typically 2.5dB) than the other Q^2-factors. This is attributed to degraded characteristics of our mode mux/demux along one polarization. Further insight on mode crosstalk can be obtained when propagating both LP01 and LP11b modes, as depicted in Fig. 3c. We keep LP11b power constant at -32dBm on the receiver and vary the power of LP01 mode. When LP01 mode reaches -36dBm, 1dB Q^2-factor penalty can already be observed, as a result of linear crosstalk. LP01 mode should reach -19dBm power to yield a reasonable 10dB Q^2-factor, i.e. a 12dB higher power than without LP11b (see LP01 only in Fig 3c). This result suggests that three-mode propagation involving LP01, LP11a, and LP11b would require progress on mode multiplexing and demultiplexing.

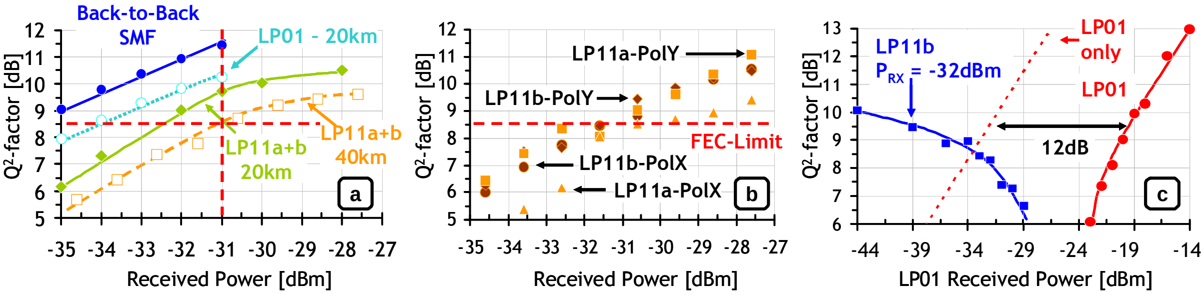

Figure 3: a. Q^2-factor versus received power for LP01 (back-to-back and 20km FMF transmission) and LP11a+b (20km and 40km FMF transmission); b. Details of Q^2-factor of the 4 mode/polarization tributaries of LP11 after 40km; c. Transmission of 2 modes (LP11b and LP01) after 40km with varying LP01 power.

5. Conclusion

The transmission of two 100Gb/s PDM QPSK signals at the same wavelength has been demonstrated over two modes of a 40km few-mode fiber. The key enablers are a reprogrammable free-space mode mux/demux, a prototype few-mode fiber with low mode coupling and two polarization- and mode-diversity coherent detectors supported by MIMO processing. This experiment paves the way to future high-capacity multimode fiber systems, even if numerous challenges still have to be solved.

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6. References

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