3x10 Gb/s mode group-multiplexed transmission over a 20 km few-mode fiber using photonic lanterns

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Abstract: We experimentally demonstrate 3x10 Gb/s mode group-multiplexed transmission with direction detection in a step-index few-mode fiber over a record reach of 20 km, enabled by low crosstalk photonic lanterns as mode group (de)multiplexers.
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1. Introduction

As the traffic of intra-datacenter networks (DCN) grows, especially with the proliferation of commercial cloud data centers, space-division multiplexing (SDM) has attracted more interest in recent years. The reason for this is that SDM increases the number of parallel, independent data channels in a single optical fiber [1]. Compared to multiple single-mode fibers (SMFs), few-mode fiber (FMF) has the potential to reduce the physical footprint of cabling within datacenters. However, due to random inter-mode crosstalk in FMFs, coherent detection and multiple-input-multiple-output (MIMO) digital signal processing (DSP) are usually required for FMF links, which can increase the physical complexity and cost of intra-DCNs. Mode-group multiplexing (MGM) can potentially eliminate the need for coherent detection and MIMO DSP. For short reach applications, crosstalk between mode groups in a fiber can be reduced to minimal levels. In MGM [2-4], degenerate modes in a mode group can be regarded as one data channel, eliminating the need for suppression of intra-group crosstalk. Another key requirement is low-crosstalk mode (de)multiplexers. In [2], 3x10 Gb/s transmission over 1 km was demonstrated using bulk multi-plane (de)multiplexers. Here, we experimentally demonstrate 3x10 Gb/s transmission with direct detection using MGM over a record reach of 20 km. The step-index FMF was designed to increase the effective index difference between mode groups, lowering mode group coupling. Low-crosstalk, mode-selective photonic lanterns (PLs) were used as (de)multiplexers.

2. Few-mode fiber

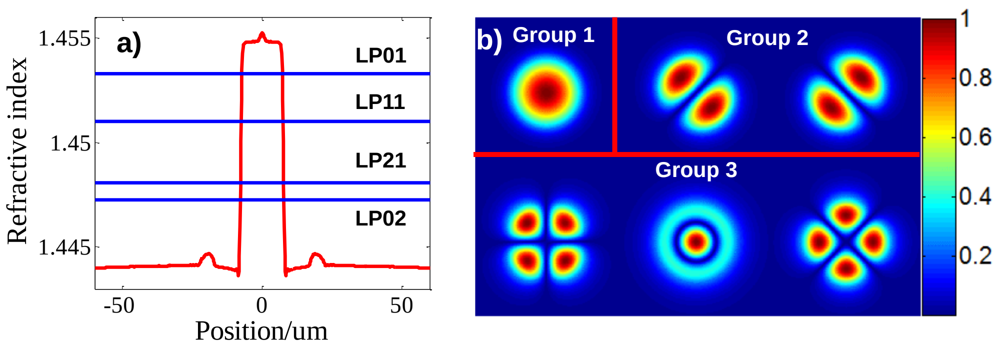

Fig. 1: (a) Refractive index profile of FMF, and effective indices of LP modes. (b) Intensity profiles of each of the supported LP modes within the three mode groups.

The FMF used in this work supports 3 mode groups at 1550 nm [5]. The index profile of the FMF and effective indices of the supported modes, with large index differences $\geq 2.3 \times 10^{-3}$ between mode groups, are shown in Fig. 1(a). Simulated mode profiles of the three mode groups are shown in Fig. 1(b). The FMF was specifically designed to increase the effective index difference between the mode groups, reducing coupling between them.

3. Mode multiplexer and demultiplexer

For direct detection FMF links, mode converters with low mode crosstalk are required to launch different spatial modes into the FMFs. Compared with high-loss power combining schemes using a passive combiner, the use of a PL is, in theory, lossless and the device can achieve low mode crosstalk as a mode converter [6, 7]. A PL consists of several SMFs encapsulated inside a low refractive index glass capillary, which is tapered to match the transmission FMF. To achieve good mode selectivity, the propagation constant of each input SMF is matched to that of the corresponding mode in the FMF. Dissimilar core fibers are used inside the capillary to fabricate a mode-selective PL.

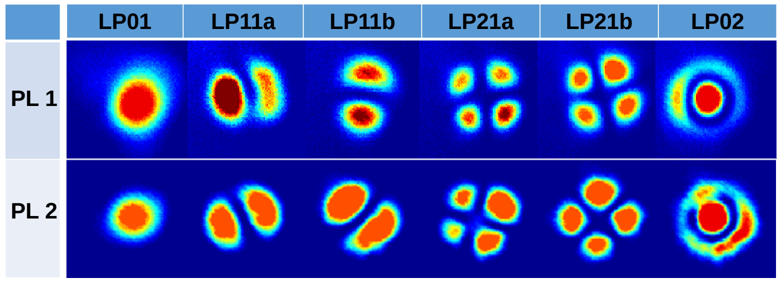

Fig. 2: Output intensity profile of six selectively-excited modes from two photonic lanterns.

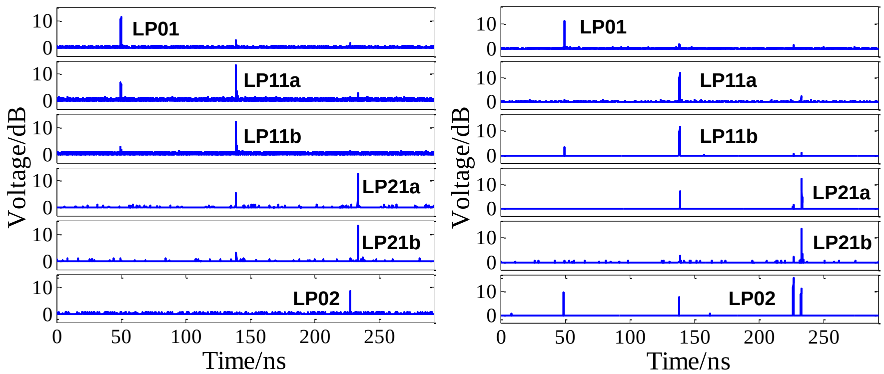

Fig. 3: Measured impulse response for (a) PL 1 and (b) PL 2. Each PL is spliced with 20 km FMF, and input pulse is launched into different modes.

Two PLs were used in the work: one as mode multiplexer, and another one as mode demultiplexer. Output images of the selectively excited modes of these two PLs are shown in Fig. 2. Six spatial modes were supported at 1550 nm. To characterize the mode crosstalk of PLs and the FMF, impulse responses of the PL-FMF combinations are shown in Fig. 3. A short pulse was launched into one input SMF of the PL to selectively excite one mode in the FMF, which was fusion spliced with the PL. The pulse would split into several pulses due to mode crosstalk within the PL and FMF. These pulses arrived at different times in the high speed few-mode detector after 20 km propagation, since different spatial modes had different group delays. From the amplitude at certain group delay, mode crosstalk of the PL together with FMF can be characterized. The two PLs reach mode-group crosstalk levels lower than 8 dB and 9 dB, respectively.

4. Transmission experiment

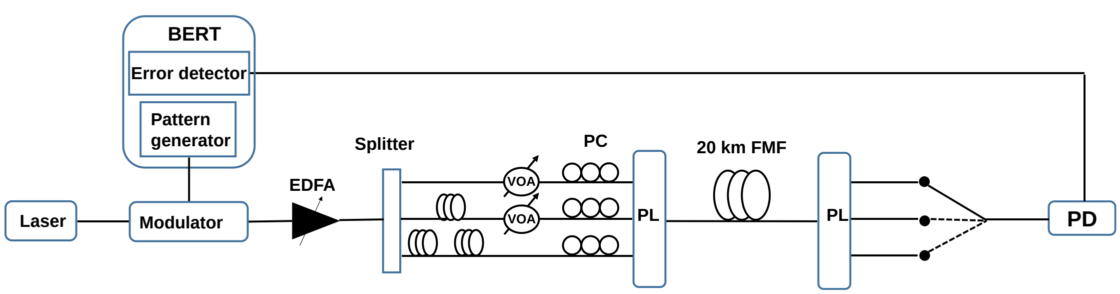

Fig. 4: MGM Transmission experiment setup. BERT: bit error ratio tester; EDFA: erbium-doped fiber amplifier; VOA: variable optical attenuator; PC: polarization controller; PL: photonic lantern; PD: photon detector.

3x10 Gb/s MGM transmission with direct detection was demonstrated using the setup shown in Fig. 4. The bit error ratio tester (BERT) was used as a pattern generator to produce a 10 Gb/s data stream of length $2^{31} - 1$ for intensity modulation of light from the transmitter laser. The signal was then amplified by an EDFA, to enable adjustment of detected power at the receiver. The signal was split into three paths with different delay lines to produce de-correlation among them. Each signal was connected to one SMF of the transmitter PL to excite the corresponding mode group. Two variable optical attenuators (VOAs) were also used to balance the power of each channel to ensure that the measured bit error ratio (BER) in each mode group was similar, as each group experienced different channel losses due to the delay lines, PLs, and the FMF. Three polarization controllers (PCs) were used to adjust the polarization state of light into the polarization-sensitive PL, in order to reduce mode crosstalk. After propagation through the 20 km FMF, the MGM signal was demultiplexed by the second PL into three SMFs. Each MGM channel was separately detected by an InGaAs PIN+TIA receiver with 10 GHz bandwidth, which was connected to the BERT to measure the BER.

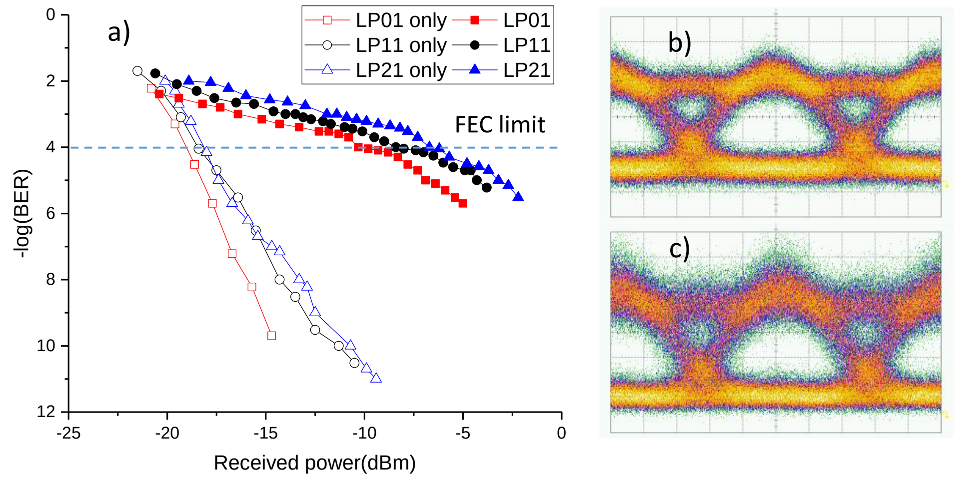

Fig. 5: (a) Measured BERs as functions of received power for 3 mode groups (Each mode group is represented by one mode). Open symbols represent separate channel transmission, and solid symbols represent simultaneous transmission. (b) Eye diagram for LP01-only transmission. (c) Eye diagram of the LP01 mode in 3-mode-group MGM transmission.

The measured BER results are shown in Fig. 5(a). When each mode group was separately launched, BERs below 10^{-10} could be achieved for each mode group. When 3 mode groups were simultaneously transmitted, measured BERs were worse than single-channel transmission, mainly due to mode crosstalk in the PLs, the FMF, and at the splicing points between them. There was about a 10 dB power penalty compared with single-channel transmission at the FEC limit of 10^{-4}. Fig. 5(b) and (c) are eye diagrams for the LP01 mode when transmitted separately and simultaneously with other mode groups, respectively.

5. Conclusion

In conclusion, we experimentally demonstrate the 3x10 Gb/s transmission over a record reach of 20 km in a FMF using mode-group multiplexing and direct detection without MIMO DSP. Mode selectivity was achieved using two photonic lanterns as the mode multiplexer and demultiplexer. The performance of the current FMF link is limited by the crosstalk of the PLs. It is possible to reduce the crosstalk of the PLs by more careful optimization of the device fabrication process. These results illustrate that mode-group multiplexing with direct detection could play a role in intra-datacenter networks and other short-reach communication applications.

6. References

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