Demonstration of stable 3x10 Gb/s mode group-multiplexed transmission over a 20 km few-mode fiber

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Abstract: We experimentally demonstrate stable 3x10 Gb/s mode group-multiplexed transmission over a 20 km few-mode fiber using OOK modulation and direct detection. Stability in transmission was achieved by combining all degenerate modes at the receiver.

OCIS codes: (060.2330) Fiber optics communications; (060.4230) Multiplexing

1. Introduction

As single-mode fiber (SMF)-based optical communication systems approach their capacity limit due to nonlinearity, space-division multiplexing (SDM), using few-mode fibers (FMFs) or multicore fibers (MCFs), has attracted more interest in recent years [1]. Coherent detection and multiple-input-multiple-output (MIMO) digital signal processing (DSP) are usually required due to inter-mode crosstalk, which will increase the complexity and cost of transmission. MIMO-based SDM transmission is likely to be too expensive for short-reach application such as intra-datacenter networks. However, in short-reach applications, it is possible to reduce crosstalk between mode groups to minimal levels so that MIMO-less mode-group multiplexing (MGM) becomes feasible over distances on the order of a few km [2,3]. In some MGM demonstrations to date, only one of the degenerate modes in a group was detected at the receiver [4]. This is feasible because degenerate modes couple strongly and therefore the probability that the received power in any one of the degenerate modes vanishes is extremely low. Nevertheless, detecting only one of degenerate modes will lead to power fluctuation due to polarization-dependent coherent crosstalk among degenerate modes. Therefore, for field applications, collecting power from all degenerate modes is essential for maintaining the signal-to-noise ratio (SNR) or bit error ratio (BER). In this work, we experimentally demonstrate stable 3x10 Gb/s MGM transmission with direct detection, and the advantages of receiving all degenerate modes in each mode group at the receiver. The step-index FMF, which was designed with large effective index difference between mode groups, and low-crosstalk mode-selective photonic lanterns (PLs) as (de)multiplexers used in the work enable a transmission distance of 20 km, much longer than previous MGM transmission demonstrations [2,3].

2. FMF and mode (de)multiplexers

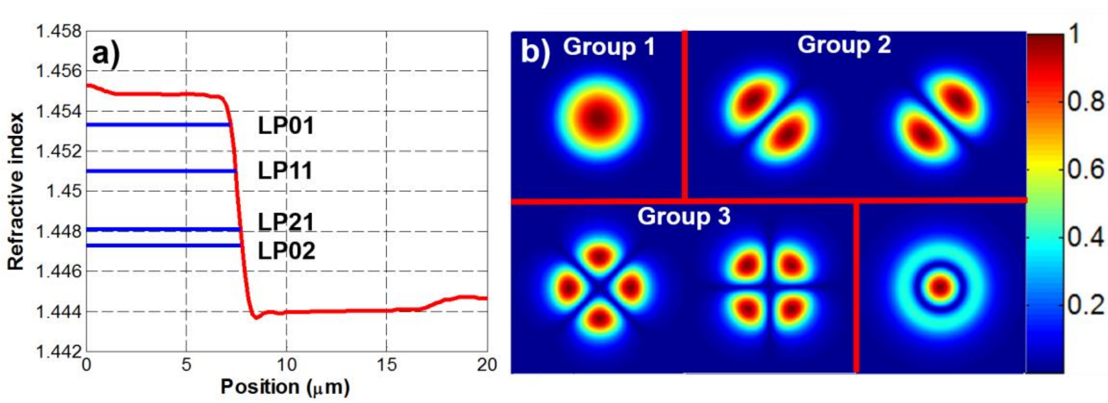

Fig. 1: (a) Refractive index profile of FMF, and effective indices of LP modes. (b) Intensity profiles of each of the supported LP modes.

The FMF was specifically designed to increase the effective index difference between the mode groups, reducing coupling between them. The FMF we used in this work supports 6 spatial modes at 1550 nm [5], and we used the first 5 modes as 3 mode groups to perform the transmission experiment. Fig. 1(a) shows the index profile and effective indices of all supported modes; the effective index differences between mode groups is $\geq 2.3 \times 10^{-3}$. Simulated mode profiles are also shown in Fig. 1(b).

Low-crosstalk mode multiplexer and mode demultiplexer are required to launch and receive different modes in the FMFs. Different components can be used as mode (de)multiplexers, among which the PL is lossless in theory, and has been shown to achieve excellent mode selectivity [6,7]. A PL consists of several SMFs encapsulated inside a low refractive index glass capillary, which is tapered to match the transmission FMF. SMFs with different core sizes are used to fabricate a mode-selective PL, and the propagation constant of each SMF is matched to that of the corresponding mode in the FMF.

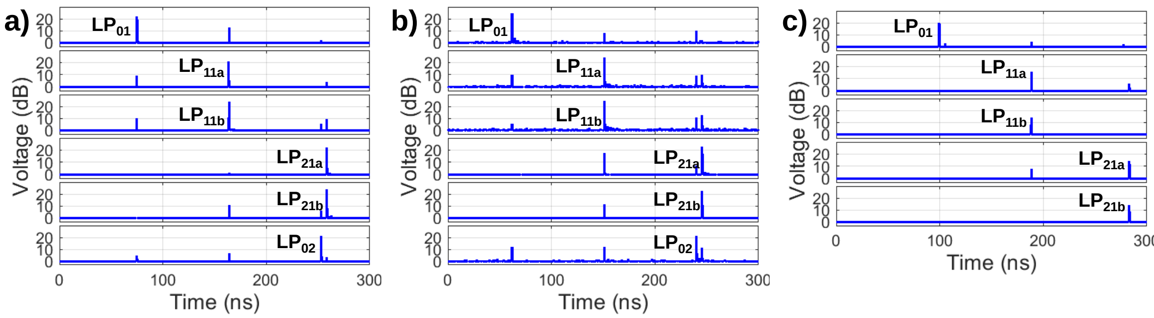

Fig. 2: Measured impulse response for (a) PL 1, (b) PL 2, and (c) PL 3. Each PL is spliced to a 20 km FMF.

Three PLs were used in the work: one as the mode multiplexer, the second one as the mode demultiplexer, and the last one as the degenerate mode combiner at the receiver. Impulse responses of the PL-FMF combinations were measured to characterize the mode crosstalk of the PLs and the FMF. Each PL was spliced to the FMF for the measurement, with results shown in Fig. 2. A short pulse was launched into one input SMF of each PL to excite one mode in the FMF, and multiple pulses appeared due to mode crosstalk and modal group delays (GDs). After 20 km propagation, the mode crosstalk could be characterized from the amplitudes of the pulses at different GD times. The first PL has mode-group crosstalk lower than -9 dB at all ports, and it was used as the mode demultiplexer. The second PL has mode-group crosstalk lower than -9 dB at all ports except LP_{21a}, so it was used as the mode multiplexer, and LP_{21b} was used as the input port for LP_{21} group transmission. The third PL has 5 working ports and mode-group crosstalk lower than -6.5 dB, which was used as the degenerate mode combiner after the mode demultiplexer.

3. Transmission experiment

Stable 3x10 Gb/s MGM transmission with direct detection was demonstrated using the setup shown in Fig. 3. A 10 Gb/s data stream of length $2^{31} - 1$ was split into three paths with different delay lines to produce de-correlation among them. Each signal was connected to one SMF of the multiplexer PL to excite the corresponding mode group. After propagation through the 20 km FMF, the MGM signal was demultiplexed by the second PL. Two degenerate LP_{11} and LP_{21} modes are combined through the third PL to be detected by the receiver to measure the BER. The propagation delays of degenerate modes were equalized by adjusting the lengths of input SMFs between the second and third PL.

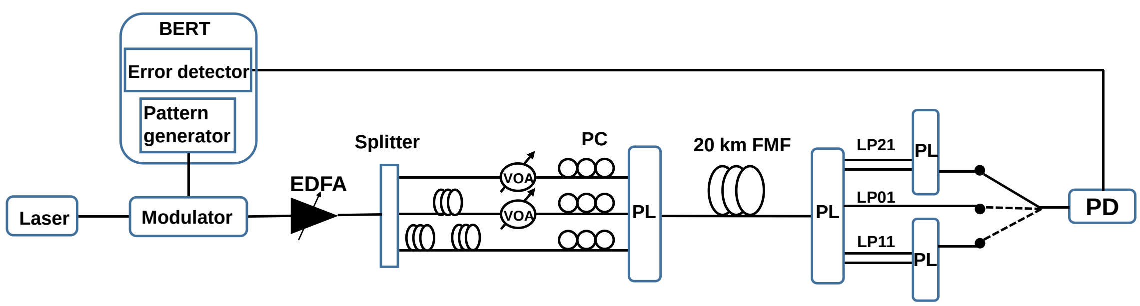

Fig. 3: Experiment setup for MGM transmission. BERT: bit error ratio tester; EDFA: erbium-doped fiber amplifier; VOA: variable optical attenuator; PC: polarization controller; PL: photonic lantern; PD: photodetector.

Before presenting the results of 3-mode-group transmission, the advantages of combining degenerate modes are first shown in Fig. 4. Fig. 4(a) plots the BERs as functions of transmitted power for receiving only one or both degenerate modes of LP_{11} or LP_{21} mode group. It shows, as expected, that combining degenerate modes can improve the sensitivity by about 3 dB. In addition, combing degenerate modes can also alleviate polarization fluctuations. As shown in Fig. 4(b), as the polarization of the transmitter laser changes, there is always one degenerate mode with large power penalty, while combing degenerate modes removes this power penalty.

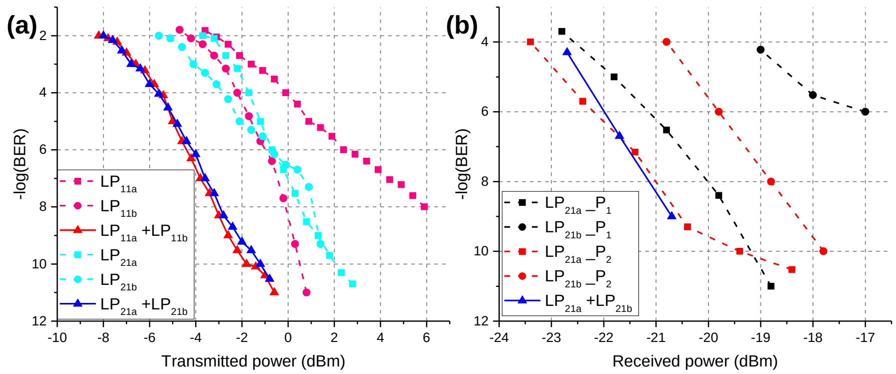

Fig. 4: (a) Measured BERs as functions of transmitted power for detecting only one of degenerate modes or both degenerate modes of the LP_{11} and LP_{21} group. (b) Measured BERs as functions of received power for detecting only one of degenerate modes or both degenerate modes of the LP_{21} group for two different transmitting laser polarizations.

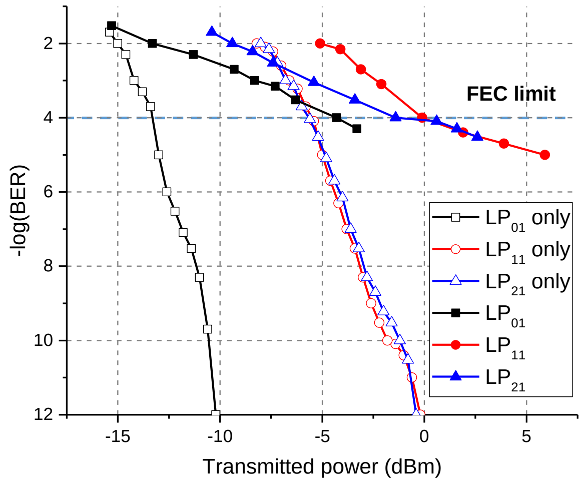

Fig. 5: (a) Measured BERs as functions of transmitted power for 3 mode groups. Open symbols represent separate mode-group transmission, and solid symbols represent MGM transmission.

Fig. 5 plots the measured BERs when each mode group was separately transmitted or simultaneously transmitted. BERs below 10^{-12} could be achieved for separate transmission of each mode group. There is about a 10 dB power penalty between LP_{01} and LP_{11} or LP_{21}, mainly due to mode-dependent loss of the FMF and PLs. Variable optical attenuators (VOAs) were used to equalize the BERs of the three mode groups in MGM transmission. The measured BERs for MGM transmission were worse due to mode crosstalk in the FMF and the PLs, but can reach the threshold for 7% FEC.

4. Conclusion

In conclusion, we experimentally demonstrate stable 3x10 Gb/s mode-group multiplexed transmission over a 20 km FMF using OOK modulation and direct detection without MIMO DSP. In addition to two PLs as the mode multiplexer and demultiplexer, a third PL was used to combine degenerate LP_{11} or LP_{21} modes at the receiver. Advantages of combining degenerate modes have been demonstrated. These results illustrate that mode-group multiplexing with direct detection can play a role in intra-datacenter networks and other short-reach applications.

5. References

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