All-optical Mode-Group Division Multiplexing Over a Graded-Index Ring-Core Fiber with Single Radial Mode

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Abstract: We demonstrate mode-group division multiplexing over 100m graded-index ring-core fiber supporting 4 LP mode-groups with a single radial index using SLM-based mode (de)multiplexers to transmit 2x10Gbps NRZ signals without MIMO equalization.

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1. Introduction

Ring-core fibers (RCFs) have been proposed for mode-division multiplexing (MDM) systems to further increase transmission capacity with low multiple-input multiple-output (MIMO) processing complexity[1-3]. In addition, RCFs have a large effective area which is beneficial for reducing nonlinear effects and sensitivity to bending[4]. To support a large number of guided modes with a large average effective index difference which enables reduced mode coupling between mode-groups, RCFs are often designed to be radially single-mode and azimuthally multimode. Another advantage of RCFs with a single radial mode is that selective mode excitation can be simply performed using compact photonic integrated circuits (PICs), such as a circular grating coupler fed by an array of single-mode waveguides[5]. However, radially varying modes are difficult to create with PICs. These features make RCFs with a single radial mode an attractive class of multimode fibers for next generation MDM systems.

The graded-index RCF used in this work supports 4 linearly polarized (LP) mode-groups with a single radial index: LP_{01}, LP_{11}, LP_{21} and LP_{31}. Each $LP_{(l>0,1)}$ mode in the RCF has two-fold spatial degeneracy in each polarization. These sets of degenerate modes form a mode-group and mix heavily in the fiber, but the optical isolation between mode-groups is large. The mode field distributions of all guided LP modes in the graded-index RCF are shown in Figure 1. In this paper, mode-group multiplexing over 100m length of graded-index RCF is performed using spatial light modulator (SLM) based multiplexer and de-multiplexer to transmit 2x10Gbps NRZ without MIMO equalization. Mode-group multiplexing transmission is conducted using two sets of mode-group combinations.

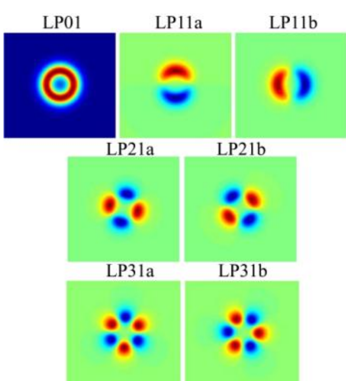

Figure 1 Mode field distributions of all guided LP modes in the graded-index ring-core fiber.

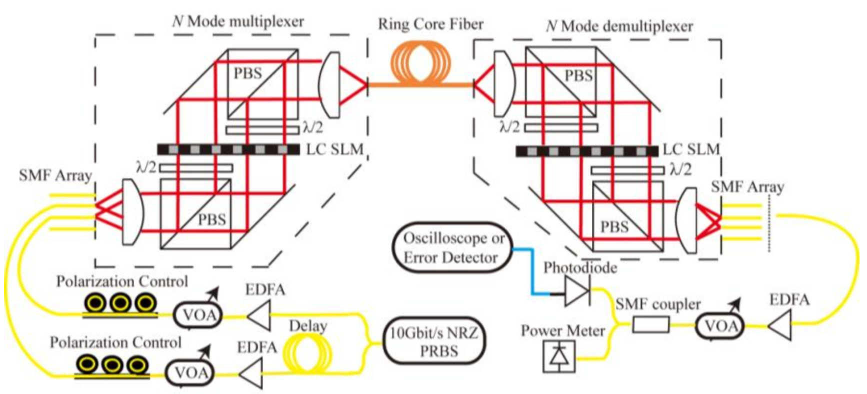

Figure 2 Mode-group multiplexing system that optically multiplexes two spatial mode-groups from separate input fiber ports into the graded-index RCF and de-multiplexes the mode-group channels to separate output fiber ports.

2. Mode channel characterization

Figure 2 shows the mode-group multiplexing system, which consists of the transmitter, SLM-based (de)multiplexers, the RCF and the detector. The SLM-based (de)multiplexers were previously used to modally characterize another RCF supporting 7 LP mode-groups [3]. This was achieved by programming phase masks (holograms) which precisely excite each supported LP mode of the RCF, onto the SLM-based (de)multiplexers. In this work, phase masks were generated using the same algorithm with less than 1% error and maximum possible light conversion efficiency (26.1%-38.1%, varies from mode to mode). Prior to performing mode multiplexing, it is necessary to modally characterize each channel that maps one input single mode fiber (SMF) port to one output SMF port by measuring mode transfer matrix of each channel individually. The SMF arrays used are standard MPO connectors with 250μm spacing between ports. Although this is a convenient and low-cost design, the relatively large spacing means that offset fiber ports suffer more optical distortions than central fiber ports. This causes channels to have different mode coupling properties. Figure 3 shows the power distributions of the measured mode transfer matrices for two channels. We can observe that the mode transfer matrix of the first channel, shown in Figure 3(a), has better modal isolation properties than that of the second channel, shown in Figure 3(b). The mode transfer matrix of the first channel, which uses optically central fiber array ports, more accurately reflects the modal coupling properties of the RCF itself. By comparison, in the second channel modal crosstalk is dominated by coupling at the multiplexer and de-multiplexer. From the mode transfer matrix of the second channel in Figure 3(b), it is seen that when launching LP_{01} (first column), the mode crosstalk with the third mode group and the fourth mode group is -9dB and -12dB respectively. However, when launching high order modes, LP_{21} and LP_{31} (third and fourth column), the crosstalk with the first mode group is -19dB and -20.6dB. Based on the characterized channel characteristics, high order modes (LP_{21} and LP_{31}) are used for the second channel and the fundamental mode LP01 is used for the first channel.

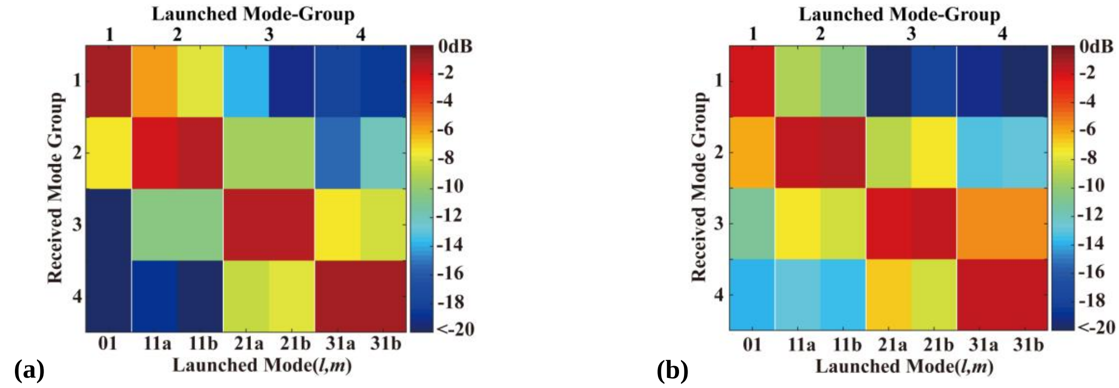

Figure 3 Power distributions aggregated by mode-group of measured mode transfer matrices of the two individual channels over 100m of the graded-index RCF. (a) first channel using central fiber array port. (b) second channel using offset fiber array port.

3. Mode-group division multiplexing performance

In the mode-group multiplexing experiment, composite phase masks are constructed at the multiplexer to precisely convert light from the first fiber port into the LP_{01} mode and from the second fiber port into a high order mode, LP_{21a} or LP_{31a}. At the de-multiplexer, the launched LP_{01} mode arrives mostly intact but with random polarization mixing. The higher order mode, LP_{21a} or LP_{31a}, arrives as a random superposition of degenerate modes in the corresponding mode-group with random polarization mixing. To de-multiplex a mode-group to a receiving fiber port, the relative amplitude and phase of all degenerate modes in that mode-group at the receiving end of the fiber is first measured. This information is then used to construct a weighted composite phase mask for the de-multiplexer. The weighting of each channel is optimized such that the received optical power of both mode-group channels are equal [6]. Figure 4 shows the measured complex coefficients of each degenerate mode in each polarization within the high-order mode group (3rd or 4th mode-group) at the de-multiplexer resulting from an LP_{21a} or LP_{31a} launch. Polarization diversity information is not measured in this experiment.

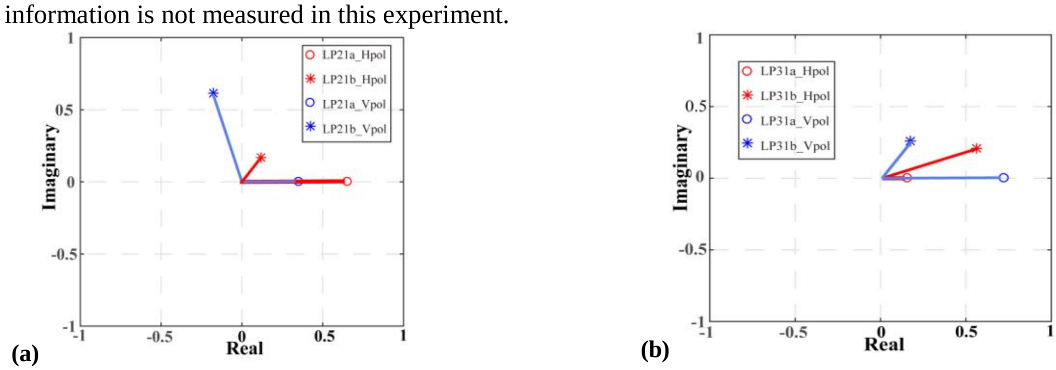

Figure 4 Measured complex coefficients of each degenerate modes in the high order mode-group at the de-multiplexer. (a) mode-group multiplexing using LP01 and LP21;(b)mode-group multiplexing using LP01 and LP31.

Figure 5 shows measured BER results as a function of the received optical power for 2x10Gbps non-return-to-zero (NRZ) 2^{31}-1 PRBS transmission. Two sets of 2 mode-group multiplexing over the 100m RCF are performed using the LP_{01} mode and one high-order mode, LP_{21} or LP_{31}. The measured isolation between the LP_{01} and LP_{21} mode-group channels was 15.6dB and the measured isolation between the LP_{01} and LP_{31} channels was 19.8dB at the start of each set of BER tests. For both sets of mode-group multiplexing, error-free ($BER<10^{-12}$) data transmission is achieved. We observe that LP_{01} single-channel operation has ~0.7dB greater power penalty at a BER of 10^{-12} than LP_{21} or LP_{31} single-channel operation. This is because that in the RCF the fundamental mode (LP_{01}) has strong mode coupling with its adjacent low order mode (LP_{11}) and suffers modal dispersion, which can be observed from the mode transfer matrix shown in Figure 3(a). For mode-group multiplexing using LP_{01} and LP_{21}, mode multiplexing operation suffers a 3.6dB power penalty at a BER of 10^{-12} compared with single channel operation. For mode-group multiplexing using LP_{01} and LP_{31}, mode multiplexing results in 1.5dB power penalty at a BER of 10^{-12} over single-channel operation due to better channel isolation. Eye diagrams of the 2 mode-group channels at 10Gbps over 100m graded-index RCF are shown in Figure 6 and it is observed that they are open and clean.

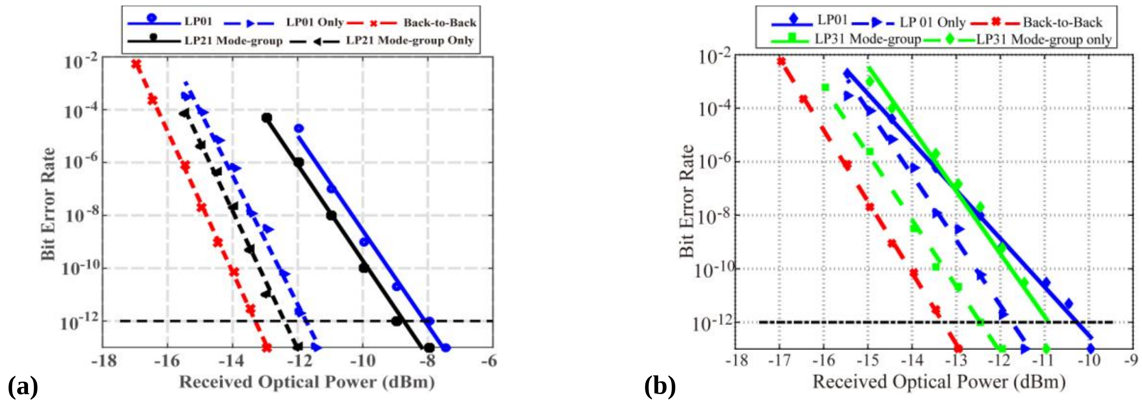

Figure 5. Measured BER curves versus received optical power at 10Gbps NRZ: (a) mode-group multiplexing using LP_{01} and LP_{21};(b)mode-group multiplexing using LP_{01} and LP_{31}.

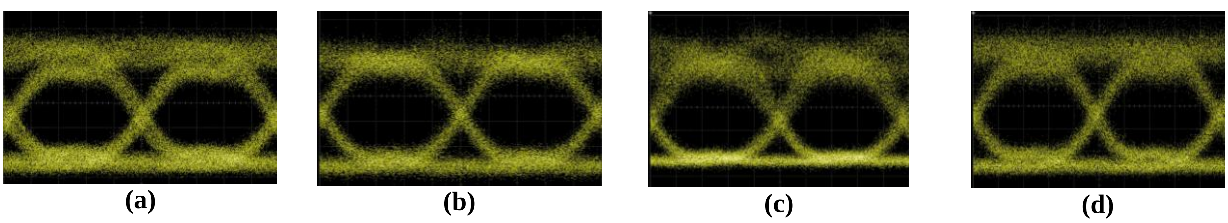

Figure 6. 2x10Gbps NRZ eye diagrams over 100m graded-index RCF: (a) Multiplexing I: LP_{01} Channel (-9dBm received power). (b) Multiplexing I: LP_{21} mode-group channel (-9dBm received power). (c) Multiplexing II: LP_{01} Channel (-11dBm received power). (d) Multiplexing II: LP_{31} mode-group channel (-11dBm received power).

4. Conclusion

Using SLM-based mode (de)multiplexers, 2x10Gbps all-optical mode-group multiplexing over a 100m novel graded-index RCF supporting 4 mode-groups with single radial index has been demonstrated without using MIMO DSP equalization. The modal properties (the mode transfer matrix) of the RCF are also characterized.

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5. References

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