All-fiber-based Selective Mode Multiplexer and Demultiplexer for Six-mode Multiplexed Signals

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Abstract: We experimentally evaluate performance of selective six-mode multiplexer based on mode selective couplers. The mode-group coupling is suppressed by -20dB, maintaining OSNR penalty of 3dB due to mode multiplexing even with use of 6×6 MIMO.

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1. Introduction

Mode-division multiplexed (MDM) techniques in few-mode fibers (FMFs) are promising for increasing fiber capacity. In the MDM systems, multiple-input multiple-output (MIMO) equalization in receivers is usually used in order to compensate for mode coupling. The computation complexity of MIMO is increased as increasing the number of multiplexed modes. In the weakly-coupled MDM system, in which the mode coupling is restricted, the size of the MIMO matrix can be decreased [1], although a selective mode multiplexer and demultiplexer are required as long as the mode coupling in the FMF transmission is suppressed.

One scheme for the selective mode multiplexing is based on matching a spatial beam pattern to a desired LP mode by using phase plates [2-4], spatial light modulators [5,6], and photonic lanterns [7,8]. Although the phase plate is the simplest scheme, the mode coupling is relatively large due to imperfection of the mode conversion. Photonic lantern is effective to excite the super modes in FMF with low loss, while it is not suitable for the selective mode excitation. Another approach is based on coupling between waveguide modes that satisfy the phase matching condition, and it is appropriate for selective mode multiplexing with low loss. Although there has been report on application of the couplers based on planar lightwave circuits (PLCs) [9] to the 500-km mode-multiplexed transmission [10], the fiber-based coupler is rather suitable for connecting to FMF for the transmission line. Mode multiplexers based on all-fiber-type couplers were reported [11-14], however, a MDM transmission experiment with more than four modes has never been demonstrated using the fiber-fused couplers.

In this paper, we experimentally evaluate performance of six-mode multiplexer based on all-fiber couplers for six-mode-multiplexed systems. The mode multiplexer is possible to multiplex the degenerated modes, namely LP11a/LP11b and LP21a/LP21b. We measure bit-error rate (BER) characteristics of six-mode-multiplexed DP-QPSK signals by using the mode multiplexer and demultiplexer based on all-fiber couplers. The crosstalk between lower three modes and higher three modes is suppressed to be smaller than -20dB, enabling to apply to weakly-coupled MDM systems with two sets of 6×6 partial MIMO. The penalty of the optical-signal-to-noise ratio (OSNR) for BER of 10-2 is suppressed by 3 dB even with the use of partial 6×6 MIMO.

2. Operation principle of mode multiplexer of all-fiber couplers

The configuration of the mode multiplexer is shown in Fig. 1(a). It is based on an asymmetric coupler composed of FMF and a single-mode fiber (SMF) with a high index ratio Δ of the core to the clad. Figure 1(b) illustrates the profile of the refractive index of the coupler. The effective index of the LP01 mode in SMF nSMFLP01, and those of LP1m modes of FMF nFMPmLPlm are also indicated. In the coupler as shown in Fig. 1(b), the LP01 mode of SMF and the LP11 mode of FMF are coupled with low loss.
mode of FMF having same effective indices are coupled, but other modes in FMF are not coupled to SMF. The effective indices \( n_{\text{SMF}}^{\text{LP01}} \) and \( n_{\text{FMF}}^{\text{LP01}} \) are adjustable by tuning the taper diameters of SMF and FMF [11]. By cascading couplers with different \( n_{\text{SMF}}^{\text{LP01}} \) phase-matching to \( n_{\text{FMF}}^{\text{LP01}} \), the mode multiplexing is achieved [12]. Although the degenerated modes such as LP\(_{11a}\) and LP\(_{11b}\) cannot be separated because they have same effective indices, they can be distinguished by the different geometries of SMF and FMF in couplers. The multiplexers for LP\(_{11a}\) and LP\(_{11b}\) are achieved by couplers with vertical and parallel geometries of SMF and FMF as shown in Fig. 1(c). For LP\(_{21a}\) and LP\(_{21b}\) couplers of the geometries of SMF and FMF relatively rotated by 45 degrees are used. Figure 2 shows the configuration of cascaded six couplers enabling mode multiplexing of six modes, namely LP\(_{01}\), LP\(_{11a}\), LP\(_{11b}\), LP\(_{21a}\), LP\(_{21b}\), and LP\(_{02}\).

If the phase matching condition is perfectly satisfied, the LP\(_{01}\) mode of SMF can be perfectly converted into the LP mode of FMF. In this case, the intrinsic loss is approaching zero. In addition, the wideband operation including full C band is possible in principle.

### 3. Experiments for performance evaluation of six-mode multiplexer

The experimental setup is shown in Fig. 3. A CW light was generated from a tunable laser, and then it was modulated by two streams of electrical Nyquist-shaped binary signals generated from two arbitrary waveform generators (AWGs). After polarization-multiplexing, we obtained Nyquist-shaped dual-polarization (DP) QPSK signals. The signal baudrate was set to be 15 Gbaud. It was split into six branches with a relative delay of 50 ns between subsequent paths. The delayed signals were mode-multiplexed by a six-mode multiplexer based on all-fiber couplers. The mode multiplexer was based on five all-fiber couplers as shown in Fig. 2. The core diameter of FMF was 10 \( \mu \)m, and \( \Delta \) was 1.3\%. The conversion loss of each coupler was smaller than 2 dB.

After that, the six-mode-multiplexed signal was demultiplexed in the same manner as the multiplexer. The output FMF of multiplexer was fusion-spliced to the input FMF of the demultiplexer. The six demultiplexed signals passed through optical bandpass filters, and they were simultaneously detected by coherent receivers based on the heterodyne detection. In this experiment, a free-running laser was used as a local oscillator (LO). The frequency between LO and the signals was set to be 9.5 GHz. The received signals were stored by three four-channel real-time oscilloscopes, and then the stored data were offline processed. The stored samples were firstly down-converted, and then the baseband signals were obtained. After that, the samples were processed by a half-symbol-spaced adaptive MIMO equalizer. The tap coefficients were updated based on decision-directed LMS algorithm. In this experiment, we compared full 12×12 MIMO with two sets of 6×6 MIMO. All the samples for six modes were simultaneously equalized for the use of 12×12 MIMO. Using 6×6 MIMO, two sets of three modes (LP\(_{01}/\text{LP}_{11a}/\text{LP}_{11b}\) and LP\(_{21a}/\text{LP}_{21b}/\text{LP}_{02}\)) were independently processed. Finally, the errors were counted.

### 4. Experiment results

Figure 4 shows the measured intensity profiles of LP\(_{11}\), LP\(_{21}\), and LP\(_{02}\) after the multiplexer. We obtained patterns...
We showed the mode multiplexer based on all-fiber couplers for six-mode multiplexed systems. The crosstalk between the lower three modes and higher three modes was suppressed by -20 dB, resulting in the OSNR penalty of 3 dB due to six-mode multiplexing even with the use of the partial 6×6 MIMO. These results suggest that the mode multiplexer is applicable to the weakly-coupled MDM systems.

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