Mode division multiplexed optical transmission enabled by all–fiber mode multiplexer

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Abstract: Mode division multiplexed optical transmission enabled by all-fiber mode multiplexer is investigated. The proposed all-fiber mode multiplexer is composed of consecutive mode selective couplers. It multiplexes or demultiplexes LP_{01}, LP_{11}, LP_{21}, and LP_{02} modes simultaneously. We demonstrate successful transmission of three spatial modes with 120 Gb/s PDM-QPSK signals over 15 km of four mode fiber by using 6x6 MIMO digital signal processing.

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

References and links

1. E. Yamazaki, S. Yamanaka, Y. Kisaka, T. Nakagawa, K. Murata, E. Yoshida, T. Sakano, M. Tomizawa, Y. Miyamoto, S. Matsuoka, J. Matsui, A. Shibayama, J. Abe, Y. Nakamura, H. Noguchi, K. Fukuchi, H. Onaka, K. Fukumitsu, K. Komaki, O. Takeuchi, Y. Sakamoto, H. Nakashima, T. Mizuochi, K. Kubo, Y. Miyata, H. Nishimoto, S. Hirano, and K. Onohara, "Fast optical channel recovery in field demonstration of 100-Gbit/s Ethernet over OTN using real-time DSP," Opt. Express **19**(14), 13179–13184 (2011).
2. L. E. Nelson, G. Zhang, M. Birk, C. Skolnick, R. Isaac, Y. Pan, C. Rasmussen, G. Pendock, and B. Mikkelsen, "A robust real-time 100G transceiver with soft-decision forward error correction," J. Opt. Commun. Netw. **4**(11), B131–B141 (2012).
3. H. S. Chung, S. H. Chang, J. Lee, and K. Kim, "Transmission performance comparison of direct detection based 100-Gb/s modulation formats for metro area optical networks," ETRI J. **34**(6), 800–806 (2012).
4. R. Essiambre, G. Kramer, P. J. Winzer, G. J. Foschini, and B. Goebel, "Capacity limits of optical fiber networks," J. Lightwave Technol. **28**(4), 662–701 (2010).
5. S. Randel, R. Ryf, A. Sierra, P. J. Winzer, A. H. Gnauck, C. A. Bolle, R. J. Essiambre, D. W. Peckham, A. McCurdy, and R. Lingle, Jr., "6×56-Gb/s mode-division multiplexed transmission over 33-km few-mode fiber enabled by 6×6 MIMO equalization," Opt. Express **19**(17), 16697–16707 (2011).
6. R. Ryf, S. Randel, A. H. Gnauck, C. Bolle, A. Sierra, S. Mumtaz, M. Esmaeelpour, E. C. Burrows, R. Essiambre, P. J. Winzer, D. W. Peckham, A. H. McCurdy, and R. Lingle, Jr., "Mode-division multiplexing over 96 km of few-mode fiber using coherent 6x6 MIMO processing," J. Lightwave Technol. **30**(4), 521–531 (2012).
7. M. Salsi, C. Koebele, D. Sperti, P. Tran, H. Mardoyan, P. Brindel, S. Bigo, A. Boutin, F. Verluise, P. Sillard, M. Bigot-Asruc, L. Provost, and G. Charlet, "Mode-division multiplexing of 2x100Gb/s channels using an LCOS-based spatial modulator," J. Lightwave Technol. **30**(4), 618–623 (2012).
8. A. Al Amin, A. Li, S. Chen, X. Chen, G. Gao, and W. Shieh, "Dual-LP_{11} mode 4×4 MIMO-OFDM transmission over a two-mode fiber," Opt. Express **19**(17), 16672–16679 (2011).
9. N. Hanzawa, K. Saitoh, T. Sakamoto, T. Matsui, S. Tomita, and M. Koshiba, "Demonstration of mode-division multiplexing transmission over 10 km two-mode fiber with mode coupler," *Optical Fiber Communication Conference (OFC)* 2011, OWA4 (2011).
10. A. Li, J. Ye, X. Chen, and W. Shieh, "Fabrication of a low-loss fused fiber spatial-mode coupler for few-mode transmission," IEEE Photon. Technol. Lett. **25**(20), 1985–1988 (2013).
11. R. Ryf, N. K. Fontaine, M. A. Mestre, S. Randel, X. Palou, C. Bolle, A. H. Gnauck, S. Chandrasekhar, X. Liu, B. Guan, R.-J. Essiambre, P. J. Winzer, S. G. Leon-Saval, J. Blandhawthorn, R. Delbue, P. Pupalaikis, A. Sureka, Y. Sun, L. Gruner-Niewsen, R. V. Jensen, and R. Lingel, Jr., "12 x 12 MIMO transmission over 130-km few-mode fiber," *Frontiers in Optics* (2012).

12. R. Ryf, N. K. Fontaine, and R.-J. Essiambre, "Spot-based mode couplers for mode-multiplexed transmission in few-mode fiber," IEEE Photon. Technol. Lett. **24**(21), 1973–1976 (2012).
13. W. V. Sorin, B. Y. Kim, and H. J. Shaw, "Highly selective evanescent modal filter for two-mode optical fibers," Opt. Lett. **11**(9), 581–583 (1986).
14. K. Y. Song, I. K. Hwang, S. H. Yun, and B. Y. Kim, "High performance fused-type mode-selective coupler using elliptical core two-mode fiber at 1550nm," IEEE Photon. Technol. Lett. **14**(4), 501–503 (2002).
15. N. Riesen and J. D. Love, "Weakly-guiding mode-selective fiber couplers," IEEE J. Quantum Electron. **48**(7), 941–945 (2012).
16. K. J. Park, K. Y. Song, Y. K. Kim, and B. Y. Kim, "All-Fiber Mode Division Multiplexer optimized for C-band," *Optical Fiber Communication Conference (OFC)* 2014, M3K.2 (2014).
17. J. D. Love and N. Riesen, "Mode-selective couplers for few-mode optical fiber networks," Opt. Lett. **37**(19), 3990–3992 (2012).

1. Introduction

In order to keep up with ever-growing data traffic, optical transmission technologies like wavelength division multiplexing, polarization division multiplexing (PDM), and multi-level modulation formats have been implemented either based on coherent detection with digital signal processing or by direct detection in shorter distance application [1–3]. However, channel capacity in a single mode fiber is limited by Shannon's theory and fiber nonlinearity [4]. In order to overcome the capacity limitation, many researchers have concentrated on space division multiplexing (SDM) that opens a new dimension for optical transmission.

Spatial mode in a fiber can be used as a separate channel for SDM transmission. Several independent signals at the same wavelength can be transmitted in separate spatial modes of the optical fiber. In order to multiplex or demultiplex the signals to and from different modes, several kind of mode multiplexers have been proposed. Mode conversion can be achieved by phase plate or spatial light modulator where mode profile is modulated to match the higher-order LP modes [5–7]. Alternatively, a long period fiber grating (LPG) can convert a LP_{01} mode to LP_{11} mode when the grating period is equal to modal beat length. After mode conversion, free-space bulk optics or fiber couplers are used to multiplex different modes [8–10]. Spot-based mode multiplexers with the design of photonic lantern or 3-D waveguide can be used because the spots are described as a coherent superposition of all the modes supported by the fiber [11,12].

Mode selective couplers (MSCs) can provide unique functions useful for mode multiplexer [13–16]. They couple LP_{01} mode of a single mode fiber (SMF) and a higher-order mode of few mode fiber (FMF). They have intrinsically low loss and they are stable and reliable when they are in the form of a fused-type coupler. We have recently reported an all-fiber mode multiplexer based on the MSCs, which multiplexes LP_{01}, LP_{11}, LP_{21} and LP_{02} modes [16]. In this paper, we experimentally demonstrate the use of the proposed all-fiber mode multiplexer to simultaneously multiplex and demultiplex multiple modes. We also demonstrate mode division multiplexing (MDM) transmission over 15 km of four mode fiber when three decorrelated 120 Gb/s PDM-QPSK signals are multiplexed over three spatial modes. The received signals are recovered by off-line multiple-input multiple-output (MIMO) digital signal processing.

2. All-fiber mode multiplexer

The excitation and separation of individual modes in a few-mode fiber can be realized by the MSC [13–16]. The MSC is comprised of a FMF arm and a SMF arm, coupling the LP_{01} mode of the SMF to a specific higher-order mode of the FMF. The phase matching condition is given by $\beta_{01}^{SMF} = \beta_{lm}^{FMF}$ when β is propagation constant of the fiber and l, m are the mode numbers. The phase-matching condition can be satisfied by pre-pulling or etching portions of the FMF and the SMF [14,16].

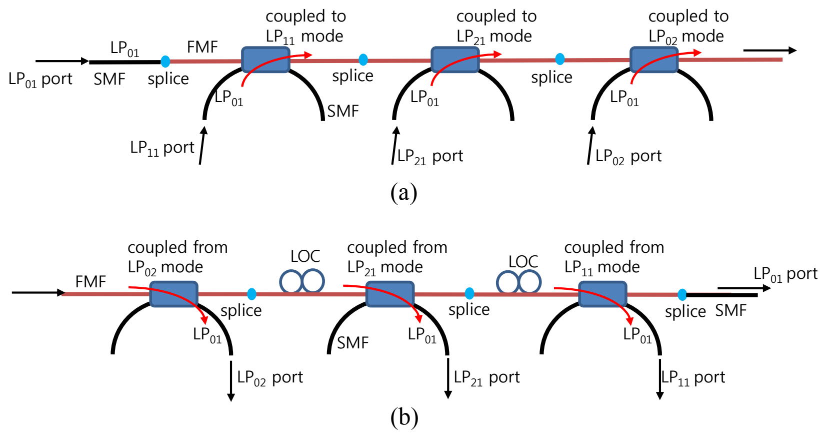

Fig. 1. (a) All-fiber mode multiplexer (b) all-fiber mode demultiplexer, SMF: single-mode fiber, FMF: few mode fiber, LOC: lobe orientation controller.

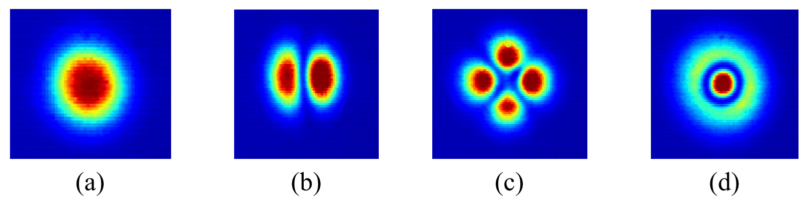

Fig. 2. Output mode intensity profiles of the mode multiplexer when signal power was launched to each input port of (a) LP_{01} mode (b) LP_{11} mode (c) LP_{21} mode (d) LP_{02} mode.

Figure 1(a) shows the mode multiplexer that is composed of three consecutive MSCs. Each MSC coupled the LP_{01} mode of the SMF to the LP_{11}, LP_{21}, or LP_{02} mode of the FMF, respectively. The MSCs were connected to each other using a commercial fusion splicer where we took care to minimize the crosstalk among the modes. The MSCs were realized in the form of polished-type coupler. The coupling efficiency was optimized for the operation in C-band wavelengths [16]. In the mode demultiplexer shown in Fig. 1(b), the order of consecutive MSCs was reversed compared to the mode multiplexer. Higher-order modes were demultiplexed first because the effective index of the higher-order modes was lower than that of the lower-order modes. The signal in higher-order modes will suffer considerable loss if the order of the MSCs is wrong. While the coupling efficiency of the MSC is dependent on the spatial lobe orientation of the asymmetric modes such as LP_{11} and LP_{21} [15], the lobe orientations are not maintained along the fiber. In order to adjust the lobe orientation, we used a typical fiber polarization controller with more turns of fiber loop as a lobe orientation controller (LOC) in the experiments. The LOC was used simply because it changed some amounts of the lobe orientation. It could not control the state of the modes completely. We monitored to minimize the bit error rates of the received signals while the LOCs were adjusted.

Mode intensity profile at the output of the mode multiplexer was monitored by an infrared camera to ensure the mode conversion and multiplexing. Figure 2 shows the measured mode intensity profiles when optical power was launched to each designated input port of the mode multiplexer. Since the mode profiles may change during the propagation, the output fiber was adjusted to show clear LP modes. The results confirm that the configuration of the consecutive MSCs shown in Fig. 1 works as a mode multiplexer. Optical losses of the mode multiplexer were measured to be 0.4 dB for LP_{01}, 0.9 dB for LP_{11}, 1.5 dB for LP_{21}, and 0.7 dB for LP_{02} mode excitation, respectively. The losses of the mode demultiplexer were measured to be 0.5 dB for LP_{01}, 1.9 dB for LP_{11}, 2.2 dB for LP_{21}, and 0.4 dB for LP_{02} mode, respectively. The loss was measured at the signal wavelength of 1543.5 nm.

The theoretical minimal loss of the MSCs approaches to 0 dB when the phase-matching condition is perfectly satisfied [15]. Phase-plate based mode multiplexer has the minimal loss of 5.5 dB because it uses beam splitters [6]. Spot-based mode multiplexer such as photonic lantern or 3-D waveguide scheme has the theoretical minimal loss of ~2dB [12]. All-fiber mode converter based mode multiplexer can have small loss, but it is not easily applied to multiplexing the higher-order modes [10]. It is obvious that the all-fiber mode multiplexer based on the MSCs has the lowest intrinsic loss compared with other approaches.

3. MDM transmission experiments

In this work, we focus on the demonstration of MDM transmission feasibility using the all-fiber mode multiplexer. The transmission measurement setup is shown in Fig. 3. Optical QPSK signal was generated by an IQ-modulator made of two parallel Mach-Zehnder modulators. IQ-modulator was driven by two independent 30-Gbaud De Brujin bit sequence of 2^{15}-length which are generated by two channel digital-to-analog converter (DAC). We used an external cavity laser (ECL) with 100 kHz linewidth operating at 1543.5 nm. Two signals with a delay of 382 ns were combined by polarization beam combiner (PBC) to generate 120 Gb/s PDM-QPSK signal. The amplified PDM-QPSK signal was combined with the output power of amplified spontaneous emission (ASE) source. Optical attenuator at the output of the ASE source was manipulated to adjust optical signal-to-noise ratio (OSNR). After an optical bandpass filter of 1.5 nm bandwidth, three copies of the signal with a relative delay of 0, 25, and 49 ns were used as the input signals of the mode multiplexer.

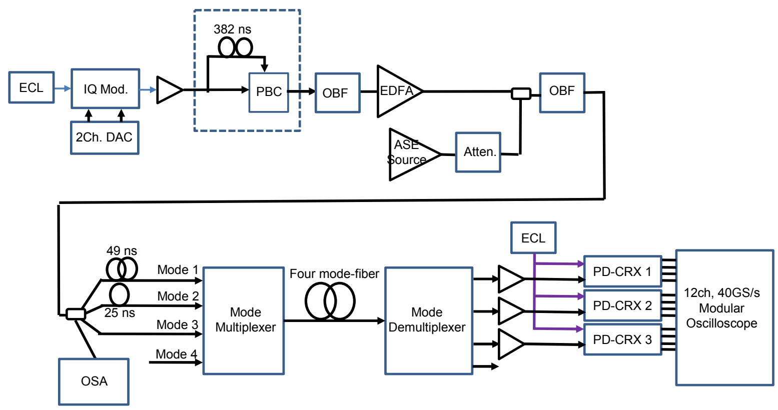

Fig. 3. Experimental setup. ECL: external cavity laser, IQ Mod.: IQ modulator, DAC: digital to analog converter, PBC: polarization beam combiner, OBF: optical bandpass filter, EDFA: Erbium doped fiber amplifier, ASE: amplified spontaneous emission, Atten.: optical attenuator, OSA: optical spectrum analyzer, PD-CRX: polarization diversity-coherent receiver.

The number of modes used in the experiments was limited by the number of available receiver channels. Three of the output signals of the mode demultiplexer were amplified by EDFAs separately and then they were fed into three polarization-diversity coherent receivers (PD-CRXs). The resulting twelve high-speed electrical signals were captured by a twelve-channel modular digital-storage oscilloscope. The sampling rate was 40 GS/s and the bandwidth was 20 GHz. A second ECL was used as a local oscillator (LO) in intradyne detection scheme. The LO frequency was adjusted to within 150 MHz of the frequency of the received signal.

The all-fiber mode multiplexer and the mode demultiplexer shown in Fig. 1 were used in the transmission experiments. The lengths of the output fiber ports of the mode demultiplexer were different from each other. Therefore, additional lengths of fiber were attached to the output ports in order to compensate the propagation delays to the receivers. All the twelve channels were synchronously acquired with the help of high-speed precise triggering of the oscilloscope. Small differences in the optical delays were carefully corrected after the data acquisition. Four million samples per channel were acquired in each measurement. They were resampled to have two samples per symbol, and then analyzed by MIMO digital signal processing with 6x6 equalizers. The equalizer coefficients were adapted by data-aided least mean squared (LMS) algorithm over the first 200000 symbols. Then, it was switched to decision-directed LMS mode [5,6]. Carrier phase was estimated by decision-directed phase-locked loop. Finally, bit error rate (BER) was evaluated over the last 2.6 million symbols per channel with decision-directed LMS algorithm.

Table 1. Measured Output Power with Back-to-back Configuration when the Output Port of the Mode Multiplexer is Directly Connected to the Input Port of the Mode demultiplexer[a]

Input port	Optical power at output port (dBm)			
	LP_{01}	LP_{11}	LP_{21}	LP_{02}
LP_{01}	−1.2	−15.1	−27.0	−37.7
LP_{11}	−14.0	−4.2	−14.4	−23.7
LP_{21}	−24.5	−11.2	−4.3	−23.4
LP_{02}	−39.7	−25.5	−22.1	−1.4

[a]Input signal power was 0 dBm.

The BER performance was verified first with back-to-back configuration where the output of the mode multiplexer was connected to the input of the mode demultiplexer directly by fusion splicing, temporarily disconnecting the transmission fiber. Table 1 shows the measured output power at the output ports of the mode demultiplexer when input signal power of 0 dBm was connected to each of the input ports of the mode multiplexer. The optical losses of the asymmetric modes of LP_{11} and LP_{21} modes in the configuration were dependent on the lobe orientation. The loss was varied by ~6 dB for LP_{11} mode and ~8 dB for LP_{21} mode when the lobe orientation was changed by adjusting the LOC. The losses of the configuration were 1.2, 4.2, 4.3, and 1.4 dB for LP_{01}, LP_{11}, LP_{21} and LP_{02} modes respectively when the losses of the LP_{11} mode and LP_{21} mode were adjusted to be minimal. The crosstalk to the different modes was quite large. For example, when the input power was connected to the LP_{01} port, the output power was −15.1 dBm at the LP_{11} port, −27.0 dBm at the LP_{21} port, and −37.7 dBm at the LP_{02} port of the mode demultiplexer. The crosstalk was considered to be generated at the MSCs and the fiber splicing points.

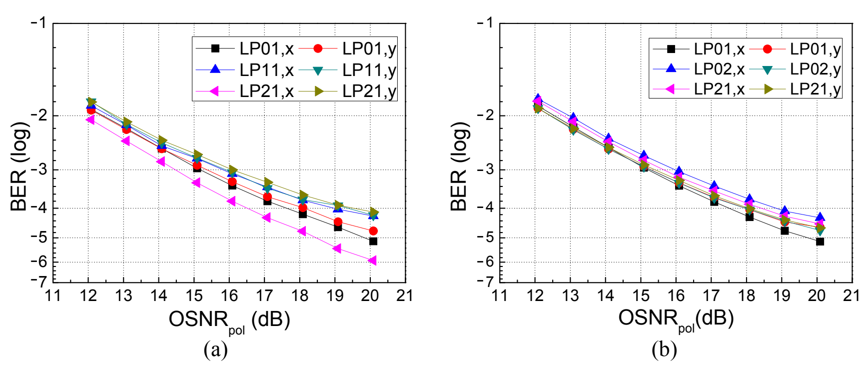

Fig. 4. BER curves for the back-to-back configuration. (a) LP_{01}, LP_{11}, LP_{21} modes are transmitted. (b) LP_{01}, LP_{21}, LP_{02} modes are transmitted. x and y are denoted for each polarization. BER: bit error rate, $OSNR_{pol}$: optical signal-to-noise ratio per polarization.

Figure 4 shows the BER curves for the back-to-back configuration with the various $OSNR_{pol}$ that is defined as the OSNR per polarization. 6x6 MIMO equalizers with a length of 128 taps were used to recover the signals. LP_{01}, LP_{11}, and LP_{21} modes were used in Fig. 4(a) and LP_{01}, LP_{21}, and LP_{02} modes were used in Fig. 4(b). The results show that the received signals were successfully recovered by 6x6 MIMO signal processing. The BERs of 10^{-3} was achieved with OSNR penalties of 1.5~3 dB in Fig. 4(a) and 2~3 dB in Fig. 4(b) compared to the theoretical limit.

At first, we used 3 km of four mode fiber that supports the propagation of LP_{01}, LP_{11}, LP_{21} and LP_{02} modes for the transmission experiments. The fiber has the same parameters as the one used in [11]. In order to measure modal differential group delay (MDGD) of the fiber, a short pulse of ~100 ps was launched into the fiber and the differences of the arrival time among the modes were measured. The MDGD was 1.55 ns for LP_{01}-LP_{11} modes, 3.46 ns for LP_{01}-LP_{21} modes, and 3.69 ns for LP_{01}-LP_{02} modes, where LP_{01} mode traveled faster than all other modes. The transmission fiber was spliced between the mode multiplexer and the mode demultiplexer as shown in Fig. 3.

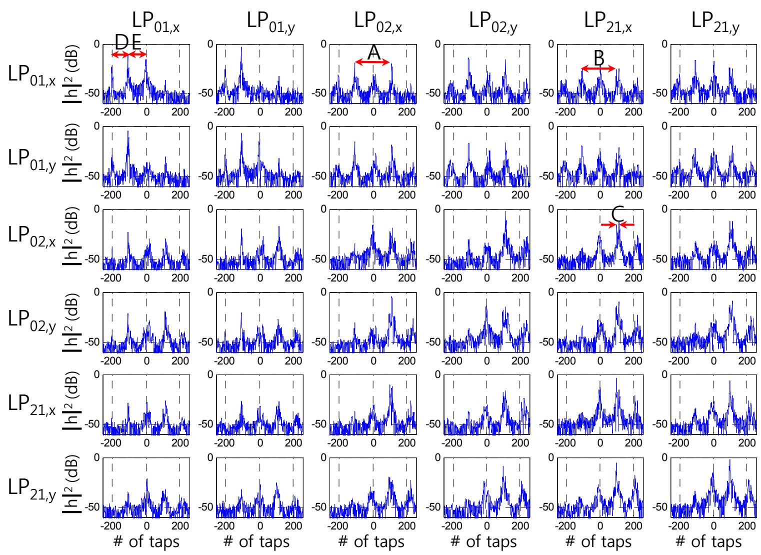

Fig. 5. Squared magnitude of the tap coefficients of 6x6 MIMO equalizers for 3km of four mode fiber.

Three copies of 120 Gb/s PDM-QPSK signal were connected to LP_{01}, LP_{21}, and LP_{02} ports of the mode multiplexer. Three output signals from LP_{01}, LP_{21}, and LP_{02} ports of the mode demultiplexer were measured. 6x6 MIMO equalizers with a length of 512 taps were used in off-line processing. The length of 512 taps corresponds to 8.53 ns in time, which is longer than the MDGD of the fiber. Figure 5 shows the squared magnitude of the tap coefficients of 6x6 MIMO equalizers, which were obtained after the convergence of decision-directed LMS algorithms. Some of the peaks shown in Fig. 5 can be explained by the MDGD of the fiber. Number of taps in the interval of A was 220, which corresponds to 3.67 ns. B and C corresponds to 3.43 ns and 0.24 ns, respectively. These are well matched to the measured MDGD among the modes of LP_{01}, LP_{21}, and LP_{02}. The intervals of D and E were measured to be 1.57 ns and 1.82 ns, respectively. D matches with the MDGD for LP_{01}-LP_{11} modes and E corresponds to the MDGD for LP_{11}-LP_{21} modes. However, they did not mean the response function of the fiber because the signal of LP_{11} mode was not received.

Figure 6 shows the BER performance vs $OSNR_{pol}$ plot when the three modes of 120 Gb/s PDM-QPSK signals were transmitted. We obtained the BER of less than 10^{-2} for all the modes, though limited number of modes were received. It demonstrated successful MDM transmission over 3 km of four mode fiber using the all-fiber mode multiplexer. The BER performance was much dependent on the state of the LOC that changed the lobe orientation of LP_{21} mode. The results shown in Fig. 6 were obtained when the BER was minimized by adjusting the LOC.

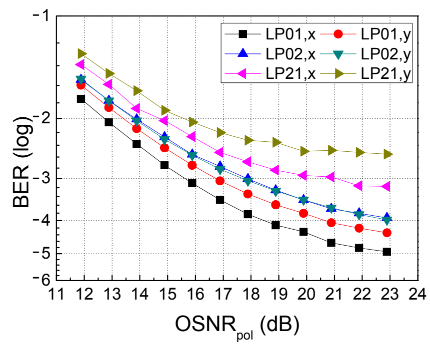

Fig. 6. BER curves after transmission over 3 km of four mode fiber. Three modes of LP_{01}, LP_{21}, and LP_{02} are transmitted. x and y are denoted for each polarization. BER: bit error rate, $OSNR_{pol}$: optical signal-to-noise ratio per polarization.

We replaced the transmission fiber to a 15 km long one to demonstrate the MDM transmission over longer distance. Fiber parameters were same as the 3 km of four mode fiber. However, the MDGD was measured to be 1.84 ns for LP_{01}-LP_{11} modes, 2.77 ns for LP_{01}-LP_{21} modes, and 2.78 ns for LP_{01}-LP_{02} modes, where LP_{01} mode traveled slower than all other modes.

Three modes of LP_{01}, LP_{21}, and LP_{02} were used for the transmission experiments. Figure 7 shows the squared magnitude of the tap coefficients of 6x6 MIMO equalizers for 15 km of four mode fiber. The peaks shown in Fig. 7 were interpreted as the same way as those shown in Fig. 5. A was 2.767 ns, B was 2.817 ns, and C was 0.05 ns. These were well matched with the MDGD among the modes of LP_{01}, LP_{21} and LP_{02}. D and E were 1.68 ns and 1.08 ns, which approximately matched with the MDGD for LP_{01}-LP_{11} modes and LP_{11}-LP_{21} modes, respectively.

Figure 8 shows the BER performance vs $OSNR_{pol}$ plot when three modes with 120 Gb/s PDM-QPSK signal are transmitted over 15 km of four mode fiber. The BER was degraded compared to the results shown in Fig. 6. However, we could obtain the BER of less than 10^{-2} for all the modes. Therefore, we conclude that mode division multiplexed transmission over 15 km of four mode fiber was successful when 120 Gb/s PDM-QPSK signals on three spatial modes were multiplexed by the all-fiber mode multiplexer.

The polarization dependent loss and the power imbalance in the transmitter side may result in the BER variation between the two polarization signals. The BER was also dependent on the state of the lobe orientation of LP_{21} mode, which probably caused the worst BER performance of the mode compared with the other modes as shown in Fig. 6 and Fig. 8. However, it was not obvious to tell the origin of the BER variation because the received signals were not recovered completely due to the limited number of received modes.

In order to improve the BER performance of the transmission, all the propagating modes of LP_{01}, LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b}, and LP_{02} should be received to form complete MIMO coherent system. In the case, all-fiber mode demultiplexer needs to separate the degenerate modes of LP_{11a}/LP_{11b} and LP_{21a}/LP_{21b} simultaneously. Three core MSC with one FMF and two SMFs is proposed for this purpose [17], but it has not been realized. Two consecutive MSCs with LP_{11} or LP_{21} mode coupling can be used when the mode evolution is controlled between the two MSCs. Although the limited number of received mode confined the BER

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performance, the results showed that the all-fiber mode multiplexer based on the MSCs can be used in MDM transmission over a length of the few mode fiber.

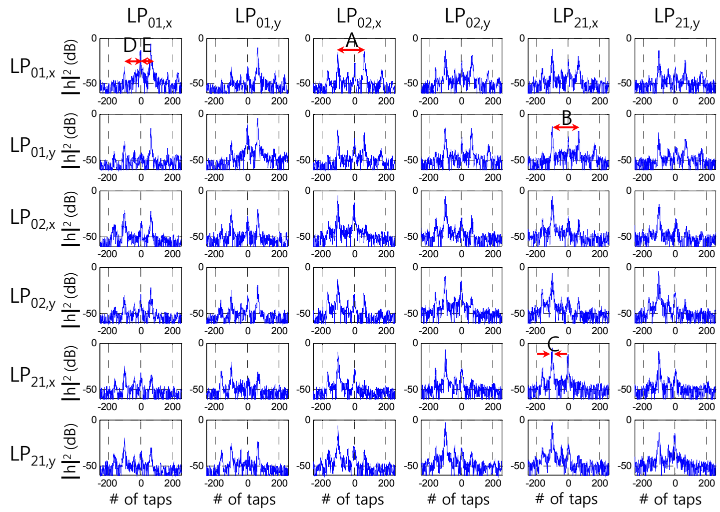

Fig. 7. Squared magnitude of the tap coefficients of 6x6 MIMO equalizers for 15 km of four mode fiber.

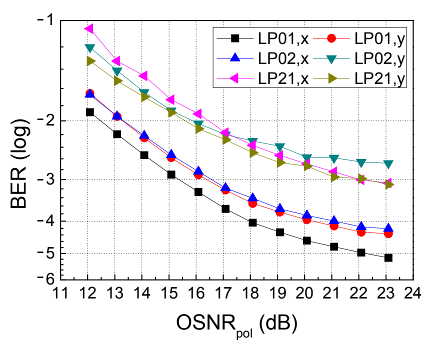

Fig. 8. BER curves after transmission over 15 km of four mode fiber. Three modes of LP_{01}, LP_{21}, and LP_{02} were transmitted. x and y are denoted for each polarization. BER: bit error rate, $OSNR_{pol}$: optical signal-to-noise ratio per polarization.

4. Conclusions

In this work, we report the all-fiber mode multiplexer consisting of multiple consecutive MSCs. We have successfully demonstrated MDM transmission of 120 Gb/s PDM-QPSK signals on the three spatial modes over 15 km of four mode fiber using the all-fiber mode multiplexer and demultiplexer. The received signals were recovered by 6x6 MIMO signal processing. The experiments prove that the all-fiber mode multiplexer can be used as an alternative for the MDM transmission. Methods to produce more efficient MSCs while suppressing the crosstalk are under investigation.

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