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All-fiber 6-mode multiplexers based on fiber mode selective couplers

SUN HYOK CHANG,[1,*] SANG-ROK MOON,[1] HAOSHUO CHEN,[2] ROLAND RYF,[2] NICOLAS K. FONTAINE,[2] KYUNG JUN PARK,[3] KWANGJOON KIM,[1] AND JOON KI LEE[1]

[1]*Optical Network Research Group, Electronics and Telecommunications Research Institute, 218 Gajeongno, Yuseonggu, Daejeon, 34129, South Korea*
[2]*Nokia Bell Labs, 791 Holmdel Rd, Holmdel, NJ, 07733, USA*
[3]*KS Photonics Inc., 45 Oncheonro, Yuseonggu, Daejeon, 34141, South Korea*
[*]*shchang@etri.re.kr*

Abstract: All-fiber 6-mode multiplexer composed of two consecutive LP_{11}-mode selective couplers (MSC), two LP_{21}-MSCs and an LP_{02}-MSC is fully characterized by wavelength-swept interferometer technique. The MSCs are fabricated by polished-type fiber couplers coupling LP_{01} mode of a single mode fiber into a higher-order mode of a few mode fiber. A pair of the mode multiplexers has minimum mode dependent loss of 4 dB and high mode group selectivity of over 15 dB. Mode division multiplexed transmission enabled by the all-fiber mode multiplexers is demonstrated over fiber spans of 117 km employing an in-line multi-mode optical amplifier. 6 modes of 120 Gb/s dual polarization quadrature phase shift keying signals combined with 30 wavelength channels are successfully transmitted.

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

References and links

1. D. J. Richardson, J. M. Fini, and L. E. Nelson, "Space-division multiplexing in optical fibres," Nat. Photonics **7**(5), 354–362 (2013).
2. 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 6×6 MIMO processing," J. Lightwave Technol. **30**(4), 521–531 (2012).
3. G. Labroille, B. Denolle, P. Jian, P. Genevaux, N. Treps, and J.-F. Morizur, "Efficient and mode selective spatial mode multiplexer based on multi-plane light conversion," Opt. Express **22**(13), 15599–15607 (2014).
4. B. Huang, N. K. Fontaine, R. Ryf, B. Guan, S. G. Leon-Saval, R. Shubochkin, Y. Sun, R. Lingle, Jr., and G. Li, "All-fiber mode-group-selective photonic lantern using graded-index multimode fibers," Opt. Express **23**(1), 224–234 (2015).
5. S. H. Chang, H. S. Chung, R. Ryf, N. K. Fontaine, C. Han, K. J. Park, K. Kim, J. C. Lee, J. H. Lee, B. Y. Kim, and Y. K. Kim, "Mode- and wavelength-division multiplexed transmission using all-fiber mode multiplexer based on mode selective couplers," Opt. Express **23**(6), 7164–7172 (2015).
6. K. J. Park, K. Y. Song, Y. K. Kim, J. H. Lee, and B. Y. Kim, "Broadband mode division multiplexer using all-fiber mode selective couplers," Opt. Express **24**(4), 3543–3549 (2016).
7. N. K. Fontaine, B. Huang, Z. S. Eznaveh, H. Chen, J. Cang, and B. Ercan, A. V.-Benitez, S. H. Chang, R. Ryf, A. Schulzgen, J. C. A. Zaharias, P. Sillard, C. Gonnet, J. E. A. Lopez, and R. A.-Correa, "Multi-mode optical fiber amplifier supporting over 10 spatial modes," *Optical Fiber Communication Conference (OFC),* OSA Technical Digest (online) (Optical Society of America, 2016), paper Th5A.4.
8. H. Chen, N. K. Fontaine, and R. Ryf, "Transfer matrix characterization of 10-mode mode-selective spatial multiplexers," in *Proceedings of IEEE Photonics Society Summer Topical Meeting* (2016), paper ME3.3.
9. J. D. Love and N. Riesen, "Mode-selective couplers for few-mode optical fiber networks," Opt. Lett. **37**(19), 3990–3992 (2012).
10. B. Huang, C. Xia, G. Matz, N. Bai, and G. Li, "Structured directional coupler pair for multiplexing of degenerate modes," *Optical Fiber Communication Conference (OFC),* OSA Technical Digest (online) (Optical Society of America, 2013), paper JW2A.25.
11. K. Igarashi, K. J. Park, D. Soma, Y. Wakayama, T. Tsuritani, and B. Y. Kim, "All-fiber-based selective mode multiplexer and demultiplexer for six-mode multiplexed signals," *Optical Fiber Communication Conference (OFC),* OSA Technical Digest (online) (Optical Society of America, 2016), paper W2A.38.
12. R. Ryf, H. Chen, and N. K. Fontaine, A. M. V.-Benitez, J. A.-Lopez, C. Jin, B. Huang, S. H. Chang, B. Ercan, M. B-Astruc, D. Molin, F. Achten, P. Sillard, R. A-Correa, "10-mode mode-multiplexed transmission with inline

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Optics EXPRESS

amplification," in *Proceedings of 42nd European Conference on Optical Communication* (ECOC, 2016), paper Tu.2.D.3.

13. R. Ryf, N. K. Fontaine, H. Chen, A. H. Gnauck, Y. Jung, Q. Kang, J. K. Sahu, S. U. Alam, D. J. Richardson, Y. Sun, and X. Jiang, L. G-Nielsen, R. V. Jensen, and R. Lingle, Jr. "72-Tb/s Transmission over 179-km all-fiber 6-mode span with two cladding pumped in-line amplifiers," in *Proceedings of 41st European Conference on Optical Communication* (ECOC, 2015), paper Tu.3.2.2.
14. H. Chen, R. Ryf, and N. K. Fontaine, A. M. V.-Benitez, J. A.-Lopez, C. Jin, B. Huang, M. B.-Astruc, D. Molin, F. Achten, P. Sillard, R. A.-Correa, "High spectral efficiency mode-multiplexed transmission over 87 km 10-mode fiber," *Optical Fiber Communication Conference (OFC),* OSA Technical Digest (online) (Optical Society of America, 2016), paper Th4C.2.

1. Introduction

In order to explore a new dimension to overcome the capacity limit of single-mode fiber (SMF) systems, space division multiplexing (SDM) technology has been intensively investigated by using the spatial modes of a multi-mode fiber (MMF) or the multiple cores in a multi-core fiber [1]. SDM in MMF, called as mode division multiplexing (MDM), can multiplex independent signals into the spatial modes acting as separate paths in the fiber.

Several kinds of mode multiplexers have been studied and demonstrated [2–6]. Beam combiners and mode converters using phase plates or spatial light modulators can excite the spatial modes directly [2]. It requires large bulk optics, and the insertion loss may increase with the number of modes. A multi-plane light conversion technique allows for efficient unitary transformation into desired set of output modes [3]. It can be built with reasonable loss and reduced size even with phase plates and lenses.

Mode multiplexers based on optical fiber can be more interesting approach due to intrinsic low loss. They can be basically compact, rugged, and directly connectable to transmission fiber. A photonic lantern adiabatically merges N SMF into a single MMF that supports N modes. The signal in each N cores will couple to an orthogonal combination of MMF modes when identical SMFs are used. The photonics lantern can have mode selectivity when the multiple fibers are different [4]. Another method is a fiber mode selective coupler (MSC) coupling LP_{01} mode of the SMF into higher order mode (HOM) of the MMF [5, 6]. Multiple modes are multiplexed by cascading several MSCs.

Recently, we proposed all-fiber mode multiplexers based on the MSCs. We succeeded to transmit signals with 3 modes of LP_{01} and two degenerate LP_{11} over 560 km of few mode fiber [5]. In this paper, we increased the number of modes to six and used the MSCs with improved performance of broad bandwidth. The all-fiber 6-mode multiplexers are fully characterized by wavelength swept interferometer (WSI) technique [7, 8]. We demonstrate 6-mode transmission combined with 30 wavelength channels over fiber spans with in-line multi-mode Erbium doped fiber amplifier (EDFA).

2. Characterization of all-fiber 6-mode multiplexers

The fabrication method of the fiber MSC was explained in [6]. In order to match the effective index of LP_{01} mode of the SMF and HOM of the few mode fiber (FMF), the SMF was tapered to tune the effective index of LP_{01} mode. The FMF with a Ge-doped step-index core was used and it guided six modes of LP_{01}, $LP_{11a/11b}$, $LP_{21a/21b}$, and LP_{02}. Each fiber was attached to quartz block and side part of the cladding was polished. The two blocks were mated to provide polished-type MSC. Typical coupling efficiency of the LP_{11}, LP_{21}, and LP_{02}-MSC was 80%, 70%, and 80% in C-band, respectively. The two polished blocks were affixed with epoxy, and any change in coupling efficiency has not been observed during the experiments.

All-fiber 6-mode multiplexer based on the MSCs is shown in Fig. 1. It employed two LP_{11}-MSCs, two LP_{21}-MSCs, and an LP_{02}-MSC. The mode multiplexer was made with single strand of the FMF to eliminate any splicing between the MSCs. Because two same LP_{11} or LP_{21}-MSC were cascaded, the mode excited by the first LP_{11} or LP_{21}-MSC should be controlled to avoid coupling out at the second LP_{11} or LP_{21}-MSC. For example, three-core MSC composed of one FMF and two SMF was proposed theoretically in order to multiplex or

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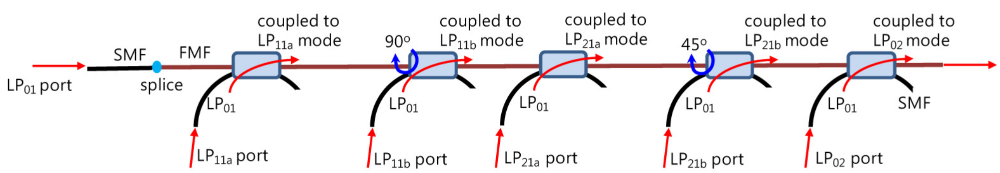
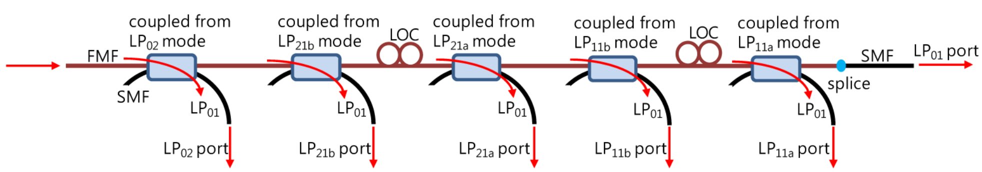
demultiplex degenerate modes efficiently [9, 10]. In other approach, an elliptic core FMF can be used for the MSC. The two LP_{11} or LP_{21} modes will have different effective index because they are not degenerate in elliptic core FMF. However, they have not been implemented experimentally.

Instead, we applied two different methods to multiplex or demultiplex the degenerate asymmetric modes. The multiplexing of LP_{11a} and LP_{11b} modes was achieved by the MSCs with vertical and parallel geometries of the SMF and the FMF. The geometry of second LP_{11}-MSC was rotated by 90° relatively to the first LP_{11}-MSC in Fig. 2(a). The geometry of the second LP_{21}-MSC was relatively rotated by 45° to the first LP_{21}-MSC [11]. Length between the two MSCs was ~5 cm to limit the change of the lobe orientation when the coupled mode at the first MSC propagated to the second MSCs. On the other hand, the lobe orientation controller (LOC) was used between the two LP_{11} or LP_{21}-MSCs in the demultiplexer of Fig. 2(b). The LOC was a typical fiber polarization controller that utilized stress-induced birefringence produced by wrapping the fiber around a few loops. The amount that the LOC could control was limited, but it was useful to find an optimized state of the mode [5].

A short length of SMF was directly spliced to the input FMF of the LP_{11}-MSC in Fig. 1(a). The LP_{01} mode of the FMF was excited by the input of LP_{01} port. All the other modes were excited by each input signal of $LP_{11a/11b}$, $LP_{21a/21b}$, and LP_{02} ports. The direction of the signal propagation was reversed in the demultiplexer of Fig. 1(b). The input signals are demultiplexed and coupled to the LP_{01} mode of the six output SMF ports.



(a)



(b)

Fig. 1. (a) All-fiber 6-mode multiplexer (b) all-fiber 6-mode demultiplexer, SMF: single-mode fiber, FMF: few-mode fiber, LOC: lobe orientation controller.

In order to fully measure the characteristics of the all-fiber 6-mode multiplexers, we used a wavelength-swept interferometer (WSI). The WSI technique was demonstrated successfully to characterize mode multiplexers and multi-mode optical amplifiers [7, 8]. It measured the amplitude and phase transfer matrix between each input and output pair. The mode-dependent loss (MDL) was analyzed by a singular value decomposition from the measured transfer matrix.

Figure 2(a) shows the set-up to characterize the MDL of the multi-mode components. The transfer matrix were measured by a scan of the WSI. Fiber delays at input and output ports were used to separate the impulse response of each input-to-output in time domain. The MDL of the system was calculated after measuring 12×12 transfer matrix with 2 polarizations and 6 spatial modes. At first, the mode multiplexer and the demultiplexer were directly spliced shown in Fig. 2(a). The fiber length between the mode multiplexer and the demultiplexer was ~4 m without any other splicing points. The LOCs in the demultiplexer were adjusted to minimize the overall MDL because the MDL was dependent on the state of the LOCs. Figure 2(d) shows that the MDL curve measured in the frequency range of 191~196 THz. It had a minimum of 4 dB around 193 THz and it grew up when the frequency was away from the minimum. The MDL curve was widely changed in accordance with the state of the LOCs. The MDL curve varied because the coupling efficiency of the MSC was dependent on the lobe orientation when the specific mode was demultiplexed. We found that the LP_{21} mode suffers relatively higher loss at the edge of the frequency range. It revealed that the LOC could not control the mode orientation well in wide bandwidth. On the other hand, the coupling efficiency of the MSC itself had a significantly broader bandwidth [6]. Nevertheless, the minimum MDL of 4 dB for a pair of the mode multiplexer was considered as good as the previously reported results of the other mode multiplexers [3, 4, 8].

In order to test the applicability of the mode multiplexers in transmission experiments, 1 m of 6-mode FMF different from the FMF used for the multiplexers was inserted between the mode multiplexer and the demultiplexer in Fig. 2(b). They were spliced each other by a commercial splicer. The 6-mode FMF was designed to have graded index (GI) core to reduce the modal dispersion [13]. It was used as transmission fiber in the experiment of Section 3. The all-fiber mode multiplexers were made with step-index core FMF. The MDL curve of Fig. 2(d) shows that the MDL is increased in the case of (b) by ~1.5 dB compared to the case of (a).

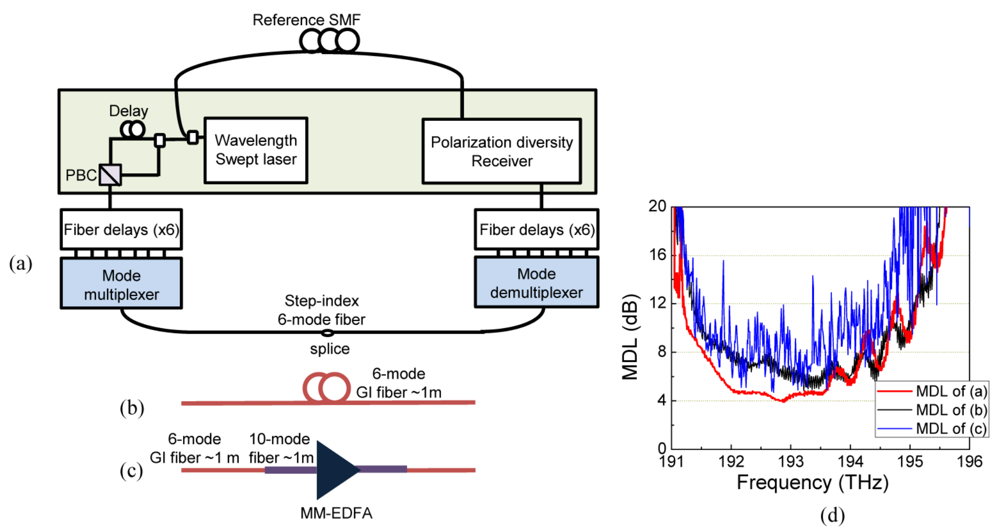


Fig. 2. Experimental set-up for measuring MDL. (a) wavelength-swept interferometer (WSI) measurement when the mode multiplexer is directly spliced to the mode demultiplexer (b) 6-mode GI fiber is connected between the mode multiplexer and the mode demultiplexer (c) The input and output of multi-mode EDFA is connected to 10-mode fiber and then 6-mode fiber. (d) Measured MDL results. PBC: polarization beam combiner, MM-EDFA: multi-mode Erbium doped fiber amplifier, GI: graded index core.

Multi-mode Erbium doped fiber amplifier (MM-EDFA) demonstrated in [7, 12] was spliced between the multiplexer and the demultiplexer as in Fig. 2(c). It was a cladding-pumped fiber amplifier that supported over 15 modes with small mode-dependent gain. The EDF had a core diameter of 24 μm and a cladding diameter of 74 μm. It was estimated to support ~26 spatial modes and the number of amplified modes were controlled by attaching the input and output fiber supporting limited number of modes. The input and output of the MM-EDFA were connected to 10-mode GI fiber and then to 6-mode GI fiber to help reducing mode-dependent splice loss. Figure 2(d) shows the MDL in the case of (c). The overall MDL of (c) was increased by ~2 dB compared to the case of (a). The fluctuations over frequency was due to higher order modes supported by the MM-EDFA. The MDL was considerable but acceptable for the transmission experiments.

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The 12×12 transfer matrix for 2 polarizations and 6 spatial modes was reduced to a 6×6 matrix by summing two polarizations for each input and output pair in order to analyze mode selectivity. Figure 3 shows the intensity of the 6×6 matrix at 193 THz where a darker color represented the higher intensity. Figure 3(a) shows the case of Fig. 2(a) for a pair of the mode multiplexer. It was observed that the multiplexers were mode-group selective. We define the mode group selectivity as the total intensity ratio between the excited mode group and the other modes with small inter-mode group crosstalk. Figure 4 shows the mode group selectivity calculated with the matrix of Fig. 3(a). It was over 15 dB in all the mode group that confirms the high mode group selectivity of the all-fiber mode multiplexer. Figure 3(b) and 3(c) shows the transfer matrix of the case of Figs. 2(b) and 2(c), respectively. It showed that the modes were gradually mixed by connecting 6-mode GI fiber and the MM-EDFA. They were almost fully scrambled after propagating the MM-EDFA.

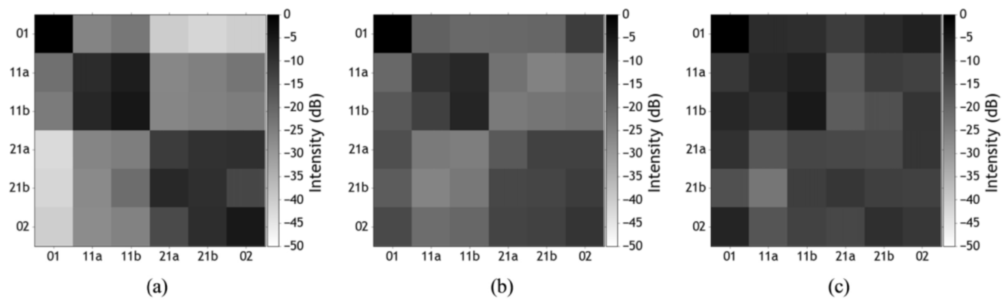

Fig. 3. Measured 6×6 transfer matrix at 193 THz. (a) in the case of Fig. 2(a). (b) in the case of Fig. 2(b). (c) in the case of Fig. 2(c).

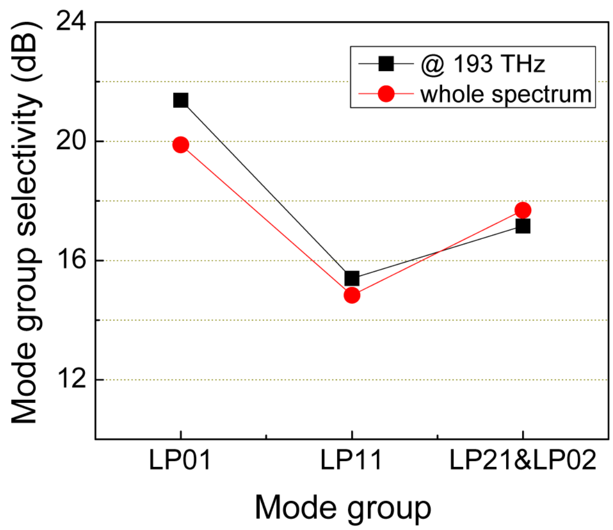

Fig. 4. Mode group selectivity defined as the total intensity ratio between the excited mode group and the other modes.

3. MDM Transmission Experiment

Figure 5 shows the experimental set-up for the MDM transmission using the all-fiber 6-mode multiplexers. Thirty wavelength channels with a 100 GHz spacing in C-band (1534.25-1557.36 nm) were generated by distributed feedback lasers (DFBs). We used a tunable laser diode (TLD) with a linewidth of 100 kHz for the channel under test. Wavelength selective switch (WSS) was used to equalize the optical power of all wavelength channels and divide

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into odd and even channels. Each group of channels was amplified by EDFA and then directed to IQ-modulator. Both of IQ-modulator were driven by independent 30 Gbaud De Bruijn bit sequences of 2^{16}-length generated by 60 GSamples/s digital-to-analog converters (DAC). The output signals of the IQ-modulators were combined by a fiber coupler. The signals entered to polarization division multiplexing stage where two polarization tributaries are delayed by 382 nsec. The resulting 120 Gb/s dual polarization quadrature phase shift keying (DP-QPSK) signal was further split into six copies with relative delays of 0, 50, 100, 150, 200, and 250 nsec. The six decorrelated signals were connected to the inputs of the all-fiber 6-mode multiplexer.

6-mode multiplexed signals were fed into a circulating loop. In order to transmit the signals over multi-turns of the loop, acousto-optic switch (AOS) was used to switch the signals. Bulk optic components of AOS, lenses, and beam splitter (BS) were aligned to support multiple modes propagation. All the four ports of the loop were pig-tailed with 15-mode (9-LP modes) GI fiber. They were spliced to ~1 m of 10-mode (6-LP modes) GI fiber and then ~1 m of 6-mode GI fiber to limit the number of modes for the transmission. It was better to reduce the mode dependent splice loss than when the 15-mode fiber ports were directly spliced to 6-mode fiber. Splicing may result in high MDL when different fibers were connected. The 15-mode GI fiber and the 10-mode GI fiber were designed to have lower modal differential group delay (MDGD). More detailed characteristics were given in [14].

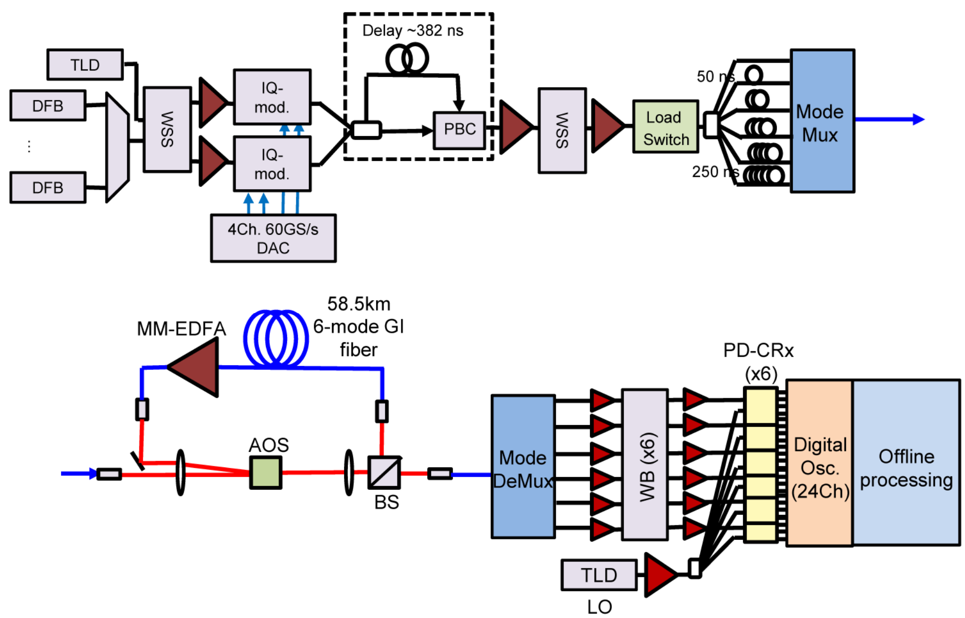

Fig. 5. Experimental set-up. TLD: tunable laser diode, DFB: distributed feedback laser, WSS: wavelength selective switch, IQ-Mod.: IQ modulator, DAC: digital to analog converter, PBC: polarization beam combiner, Mux: multiplexer, DeMux: demultiplexer, MM-EDFA: multi-mode Erbium doped fiber amplifier, AOS: acousto-optic switch, WB: wavelength blocker, FMF: few-mode fiber, PD-CRX: polarization diversity-coherent receiver, LO: local oscillator, OSC.: oscilloscope.

We performed transmission over a link of 58.5 km 6-mode GI fiber followed by the MM-EDFA. The fiber span was composed of four spools with different MDGD so that the total MDGD of the span was fully compensated. The MM-EDFA tested in Fig. 2(c) was used as an in-line amplifier to compensate 19.5 dB loss of the fiber and the other optical components in the loop. The signals were directed out by a beam splitter (BS) and then demultiplexed by the all-fiber 6-mode demultiplexer. Wavelength channel under test was filtered by wavelength blocker (WB) and then amplified. Six polarization diversity coherent receivers (PD-CRx) were used to detect the received signals. Twenty four electrical signal waveforms in a time interval of 100 μsec were simultaneously captured by a modular digital oscilloscope operating at a sampling rate of 40 GS/s and a bandwidth of 20 GHz.

The captured waveforms were processed offline using a 12×12 frequency domain equalizer with T/2-spaced taps. Data-aided least mean squares (LMS) algorithm using a known signal sequence was used to adapt the equalizer coefficients. The convergence step size of the LMS algorithm was small to provide low bit error rate (BER) so that the captured signals were repeatedly used to obtain converged equalizer coefficients. Decision-directed carrier recovery was used. Then, it was switched to decision-directed LMS mode to measure the BER. The BER was evaluated over 2.5 million symbols.

Figure 6 shows the BER curves as a function of the wavelength channels measured after two turns of the circulating loop. The BERs were averaged over 6 modes of 120 Gb/s DP-QPSK signals. The BERs of all the wavelength channels were under the limit of the state-of-the-art soft-decision forward error correction (SD-FEC). Because the BER of each mode was much different, the total BER was limited by the BER of LP_{21} mode signals. On the other hand, the BERs of LP_{01} mode were smaller than 2×10^{-5} in all the wavelengths. Lower MDL of the transmission link will be needed for longer distance transmission.

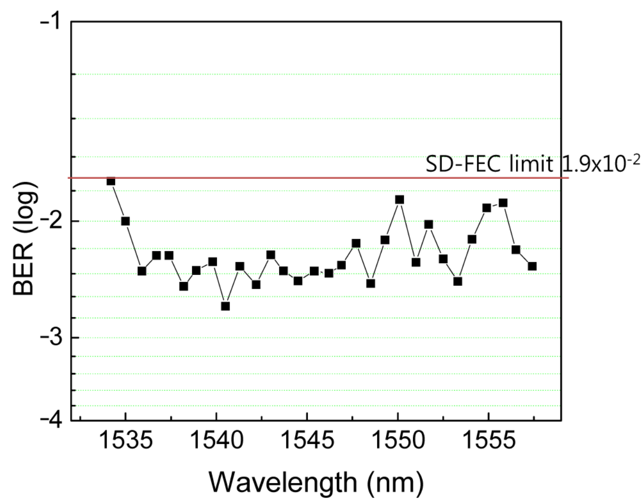

Fig. 6. Measured BER by obtaining over 6 modes of 120 Gb/s DP-QPSK signals after 2 turns of the circulating loop. BER: bit error rate, SD-FEC: soft decision-forward error correction.

4. Conclusions

The all-fiber 6-mode multiplexer composed of two LP_{11}-MSCs, two LP_{21}-MSCs, and one LP_{02}-MSC was characterized by the WSI technique. We measured that a pair of the multiplexer and the demultiplexer had the minimum MDL of 4 dB and the mode group selectivity of over 15 dB. In the MDM transmission using the all-fiber 6-mode multiplexers, we successfully demonstrated that 6 spatial modes of 120 Gb/s DP-QPSK signals combined with 30 wavelength channels were transmitted over two spans of 58.5 km fiber. These results show that the all-fiber mode multiplexer based on the MSCs is applicable to MDM transmission over long length of fiber. It can be expected that performance of the all-fiber mode multiplexer will be improved by providing efficient multiplexing of degenerate asymmetric modes.

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