DSP-Free IM/DD MDM Optical Interconnection Based on Side-polished Degenerate-mode-selective fiber Couplers

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Abstract: Low-insertion-loss degenerate-mode-selective fiber couplers for mode demultiplexing are designed and fabricated with side-polishing and mating process, based on which stable 5-LP-mode DSP-free IM/DD MDM optical interconnection over 10 km weakly-coupled FMF are experimentally demonstrated. © 2022 The Author(s)

1. Introduction

Mode division multiplexing (MDM) transmission technique based on few-mode fibers (FMF) has attracted great attention as a promising approach to enhance the capacity of optical fiber communication systems especially for short-reach optical interconnection [1,2]. Weakly-coupled transmission scheme by suppressing the modal crosstalk of the FMFs and mode multiplexer/demultiplexer (MUX/DEMUX) as much as possible are welcomed, in which each linearly-polarized (LP) mode can be considered as independent spatial channel to avoid inter-mode multiple-input-multiple-output digital signal processing (MIMO-DSP). However, because degenerate LP_{mna} and LP_{mnb} ($m \geq 1$, $n \geq 1$) modes in a circular-core FMF may experience random coupling during fiber transmission due to imperfect fiber fabrication and external perturbations, each pair of degenerate modes should be considered as a whole channel, which is not compatible with conventional single-mode intensity-modulation/direct-detection (IM/DD) optical transceivers. Recently, we have experimentally proposed a prototype system for DSP-free 4-LP-mode MDM transmission based on a weakly-coupled FMF [3], in which the intensity-modulation signal is excited into only one spatial orientation of a degenerate mode at the transmitter, while degenerate-mode-selective couplers (DMSC) for LP_{11} and LP_{21} modes are applied to demultiplex both spatial orientations simultaneously to realize DSP-free direct detection. However, previous DMSCs fabricated by fused-tapering process have quite-large cascading insertion loss especially for high-order LP modes, which prevents the practical implementation. In this paper, DMSCs for LP_{11}, LP_{21} and LP_{31} modes with low insertion loss and modal crosstalk for mode demultiplexing are designed and fabricated with side-polishing and mating process, based on which 5-LP-mode MDM transmission with OOK modulation and DSP-free direct detection over 10 km weakly-coupled FMF are experimentally demonstrated.

2. Design and fabrication of the mode DEMUX based on DMSCs

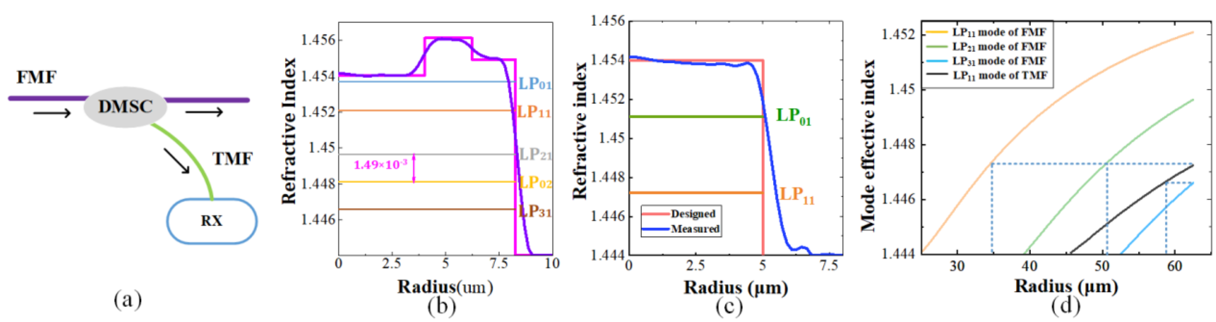

Fig. 1. (a) Structure of the DMSC. (b) Refractive index profile of the 6-LP-mode FMF. (c) Refractive index profile of the TMF. (d) n_{eff} of the LP_{11}/LP_{21}/LP_{31} modes of the FMF and the LP_{11} mode of the TMF versus the tapered radius.

The structure of a DMSC is shown in Fig. 1(a), which selectively demultiplexes both LP_{mna} and LP_{mnb} modes simultaneously into the LP_{11} modes of a TMF [4]. A mode DEMUX can be realized by cascading a set of regular mode-selective couplers (MSC) for non-degenerate modes and a set of DMSCs for degenerate modes. We adopt a weakly-coupled double-ring-core FMF as the transmission fiber [5], the index profile of which and n_{eff} of supported modes are depicted in Fig. 1(b). The FMF supports 6 LP modes with a min $|\Delta n_{eff}|$ up to 1.49×10^{-3} among all modes. In this work, we only use the first 5 LP modes for transmission since the highest-order LP_{12} mode have large transmission loss. The TMF for fabricating the DMSCs is designed with high index for phase matching, whose index profile is shown in Fig. 1(c). To achieve phase matching with different degenerate modes, the TMF or the

FMF should be pre-tapered with different radii. The tapering radii for different modes can be determined by numerical simulations, as depicted in Fig. 1(d). The crossing points among dashed lines with solid lines correspond to tapering radii for the fabrication of the DMSCs for all the modes. For the fabrication of LP_{11} and LP_{21} DMSCs, the radii of the FMF are tapered to 34 and 51 um, respectively, while the radius of the TMF is tapered to 57 um for the fabrication of the LP_{31} DMSC. The residue cladding thickness of the TMF or FMF is determined by oil drop experiment in the polishing process [6].

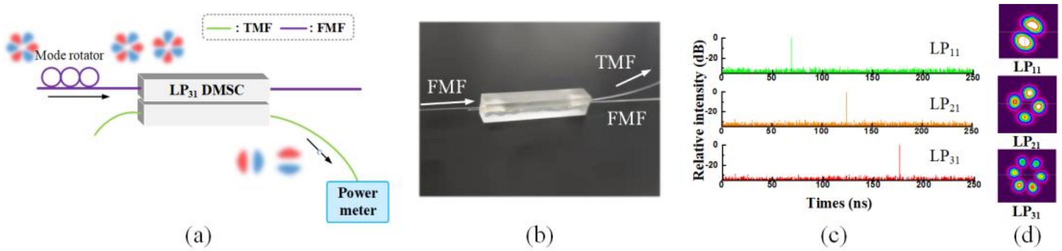

Fig. 2. (a) Scheme for mating DMSC. (b) The fabricated LP_{31} DMSC. (c) Impulse responses of the DMSCs combined with 10 km FMF. (d) Mode patterns after 10 km transmission.

For the mating process of DMSC fabrication, LP_{31} DMSC is taken as an example, as shown in Fig. 2(a). The target degenerate mode should be injected into the FMF and the output power should be detected from the output of the TMF. We use a designed fixture to adjust the position of two half couplers and twist the FMF by mode rotator to rotate the mode-field orientation of the input mode. When the output power gets stable and reaches the maximum, the coupler is fixed. The fabricated LP_{31} DMSC is shown in Fig. 2(b). The impulse responses of three DMSCs combined with 10 km double-ring-core FMF are measured and the results are shown in Fig. 2(c). LP_{11} mode is launched into each output port of the DMSCs one by one to selectively excite each LP mode in the FMF. The pulses arrive at different times in the photodetector due to different group delays. We can see 3 LP modes are exited with a high modal selectivity. The mode patterns after 10 km transmission are captured by a charge coupled device (CCD) camera (Newport, LBP2-IR2) and shown in Fig. 2(d).

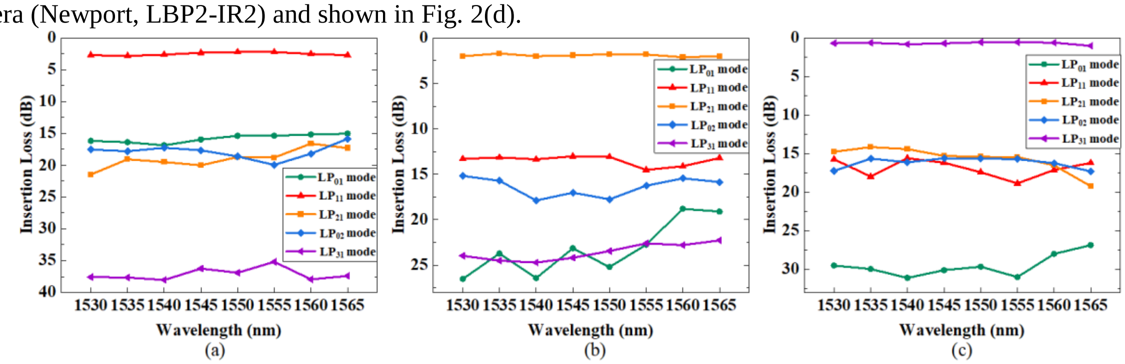

Fig. 3. (a) Insertion loss and modal crosstalk performance of the LP_{11} DMSC over the C-band. (b) Insertion loss and modal crosstalk performance of the LP_{21} DMSC over the C-band. (c) Insertion loss and modal crosstalk performance of the LP_{31} DMSC over the C-band.

To further test the modal selectivity and insertion loss of the fabricated DMSCs, we inject 0-dBm LP_{01}, LP_{21}, LP_{21}, LP_{02} and LP_{31} modes and measure the output power, respectively. The results are shown in Fig. 3. The worst modal crosstalk of all modes for the LP_{11}, LP_{21} and LP_{31} DMSCs are 15.02 dB, 13 dB and 14.1 dB, respectively over the C-band. And the insertion loss of the LP_{11}, LP_{21} and LP_{31} DMSCs is 2.2 dB, 1.77 dB and 0.54 dB respectively at 1550nm. To evaluate the power stability of the DMSCs, we inject 0-dBm randomly rotated modes over the C-band. The mode rotator is randomly adjusted 50 times at each wavelength and the power variation is less than 2.8 dB, 1.9 dB and 1 dB for the LP_{11}, LP_{21} and LP_{31} DMSCs respectively over the C-band.

Table 1. Modal crosstalk and insertion loss matrix of the MDM link at 1550 nm (Unit: dB)

	LP_{01} out	LP_{11} out	LP_{21} out	LP_{02} out	LP_{31} out
LP_{01} in	-5.05	-18.18	-20.2	-30.04	-27.6
LP_{11} in	-16.1	-7.7	-16.47	-24.26	-20.82
LP_{21} in	-34.31	-25.41	-7.2	-31.14	-22.06
LP_{02} in	-31.33	-23.69	-21.57	-6.25	-18.43
LP_{31} in	-40.01	-40.07	-27.42	-25.18	-7.15

5-LP-mode MUX is fabricated by the side-polishing and mating process as well. The modal crosstalk matrix of the entire MDM link (mode MUX and DEMUX and 10 km FMF) at 1550 nm is measured and the results are shown in Table 1. The modal crosstalk between any two LP modes can be suppressed to less than -16.47 dB and the insertion loss for any LP mode is lower than 7.7 dB.

4. DSP-Free IM/DD MDM Transmission

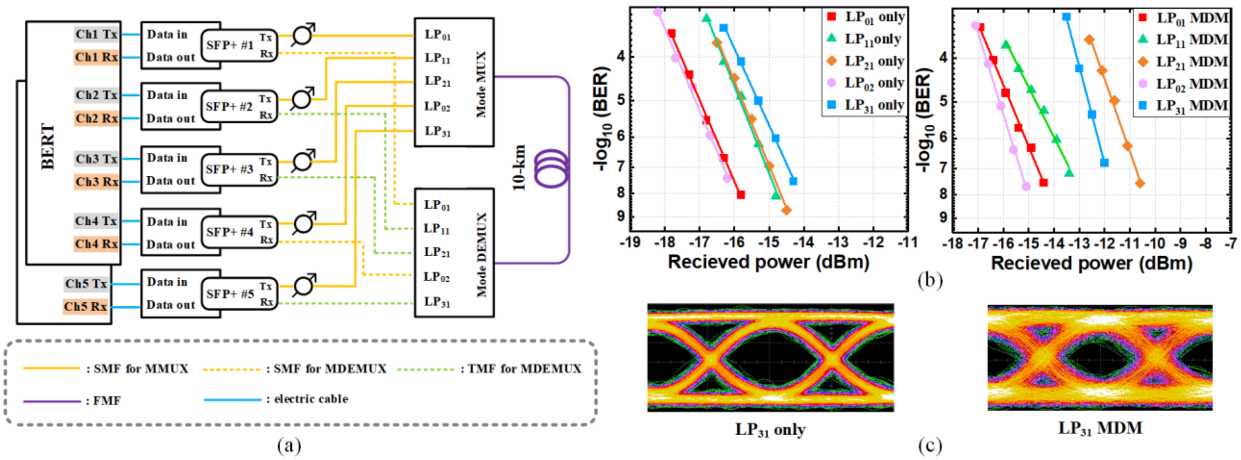

Fig. 4. (a) Experimental setup of the 5-LP-mode MDM transmission. (b) Measured BER curves one-by-one transmission and MDM transmission over 10-km FMF. (c) LP_{31}-mode eye diagrams of one-by-one transmission and MDM transmission over 10-km FMF.

DSP-free 5×10 Gb/s MDM transmission over 10-km of weakly-coupled FMF is demonstrated with the experimental setup shown in Fig. 4(a). At the transmitter, two BERTs (Sinolink, BERT34N) generate five-channel 10 Gbps PRBS (2^7-1, 2^{11}-1, 2^{15}-1, 2^{23}-1, 2^{25}-1) electric signals simultaneously. The electric signals modulate the SFP + Tx by the SFP + driver boards. The output optical power of each SFP + Tx is about 0 dBm. Five single-mode variable optical attenuators (VOA, EXFO FVA 600) are utilized after each Tx to balance the optical power of each channel and enable the adjustment of detected power at the SFP + Rx. The detected signals by the SFP + Rx are sent back to the BERT for real-time BER calculation. The BER performance of one by one transmission and MDM transmission for each LP mode is then measured. The results are shown in Fig. 4(b). The worst penalty of the 5 LP modes in MDM transmission is less than 4 dB compared to only by one transmission. The receiver sensitivity penalty mainly comes from the modal crosstalk of the FMF transmission and mode MUX/DEMUX. Eye diagrams of LP_{31} mode only 10 km transmission and LP_{31} MDM 10 km transmission are shown in Fig. 4(c).

5. Conclusion

Low-insertion-loss DMSCs for mode multiplexing/demultiplexing are designed and fabricated with side-polishing processing. Modal selectivity and power stability of the DMSCs are experimentally verified. Based on these, we experimentally demonstrate a real-time 5×10 Gb/s MDM transmission over a 10 km weakly-coupled FMF using OOK modulation and DSP-free direct detection. These results illustrate that real-time transmission of more LP modes is feasible in short-reach applications. *This work was supported by NSFC (61771024, 61627814, 61690194, 61901009 and U20A20160), Projects Foundation of YOFC (SKLD2003), Postdoc. RFC (BX20200003, 2018M641086 and 2020M680236).*

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