# A Kind of Low-modal-crosstalk Mode DEMUX for Stable DSP-free IM/DD MDM Transmission

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**Abstract:** A low-modal-crosstalk 4-LP-mode demultiplexer with orthogonal combiner for degenerate mode reception is designed and fabricated by side-polishing processing, based on which DSP-free IM/DD MDM-WDM transmission over 20-km weakly-coupled FMF are experimentally demonstrated. 

## 1. Introduction

Mode division multiplexing (MDM) transmission technique utilizing linearly-polarized (LP) modes in few-mode fibers (FMFs) has attracted great attention as a promising approach to enhance the capacity of optical fiber communication systems [1-2]. For short-reach scenarios such as optical interconnection in datacenters and supercomputers, weakly-coupled transmission schemes by suppressing the modal crosstalk of the FMFs and mode multiplexers/demultiplexers (MMUX/MDEMUX) as much as possible are welcomed, in which each LP mode can be considered as independent spatial channel to avoid complex intermodal multiple-input-multiple-output (MIMO) digital signal processing (DSP) [3]. However, both degenerate $LP_{mn}$ ($m\geq1$, $n\geq1$) modes should be simultaneously demultiplexed by a MDEMUX to deal with the strong coupling between them during optical fiber transmission. Recently, we have proposed a DSP-free intensity-modulation/direct-detection (IM/DD) MDM transmission scheme based on degenerate-mode-selective couplers (DMSC) [4-5], in which both spatial orientations are demultiplexed simultaneously to the $LP_{11}$ mode of a two mode fiber (TMF) for detection. However, the presence of $LP_{01}$ mode in the TMF will lower the modal selectivity if the phase-matching condition is satisfied for multiple mode pairs at the same time. In this paper, a low-modal-crosstalk 4-LP-mode MDEMUX with orthogonal combiner for degenerate mode reception is designed and fabricated by side-polishing processing, based on which stable 4-LP-mode 4-wavelength DSP-free IM/DD MDM-WDM hybrid optical transmission over 20-km weakly-coupled FMF are experimentally demonstrated.

## 2. Design, fabrication and characteristics of the proposed MDEMUX

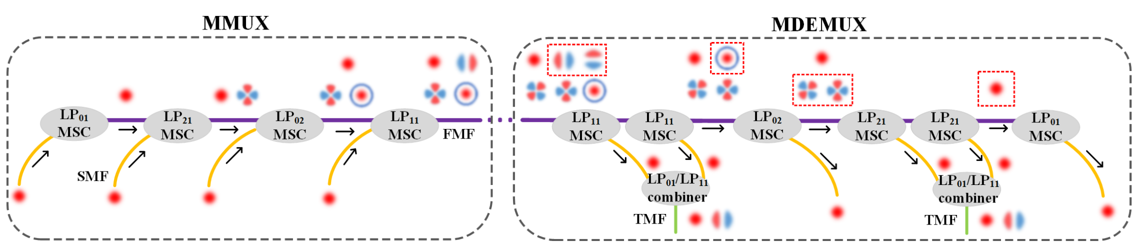


Fig. 1. Structure of the 4-LP-mode MMUX and MDEMUX.

The structure of the proposed 4-LP-mode MDEMUX is shown in Fig. 1, in which the structure of corresponding MMUX is also depicted. The MMUX consists of cascaded $LP_{01}$, $LP_{21}$, $LP_{02}$ and $LP_{11}$ mode-selective-couplers (MSC) orderly to selectively multiplex each LP modes. While in the MDEMUX, both spatial orientations in each degenerate LP mode need to be demultiplexed simultaneously. So two cascaded orthogonal MSCs are utilized to demultiplex the signals into the $LP_{01}$ mode of two SMFs, and then a $LP_{01}/LP_{11}$ combiner is utilized to multiplex the two signals into mutually orthogonal $LP_{01}$ and $LP_{11}$ modes of the TMF. The combined signals can be simultaneously detected by a spatially-coupled photodetector (PD) or a PD with few-mode/multimode pigtail fibers. For the other non-degenerate LP modes, regular MSCs are utilized for mode demultiplexing. So the 4-LP-mode MDEMUX consists of cascaded two $LP_{11}$ MSCs followed by an orthogonal combiner, a $LP_{02}$ MSC, two $LP_{21}$ MSCs followed by an orthogonal combiner, and a $LP_{01}$ MSC. It should be noted that the two branches before the orthogonal combiners should have the same length to avoid temporal broadening of signal. Compared to previous MDEMUX scheme

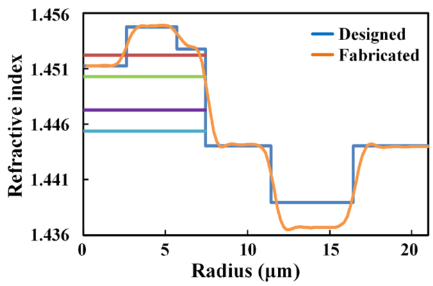

Fig. 2. Designed and fabricated index profile of the TRC-FMF.

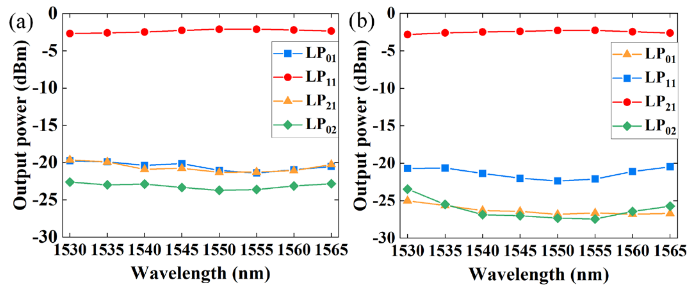

Fig. 3. Modal crosstalk and IL performance of (a) $LP_{11}$ and (b) $LP_{21}$ demultiplexers.

based on DMSCs, the proposed scheme can avoid the confliction of phase-matching condition among multiple mode pairs and can achieve lower modal crosstalk.

The transmission fiber is a weakly-coupled triple-ring-core (TRC) FMF, whose index profile and $n_{\mathrm{eff}}$ of supported modes are depicted in Fig. 2. It supports 4 LP modes with a normalized frequency $V$ of 4.8 and a refractive index difference between the fiber core and cladding ($\Delta n$) of 0.6%. The ring perturbations are applied to increase the $n_{\mathrm{eff}}$ spacing among all LP modes and a min $|\Delta n_{eff}|$ up to $1.89 \times 10^{-3}$ is achieved. We also utilized the TRC-FMF for the fabrication of MSCs in the MMUX and MDEMUX. The MSCs are fabricated with side-polishing and mating processing [6], in which two half couplers of FMF and SMF embedded in quartz blocks are firstly side-polished and then are mated together. At the polished surfaces, light can leak from one core and couple to the other one into a specific mode if phase-matching condition is satisfied.

We firstly test the modal selectivity and insertion loss (IL) of the fabricated $LP_{11}$ and $LP_{21}$ demultiplexers by injecting 0-dBm $LP_{01}$, $LP_{21}$, $LP_{21}$ and $LP_{02}$ modes and measure the output power, respectively. The results are shown in Fig. 3(a) and (b). The red symbols are for the IL while the symbols with other colors are for the modal crosstalk. It can be seen that the modal crosstalk of all modes are lower than -19.6 dB over the C-band. And the IL of the $LP_{11}$ and $LP_{21}$ demultiplexers are 2.1 dB and 2.3 dB respectively at 1550nm. Then the MSCs are cascaded orderly as shown in Fig. 1 to form the whole 4-LP-mode MMUX/MDEMUX and the modal crosstalk and IL matrix for back-to-back (B2B) case at 1550 nm are measured. The results are shown in Table 1. It can be seen that the worst modal crosstalk between any two LP modes is -18.51 dB ($LP_{01}$ to $LP_{11}$) and the IL are lower than 3.81 dB ($LP_{21}$). Fig. 4 depicts the photo of the 4-LP-mode MMUX and MDEMUX and output mode patterns of the MMUX at 1550 nm.

Table 1. Modal crosstalk and IL matrix for B2B case (Unit: dB)

| | $LP_{01}$ out | $LP_{11}$ out | $LP_{21}$ out | $LP_{02}$ out |
|---|---|---|---|---|
| $LP_{01}$ in | -1.82 | -22.23 | -25.24 | -28.88 |
| $LP_{11}$ in | -22.79 | -3.7 | -24.16 | -24.47 |
| $LP_{21}$ in | -31.1 | -22.43 | -3.81 | -27.52 |
| $LP_{02}$ in | -30.01 | -23.72 | -28.15 | -2.68 |

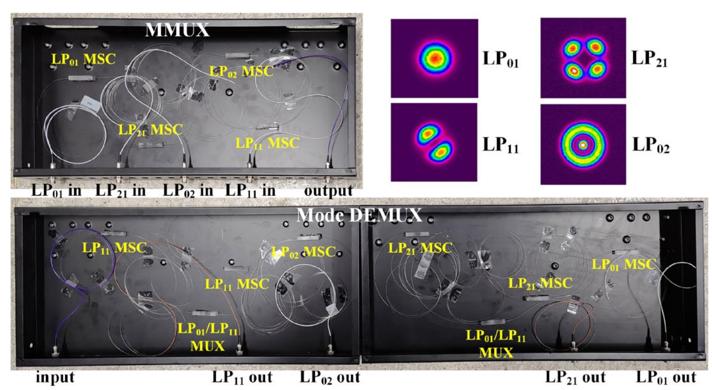

Fig. 4. The photo of the cascaded 4-LP-mode MMUX/MDEMUX and output mode patterns of the MMUX at 1550 nm.

## 3. Experimental setup and results for IM/DD MDM-WDM transmission

Stable DSP-free 4 modes × 4λ × 10 Gb/s MDM-WDM transmission over 20-km TRC-FMF is demonstrated with the experimental setup shown in Fig. 5(a). At the transmitter, two bit-error-ratio testers (BERT, Sinolink, BERT34N) generate eight-channel 10 Gbps pseudo-random binary sequences (PRBS, $2^7$-1, $2^9$-1, $2^{11}$-1, $2^{15}$-1 by each BERT) electric signals simultaneously. The electric signals modulate eight SFP+ transmitters (Tx) by the SFP+ driver boards. The central wavelengths $\lambda_1$~$\lambda_8$ of the eight SFP+ Txs are 1549.71, 1550.13, 1550.51, 1550.94, 1551.32, 1551.74, 1552.14, 1552.55 nm respectively for dense wavelength division multiplexing (DWDM). In our experiment, wavelength-interleaving (WI) scheme is adopted to suppress signal-to-crosstalk beating interference [7]. The odd-wavelength signals ($\lambda_1$, $\lambda_3$, $\lambda_5$, $\lambda_7$) with 100G channel spacing are multiplexed by a single-mode wavelength-division-multiplexer and then is divided by one 1×2 optical coupler (OC) to generate two paths WDM

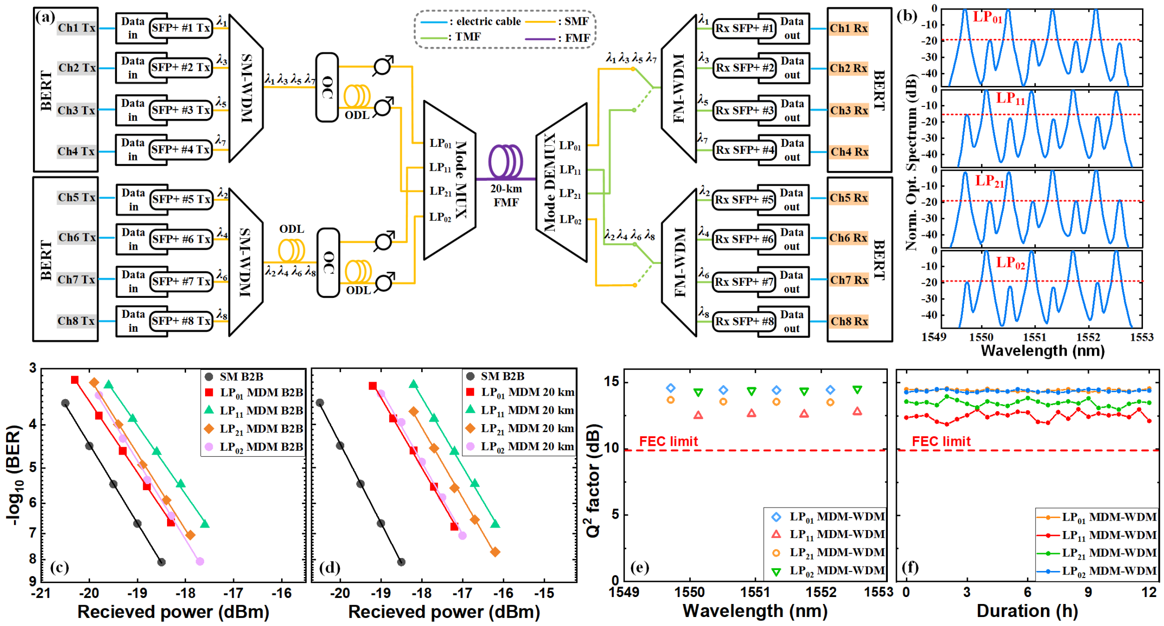


Fig. 5. (a) Experimental setup of the 4-LP-mode MDM-WDM transmission. (b) Received normalized optical spectra of the four LP modes. Measured BER curves of MDM in (c) B2B case and (d) 20-km transmission. (e) $Q^2$ factors of each mode and wavelength under MDM-WDM 20-km transmission. (f) $Q^2$ factors of each mode versus duration time.

signals. The even-wavelength signals ($\lambda_2$, $\lambda_4$, $\lambda_6$, $\lambda_8$) are multiplexed similarly and optical delay line (ODL) is utilized to de-correlate the signals. Four SM variable optical attenuators are followed to balance the optical power of each channel and enable the adjustment of detected power at the SFP+ receivers (Rx). Then the odd-wavelength WDM signals are multiplexed into $LP_{01}$ and $LP_{21}$ modes, while the even-wavelength WDM signals are multiplexed into $LP_{11}$ and $LP_{02}$ modes respectively by the MMUX. After 20-km transmission, each LP mode is demultiplexed by the MDEMUX and then two few-mode wavelength-division-multiplexers are utilized to demultiplex the odd-wavelength and even-wavelength signals respectively. Then the demultiplexed signals are detected by the SFP+ Rxs and BERTs for real-time BER calculation. Fig. 5(b) shows the received normalized optical spectra of the four LP modes at a received power of -17 dBm. It can be seen that the modal crosstalk of adjacent channels are all lower than -17.5 dB. The BER performance of MDM transmission in B2B and 20-km case for each LP mode at $\lambda_5$ ($LP_{01}$ and $LP_{21}$) and $\lambda_6$ ($LP_{11}$ and $LP_{02}$) are then measured. The results are shown in Fig. 5(c)-(d). We can find that the worst receiver sensitivity penalty of the 4 LP modes in MDM B2B case is less than 1.5 dB compared to SM B2B thanks to the low modal crosstalk of the mode MUX/DEMUX. Extra 1.5 dB receiver sensitivity penalty for the worst mode ($LP_{11}$) can be observed under 20-km transmission. This penalty mainly comes from dispersion and distributed modal crosstalk along transmission. $Q^2$ factors of each mode per wavelength under MDM-WDM 20-km transmission are then measured at a received power of -17 dBm and the results are depicted in Fig. 5(e). It can be seen that the $Q^2$ factors are all above the forward error correction (FEC) limit (9.8 dB at the BER of $1\times10^{-3}$). Finally, a 12-hours continuous transmission testing are carried out to evaluate the stability of the proposed system. The $Q^2$ factors of each LP mode at $\lambda_5$ or $\lambda_6$ every 30 minutes are measured and the results are shown in Fig. 5(f). We can find that the $Q^2$ factors are all above the FEC limit and the variation for each mode is less than 1.3 dB, which demonstrates the feasibility and stability of our system.

## 4. Conclusion

A low-modal-crosstalk all-fiber 4-LP-mode MDEMUX with optical power combiner for degenerate mode reception is designed and fabricated. Then stable real-time 4 modes × 4λ × 10 Gb/s MDM-WDM transmission over 20-km TRC-FMF using OOK modulation and direct detection is experimentally demonstrated. This work is beneficial to practical implementation of MDM technique in short-reach transmission applications. *This work was supported by the (NSFC, 62101099 and U20A20160), Pengcheng Zili Funding (PCL2021A04).*

## 5. References

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