Front. Optoelectron. 2019, 12(1): 31–40
https://doi.org/10.1007/s12200-018-0834-9

REVIEW ARTICLE

Weakly-coupled mode division multiplexing over conventional multi-mode fiber with intensity modulation and direct detection

Juhao LI (✉)[1], Zhongying WU[1], Dawei GE[1], Jinglong ZHU[1], Yu TIAN[1], Yichi ZHANG[2], Jinyi YU[1], Zhengbin LI[1], Zhangyuan CHEN[1], Yongqi HE[1]

1 State Key Laboratory of Advanced Optical Communication Systems and Networks, Peking University, Beijing 100871, China
2 Wuhan Research Institute of Posts and Telecommunications, Wuhan 430074, China

Abstract Multi-mode fiber (MMF) links are expected to greatly enhance capacity to cope with rapidly increasing data traffic in optical short-reach systems and networks. Recently, mode division multiplexing (MDM) over MMF has been proposed, in which different modes in MMF are utilized as spatial channels for data transmission. Strongly-coupled MDM techniques utilizing coherent detection and multiplex-input-multiplex-output (MIMO) digital signal processing (DSP) are complex and expensive for short-reach transmission. So the weakly-coupled approach by significantly suppressing mode coupling in the fiber and optical components has been proposed. In this way, the signals in each mode can be independently transmitted and received using conventional intensity modulation and direct detection (IM-DD). In this paper, we elaborate the key technologies to realize weakly-coupled MDM transmission over conventional MMF, including mode characteristic in MMF and weakly-coupled mode multiplexer/demultiplexer (MUX/DEMUX). We also present the up-to-date experimental results for weakly-coupled MDM transmission over conventional OM3 MMF. We show that weakly-coupled MDM scheme is promising for high-speed optical interconnections and bandwidth upgrade of already-deployed MMF links.

Keywords multi-mode fiber (MMF), mode division multiplexing (MDM), weak mode coupling, intensity modulation and direct detection (IM-DD)

Received May 17, 2018; accepted September 6, 2018

E-mail: juhao_li@pku.edu.cn

Invited Paper

1 Introduction

Multi-mode fiber (MMF) has been widely deployed in short-reach applications such as local area networks (LAN), indoor networks or datacenter networks (DCN) because of its low cost, easy installation and maintenance. In recent years, with the rapid increasing of internet traffic and the emergence of new applications such as clouding computing, big data or virtual reality, there is an urgent need to enhance the transmission capacity of the MMF links to satisfy bandwidth demand. However, the capacity of MMF links is limited by modal dispersion induced by the differential mode delay (DMD) [1]. According to IEEE 802.3 standards, these limitations correspond to a maximum reach of several hundreds of meters MMF at the data rate of 10-Gb/s [2,3].

In order to increase capacity of the MMF links, several approaches have been proposed in the past years, which can be divided into two categories. One is to mitigate the influence of modal dispersion to increase data rate per channel. For examples, electrical dispersion compensation (EDC) with different kinds of digital equalizers can be utilized to recover the deteriorated signal [4,5]. Mode-selective excitation with spatial light modulator (SLM) or phase plate can be used to launch signal into a specific mode of MMF [6,7]. In mode filtering approaches, single-mode fibers (SMF) or photonic crystal fibers (PCF) are used to filter out higher-order modes [8,9]. These methods have been verified at the wavelength of 850, 1310 and 1550 nm. The other category is to increase the number of transmission channels in MMF using wavelength division multiplexing (WDM). More than 100-Gb/s MMF transmission has been reported using S-band WDM or C-band

WDM [10,11].

Recently, mode division multiplexing (MDM) has been investigated to overcome the barrier of capacity limit of MMF [12,13], which can be considered as another promising approach to increase transmission channels. In this approach, spatial modes in MMF are exploited as different spatial channels and the capacity of MMF can be enhanced by a factor of the number of available modes. Moreover, the MDM technique can be easily combined with WDM to further increase transmission channels. For example, MDM-WDM transmission using 6 linearly polarized (LP) modes and 32 C-band WDM channels over 17-km OM3 MMF has been experimentally demonstrated, and coherent detection and multiple-input-multiple-output (MIMO) digital signal processing (DSP) are utilized to demultiplex MDM signals for each wavelength [14]. However, coherent detection and MIMO DSP are not preferred for optical short-reach transmission systems and networks based on MMF because of huge cost and complexity. A better approach is to significantly reduce modal-crosstalk induced by mode coupling, so that signals could be independently transmitted and received in different spatial modes. In this way, conventional intensity modulation and direct detection (IM-DD) scheme can be adopted.

In previous works, mode group division multiplexing (MGDM) technology has been proposed and demonstrated. For examples, 8 mode groups have been identified as one-by-one spatially transmission channels for the OM4 fiber [15]. 3×10-Gb/s transmission over 20-m large-core MMF has been demonstrated by utilizing mode-selective spatial filter (MSSF) [16]. However, due to the lack of mode selectivity, the number of multiplexed channels and transmission distance of MMF are both limited. $4\times$ 50-Gb/s bidirectional transmission over 4.4-km OM2 MMF with direct detection has been demonstrated, in which multi-plane light conversion (MPLC) technique is utilized to perform mode group multiplexing/demultiplexing [17]. But it should be noted that because the modal-crosstalk is very large from the MPLC component itself and its mode mismatching with MMF, bidirectional transmission has to be adopted to mitigate it and only 2 independent mode groups are supported for unidirectional transmission. Moreover, the transmission distance of MMF is no more than 5-km.

In this paper, we investigate weakly-coupled MDM transmission over MMF with simple IM-DD, in which both the fiber and mode multiplexer/demultiplexer (MUX/DEMUX) should achieve very low modal-crosstalk. Conventional MMFs such as OM3 support large number of spatial modes, but most of them have strong mode coupling and are not suitable for weakly-coupled transmission. It is important to investigate the characteristic of modes in MMF to clearly uncover how far we can go towards weakly-coupled MDM over conventional MMF. There are several approaches to realize mode multiplexing/demultiplexing. There are free-space bulk optical components, such as phase plate, SLM, are incompatible with optical fiber-based transmission link because of their bulkiness [15,18]. In the planar lightwave circuit (PLC) platform, multimode interference devices (MMI), asymmetric Y-junctions, T-shaped couplers and multi-pass cavity have been proposed [19–22]. The third method is to realize mode multiplexing/demultiplexing in the optical fiber platform. Unlike previous work such as mechanically-induced long-period fiber gratings or photonic lanterns [23–27], we focus on the suppression of modal-crosstalk. We utilize all-fiber fused mode-selective couplers (MSCs) to construct low modal-crosstalk MUX/DEMUX, which have the advantages of low loss, high mode conversion efficiency, good compactness and compatibility with current MMF systems [28–31]. Firstly, we validate the feasibility of weakly-coupled MDM transmission over OM3 MMF by utilizing cascaded MSCs. On this basis, by combining cascaded MSCs and wavelength interleaving technology, we further explore the feasibility of weakly-coupled MDM transmission over longer distance MMF.

The rest of the paper is structured as follows. In Section 2, we present the architecture of weakly-coupled MDM system with direct detection. In Section 3, we analyze the modes in OM3 MMF and select multiple modes for weakly-coupled MDM transmission. In Section 4, we elaborate the design and fabrication of all-fiber mode MUX/DEMUX. In Section 5, we present the up-to-data experimental demonstrations of weakly-coupled MDM transmission over conventional OM3 MMF. Finally, we conclude this paper in Section 6.

2 Architecture of weakly-coupled MDM system

The architecture of weakly-coupled MDM transmission over MMF is illustrated in Fig. 1. The signals are generated by n transmitters (Tx 1 – Tx n). Then the n paths optical signals are converted to n different independent modes and simultaneously multiplexed into MMF by the mode MUX. After MMF transmission, these optical signals of different independent modes are converted back to individual

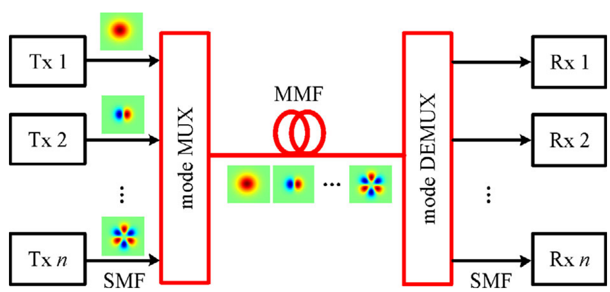


Fig. 1 Architecture of weakly-coupled MDM system

optical signals of the fundamental modes and demultiplexed into SMF by the mode DEMUX. After that these individual signals of the LP_{01} modes are distributed to different receivers (Rx 1 – Rx n). Owing to the low modal-crosstalk of the mode channels and mode MUX/DEMUX, the signal is individually detected without MIMO DSP.

3 Characterization of modes in OM3 MMF

The MMF we investigated is conventional graded-index Corning OM3 with parabolic refractive index profile. The fiber core and cladding diameters are 50 and 125 μm, respectively. The relative refractive index difference between the fiber core and cladding is 1%. The OM3 MMF supports more than 100 modes at the wavelength of 850 nm in S-band, as well as 36 modes at the wavelength of 1550 nm in C-band. Weakly-coupled MDM transmission over MMF could be realized in both wavebands. In this work, we focus on MDM in C-band, which has two remarkable advantages. On the one hand, the number of the supported modes in MMF in C-band is significantly reduced compared with S-band, thus using C-band for data transmission has better mode selectivity, easier management of modes and lower system design complexity, such as mode multiplexing/demultiplexing scheme [32,33]. On the other hand, WDM schemes in C-band are much mature than those in S-band, which will benefit the combination of MDM and WDM to further increase transmission channels.

Figure 2 shows the simulated effective refractive indices of modes in OM3 MMF as a function of fiber core radius at the wavelength of 1550 nm. We can see that some modes have close effective refractive index and strong mode coupling will occur if they are simultaneously excited for data transmission. According to the coupled mode theory, large effective refractive index difference (Δn_{eff}) between the propagation modes is one of ways to suppress modal-crosstalk induced by mode coupling [34]. To implement weakly-coupled MDM transmission over MMF using IM-DD, our scheme is to choose only one mode among a mode group consisting of multiple close modes and further establish a subset according to a threshold of (Δn_{eff}). It should be noted that the threshold maybe varied for different transmission requirements such as length of the transmission link. In this work, we choose empirical Δn_{eff} of 1×10^{-3} as the criteria to limit modal-crosstalk [35]. Some higher-order modes are not suitable for weakly-coupled transmission because they have very close effective refractive indices with adjacent modes and signal power will decrease rapidly during fiber transmission because of mode coupling. Besides, another aspect to suppress mode coupling is to reduce the field overlap between the selected modes. The mode coupling of the fiber increases as the transmission distance, which influences the number of available modes. In this paper, we select LP_{01}, LP_{11}, LP_{21} and LP_{31} modes as independent spatial channels. The Δn_{eff} is about 2.17×10^{-3} between LP_{01} and LP_{11} modes, 1.80×10^{-3} between LP_{11} and LP_{21} modes, 1.61×10^{-3} between LP_{21} and LP_{31} modes, all of which are larger than the minimum required Δn_{eff} of 1×10^{-3} to limit modal-crosstalk.

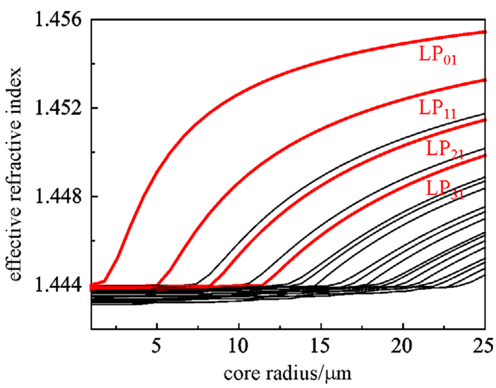


Fig. 2 Effective refractive indices of the spatial modes as a function of fiber core radius at the wavelength of 1550 nm. The red lines indicate the selected spatial modes as independent spatial channels

4 All-fiber mode MUX/DEMUX

Figure 3(a) gives the schematic diagram of all-fiber mode MUX that consists of four cascaded low modal-crosstalk

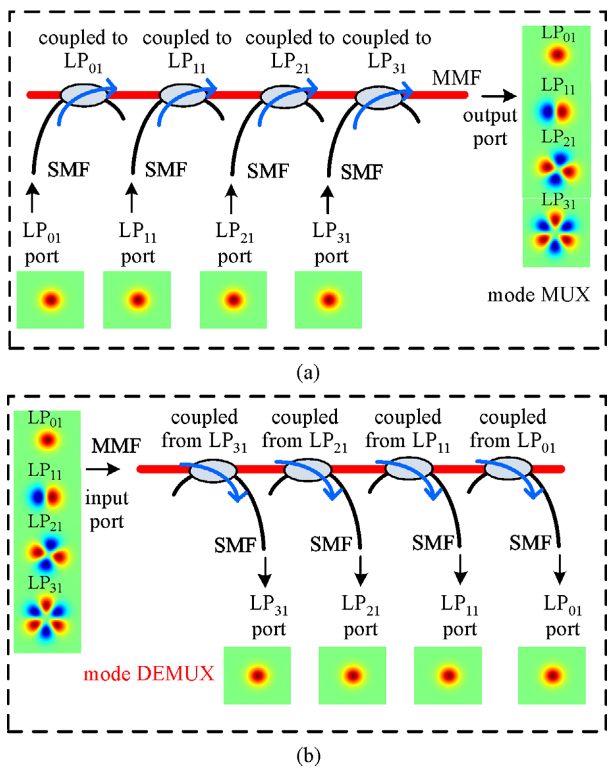


Fig. 3 Schematic diagrams of (a) all-fiber mode MUX and (b) all-fiber mode DEMUX

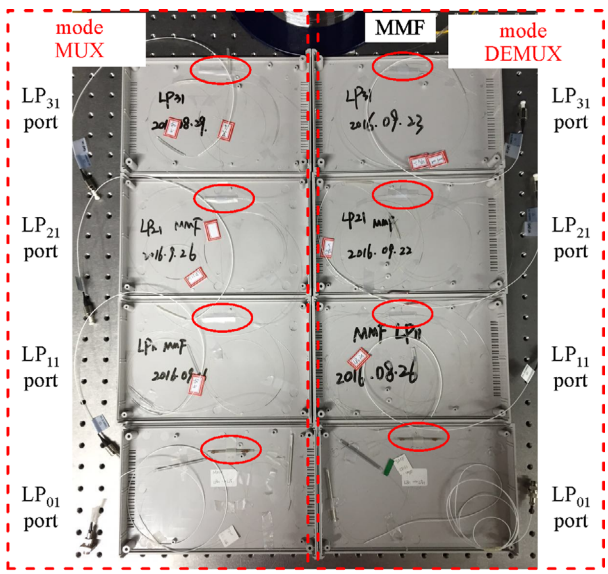
MSCs. The MSC is realized in the form of fused-type coupler, which is fabricated by heating and tapering SMF (Coring SMF-28) and MMF (Corning OM3 MMF) based on phase-matching. The phase-matching condition is given by [28–31]

$$\beta_{01}^{\mathrm{SMF}} = \beta_{01}^{\mathrm{MMF}},$$

where β represents the propagation constant of a specific spatial mode in fiber. The phase matching condition can be satisfied by pre-tapering the SMF or MMF based on the propagation constant of the fiber. At a specific coupler diameter, the launched fundamental mode in SMF arm can be converted into the selected modes in MMF arm over a broad wavelength range. It is worth noting that due to the larger size mismatching between the fiber core diameters of the SMF (8.2 μm) and MMF (50 μm), the SMF could not be directly connected to the MMF. The splicing of the SMF and MMF would result in strong mode coupling between LP_{01} mode in SMF and other higher-order modes in MMF, which cannot maintain pure LP_{01} mode from SMF to MMF. In order to excite pure LP_{01} mode in MMF, the MSC from LP_{01} mode of SMF arm to LP_{01} mode of MMF arm is also fabricated. Then the MMF arms of these MSCs are directly spliced by the commercial fusion splicer. In this way, the excited modes (LP_{01}, LP_{11}, LP_{21} and LP_{31}) in each MMF arm could be multiplexed together at the output port of mode MUX. Figure 3(b) shows the structure of all-fiber mode DEMUX, in which the order of cascaded MSCs is inverse to the mode MUX. Because the higher-order modes have lower effective refractive indices than lower-order modes, they are firstly demultiplexed in the mode DEMUX. If the order of the cascaded MSCs is changed, the signals carried by the higher-order modes may suffer large loss. The mode MUX/DEMUX could support more modes by cascading more MSCs.

The degenerated modes such as LP_{11a} and LP_{11b} are considered as a whole mode and only one degenerated mode LP_{11a} is excited to suppress modal-crosstalk. In the experiment, the relative angle of the connectors at the input port of mode DEMUX is manually adjusted to demultiplex the excited mode [36]. In fact, the modes in the same mode group have strong mode coupling after fiber transmission. Therefore, these modes should be simultaneously detected to avoid power loss at the receiver side. There are some possible approaches for the reception of mode group, such as adopting orthogonal demutiplexers and adding them after optical/electrical conversion or fabricating mode-group selective coupler, which converts each pair of high-order degenerate modes into the LP_{11} degenerate modes of a two-mode fiber (TMF), and simultaneously receives them utilizing a photodiode with TMF pigtail.

Figures 4(a) and 4(b) show the picture of fabricated 4-mode all-fiber mode MUX and mode DEMUX, respectively. The red circles in Figs. 4(a) and 4(b) show the MSCs. Figure 5 shows the mode patterns of the LP_{01}, LP_{11}, LP_{21} and LP_{31} modes at the output port of the mode MUX. We can see that signals in fundamental mode of SMF could be successfully converted to the selected spatial modes in MMF. We have also measured the modal-crosstalk of the fabricated mode MUX/DEMUX in back-to-back (BTB) configuration, in which the output port of mode MUX and input port of mode DEMUX are directly connected. We measure optical power at the output ports of mode DEMUX when the input signal of 0 dBm is launched to each of the input ports of the mode MUX, and the results are shown in Table 1. The diagonal elements are the insertion losses of a pair of mode MUX/DEMUX and the non diagonal elements are the modal-crosstalk. From Table 1, we can see that the insertion losses of LP_{01}, LP_{11}, LP_{21} and LP_{31} modes are 9.5, 17.3, 17.8 and 18.2 dB, respectively. The modal-crosstalk between the adjacent modes is less than −16 dB. Both the insertion loss and modal-crosstalk of the mode MUX/DEMUX can be reduced by precisely controlling the coupler cross-section geometry and optimizing fabricating parameters of the MSCs, such as pulling length or flame temperature.



(a) (b)

Fig. 4 Picture of the fabricated (a) mode MUX and (b) mode DEMUX. The red circles indicate the MSCs

Table 1 Output optical power at the output ports of mode DEMUX in BTB configuration

input port (0 dBm)	optical power at the output port/dBm			
	LP_{01}	LP_{11}	LP_{21}	LP_{31}
LP_{01}	−9.5	−36.7	−36.6	−38.3
LP_{11}	−27.9	−17.3	−33.2	−36.3
LP_{21}	−35.5	−33.2	−17.8	−34.6
LP_{31}	−39.2	−37.4	−35.2	−18.2

In a real MMF, the propagation constants of the modes are definitely different from the theoretical ones. There will be extra loss and modal-crosstalk in the mode MUX/DEMUX due to the mismatch of the MMFs. With the improvement of fiber fabricating technology, the propagation constants of the modes in real MMF are very close to the theoretical ones. The extra loss and modal-crosstalk will be further reduced. Moreover, the fabrication of MUXs and DEMUXs is similar to commercial single-mode optical coupler. Therefore, the MUXs have a good commercial application prospects.

5 Experimental setup and results

In this section, we present the up-to-date experimental results of weakly-coupled MDM transmission over conventional MMF. In weakly-coupled MDM system, modal-crosstalk in MMF increases as the transmission distance and it acts like receiver noise and will degrade the signal-to-noise ratio (SNR). The number of available mode channels varies with the transmission distance of MMF. For a short transmission distance of 500-m OM3 MMF, 10-Gb/s on-off-keying (OOK) signals in four modes (LP_{01}, LP_{11}, LP_{21} and LP_{31}) can be simultaneously transmitted and received. However, for a longer distance MMF transmission beyond 10 km, the smaller $\Delta n_{\rm eff}$ between LP_{21} and LP_{31} modes would result in larger modal-crosstalk and the SNR of LP_{31} mode will be rapidly degraded. Thus, only three low-order modes (LP_{01}, LP_{11} and LP_{21}) are excited for data transmission in Section 5.2.

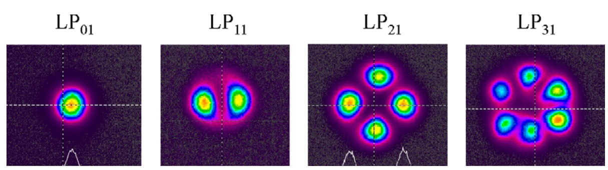


Fig. 5 Mode patterns at the output port of mode MUX when signal power is launched to each input port

5.1 4-mode MDM transmission over 500-m OM3 MMF

Figure 6 shows the experimental setup for 4-mode MDM transmission over 500-m conventional OM3 MMF. At the transmitter side, two distributed feedback lasers (DFB) have wavelength of 1550 nm. 10-Gb/s optical OOK signals are generated using two optical intensity modulators (IM). The IMs are driven by $2^{11}-1$ and $2^{15}-1$ pseudo-random binary sequences (PRBS), which are generated by two output ports of the pulse pattern generator (PPG). Two Erbium-doped fiber amplifiers (EDFA) are utilized to pre-amplify the two signals. Two 1×2 optical couplers (OC) are used to divide the two signals into four branches. Optical delay lines (ODL) with different length are used to de-correlate the signals. Variable optical attenuators (VOA) are utilized to adjust the optical power launched into the mode MUX. Then the four branches are converted into the LP_{01}, LP_{11}, LP_{21} and LP_{31} modes by the mode MUX and launched into the MMF. After 500-m OM3 MMF transmission, the MDM signals are converted into the fundamental mode of the SMFs by the mode DEMUX. At the receiver side, each signal is detected by a photo detector (PD) and the bit-error-rate (BER) is measured by a bit-error-rate tester (BERT). VOA and EDFA are utilized to adjust the optical power fed into the PD.

Figure 7(a) shows the BER curves of received 10-Gb/s OOK signals in the case of one-mode transmission over 500-m OM3 MMF. The BER curve for single-mode BTB is also depicted as reference, in which the output port of IM is connected to the input port of PD. Due to the limitation of our BERT, the BERs of the signals cannot be measured when they are lower than 10^{-9}. For the BER of 10^{-3}, it can be lower than 10^{-12} after forward error correction (FEC), which can satisfy the communication requirement. The BTB receiver sensitivity at the BER of 10^{-3} is about -32.2 dBm. The receiver sensitivities when only LP_{01}, LP_{11}, LP_{21} or LP_{31} modes is transmitted are about -32.0, -31.9, -31.7 and -31.6 dBm. The optical eye diagrams of the received 10-Gb/s OOK signals in the case of one-mode transmission are shown in Fig. 8(a). We can see that

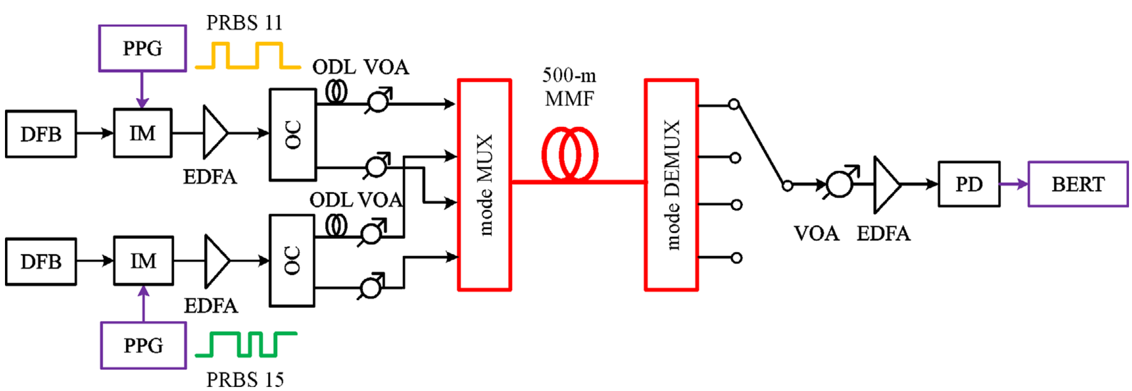


Fig. 6 Experimental setup for 4-mode MDM transmission over 500-m OM3 MMF

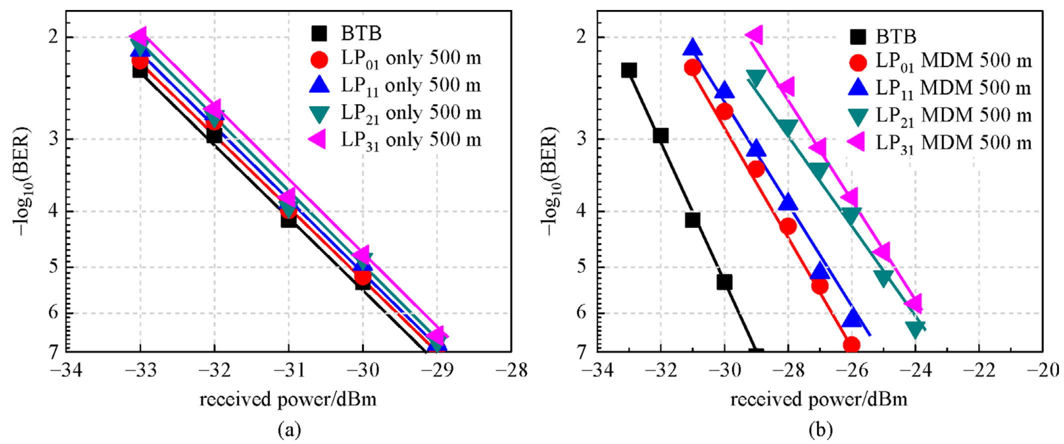


Fig. 7 BER curves of the received 10-Gb/s OOK signals for (a) one-mode and (b) 4-mode MDM transmission over 500-m OM3 MMF

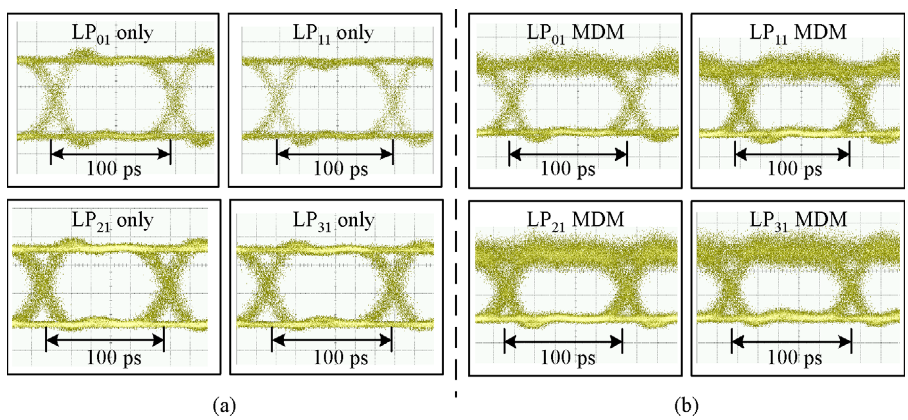


Fig. 8 Optical eye diagrams of the received 10-Gb/s OOK signals for (a) one-mode and (b) 4-mode MDM transmission over 500-m OM3 MMF

similar eye diagrams are obtained for these received 10-Gb/s OOK signals in each mode. Compared with the single-mode BTB transmission, we can see that the penalty of receiver sensitivity is less than 0.5 dB for all modes after 500-m OM3 MMF transmission. Figures 7(b) and 8(b) illustrate the BER curves and optical eye diagrams of received 10-Gb/s OOK signals after 4-mode MDM transmission over 500-m OM3 MMF, respectively. From the eye diagrams in Fig. 8, we can see that all the signals have clear open degree. Therefore, there is no error floor after 4-mode MDM transmission over 500-m MMF. The receiver sensitivities for the received 10-Gb/s OOK signals in LP_{01}, LP_{11}, LP_{21} and LP_{31} modes are about −29.8, −29.4, −28.0 and −27.4 dBm. Compared with BTB case, the 10-Gb/s OOK signals transmitted in LP_{01}, LP_{11}, LP_{21} and LP_{31} modes experience the receiver sensitivity penalties of 2.4, 2.8, 4.2 and 4.8 dB after 4-mode MDM transmission over 500-m OM3 MMF, respectively. For LP_{21} and LP_{31} modes transmission, the modal-crosstalk is larger than the lower-order modes (LP_{01} and LP_{11}), so the receiver sensitivity penalties for LP_{21} and LP_{31} mode is higher than for LP_{01} and LP_{11} modes after transmission. The penalty could be further reduced by optimizing the design and fabricating parameters of the mode MUX/DEMUX.

5.2 3-mode MDM-WDM transmission over 21-km OM3 MMF

Figure 9 illustrates the experimental setup for 3×4×10-Gb/s MDM-WDM transmission. At the transmitter side, two laser banks consisting of 4 DFB lasers and polarization maintaining optical couplers (PM-OC) are utilized to generate WDM optical carriers. 4×10-Gb/s WDM OOK signals are generated using the similar method in Section 5.1. One EDFA is utilized to pre-amplify the upper branch WDM signals. Then they are divided into two paths by one 1×2 OC. ODL is utilized to de-correlate the signals. The three branches are converted into the LP_{01}, LP_{11} and LP_{21} modes by mode MUX. The transmission link is composed of four MMF spans, with the length of 7, 5, 5 and 9 km, respectively. After MMF transmission, the MDM-WDM

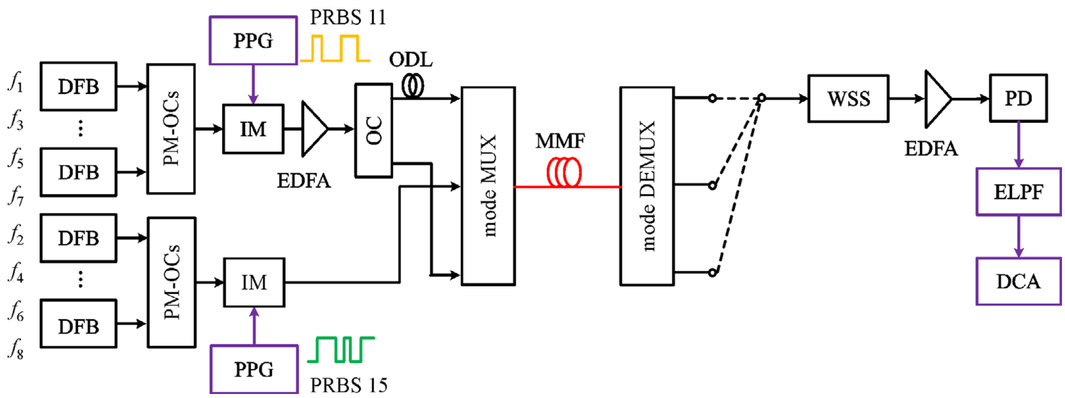


Fig. 9 Experimental setup for 3×4×10-Gb/s MDM-WDM transmission

signals are converted into the fundamental mode in SMFs by the mode DEMUX. At the receiver side, the wavelength channel under test is separated by a wavelength selective switch (WSS) with 100-GHz optical bandwidth and is detected by a PD. An electrical low-pass filter (ELPF) with 7.2-GHz electrical bandwidth is utilized to suppress signal-to-crosstalk beating interference (SCBI). The Q-factor and electrical eye diagram are measured by digital communication analyzer (Agilent infiniium DCA 86100A).

In our experiment, two transmission schemes are considered. For conventional MDM-WDM transmission, which is named as wavelength-aligned (WA) transmission, the wavelengths of f_1 (f_2), f_3 (f_4), f_5 (f_6) and f_7 (f_8) are tuned to 1548.71, 1549.51, 1550.31 and 1551.11 nm. For wavelength-interleaved (WI) transmission [37], the wavelengths of f_1, f_3, f_5 and f_7 keep unchanged, while the wavelengths of f_2, f_4, f_6 and f_8 are tuned to 1548.31, 1549.11, 1549.91 and 1550.71 nm, resulting a 0.4-nm wavelength shift compared with f_1, f_3, f_5 and f_7. Figure 10(a) shows the transmitted optical spectra in WA

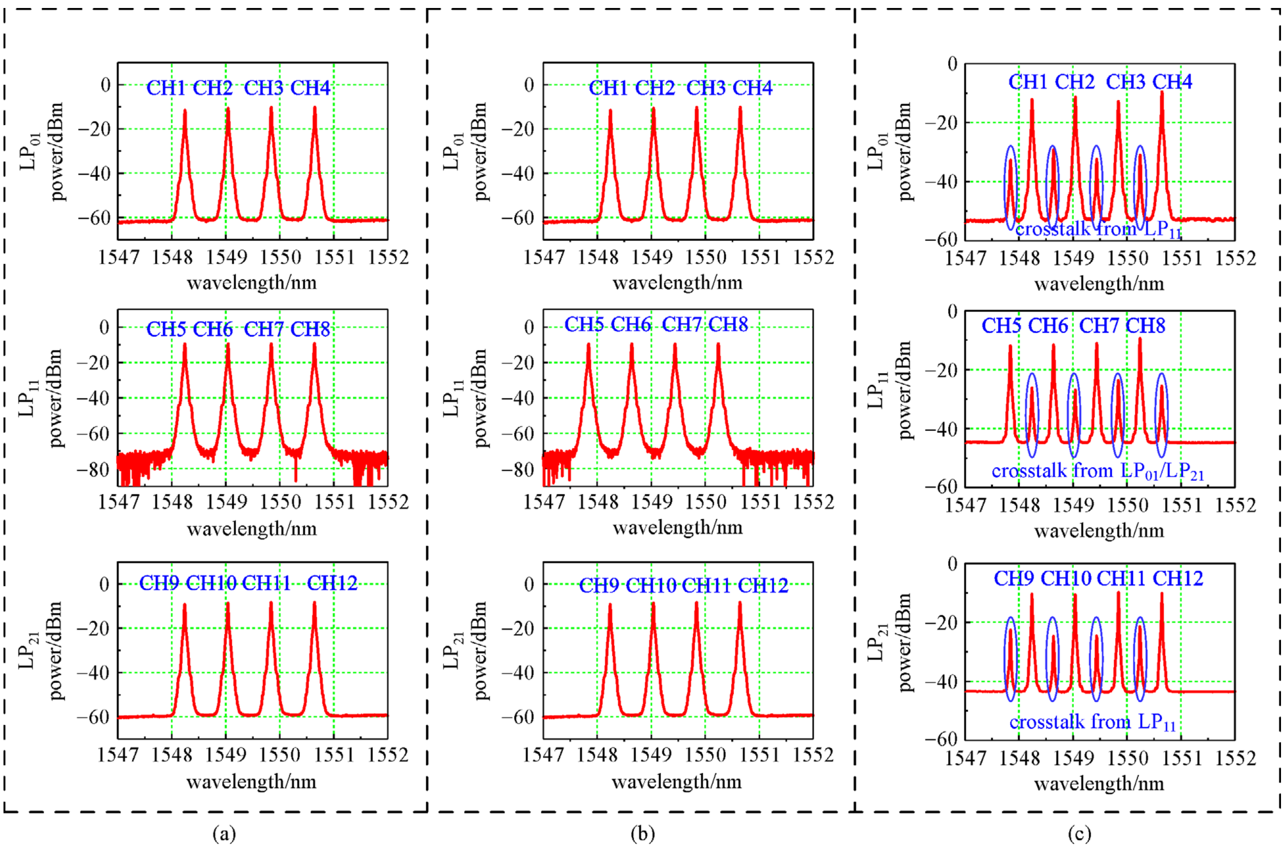


Fig. 10 Optical spectra of (a) transmitted WDM signals in WA scheme, (b) transmitted WDM signals in WI scheme and (c) received WDM signals after WI transmission over 7-km MMF

scheme. Figures 10(b) and 10(c) show the transmitted and received optical spectra in WI scheme. The modal-crosstalk from adjacent modes is labeled by the blue circles in Fig. 10(c).

Figures 11(a)–11(c) show the *Q*-factors of signals versus transmission distance. It can be seen that signals transmitted in LP_{01} mode have the best transmission performance in both schemes, followed by the signals transmitted in LP_{11} and LP_{21} modes, which is consistent with the modal-crosstalk in each mode. In WA scheme, the signals could be only transmitted over 12-km OM3 MMF before the worst *Q*-factor approaching the FEC limit. For WI transmission, signals transmitted in LP_{01}, LP_{11} and LP_{21} modes have larger *Q*-factors than these in WA scheme. The average *Q*-factor improvements are about 2.6, 3.2 and 3.7 dB for the received signals in LP_{01}, LP_{11} and LP_{21} modes after 12-km OM3 MMF transmission. By using WI scheme, the OM3 MMF transmission distance of the LP_{01}, LP_{11} and LP_{21} modes could be extended from 12 km expended up to 21 km. Figures 12(a)–12(c) show the electrical eye diagrams of CH2, CH6 and CH10 in WA and WI schemes, respectively. We can see that the signals in WI scheme have better eye diagram opening degree that these in WA scheme.

6 Conclusion

In conclusion, we elaborate the key technologies to realize weakly-coupled MDM to increase the transmission capacity for short-reach systems and networks, including characterization of modes in OM3 MMF and weakly-

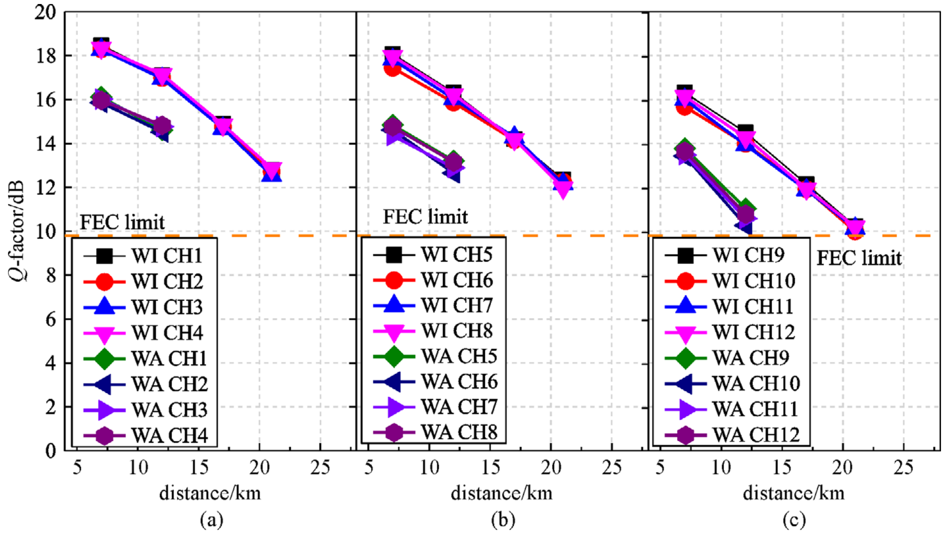


Fig. 11 *Q*-factors of received WDM channels on (a) LP_{01}, (b) LP_{11} and (c) LP_{21} modes in the scenarios of WA and WI transmission schemes

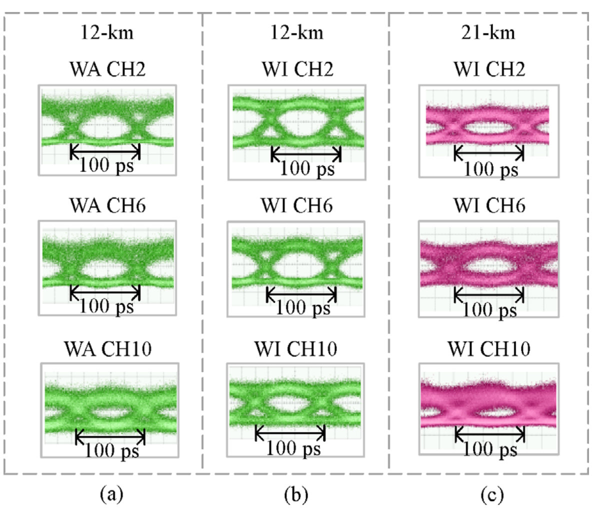


Fig. 12 (a)–(c) Electrical eye diagrams of CH2, CH6 and CH10 in WA and WI schemes

coupled mode MUX/DEMUX. Multiple weak coupling modes are selected as independent spatial channels for data transmission. All-fiber mode MUX/DEMUX consisting of cascaded MSCs are designed and fabricated to achieve mode multiplexing and demultiplexing. Thanks to the low modal-crosstalk of the mode channels and mode MUX/ DEMUX, no coherent detection or MIMO DSP is required for signal detection. We also present up-to-date weakly-coupled MDM transmission experiments with OOK modulation and simple direct detection. Experimental results validate the feasibility of weakly-coupled MDM transmission for capacity enhancement in optical short-reach systems and networks.

Acknowledgements The work was supported by the National Natural Science Foundation of China (Grant Nos. 61771024, 61627814, 61505002, 61690194 and 61605004), and Fundamental Research Project of Shenzhen Science and Technology Foundation (Nos. JCYJ 20170412153729436 and 20170307172513653).

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Dr. **Juhao Li** received the B.S. and Ph.D. degrees from Department of Electronics Engineering, Peking University, China in 1999 and 2009, respectively. During 1999–2000, he had been engaged in ZTE Corporation. In 2009 he worked in the State Key Laboratory of Advanced Optical Communication Systems & Networks at Peking University, firstly as a Postdoctoral Research Scientist, as a Lecturer from 2011, as an Associate Professor from 2012. His current research interests include high-speed optical fiber transmission systems and networks, design of optical fibers and components for optical communication, optical spatial division multiplexing techniques. He authored more than 140 papers, including about 60 SCI papers and more 25 OFC conference papers. He holds 4 authorized and 15 pending patents.