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Beyond 1.6 Tb/s net rate PAM signal transmission for rack-rack optical interconnects with mode and wavelength division multiplexing

Dongdong Zou, Fan Li, Wei Wang, Zixuan Zhang, Jinkun Hu, Jianping Li, Qi Sui, Chao Lu and Zhaohui Li

Abstract—**In this paper, a beyond 1.6 Tb/s net rate pulse amplitude modulation (PAM) communication system is experimentally demonstrated for 20 m rack-rack optical interconnects with low cost intensity modulation direct detection (IM-DD) architecture, which is enabled by mode division multiplexing (MDM) and wavelength division multiplexing (WDM). The MDM with three linearly polarized modes is realized by a multiplane light conversion (MPLC) mode multiplexer with the maximum modal crosstalk less than – 20 dB. The experimental results show that 2.01 Tb/s (1.84 Tb/s net rate) PAM-6 signal carried on three modes and four wavelengths is successfully transmitted over 20 m standard OM2 multimode fiber (MMF) with the BERs of received signals from all channels below hard decision forward error correction (HD-FEC) threshold of 3.8×10^{-3}. Look-up table (LUT) pre-distortion and Volterra nonlinear equalizer (VNLE) are employed for nonlinear impairment mitigation to improve the system performance. Compared to linear feedforward equalizer (FFE), 0.3 dB and 1 dB receiver sensitivity improvements are obtained by LUT and VNLE, respectively. To the best of our knowledge, our proposed scheme achieves the highest bit rate of 167.5 Gb/s per wavelength in MDM system with IM-DD structure. The experimental results show that our proposed PAM MDM communication scheme is a promising candidate for future 1.6Tb/s short reach rack-rack optical interconnects.**

Index Terms—**Mode division multiplexing (MDM), multimode fiber (MMF), rack-rack optical interconnects, pulse amplitude modulation (PAM), optical fiber communication, intensity modulation direct detection (IM-DD).**

I. Introduction

THE ever-increasing demands for broadband applications such as internet of thing (IoT), artificial intelligence (AI) and cloud services lead to more stringent requirements for datacenter interconnects (DCI), such that the transmission capacity can achieve 800 Gb/s or even 1.6 Tb/s in the near future [1]-[4]. According to the "Cisco Global Cloud Index: Forecast and Methodology, 2016-2021" [5], the global internet traffic will increase from 6.8 ZB in 2016 to 20.6 ZB in 2021, and 99% of the global internet traffic is closely related to datacenters. Among the applications in datacenters, the machine-to-machine traffic shows an exponentially higher rate than the machine-to-user. More detailly, the internet traffic generated in intra-datacenters occupies 71.5% of the whole traffic generated in datacenter. Consequently, the network connecting the racks in the intra-datacenters plays a crucial role from the performance perspectives [6]-[7]. With the rapidly increasing demand of communication capacity in rack-rack interconnects, the conventional coaxial cable based electrical interconnects cannot satisfy the requirements. Alternatively, the optical interconnects as a promising solution can provide ultra-high communication capacity. For the rack-rack interconnects in intra-datacenters, the communication distance is usually within the range of several to tens of meters. In such a short reach application, the system cost and complexity are the two vital concerns. Intensity modulation direct detection (IM-DD) architecture is a mature solution for short reach applications due to its low cost, low power consumption and low system complexity. Recently, many advanced modulation formats such as pulse amplitude modulation (PAM) [8]-[15], carrier less amplitude/phase modulation (CAP) [16]-[19] and discrete multitone (DMT) [20]-[26] have been widely discussed to enhance the system spectrum efficiency in optical IM-DD

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(*Corresponding Author: Fan Li, and Jianping Li.*)

D. Zou, F. Li, W. Wang and Z. Zhang are with the Key Laboratory of Optoelectronic Materials and Technologies, Sun Yat-Sen University, Guangzhou 510275, China and School of Electronics and Information Technology, Sun Yat-Sen University, Guangzhou 510275, China (e-mail: lifan39@mail.sysu.edu.cn).

J. Hu and Q. Sui are with the Provincial Key Laboratory of Optical Fiber Sensing and Communications, Institute of Photonics Technology, Jinan University, Guangzhou 510632, China. (e-mail: suiqi.sjtu@gmail.com).

J. Li is with School of Information Engineering, Guangdong University of Technology, Guangzhou 510006, China. (e-mail: jianping@gdut.edu.cn).

C. Lu is with Department of Electronic and Information Engineering, Photonics Research Centre, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong. (e-mail: chao.lu@polyu.edu.hk)

Z. Li is the Key Laboratory of Optoelectronic Materials and Technologies, and School of Electronics and Information Technology, Sun Yat-Sen University, Guangzhou 510275, China, and he is also with Southern Laboratory of Ocean Science and Engineering (Guangdong, Zhuhai), Zhuhai, 519000, China (e-mail: lzhh88@mail.sysu.edu.cn).

system. In addition, utilizing the digital signal processing (DSP) algorithms such as feedforward equalizer (FFE) [27]-[28] and Volterra nonlinear equalizer (VNLE) [29]-[30] are also the effective way to improve the system performance.

Mode division multiplexing (MDM) is considered as a promising technique for optical fiber communication [31]-[38], which can effectively enhance the system capacity and has drawn wide attention in the past few years. However, the biggest obstacle of the MDM is the modal crosstalk induced system performance degradation. MDM is more attractive for coherent communication systems where the multiple input and multiple output (MIMO) algorithm with huge computation complexity can be applied for modal crosstalk cancellation [31]-[33]. In short reach applications with IM-DD MDM architecture, direct modal crosstalk cancellation utilizing MIMO processing is impossible as the phase information is lost after the square-law direct detection. Thus, the transmission distance of the MDM IM-DD system is significantly limited by the modal crosstalk [34]-[38]. Recently, K. Benyahya *et al* have made a lot of efforts in MDM IM-DD transmission system with DMT modulation format [35]-[36]. As reported, the linearly polarized mode group division multiplexing (MGDM) scheme is employed in their system, in which the signal carried on the modes within a mode group are collected to one receiver. In [35], 68.8 Gb/s per channel and 5 Tb/s WDM MDM DMT signal transmission is achieved over 2.2 km OM2 MMF. In [36], by employing 88 GSa/s DAC and more channels in WDM, the data rate can be improved to 90.6 Gb/s per channel and 14.6 Tb/s in total. Although Chow's bit-loading technique is applied in such a DMT system, the single channel and single mode rate is still below 100 Gb/s. In [37], the author demonstrates the 240 Gb/s MDM DMT signal transmission based on two cylindrical vector beams multiplexing for 5-m backplane optical interconnection. The multiplexing and demultiplexing are realized by a free-space optical system built by themselves. In the experiments mentioned above, all the modulation formats are DMT. Considering that PAM is the most widely used modulation format in commercial optical DCI due to its lower system cost and power consumption in DSP compared to DMT, it is more practical to investigate high date rate MDM transmission system based on PAM modulation format for next generation rack-rack optical DCI.

In this paper, we extend the results of our work reported on OFC 2020 [38] in which only MDM scheme is employed in IM/DD PAM system to realize 500 Gb/s per wavelength data transmission. In order to achieve 1.6 Tb/s communication capacity for next generation rack-rack optical interconnects, we experimentally demonstrate the transmission and reception of 2.01 Tb/s (1.84 Tb/s net rate) PAM-6 signal by combing MDM with wavelength division multiplexing (WDM) of 4 carriers over 20 m OM2 MMF. At the transceiver, multiplexing/demultiplexing of three linearly polarized modes MDM is realized by a multiplane light conversion (MPLC) mode multiplexer and demultiplexer with modal crosstalk less than –20 dB. As the transmission distance is only 20-m, no specific DSPs are adopted for modal crosstalk cancellation. Meanwhile, look up table (LUT) pre-distortion and VNLE schemes are used to mitigate the system nonlinear impairments. The experimental results show that the bit-error-rate (BER) of 167.5 Gb/s PAM-6 signal with linear FFE for channel equalization is below hard decision forward error correction (HD-FEC) threshold of 3.8×10^{-3} in OBTB transmission. The LUT pre-distortion and VNLE can improve the system receiver sensitivity by 0.3 dB and 1 dB, respectively. In the MDM with WDM communication system, the BER of received signal cannot reach HD-FEC threshold over 20 m MMF transmission when linear FFE is utilized for channel equalization. With the application of nonlinear compensation schemes, 1.84 Tb/s net rate PAM-6 signal carried on three modes and four wavelengths is successfully transmitted over 20 m standard OM2 MMF, and the BERs of received signal from all channels are below 3.8×10^{-3}. To the best of our knowledge, our investigated single carrier MDM PAM communication scheme achieves the highest bit rate per wavelength in MDM system with cost-effective IM-DD structure. The experimental results show that our proposed PAM communication scheme combing MDM and WDM is a promising candidate for future 1.6 Tb/s short reach rack-rack optical interconnects in DCI.

The rest of this paper is organized as follows. Section II describes the principles of linearly polarized MDM, LUT pre-distortion and VNLE. Section III gives out the experimental setup and results discussion. Finally, we summarize this paper in Section IV.

II. Principle

In this section, the principles of MDM, LUT pre-distortion and Volterra series nonlinear compensation technique are discussed as below.

A. Linearly polarized MDM

In our experiments, the linearly polarized MDM is realized

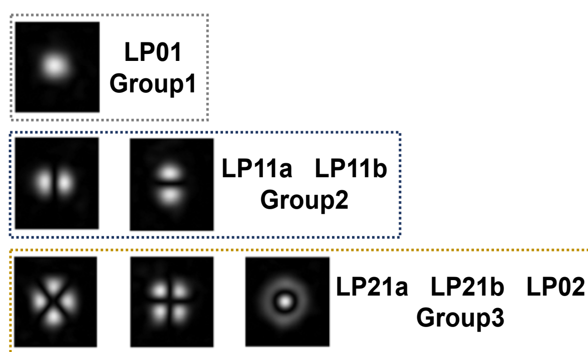

Fig. 1 Supported modes of the utilized MPLC-based mode multiplexer

TABLE 1

MODE CROSSTALK OF MODE (De)MUTIPLEXER

Input \ Crosstalk (dB)	LP01	LP11a	LP21a
LP01		-27.71	-25.03
LP11a	-26.5		-23.42
LP21a	-26.7	-23	

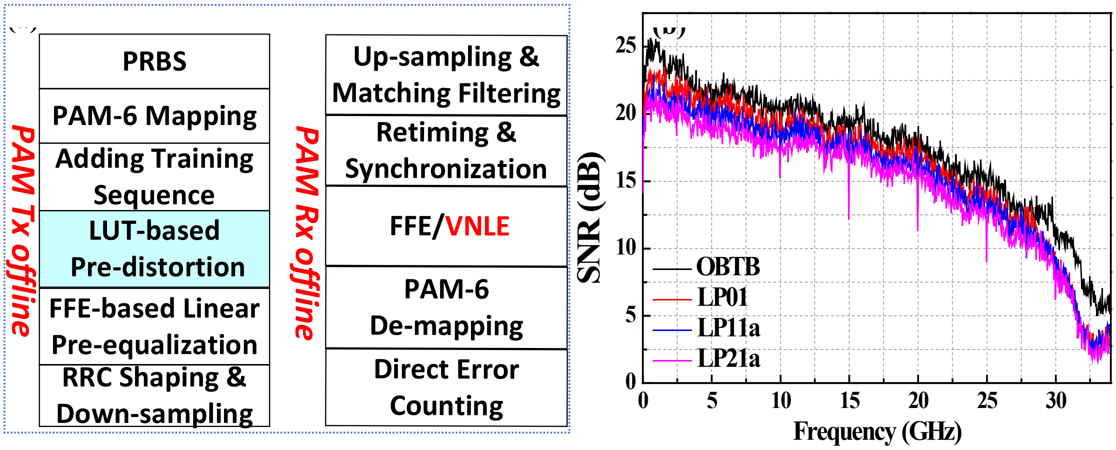

Fig. 2. (a) Detailed offline DSPs for PAM signal generation and reception. (b) Measured SNR of different modes in single wavelength system.

by utilizing a MPLC-based mode multiplexer PROTEUS-S-6 from Cailabs. The loss of this mode multiplexer/demultiplexer and 20 m OM2 fiber is about 10 dBm in total. As shown in Fig. 1, this multiplexer can support mode multiplexing of up to three mode groups including six modes in C band. Instead of MGDM, only one mode from each mode group is selected to achieve MDM in our scheme, which can efficiently reduce the modal crosstalk within one mode group. In our experiments, LP01, LP11a and LP21a are selected as the multiplexed modes for signal delivery. The modal crosstalk between the three selected modes in PROTEUS-S-6 mode multiplexer is given out in Table 1. We can find that the maximum modal crosstalk between each mode is lower than –20 dB.

B. LUT pre-distortion

The principle of LUT pre-distortion based nonlinear distortion cancellation technique is detailly described in [39], in which the nonlinear distortion of a symbol is considered to depend on the transmitted symbol pattern. If the memory length and the modulation format of LUT scheme are N and PAM-M, N PAM-M symbols are considered as a pattern. Our target is to obtain the magnitude error of the middlemost symbol of each pattern in calibration stage and then compensate it in transmission stage. For example, if the memory length is 3, our target is to obtain the magnitude error of the second symbol of each pattern. In the calibration stage, we need to obtain the magnitude error of the target symbol of each pattern according to the transmitted and received training sequences (TS), and then record it in the error table. In the transmission stage, we need to determine the pattern of each transmitted symbol belongs to, and then compensate the nonlinear distortion according to the error table obtained in calibration stage. It is worth noting that the TS utilized in calibration stage for error table generation and the transmitted symbols for BER calculation in transmission stage are independent. In our experiments, the memory length of LUT pre-distortion processing is selected at 3 to reduce the calculation complexity, and case of the pattern is 6^3=216.

C. Volterra series based nonlinear compensation

VNLE has been widely discussed for nonlinear impairments cancellation to enhance the system performance in optical fiber communication system. The detailed principle of VNLE can be found from [29], [30], [40], which is not discussed here anymore. In this paper, 3-order VNLE is applied for nonlinear impairments cancellation, and the memory length of 1st, 2nd and 3rd order Volterra kernel are optimized to 121, 13, and 9, respectively.

III. EXPERIMENTAL SETUP AND RESULTS

In this section, the offline DSP for the single wavelength MDM and WDM MDM systems are given out at first. Then, the detailed experimental setup and results of the aforementioned systems are presented in two independent subsections.

The offline DSP at the transceiver for PAM signal generation and reception are shown in Fig. 2(a). At the transmitter, a 2^{20}-1 points pseudo-random binary sequence (PRBS) is generated and mapped into PAM-6 symbols. The first 4096-point PAM-6 symbols are used as the TS for receiver side synchronization and equalization. The optional digital nonlinear pre-distortion based on LUT algorithm with memory length of 3 is employed to compensate the nonlinear impairments. The linear pre-equalization is implemented with 11-taps finite impulse response (FIR) filter in which the taps coefficients are obtained from the receiver side FFE at the calibration stage to compensate the bandwidth limitation induced inter-symbol interference (ISI). A square root raised cosine (SRRC) filter with 0.125 roll-off factor is applied to realize the Nyquist shaping for PAM signal, and the pulse-shaped signal is resampled before uploading into the DAC. The measured SNRs of the three independent modes versus frequency in MDM system are shown in Fig. 2(b). Higher order mode channels show poor SNR performance due to the modal coupling induced crosstalk in the same mode group. The offline DSPs at the receiver includes re-sampling, matching filtering, retiming, synchronization, FFE or VNLE, PAM-6 signal de-mapping and error counting.

A. Single wavelength MDM transmission

In single wavelength system, we experimentally demonstrate the transmission of three modes 502.5 Gb/s PAM-6 signal over 20 m OM2 fiber. The experimental setup is depicted in Fig. 3(a). The signal generated offline is uploaded into an 80 GSa/s Fujitsu DAC with 16.7 GHz 3-dB bandwidth. Then the output signal is amplified by a single-ended driver with 20-dB gain and 30 GHz bandwidth. A 3-dB attenuator (ATT) is placed at the input port of amplifier to eliminate the nonlinear distortions. After that, the signal is injected into a 40 GHz Mach-Zehnder

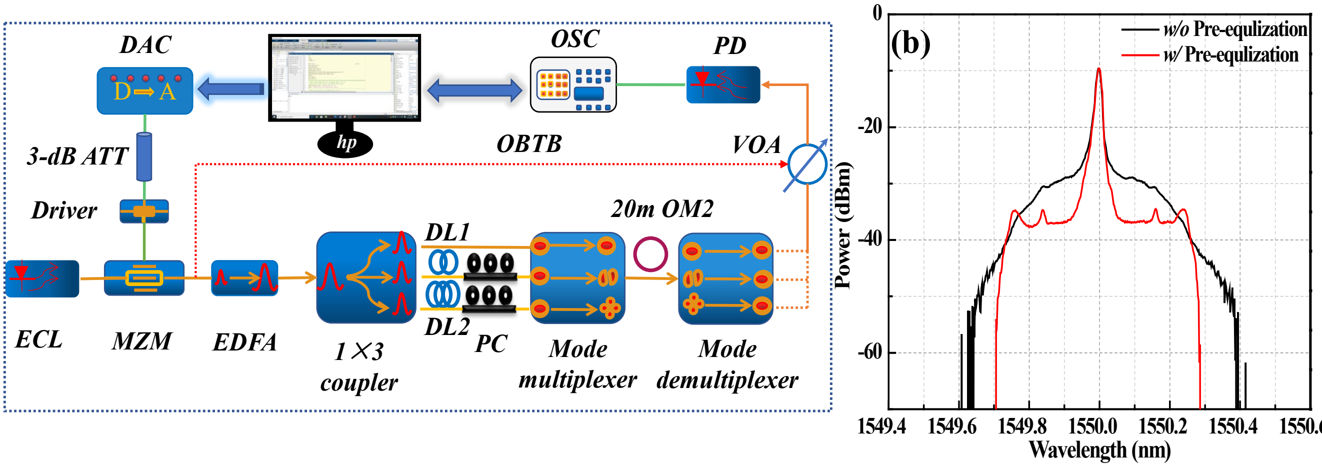

Fig. 3. (a) the experimental setup of the single wavelength MDM system. (b) optical spectrum of the signal with and without pre-equalization in single wavelength system.

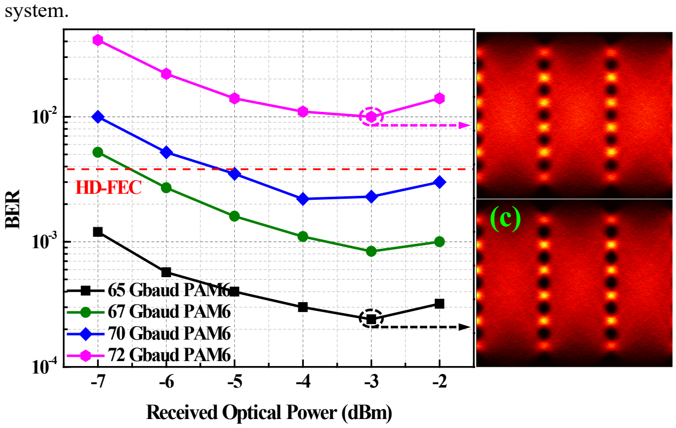

Fig. 4 Measured BER versus ROP of PAM-6 signal with the Baud rate from 65 Gbaud to 70 Gbaud in OBTB case.

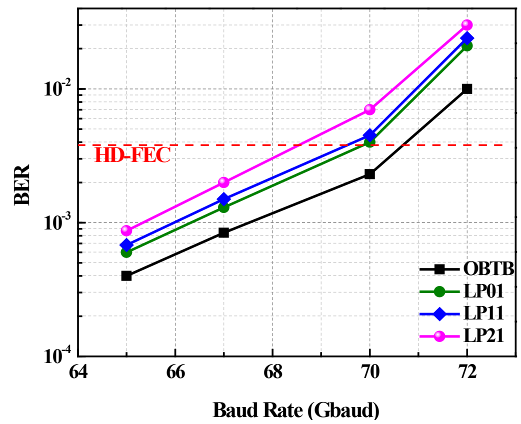

Fig. 5 Measured BER versus Baud rate of PAM-6 signal in single wavelength MDM system at -3 dBm ROP.

modulator (MZM) to modulate the 1550 nm optical carrier generated from an external cavity laser (ECL) with 16 dBm optical power. The optical spectra of PAM-6 signal with and without linear pre-equalization are shown in Fig. 3(b). It can be observed that the bandwidth limitation induced power attenuation has been compensated. The modulated optical signal is amplified by an erbium-doped fiber amplifier (EDFA) and then a 1×3 coupler is cascaded as a power splitter. The EDFA is employed to compensate the power loss induced by coupler and mode multiplexer. As depicted in Fig. 3(a), different delay lines (DLs) and polarization controllers (PCs) are added at the 2nd and 3rd input ports of the mode multiplexer. The DLs are used to remove the corrections between different modes, and the PCs are employed to achieve the maximum mode conversion efficiency as the multiplexer is polarization dependent. The PCs can be avoided by using the polarization-maintaining-fiber (PDF) between the coupler and multiplexer. LP01, LP11a, and LP21a modes from the mode division multiplexer are selected to deliver signal and then transmitted over a 20-m OM2 MMF. After OM2 MMF transmission, all the modes are de-multiplexed to fundamental Gaussian mode by the mode demultiplexer. In this paper, as no specific DSP is utilized for mode de-multiplexing, signals carried on three different modes are captured separately and the BERs are also calculated separately. At the receiver, a variable optical attenuator (VOA) is added to adjust the received optical power (ROP), and the optical signal is detected by a 40-GHz photodiode (PD). After that, the converted signal is captured by a LeCroy real-time Oscilloscope (OSC) with 80-GSa/s sampling rate and processed offline in MATLAB.

At the beginning stage, we test the BER performance of PAM signals with different baud rates in optical back-to-back (OBTB) case to find the maximum achievable capacity of this MDM system. As shown in Fig. 4, the BER performance of 70 Gbaud PAM-6 signal in OBTB transmission at –5 dBm ROP is under the HD-FEC threshold of 3.8×10^{-3}. However, the transmission of 72 Gbaud PAM-6 signal cannot be achieved with the BER below 3.8×10^{-3}. The eye diagrams of recovered 65 Gbuad and 70 Gbaud PAM-6 signals with –3 dBm ROP are shown in Figs. 4(b) and 4(c), respectively. We can find that when the ROP is higher than –3 dBm, the system BER performance will degrade as shown in Fig. 4. This is caused by the signal optical to electric conversion induced nonlinearity in PD. Thus, we test the BER performance of PAM-6 signals with the baud rates from 65 to 72 Gbaud at –3 dBm ROP to obtain the maximum transmission capacity supported by the single wavelength MDM system. As shown in Fig. 5, the LP01 mode shows the best BER performance and the LP21a in the highest mode group shows the worst BER performance. The reason is that the higher mode group suffers more serious modal coupling induced crosstalk. In Fig. 5, we can find that the BER of the 70 Gbaud PAM-6 signal carried on LP21a mode cannot reach the HD-FEC threshold of in single wavelength MDM system transmission. In our later experiments, limited by the way we test, the signal carried on each mode is the 67 Gbaud PAM-6

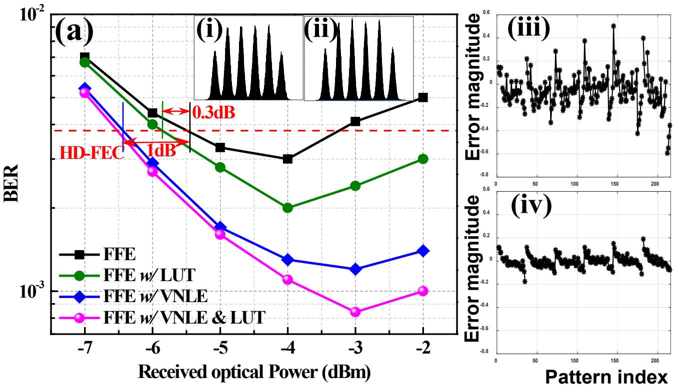

Fig. 6 Measured BER versus ROP of 67 Gaud PAM-6 signal in OBTB transmission.

signal. In fact, the baud rate of the PAM-6 signal carried on each mode can be different to achieve the maximum transmission rate. Fig. 6 gives out the measured BER performance versus ROP of the 67 Gbaud PAM-6 signal in OBTB transmission. The LUT pre-distortion and VNLE can improve the system receiver sensitivity by 0.3-dB and 1-dB at the BER of 3.8×10^{-3}, respectively. The histograms of recovered PAM-6 signal with linear FFE and VNLE for channel equalization are shown in Fig. 6 as the insets (i) and (ii), respectively. We can see that the signal nonlinear distortions between the PAM-6 symbols are alleviated by VNLE effectively. The corresponding magnitude error versus pattern index are given out in insets (iii) and (iv), respectively. Obviously, the VNLE scheme can also reduce the pattern dependent symbol error. This can be explained by that the VNLE reduces the nonlinear distortion of each symbol. When we depict the pattern dependent symbol error, it is no doubt that the magnitude error is reduced. Fig. 7 gives out the BER performance versus ROP of 67 Gbaud PAM-6 signal carried on LP01, LP11a, and LP21a modes in MDM system. 167.5 Gb/s PAM-6 signal carried on each mode is successfully transmitted over 20 m OM2 MMF with the BER below 3.8×10^{-3}. As three modes are applied in the single wavelength MDM system for signal transmission, the total capacity is 502.5-Gbit/s. After removing 7% FEC and 1.87% Ts overheads, the net data rate is 462.28 Gbit/s.

B. WDM MDM transmission

The transmission of three modes MDM 502.5 Gb/s PAM-6 signal is realized in a single wavelength IM-DD system. In

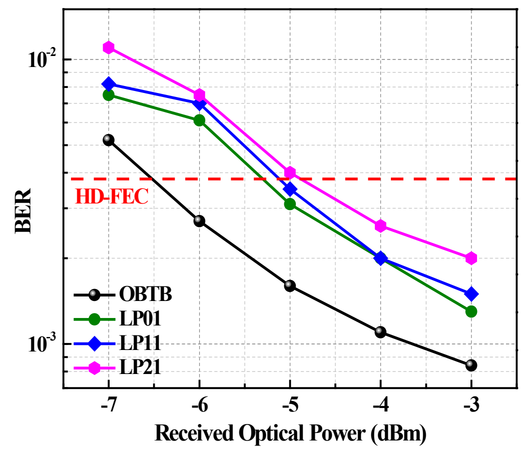

Fig. 7 Measured BER versus ROP of 67 Gbaud PAM-6 signal in single wavelength MDM system.

order to achieve the 1.6 Tb/s transmission rate for next generation high speed rack-rack optical interconnects, we experimentally investigate the MDM experiments in WDM system with four optical carriers. The experimental setup is depicted in Fig. 8 (a). At the transmitter, four optical carriers with the wavelength of 1550 nm, 1550.8 nm, 1551.6 nm, and 1552.4 nm are generated from two ECLs. The 1550 nm and 1551.6 nm optical carriers are coupled into one modulator. The other two optical carriers are coupled into another modulator with the same bandwidth. Then, the modulated optical signals are combined by a coupler and amplified by an EDFA. The optical spectrums of the signals carried on the four optical carriers are shown in Fig. 8(b). We can find that the signals carried on 1550 nm and 1551.6 nm optical carriers show higher SNR. The reason is that the two electric drivers utilized in two branches as shown in Fig. 8(a) have different performance. Thus, when measuring the BER performance of signals carried on different optical carriers, the target signal is always generated from the brunch 1. Transmitting over the MDM system, a Finisar wave shaper (WS) with 6 dB insertion loss and 60 dB extinction ratio is utilized to separate the signal from different channel. Additionally, the experimental setup of WDM MDM system is the same as single wavelength MDM system. The measured BER performance versus ROP of 2.0 Tb/s PAM-6 signal in WDM MDM system is shown in Fig. 9. Obviously, the 167.5 Gb/s PAM-6 signal carried on each wavelength and each mode can be successfully transmitted in four wavelengths and three modes WDM MDM system with

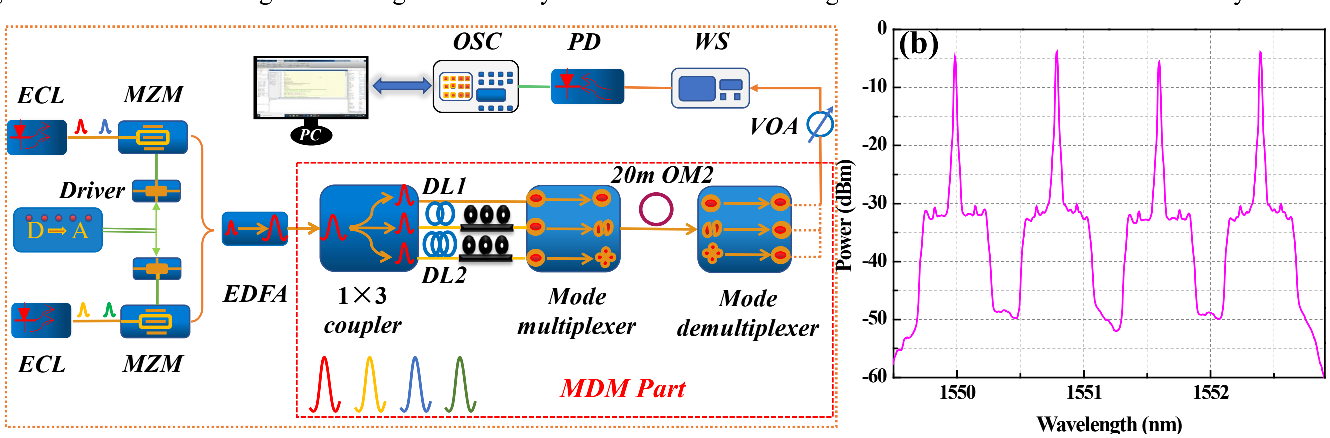

Fig. 8 (a) The experimental setup of WDM MDM system (b) The optical spectrum of the signal in WDM system.

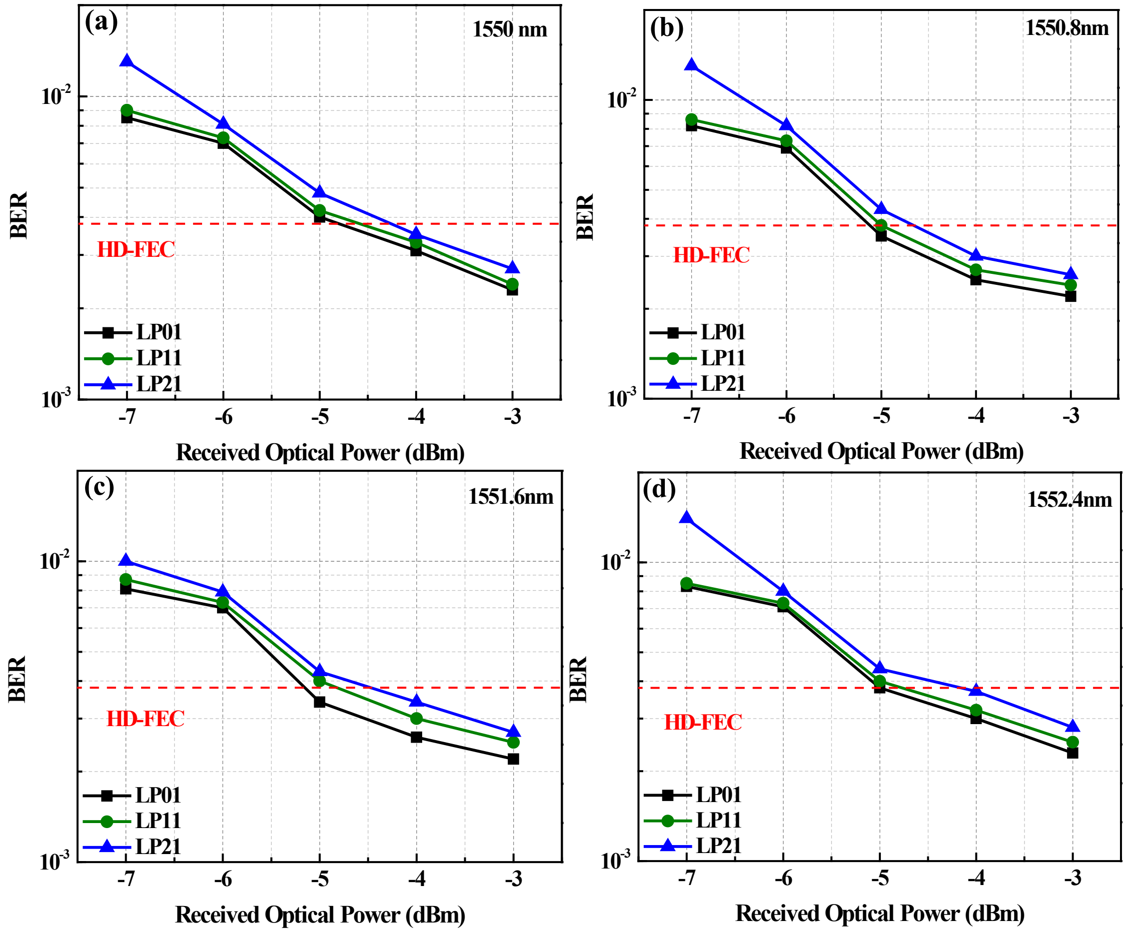

Fig. 9 Measured BER versus ROP of 67Gbaud PAM-6 signal carried on (a) 1550 nm (b) 1550.8 nm (c) 1551.6 nm (d) 1552.4 nm optical carrier in WDM MDM system.

the BER below HD-FEC threshold of 3.8×10^{-3}. The total data rate is 2.01 Tb/s, and the total net rate is 1.84 Tb/s after removing 7% FEC and 1.87% TS overheads. In our WDM system, only 4 optical carriers with 0.8 nm (100 GHz) channel spacing are utilized to achieve beyond 1.6 Tb/s transmission rate. In fact, more optical channels can also be multiplexed even for the whole C-band. Taking the system spectrum efficiency (SE) into consideration, we can enhance the system SE by reducing the channel spacing to 70 GHz at least as the baud rate of the transmitted signal is 67 Gbaud. The BER performance of the system with 70 GHz channel spacing will be similar to the one with 100 GHz, because the nonlinear effect and signal crosstalk between the channels can be omitted as the system launched power is small and the transmission distance is only 20 m. As for mode multiplexing, only one mode from each mode group is selected to achieve MDM. In order to make full use of the multiplexer, 6 modes can be multiplexed at most, and the system capacity can be increased to 6×167.5 Gb/s/λ. However, the system performance will be seriously degraded by the modal crosstalk between one mode group. In addition, the system transmission distance is also limited by the modal crosstalk. As no specific DSP is employed for modal crosstalk cancellation in our system, only 20 m transmission distance is demonstrated. In the future, both the multiplexed modes and the transmission distance can be extended by effective modal crosstalk elimination algorithms such as deep learning.

IV. Conclusion

In conclusion, a beyond 1.6 Tb/s WDM MDM communication system is experimentally investigated for 20 m short reach rack-rack optical interconnects with low-cost IM-DD architecture. At the transceiver, the MDM with three linearly polarized modes is realized by a MPLC mode multiplexer and demultiplexer with modal crosstalk less than –20 dB. The nonlinear mitigation schemes including LUT pre-distortion and VNLE are discussed to mitigate the system nonlinear impairments. The experimental results show that the LUT and VNLE can enhance the receiver sensitivity of the 67 Gbaud PAM-6 system by 0.3 dB and 1 dB, respectively, in OBTB case at a BER of 3.8×10^{-3}. In WDM MDM communication system with the implementation of nonlinear compensation schemes, three modes and four wavelengths division multiplexed 1.84 Tb/s net rate PAM-6 signal is successfully transmitted over 20 m OM2 fiber with a BER below 3.8×10^{-3}. To the best of our knowledge, our investigated single carrier MDM PAM communication scheme achieves the highest bit rate of 167 Gb/s per wavelength in MDM system with cost-effective IM-DD structure. The experimental results show that our proposed WDM MDM PAM communication scheme is a promising candidate for future 1.6 Tb/s short reach rack-rack optical interconnects in DCI.

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