Single λ 500-Gbit/s PAM Signal Transmission for Data Center Interconnect Utilizing Mode Division Multiplexing

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Abstract: Single wavelength 502.5-Gbit/s MDM-PAM-6 signal transmission over 20-m OM2 fiber with BER below HD-FEC threshold (3.8×10^{-3}) is demonstrated for 400-G Data Center Interconnect without DSP for mode de-multiplexing. This scheme shows good potential for future 800-G/1.6-T DCI.

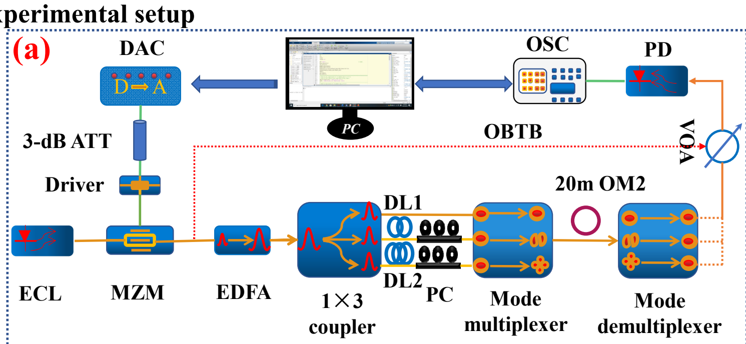
OCIS codes: (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems

1. Introduction

Recently, the demands of high data-rate transmission system have been emerging due to the development of the internet of thing, artificial intelligence (AI), cloud services. Many advanced technologies such as wavelength division multiplexing (WDM), polarization division multiplexing (PDM) with coherent detection have been proposed to fulfill these burgeoning demands. In short reach applications, cost and power consumption become very sensitive, which makes the intensity modulation with direct detection (IM/DD) [1-4] more practical than coherent detection scheme with high spectral efficiency. In order to break the bottleneck of SMF-based transmission system to significantly improve the transmission capacity in IM/DD system, mode division multiplexing (MDM) technique combined with advanced modulation formats and digital signal processing (DSP) algorithms have been extensively studied recently [5-8]. K. Benyahya et al have made a lot of efforts in IM/DD MDM transmission system based on discrete multitone (DMT) modulation format [7, 8]. As reported in [7], 68.8-Gbit/s per channel and 5-Tbit/s WDM MDM DMT signal transmission is achieved over 2.2-km OM2 multi-mode fiber (MMF). In [8], by employing 88-GSa/s DAC and more channels in WDM, the data rate can be improved to 90.6-Gbit/s per channel and 14.6-Tbit/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-Gbit/s. In [9], a 3×104-Gbit/s single λ IM/DD MDM DMT system is demonstrated based on a silicon micro-ring modulator in an integrated MDM network. While pulse amplitude modulation (PAM) is the most widely used modulation format in commercial optical data center interconnects (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.

In this paper, we experimentally demonstrate the transmission of single wavelength 502.5-Gbit/s PAM-6 signal in an IM/DD system enabled by MDM with three modes for rack to rack optical interconnects. With Volterra nonlinear equalizer (VNLE) for nonlinear distortion compensation, 502.5-Gbit/s PAM-6 signal is successfully transmitted over 20-m OM2 MMF with the bit error ratio (BER) below hard decision forward error correction (HD-FEC) threshold of 3.8×10^{-3}. To the best of our knowledge, it is the first time to achieve beyond 500-Gbit/s/λ (167.5-Gbit/s per mode) signal transmission with IM/DD architecture. No DSP is used for mode de-multiplexing, which makes it a promising potential solution for 800-G/1.6-T rack-to-rack interconnects.

2. Experimental setup



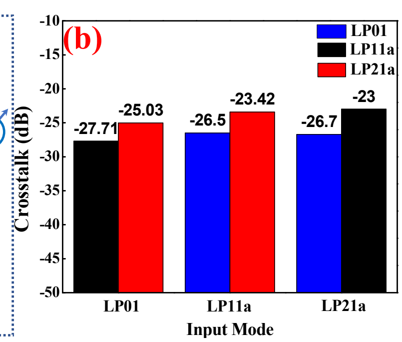


Fig. 1. (a) The experimental setup for MDM communication system (b) Intermodal crosstalk of the MDM system

In this section, the experimental setup and offline DSP blocks are discussed. As shown in Fig. 1, the signal is generated offline in MATLAB and then 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 effects. Then the signal is injected into a 40-GHz Mach-Zehnder modulator (MZM) to modulate the 1550-nm optical carrier generated from an external cavity laser (ECL) with 16 dBm power. 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. As depicted in Fig. 1, different delay lines (DLs) and polarization controllers (PCs) are added at the 2nd and 3rd input ports of the mode multiplexer to remove corrections and suppress crosstalk between different modes, respectively. LP01, LP11a, and LP21a modes from the mode division multiplexer are applied to carry signal and then transmitted over a 20-m OM2 MMF. After MMF transmission, different modes are de-multiplexed to fundamental Gaussian modes by the mode demultiplexer. Crosstalk between the above-mentioned three modes is measured and shown in Fig. 1(b), in which all intermodal crosstalks are less than −23-dB. In this paper, as DSP is not necessary for mode de-multiplexing, BERs of signal carried on three different modes are captured and tested separately. In 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 electric signal is captured by a LeCroy real-time Oscilloscope (OSC) with 80-GSa/s sampling rate and processed offline in MATLAB as shown in Fig. 2. In the transmitter, pseudo-random binary sequences (PRBS) are generated firstly, and then mapped into PAM-6 symbols. The first 4096-point PAM-6 symbols are considered as the training sequence (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, and the linear pre-equalization is implemented with 11-taps finite impulse response (FIR) filter 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 shaped signal is resampled before uploading into the DAC. The measured SNRs of three independent modes in MDM system are shown in Fig. 2 as the inset (i). Higher order modes show poor SNR performance due to the mode coupling induced crosstalk in the same mode group. The optical spectra of PAM-6 signal with and without linear pre-equalization are shown in Fig. 2 as the inset (ii). It can be observed that the bandwidth limitation induced power attenuation has been compensated. The offline DSPs in the receiver including up-sampling, matching filtering, retiming, synchronization, feedforward equalization (FFE) or VNLE, PAM-6 signal de-mapping and error counting.

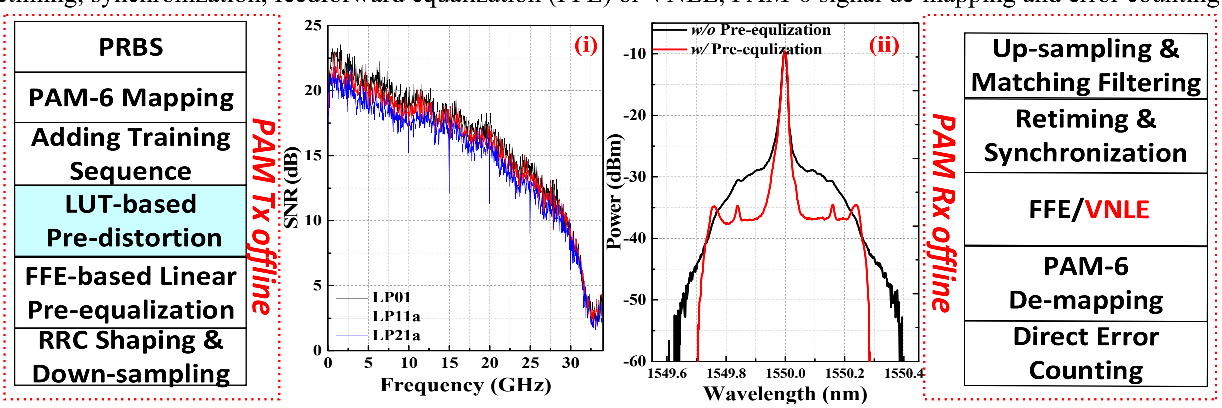


Fig. 2. The offline DSP for PAM transceiver. (i) Channel response and (ii) Optical spectra.

The principle of LUT nonlinear pre-distortion is described in [1], which is not discussed in this paper. In the VNLE, the time domain P_{th} order Volterra series is given by

$$y(n)=\sum_{p=1}^{P}\sum_{k_1=0}^{N-1}\dots\sum_{k_p=0}^{N-1}h_p(k_1,\dots,k_p)x(n-k_1)\dots x(n-k_p). \tag{1}$$

where $x(n)$ and $y(n)$ are the input and output signals, respectively. P is the order of Volterra kernel and N is the memory length. h_p is p_{th}-order Volterra kernel. In this paper, we employ 3_{th}-order VNLE, and the complexity of VNLE can be reduced by choosing different memory length for each order, which can be expressed as

$$y(n)=\sum_{k_1=0}^{N_1-1}h_1(k_1)x(n-k_1)+\sum_{k1=0}^{N_2-1}\sum_{k2=k1}^{N_2-1}h_2(k_1,k_2)x(n-k_1)x(n-k_2)+\sum_{k_1=0}^{N_3-1}\sum_{k_2=k1}^{N_3-1}\sum_{k_3=k_2}^{N_3-1}h_3(k_1,k_2,k_3)x(n-k_1)x(n-k_2)x(n-k_3). \tag{2}$$

where N_1, N_2, N_3 are memory length of the 1st, 2nd, and 3rd Volterra kernel, usually $N_1>N_2>N_3$. In this paper, N_1, N_2 and N_3 are optimized to 121, 13 and 9, respectively.

3. Results and discussion

In the calibration stage, the system receiver sensitivity is tested in optical back-to-back (OBTB). We transmit the PAM-6 signal with data rate from 65-Gbaud to 72-Gbaud, and the BER performance versus ROP has shown in Fig.

3 (a). PAM-6 signal with data rate below 70-Gbaud can be successfully transmitted with BER under HD-FEC threshold of 3.8×10^{-3} in OBTB. The eye diagrams of recovered 65-Gbuad and 70-Gbaud PAM-6 signal with −3-dBm ROP are shown as insets (i) and (ii) in Fig. 3, respectively. Then, BER versus the signal baud rate in MDM system at −3-dBm ROP is measured and shown in Fig .3(b), the BER of 70-Gbaud PAM-6 carried on LP21a mode is the worst and even higher than HD-FEC threshold. In the following MDM experiments, the baud rate of PAM-6 signal is set to 67-Gbaud. Fig. 4(a) shows the BER performance versus ROP of 67-Gbuad PAM-6 signals in OBTB transmission. At BER of HD-FEC threshold, LUT and VNLE can reduce the required ROP by 0.3-dB and 1-dB, respectively. The histograms of recovered PAM-6 signal with FFE and VNLE are shown in Fig. 4 as the insets (i) and (ii), respectively. The corresponding magnitude errors versus pattern index are given out in insets (iii) and (iv), respectively. Both nonlinear equalizers can effectively improve the system BER performance and VNLE outperforms LUT at the nonlinear distortion compensation in this paper. The BER performance versus ROP of the signal carried on LP01, LP11a, and LP21a modes in MDM system are shown in Fig. 4(b). 167.5-Gbit/s PAM-6 signal carried on each mode is successfully transmitted over 20-m MMF with BER below 3.8×10^{-3}. As three modes are applied in the MDM transmission, the total capacity is 502.5-Gbit/s. After removing 7% FEC and 1.87% TSs overhead, the net data rate is 457.9-Gbit/s.

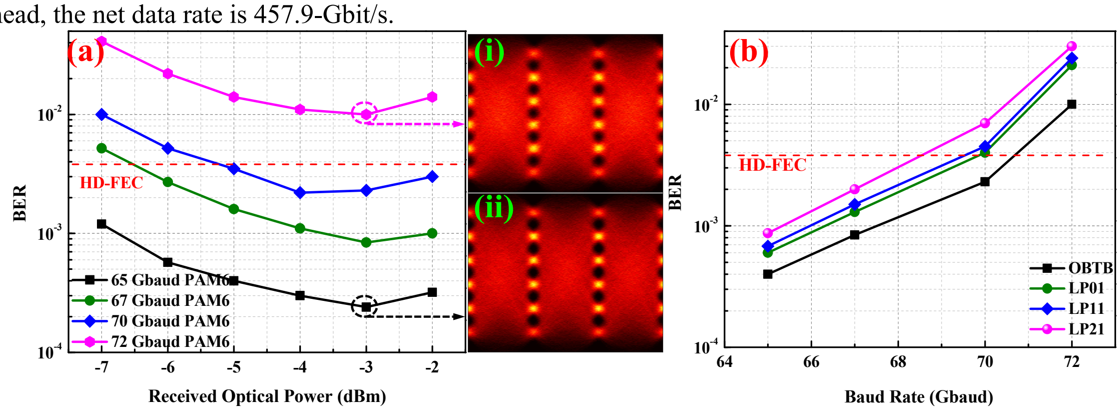


Fig. 3. (a) BER versus ROP of PAM-6 signal with different baud rate in OBTB, (b) BER versus baud rate of PAM-6 signal in MDM system.

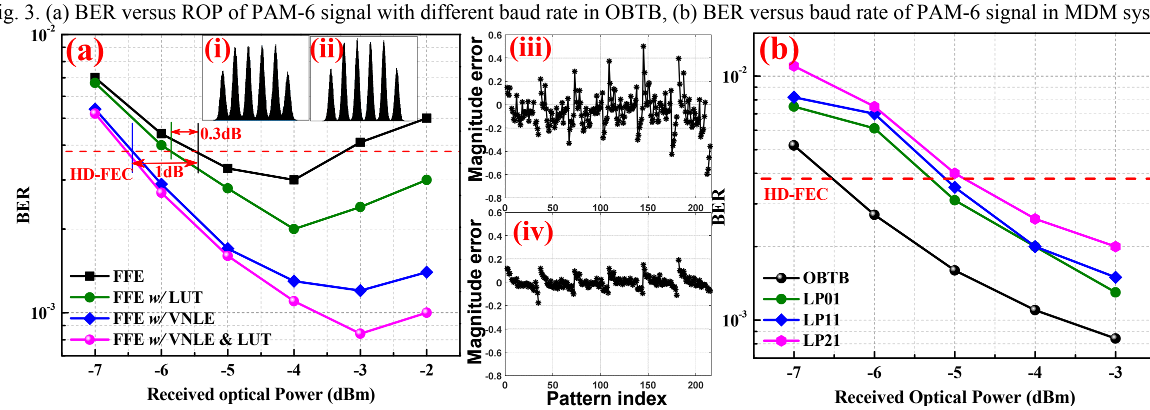


Fig. 4. BER versus ROP of 67-Gbuad PAM-6 (a) in OBTB, (b) in MDM system transmission with three modes. Histograms of recovered PAM6 signal with (i) FFE and (ii) VNLE; Magnitude error versus the pattern index of recovered PAM-6 signal with (iii) FFE and (iv) VNLE

4. Conclusion

In this paper, we experimentally demonstrate the single wavelength 502.5-Gbit/s PAM-6 signal transmission in an IM/DD MDM system with three modes, in which the data rate of signal carried on each mode is 167.5-Gbit/s. To the best of our knowledge, it is the first time to achieve beyond 500-Gbit/s/λ signal transmission with IM/DD architecture. Enabled by VNLE for nonlinear distortion compensation, BERs of signal carried on three different modes after 20-m OM2 fiber are all below HD-FEC threshold of 3.8×10^{-3}. The proposed scheme in this paper is a promising candidate for future 800-G/1.6-T ultra-short reach DCI.

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