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100G PAM-6 and PAM-8 Signal Transmission Enabled by Pre-Chirping for 10-km Intra-DCI Utilizing MZM in C-band

Dongdong Zou¹, Fan Li¹, Zibin Li¹, Wei Wang, Qi Sui, Zizheng Cao², and Zhaohui Li¹

Abstract—In this paper, we experimentally demonstrate the transmission of 100G PAM-6 and PAM-8 signals for 10-km intra-data center interconnects (intra-DCI) in C-band, which is enabled by pre-chirping technique utilizing a commercial dual-arm Mach-Zehnder modulator (MZM). At the transmitter side, the use of pre-chirping technology can overcome frequency selective fading (FSF) caused by fiber dispersion (CD) in intensity modulation and direct detection (IM/DD) systems. The pre-chirping is realized by adjusting the bias voltage of dual-arm MZM operating at single driven state. At the receiver, Volterra Non-Linear Equalizer (VNLE) is used to eliminate nonlinear impairments caused by pre-chirping. With the joint pre-chirping and nonlinear elimination in single driven dual-arm MZM based IM/DD system, 45-Gbaud PAM-6 and 40-Gbaud PAM-8 signals are successfully transmitted over 10-km single mode fiber (SMF) with a bit-error-ratio (BER) below 3.8×10^{-3} . While in the chirp-free IM/DD system with dual-arm MZM operating at push-pull state, BERs of 45-Gbaud PAM-6 and 40-Gbaud PAM-8 signals over 10-km SMF transmission deteriorate dramatically to nearly 1×10^{-1} . The experimental results show that our proposed pre-chirping scheme can effectively enhance the robustness of IM/DD systems against the CD-induced FSF, and this scheme is a promising candidate for 10-km 100G intra-DCI.

Index Terms—10-km intra-datacenter interconnect (intra-DCI), dual-arm Mach-Zehnder modulator (MZM), intensity modulation with direct detection (IM/DD), pre-chirping, pulse amplitude modulation (PAM), volterra non-linear equalizer (VNLE).

I. INTRODUCTION

WITH the tremendous increasing bandwidth demand in broadband applications such as cloud computing/storage, artificial intelligence (AI), high definition television (HDTV) and so on, the traffic in data center has experienced exponential growth in last decade. Optical interconnections, which can provide ultra-high capacity data transmission for data center interconnects (DCI), have attracted much attention [1]–[5]. For short reach DCI applications such as 10-km intra-DCI, intensity modulation and direct-detection (IM/DD) architecture is widely considered as a preferable solution compared to coherent communication architecture due to its lower cost, lower power consumption and smaller footprint. Solutions for 400-gigabit Ethernet (GbE) are standardized in the IEEE Standard 802.3bs-2017 [6], [7], in which 8/4 parallel lanes with 50/100-Gbit/s/ λ transmission rate are implemented. While with the ever-increasing data rate requirements in optical interface, low-cost IM/DD system will suffer from enormous challenges. To further improve the capacity of single optical carrier, either a higher modulation format or a higher symbol rate can be adopted to achieve desired data rate signal transmission. Higher modulation format requires higher system signal to noise ratio (SNR) to obtain a target bit-error-ratio (BER). Higher symbol rate data transmission means that larger system available bandwidth is required. To solve the aforementioned issues for 100G and beyond signal transmission with IM/DD architecture, advanced modulation formats with effective digital signal processing (DSP) algorithms have been extensively studied [8]–[24]. In single carrier pulse amplitude modulation (PAM) communication systems, faster-than-Nyquist (FTN) technique is proposed to achieve higher symbol rate signal transmission within the limited system bandwidth. Q. Zhang *et al.* demonstrated the transmission of 90-Gbaud PAM-4 signal over 2-km single mode fiber (SMF) in an IM/DD system with 7.5-GHz 3-dB bandwidth enabled by FTN technique [13]. Q. Hu *et al.* reported the transmission of 84-Gbaud FTN PAM-4 signal within a 33-GHz bandwidth in IM/DD system utilizing Tomlinson-Harashima

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precoding, and only linear equalizer used at the receiver, which greatly reduces the system complexity [14]. In multi-carrier communication systems, spectral efficiency frequency division multiplexing (SEFDM) technique is proposed to reduce the system bandwidth requirement for high data rate transmission. B. Yu *et al.* experimentally demonstrated the transmission of 150-Gbit/s SEFDM signal over 2-km SMF with 33.3% spectral gain compared to orthogonal frequency division multiplexing (OFDM) by employing log-MAP Viterbi decoder [23].

Nevertheless, the transmission distances of all the systems mentioned above are only a few kilometers. The main challenge is that the fiber chromatic dispersion (CD) has a great impact on high baud rate signal. With the increase of transmission distance, the CD induced inter-symbol interference (ISI) will be more serious. In addition, the CD caused frequency selective fading (FSF) is an enormous challenge for IM/DD systems, and it seriously limits the transmission distance [25], [26]. For high baud rate signal, FSF null points will occur periodically within the signal bandwidth after fiber transmission, which will extremely deteriorate the system performance. In IM/DD systems, electrical CD compensation cannot be realized on the receiver after optical-to-electrical (O/E) conversion as the phase information disappears after square-law direct detection. Single sideband (SSB) [27], [28], vestigial sideband (VSB) [29] modulation, adaptive bit-power loading (ABPL) [30], bias control [31] and pre-dispersion [32]–[34] schemes have been proposed to cope with the CD induced FSF and extend the transmission distances for IM/DD systems. For SSB or VSB modulation, a narrowband optical filter at the output of double sideband (DSB) transmitter is used for SSB or VSB signal generation. However, due to the fluctuation of optical carrier, accurate wavelength control is required, which increases the cost and complexity of the system, and makes it impractical. For ABPL, it is very costly to obtain the channel information for transmitter through round-trip feedback. In the pre-dispersion scheme, serious modulation nonlinearity is introduced due to the higher order expansion terms of the exponential function.

In this paper, we experimentally demonstrate the transmission of 100G PAM-6 and PAM-8 signals for 10-km intra-DCI in C-band, which is enabled by pre-chirping technique utilizing commercial dual-arm Mach-Zehnder modulator (MZM). Pre-chirping is implemented by adjusting the bias voltage of dual-arm MZM operating at single driven state. By optimizing the bias voltage of MZM, we can obtain the optimum chirp factor to mitigate the CD induced FSF. However, the bias voltage with optimized chirp factor could deviate from the optimum linear modulation region of MZM, and the modulation nonlinearity is introduced. The chirp factor and modulation nonlinearity should be both taken into consideration during optimizing the bias voltage of MZM. Fortunately, the signal nonlinear distortions during electrical-to-optical (E/O) modulation can be mitigated by Volterra Non-Linear Equalizer (VNLE). Thus, more negative chirp can be introduced to resist the FSF. The experimental results show that 45-Gbaud PAM-6 and 40-Gbaud PAM-8 signals are successfully transmitted over 10-km SMF with the BERs still under the hard-decision forward-error-correction (HD-FEC) threshold 3.8×10^{-3} , and the VNLE improves the

system receiver sensitivity by more than 1-dB. With a received optical power (ROP) of 1-dBm, the BERs of 120-Gbit/s PAM-8 signal over a 10-km SMF transmission in conventional chirp-free and proposed pre-chirping systems are 8×10^{-2} and 3×10^{-3} , respectively. The proposed pre-chirping based FSF mitigation scheme improves the system BER performance significantly in 10-km 100G intra-DCI.

The rest of this paper is organized as follows. Section II describes the principles of pre-chirping technique 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 pre-chirping scheme and Volterra series based nonlinear compensation technique are discussed in detail.

A. Pre-Chirping in MZM

In this paper, dual-arm MZM is employed for signal E/O modulation. The output electric field E of MZM is given by

$$\begin{aligned} E &= E_0/2 \exp\left(j\frac{\pi}{V_\pi}V_1(t)\right) + E_0/2 \exp\left(j\frac{\pi}{V_\pi}V_2(t)\right) \\ &= E_0 \cos\left(\frac{\pi}{V_\pi} \frac{V_1(t) - V_2(t)}{2}\right) \exp\left(j\frac{\pi}{V_\pi} \frac{V_1(t) + V_2(t)}{2}\right). \end{aligned} \quad (1)$$

where E_0 is the amplitude of input optical carrier, $\cos(\cdot)$ term and $\exp(\cdot)$ term are the modulated signal and introduced modulation chirp, respectively. $V_1(t)$ and $V_2(t)$ are electrical signals driven on the two arms. MZM can be operated with chirp-free when differential signals ($V_1(t) = -V_2(t)$) are used to drive MZM, which is known as the push-pull state. According to the principle described in [24], [25], the intensity of modulated signal over fiber transmission can be described as

$$I_f = I_0 \sqrt{1 + \alpha^2} \left| \cos\left(\frac{\pi DL f^2 \lambda^2}{c} + \arctan(\alpha)\right) \right|. \quad (2)$$

where α , D and L are the chirp parameter, dispersion factor and transmission distance, respectively. λ , f and c are the wavelength of optical carrier, frequency of baseband signal and the speed of light, respectively. According to (2), we can obtain the relationship between the frequency of k -th fading null point f_k and chirp parameter α after fiber transmission as

$$\frac{f_k^2 \lambda^2 \pi DL}{c} + \arctan(\alpha) = \pm \frac{2k+1}{2} \pi, k = 0, 1, \dots, N. \quad (3)$$

$$f_k^2 L = \frac{c}{2D\lambda^2} \left(2k+1 - \frac{2}{\pi} \arctan(\alpha) \right). \quad (4)$$

Figure 1 depicts the measured system channel response by transmitting 20-GHz DMT training signal over 80-km SMF in C-band (1552.43-nm), and bandwidth limitation is compensated by zero-forcing (ZF) pre-equalization. We can observe 4 FSF null points within 20-GHz bandwidth over 80-km SMF transmission. $f_k^2 L$ versus $2k$ shows a straight line whose slope yields the dispersion factor according to (4). An example of this linear

Fig. 1. Channel response of our system which is measured by transmitting 20-GHz DMT signal over 80-km SMF.

Fig. 2. Measured $f_k^2 \cdot L$ versus $2k$ described in (4). We can calculate the dispersion factor from the slope of this line. Where k , f_k and L are the order of FSF, frequency of k -th order FSF and transmission distance, respectively.

regression measured in our experiments is shown in Fig. 2. The experimental results show a good linear law, which agree well with (4). According to the slope of this line shown in Fig. 2, we can obtain the dispersion factor as

$$D = c / (2\lambda^2 \cdot \text{slope}). \quad (5)$$

The calculated dispersion factor is 17.7-ps/nm/km in our system. Finally, we can calculate the chirp factor of MZM according to the obtained dispersion factor and frequency of the first fading dip as

$$\alpha = \tan \left(-\frac{1}{2}\pi - \frac{f_0^2 \lambda^2 D L}{c} \pi \right) \quad (6)$$

B. Volterra Series Based Nonlinear Compensation

Pre-chirping is achieved by adjusting the bias voltage of single driven dual-arm MZM to alleviate FSF caused by CD during fiber transmission. However, the bias voltage with optimized chirp factor always deviates from the linear modulation region

of MZM, and the modulation nonlinearity is introduced. In order to compensate the aforementioned signal nonlinear distortion, nonlinear compensation techniques such as look-up-table (LUT) [35] nonlinear pre-distortion and VNLE can be employed. In this paper, we choose VNLE as the nonlinear mitigation scheme by taking the performance and practicability of the proposed scheme into consideration. In VNLE, the time domain P -order Volterra series is given by

$$y(n) = \sum_{p=1}^P \sum_{k_1=0}^{N-1} \dots \sum_{k_p=0}^{N-1} h_p(k_1, \dots, k_p) x(n-k_1) \dots x(n-k_p). \quad (7)$$

where $x(n)$ and $y(n)$ are the input and output signals, respectively. N and p are the memory length and the order of Volterra kernel, respectively. h_p is p -th-order Volterra kernel. In this paper, 3-order VNLE is applied for nonlinear impairments cancellation. The complexity of VNLE is reduced by choosing different memory length for each order, which can be expressed as

$$\begin{aligned} y(n) = & \sum_{k_1=0}^{N_1-1} h_1(k_1) x(n-k_1) \\ & + \sum_{k_1=0}^{N_2-1} \sum_{k_2=k_1}^{N_2-1} h_2(k_1, k_2) x(n-k_1) x(n-k_2) \\ & + \sum_{k_1=0}^{N_3-1} \sum_{k_2=k_1}^{N_3-1} \sum_{k_3=k_2}^{N_3-1} h_3(k_1, k_2, k_3) x(n-k_1) \\ & \times x(n-k_2) x(n-k_3). \end{aligned} \quad (8)$$

where N_1 , N_2 and N_3 are the memory length of 1st, 2nd and 3rd order Volterra kernel, respectively. In this paper, N_1 , N_2 , and N_3 are optimized to 31, 15, and 11, respectively.

III. EXPERIMENTAL SETUP AND RESULTS

The schematic of the experimental setup and DSPs in transceiver for PAM signal generation and reception are presented in Fig. 3. First, a 2^{20} -point pseudorandom binary sequence (PRBS) is generated offline in MATLAB and mapped into PAM- N symbol. The first 2048 PAM- N symbols are considered as training sequences (TSs) for receiver side synchronization and channel estimation. Next 129024 PAM- N symbols are the payload signal. After that, linear pre-equalization with 21-taps finite impulse response (FIR) filter is implemented to compensate the bandwidth limitation induced ISI. The taps coefficients of FIR are obtained from the receiver side feed-forward equalizer (FFE) in the calibration stage. Nyquist shaping for PAM- N signal is realized by a root raised cosine (RRC) filter with 0.125 roll-off factor. Then, the shaped signal is re-sampled to 86-GSa/s. The generated signal is uploaded into an 86-GSa/s sampling rate Fujitsu DAC with 16.7-GHz 3-dB bandwidth and 8-bit resolution. A 3-dB electrical attenuator is used to alleviate the nonlinear distortions induced by nonlinear amplification and modulation. A single-ended 30-GHz electrical amplifier (EA) with 20-dB gain is employed to boost the PAM- N signal.

Fig. 3. Transceiver DSPs and experimental setup.

The amplified electrical signal is driven on a 40-GHz dual-arm MZM (FTM 7937/7939) to achieve E/O modulation. In order to optimize the chirp factor for signal over fiber transmission in proposed pre-chirping scheme, we employ the FTM 7937 MZM operating at single driven state to realize the signal E/O modulation. FTM 7939 MZM, which can be considered as FTM 7937 MZM operating at push-pull state, is employed for conventional chirp-free E/O modulation. Optical carrier is generated from an external cavity laser with 16-dBm optical power operating at 1552.43-nm. The generated optical signal is fed into 0/10-km SMF for data transmission. On the receiver side, a variable optical attenuator (VOA) is used to adjust the ROP. A photodiode (PD) (Agilent 11982A) with 14.5-GHz 3-dB bandwidth is applied to detect the optical signal. The detected signal is sampled by a LeCroy real time oscilloscope (OSC) with 80-GSa/s sampling rate and processed offline in MATLAB. The receiver side offline DSPs include down-sampling, Root Raised Cosine (RRC) based match filtering, retiming, synchronization, feedforward equalizer and decision feedback equalizer (FFE-DFE) or VNLE based time domain equalization, PAM- N signal de-mapping and direct error counting.

In order to verify the effectiveness of the proposed pre-chirping scheme, we compare the BER of conventional chirp-free scheme with the proposed pre-chirping scheme in two subsystems, 45-Gbaud PAM-6 and 40-Gbaud PAM-8, over 10-km SMF transmission. The measured results are presented as follows.

A. 45-Gbaud PAM-6 Transmission System

At first, we use the method presented in Subsection A of the II section to calculate the chirp factor of MZM. The measured channel response and calculated chirp factor of the conventional chirp-free system are shown in Fig. 4, which are obtained by transmitting 20-GHz DMT training signal over 80-km SMF. The measured channel response is shown in Fig. 4(a). 4 FSF null points induced by fiber CD can be observed within 20-GHz

Fig. 4. (a) Measured channel response of chirp-free system over 80-km SMF transmission, (b) Calculated chirp factor versus bias voltage of MZM in chirp-free system.

signal bandwidth, and the FSF null points maintain almost at the same for different bias voltages in chirp-free system. According to the obtained frequency of the first fading null point, we can calculate the chirp factor of MZM. The theoretical chirp factor of chirp-free system should maintain at 0 with different bias voltages. In Fig. 4(b), we can find that a small negative chirp exists in chirp-free system with the fluctuation of 0.025. The main reason is that signals driven on two arms are not exactly differential due to the imperfections of the dual-arm MZM. Such a small chirp can be approximately considered as chirp-free. Then we test the optimum bias voltage for 45-Gbaud PAM-6 signal over a 0/10-km SMF transmission in a conventional chirp-free system. During the optimization of bias voltage for chirp-free system, modulation linearity is the only concern for different transmission distances. The measured results are shown in Fig. 5. We can see that the optimum bias voltages for chirp-free system in optical back-to-back (OBTB) and over a 10-km SMF transmission are the same. In Fig. 6, we give out the measured BER performance versus ROP of 45-Gbaud PAM-6 signal over a 0/10-km SMF transmission in chirp-free system. In OBTB case, VNLE can reduce the required ROP by 1.1-dB at the BER of HD-FEC threshold 3.8×10^{-3} . However, the BER of 45-Gbaud PAM-6 signal is much higher than 3.8×10^{-3} in a conventional chirp-free system over a 10-km SMF transmission. The envelope of the electrical spectrum of received PAM-6 signal over a 10-km SMF transmission is shown as the inset in Fig. 6. It is clear that the CD induced FSF is appeared within the signal bandwidth, which seriously deteriorates the signal quality.

In our proposed scheme, appropriate negative chirp is introduced to overcome the CD induced FSF by adjusting the bias voltage of the single driven dual-arm MZM. The measured channel response versus bias voltage of DMT training signal over an 80-km SMF transmission in proposed pre-chirping system is shown in Fig. 7(a). We can find that the frequencies of FSF null points change with the bias voltage, which is different from the previous chirp-free system. Although there are also 4 FSF

Fig. 5. Measured BER performance of 45-Gbaud PAM-6 signal versus bias voltage of MZM in chirp-free system.

Fig. 6. Measured BER performance versus received optical power of 45-Gbaud PAM-6 signal in conventional chirp-free system at 2.45 V bias voltage.

null points, the frequency of the each FSF null point is higher than that in pretested conventional chirp-free system. It means that pre-chirping can be used to suppress the FSF inside the signal bandwidth to enhance the 3-dB bandwidth of the system. Fig. 7(b) shows the calculated chirp factor versus bias voltage of dual arm MZM operating at single driven state. With the increase of bias voltage from -1 V to 1 V, the introduced chirp factor decreases almost linearly from -0.67 to -0.97 . Then we test the optimum bias voltage for 45-Gbaud PAM-6 signal over a 0/10-km SMF transmission in the proposed pre-chirping system, and the experimental results are shown in Fig. 8. In OBTB case, the optimum bias voltages for PAM-6 signal without and with VNLE both are -0.55 V, namely the optimum linear modulation point. The optimum bias voltages for signal over a 10-km SMF

Fig. 7. (a) Measured channel response versus bias voltage of MZM in pre-chirping system over an 80-km SMF transmission. (b) Calculated chirp factor versus bias voltage of MZM.

Fig. 8. BER performance of 45-Gbaud PAM-6 versus bias voltage of MZM in pre-chirping system over a 0/10-km SMF transmission.

Fig. 9. Measured BER performance versus ROP of 45-Gbaud PAM-6 signal in proposed pre-chirping system.

transmission without and with VNLE are -0.15 V and 0.05 V, respectively. The optimum bias voltage increases from -0.55 V to -0.15 V due to the trade-off between FSF suppression and introduced nonlinear impairments. When VNLE is adopted for nonlinear distortions mitigation, optimum bias voltage further increases from -0.15 V to 0.05 V, which means that more negative chirp is preferable to suppress the FSF induced system BER performance deterioration. The histograms of recovered 45-Gbaud PAM-6 signal over a 10-km SMF transmission without and with VNLE are shown as insets (i) and (ii) in Fig. 8, respectively, in which MZM is biased at optimum pre-chirping point. We can see the pre-chirping induced nonlinear distortions from inset (i), and it is eliminated by VNLE as shown in inset (ii). Fig. 9 shows the measured BER performance versus ROP of 45-Gbaud PAM-6 signal over a 0/10-km SMF transmission. In OBTB case, 1.1-dB receiver sensitivity improvement can be achieved by VNLE at a BER of HD-FEC threshold 3.8×10^{-3} . When the transmission distance extends to 10-km, the BER cannot reach 3.8×10^{-3} due to the pre-chirping induced nonlinear distortions. Fortunately, the nonlinear impairments can be effectively suppressed by VNLE. The BER performance of 45-Gbaud PAM-6 signal over a 10-km SMF transmission is improved from 1.2×10^{-2} to 1.24×10^{-3} at the ROP of 1-dBm. For 45-Gbaud PAM-6 signal over a 10-km SMF transmission, the BER performance of conventional chirp-free scheme and our proposed optimized pre-chirping scheme are 7×10^{-2} and 1.24×10^{-3} at 1-dBm ROP, respectively. It is no doubt that our proposed scheme outperforms the convention chirp-free scheme.

B. 40-Gbaud PAM-8 Transmission System

For 45-Gbaud PAM-6 signal, the raw data rate is 112.5-Gbit/s. After removing the 7% FEC and 1.59% TSs overheads, the net rate is 103.49-Gbit/s. However, the transmitted PAM-6 symbol is not a standard uniform distribution. Then we verify our proposed pre-chirping scheme in 40-Gbaud uniform distributed PAM-8

Fig. 10. Measured BER performance of 40-Gbaud PAM-8 versus bias voltage of MZM in conventional chirp-free system with 1-dBm ROP.

Fig. 11. Measured receiver sensitivity of 40-Gbaud PAM-8 signal in conventional chirp-free system at 2.45 V bias voltage.

transmission system, in which the raw data rate and the net rate are 120-Gbit/s and 110.39-Gbit/s, respectively.

We test the BER performance of 40-Gbaud PAM-8 signal over a 0/10-km SMF transmission in conventional chirp-free system at first. The measured BER performance versus bias voltage at 1-dBm ROP is shown in Fig. 10. It is clear that the optimum bias voltages for 40-Gbaud PAM-8 signal in OBTB and over a 10-km SMF transmission are both 2.45 V. This result agrees well with 45-Gbaud PAM-6 signal transmission in chirp-free system. The measured receiver sensitivity of 40-Gbaud PAM-8 signal over a 0/10-km SMF transmission in the conventional chirp-free system is shown in Fig. 11. VNLE can improve the receiver sensitivity by 1.2-dB at a BER of 3.8×10^{-3} in OBTB case. After a 10-km SMF transmission, the BER of 40-Gbaud

Fig. 12. Measured BER performance of 40-Gbaud PAM-8 signal versus bias voltage of MZM in proposed pre-chirping system with 1-dBm ROP.

PAM-8 signal deteriorates to 8×10^{-2} in conventional chirp-free system due to CD induced FSF. The envelope of the electrical spectrum of received 40-Gbaud PAM-8 signal over a 10-km SMF transmission is given out as the inset in Fig. 11. The fiber CD induced FSF null point is located within the signal bandwidth, which seriously degrades the quality of signal.

In order to realize 10-km transmission distance with the BER below HD-FEC threshold for 40-Gbaud PAM-8 signal, we investigate this experiment in our proposed pre-chirping system. We first test the optimum bias voltage for 40-Gbaud PAM-8 signal over a 0/10-km SMF transmission. The results are shown in Fig. 12, which show a good consistency with 45-Gbaud PAM-6 signal transmission. In OBTB case, the optimum bias voltages for signal without and with VNLE for channel equalization both are -0.55 V. Over a 10-km SMF transmission, the optimum bias voltages for signal without and with VNLE equalizer are changed to -0.15 V and 0.05 V, respectively. The reason is mentioned in results discussion of above-mentioned 45-Gbaud PAM-6 transmission system. Figs. 13(a) and 13(b) show the histograms of recovered PAM-8 signal with FFE-DFE for channel equalization in OBTB and over a 10-km SMF transmission when MZM is biased at 0.05 V (optimum pre-chirping bias voltage for 10-km transmission), respectively. We can find that the signal distortions show a single side distribution rather than symmetric distribution. The single side distribution of distortion is caused by nonlinear modulation, which can be eliminated by VNLE. Figs. 13(c) and 13(d) give out the corresponding histograms of recovered PAM-8 signal after employing VNLE for signal equalization. The pre-chirping induced nonlinear distortions disappear. The measured BER performance versus ROP of 40-Gbaud PAM-8 signal over a 0/10-km SMF transmission in proposed pre-chirping system is shown in Fig. 14. A 1.2-dB receiver sensitivity improvement is obtained in OBTB at a BER of 3.8×10^{-3} when VNLE is applied for nonlinear impairments compensation. Over a 10-km SMF transmission, the VNLE

Fig. 13. Histograms of recovered 40-Gbaud PAM-8 signals (a) in OBTB and (b) over a 10-km SMF transmission with FFE-DFE for channel equalization, (c) in OBTB and (d) over 10-km transmission with VNLE for channel equalization in proposed pre-chirping system when MZM is biased at 0.05 V (optimum pre-chirping point for 10-km transmission).

Fig. 14. Measured BER performance versus ROP of 40-Gbaud PAM-8 signal in proposed pre-chirping system.

can improve the BER performance of 40-Gbaud PAM-8 from 2×10^{-2} to 3×10^{-3} . Our proposed pre-chirping scheme achieves 10-km transmission distance for 40-Gbaud PAM-8 signal in C-band. Compared with conventional chirp-free scheme, the proposed pre-chirping scheme effectively reduces the BER of 40-Gbaud PAM-8 signal over a 10-km SMF transmission from 8×10^{-2} to 3×10^{-3} . The envelope of the electrical spectrum of received 40-Gbaud PAM-8 signal over a 10-km SMF transmission in pre-chirping system is presented as the inset of Fig. 14. Apparently, the CD induced FSF disappears within the signal bandwidth by employing pre-chirping scheme. The recovered time domain PAM-8 signals without and with VNLE for signal equalization in OBTB case at 1-dBm ROP are shown in Figs. 15(a) and 15(b), respectively. VNLE reduces the distortions of PAM-8 symbols effectively. Fig. 15(c) depicts the

Fig. 15. Recovered time domain PAM-8 signals in OBTF transmission (a) without VNLE, (b) with VNLE. Eye diagrams of recovered PAM-8 signals over 10-km SMF transmission (a) without VNLE, (b) with VNLE.

eye diagram of recovered PAM-8 signal with linear FFE-DFE for channel equalization over a 10-km SMF transmission in proposed pre-chirping system at 1-dBm ROP. The eye diagram shows poor opening, especially in high level areas which suffer from the nonlinear distortions caused by pre-chirping. The corresponding eye diagram of PAM-8 signal with VNLE is shown in Fig. 15(d). The eye diagram becomes more opening and the nonlinear distortions are eliminated.

IV. CONCLUSION

In conclusion, we propose and experimentally demonstrate 100G PAM-6 and PAM-8 signal transmission in a dual-arm MZM based IM/DD system for 10-km intra-DCI, in which pre-chirping technique is investigated for the CD induced FSF suppression. To optimize the chirp factor for signal over fiber transmission, only one arm of dual-arm MZM is driven by signal and the bias voltage is adjusted. Unfortunately, the optimum bias voltage always deviates from the linear modulation region, and the modulation nonlinearity is introduced. Thus, VNLE is employed on the receiver side to mitigate the nonlinear distortions. The experimental results show that with the employing of pre-chirping and VNLE, both 45-Gbaud PAM-6 and 40-Gbaud PAM-8 signals are successfully transmitted over a 10-km SMF in an MZM based IM/DD system with the BER still below 3.8×10^{-3} . Compared with conventional chirp-free scheme (MZM operating at push-pull state), the BER of 40-Gbaud PAM-8 signal over a 10-km SMF transmission at a 1-dBm ROP can be reduced from 8×10^{-2} to 3×10^{-3} in proposed pre-chirping system. Apparently, pre-chirping technique effectively improve the system BER performance by enhancing the system robust to the CD caused impairments. The results show that the scheme we proposed is a promising solution for 10-km 100G intra-DCI.

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