Adjustable Chirp to Enhance Chromatic Dispersion Tolerance for PAM4 Transmission in Intra Data Center Communications

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***Abstract*—We investigate the feasibility of using an induced frequency chirp on a dual-drive optical intensity modulator to increase the chromatic dispersion tolerance of 50G and 100G PAM4 signals, for intra-data center applications. Simulated results show that it is possible to extend the maximum transmission distance up to 44% with proper optimization of the modulator extinction ratio and of the attenuation of the driving electrical signal on one of the modulator arms.**

***Index Terms*—chirp, chromatic dispersion, data center interconnect, pulse amplitude modulation.**

I. Introduction

The constant growth of cloud based services and applications is the main driver of the rapid expansion of data centers in number, size and throughput. With a massive amount of data to process, store and deliver to billions of connected terminals, high and diverse traffic flows between data centers (inter data center) and within the same data center (intra data center) must be ensured. This is particularly true for the intra data center case, in a scenario where the number of servers inside data centers keeps increasing, as well as machine to machine traffic between servers that are connected by several kilometers of cables, still remaining in the same data center. To satisfy this demand, it is important to develop compact transceiver modules capable to transmit high data rates, minimizing the impact on cost and power consumption. Intensity modulation with direct detection (IM-DD) at high bit rate per lane (50 and 100 Gb/s) is the primary technology for future intra data center interconnect modules, as it offers high efficiency at a limited complexity when compared to coherent transmission, mostly used in metro or long-haul interconnects. Therefore, viable technologies to enable transmission of multilevel pulse amplitude modulated signals at high symbol rates have been widely investigated. Four-level pulse amplitude modulation (PAM-4) has been chosen as the most suitable format to enable 50G and 100G per lane for long reach intra data center connectivity [1], over distances that usually range from 2 km to up to 10-20 km of standard single-mode fiber (SSMF). However, IM-DD transmission in the C band suffers from strong limitations imposed by chromatic dispersion (CD) in the optical fiber, even at relatively short distances. As it is not possible to digitally compensate for CD in IM-DD systems, and optical dispersion compensation is not attractive as it increases the system complexity, several techniques to counteract the effect of CD on PAM-4 signal transmission have been proposed. Among them, it was demonstrated that inducing a frequency shift (chirp) on a dual-drive optical Mach-Zehnder modulator (DD-MZM) generates a pre-distortion on the transmitted optical signal which increases its tolerance to CD [2], [3]. This technique allows to extend the maximum transmission distance without increasing the system's complexity.

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In this paper we investigate the improvement provided by the induced frequency chirp on a DD-MZM on PAM-4 signal transmission at high data rates (26.5625 Gbaud and 53.125 Gbaud, corresponding to a line rate of 53.125 and 106.25 Gb/s, respectively). We show an improvement of more than 37% in the system reach in both cases, at KP4 pre-FEC bit error rate (BER) of 2.4×10^{-4}.

The remainder of this paper is structured as follows: Section II describes the optical simulator and the methodology employed on the simulations, Section III presents and discusses the obtained results, and Section IV concludes the paper.

II. Simulations

Simulations were carried out using an optical simulator built on GNU Octave, a free-software under General Public License intended for numerical computations [4]. The optical simulator emulates the different blocks of an optical link from the transmitter to the receiver, as illustrated in Fig. 1.

At the transmitter side, 2^{18} pseudo-random bit sequences (PRBS) are mapped onto the four level symbols of PAM4 signaling and upsampled to two samples per symbol. A digital-to-analog converter (DAC) block converts the signal to the analog domain by upsampling it to 32 samples per symbol, and it also filters the electrical signal through a 5th-order low-pass Bessel filter to emulate a bandwidth (BW) limitation of 40 GHz. The electrical PAM-4 signal drives an optical dual-drive Mach-Zehnder modulator (DD-MZM) with

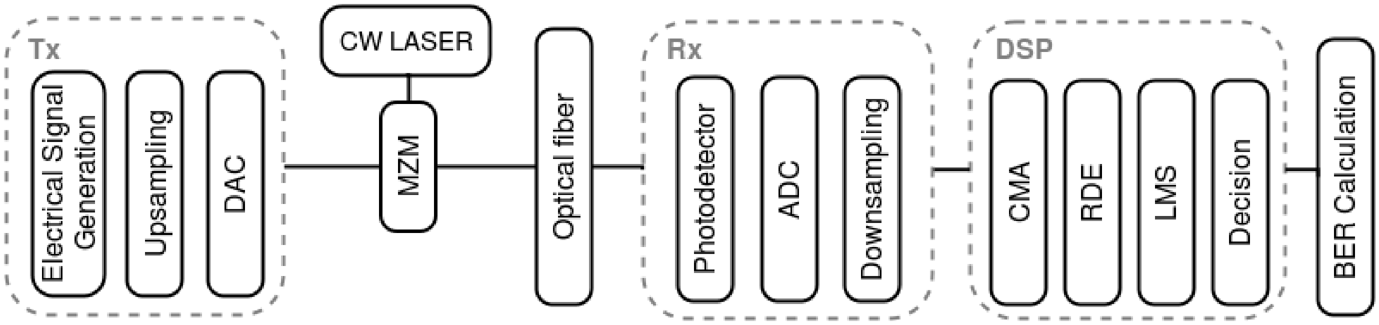

Fig. 1. Diagram of the optical simulator composed by the transmitter (Tx), channel (optical fiber), receiver (Rx), and off-line digital signal processing (DSP) blocks.

$V\pi$ of 3 V and insertion loss of 12 dB, which modulates a continuous-wave (CW) laser with +12 dBm optical power and 100 kHz linewidth, and it also imposes a 50 GHz BW limitation through a 4th-order low-pass Gaussian filter. The channel emulates the signal propagation along the optical fiber (with variable length) considering only the effects from chromatic dispersion, according to [5]:

$$E(z, \omega) = E(0, \omega)\text{exp}(i\beta_2\omega^2 z/2), \tag{1}$$

where $E(z, \omega)$ is the Fourier transform of the signal along the fiber at position z, ω is the angular frequency of the signal, and β_2 is the group-velocity dispersion (GVD) parameter.

At the receiver side, a photodetector (PD) converts the optical signal back into the electrical domain. The analog-to-digital converter (ADC) converts the electrical analog signal to digital with a sampling rate of two samples per symbol, and it also imposes a 40 GHz BW limitation at the receiver side by filtering the signal through a 5th-order low-pass Bessel filter.

The digital signal processing (DSP) is accomplished using three adaptive filters: constant modulus algorithm (CMA) [6], radius directed equalization (RDE) [7], and least-mean-square (LMS) [8], with 6, 6, and 14 taps, respectively. Finally, the signal is decided and the BER is calculated.

The DD-MZM is the key component in our simulations, since it enables pre-compensation of the chromatic dispersion through an induced chirp in the modulator response, which can be adjusted by unbalancing the splitting/combining ratios in the MZM arms, as detailed in the next subsections.

A. Extinction ratio

An ideal DD-MZM has the same splitting/combining ratios between its arms, i.e., $50\%/50\%$, resulting in infinite extinction ratio (ER) and zero chirp. In practice, those ratios are not exactly equal, therefore the MZM in the optical simulator is modeled as follows [9]:

$$E(t) = \frac{1}{2}\,\exp\left(\frac{j\pi V_1(t)}{V_\pi}\right) + \frac{\gamma}{2}\,\exp\left(\frac{j\pi V_2(t)}{V_\pi}\right), \tag{2}$$

where $E(t)$ is the optical output from the modulator, $V\pi$ is the bias voltage, $V_1(t)$ and $V_2(t)$ are the voltages at the arms 1 and 2 of the modulator, respectively. The parameter γ ranges between zero and one to emulate a non-ideal device and it is related to the modulator's ER (δ) according to [9]:

$$\gamma = \frac{(\sqrt{\delta} - 1)}{(\sqrt{\delta} + 1)}. \tag{3}$$

Then, from (3), for an ideal device $\delta \to \infty$ and $\gamma \to 1$. In order to find an optimum pre-distortion to mitigate the effect of chromatic dispersion, we carried out a set of simulations in which we varied the modulator's ER from 0 dB to 40 dB, unbalancing the splitting/combining ratios in the modulator arms to adjust the induced chirp in the MZM.

Our simulations allow to determine the optimum value of the ER for each case under study. However, in practice, the ER of a modulator is not tunable, since it is related to the manufacturing parameters of the device. For this reason, we also investigated a second approach that makes use of an electrical attenuator into one of the two arms of the modulator.

B. Attenuation

To emulate a device that could be adjustable in practice, we included an attenuation factor (α) into one arm of the modulator, as expressed by:

$$E(t) = \frac{1}{2}\,\exp\left(\frac{j\pi V_1(t)}{V_\pi}\right) + \frac{\gamma}{2}\,\exp\left(\frac{j\pi V_2(t)\ \boldsymbol{\alpha}}{V_\pi}\right). \tag{4}$$

Then, for a fixed finite ER, we ranged α from 0 (maximum attenuation) to 1 (no attenuation). In this case, the attenuation is responsible for inducing a chirp by unbalancing the signal between the modulator's arms.

Results for both ER and attenuation variations are presented in the next section for PAM4 transmissions at baud rates of 26.5625 Gbaud and 53.125 Gbaud.

III. Results and discussion

Figure 2(a) and 2(b) show the simulation results of BER as a function of the DD-MZM ER, with fixed attenuation coefficient α of 1. For the two symbol rates, three values of transmission distance were considered, namely 4, 4.5 and 5.5 km at 53.125 Gbaud (100G channel rate) and 14, 16 and 18 km at 26.5625 Gbaud (50G channel rate). Results show an

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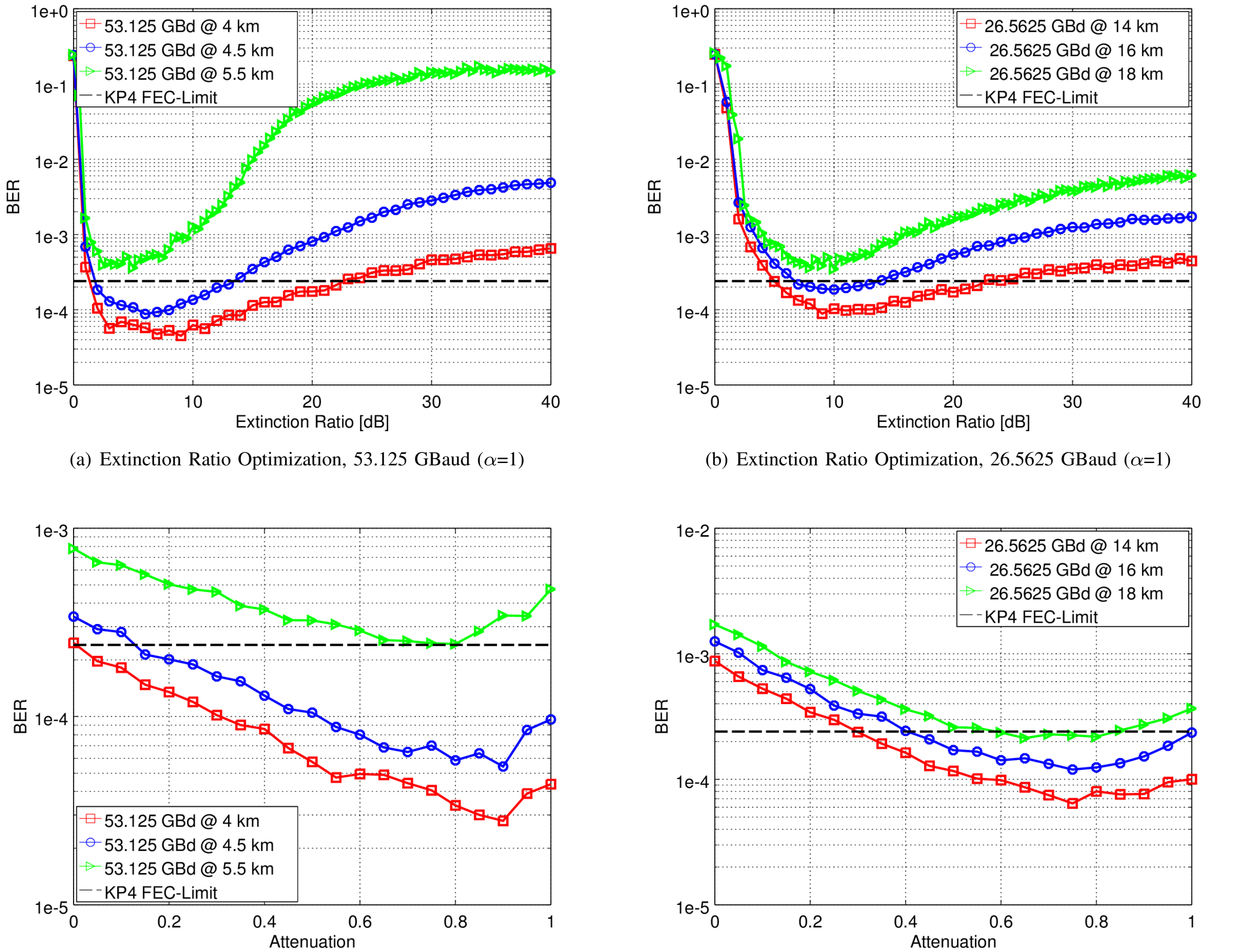


(a) Extinction Ratio Optimization, 53.125 GBaud (α=1)

(b) Extinction Ratio Optimization, 26.5625 GBaud (α=1)

(c) α Optimization, 53.125 GBaud (ER=6dB)

(d) α Optimization, 26.5625 GBaud (ER=10dB)

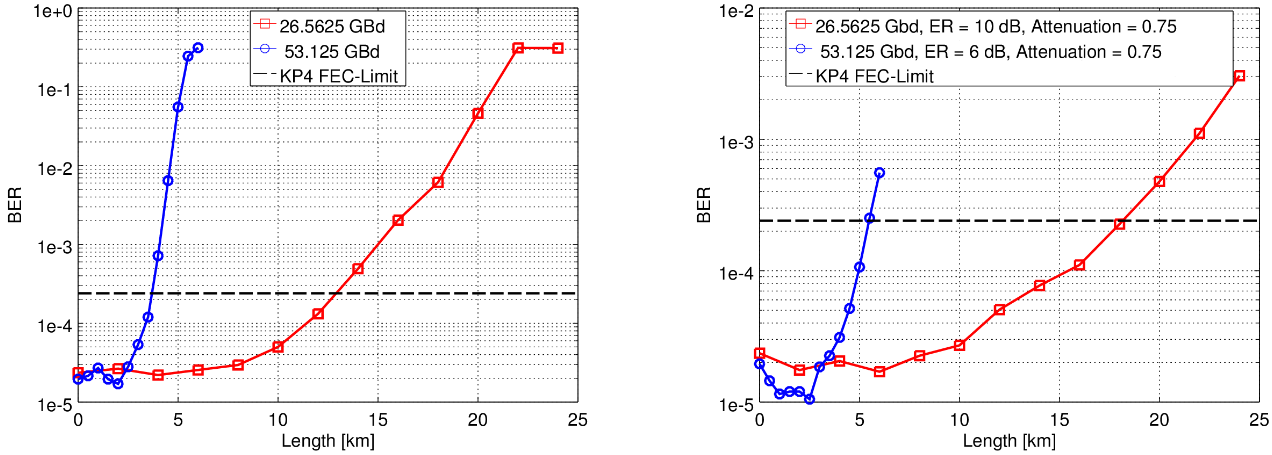
Fig. 2. DD-MZM optimization to improve chromatic dispersion tolerance by adjusting the extinction ratio and attenuation (α) at two different baud rates: 53.125 GBaud and 26.5625 GBaud.

optimal value of the ER of $\sim$10 dB for the 50G case and of $\sim$6 dB at 100G, for all the considered link distances. After determining the optimal value of the ER, we then varied the α coefficient of the electrical driving signal on one arm of the DD-MZM and evaluated the BER in order to determine the optimal α parameter.

Meanwhile, as shown in Fig. 2(c) and 2(d), the optimal value of α was found to be $\sim$0.75 for the 50G and 100G cases, at the longest transmission distance (18 km and 5.5 km for 50G and 100G, respectively). Finally, Fig. 3 shows transmission results of BER vs distance at the two line rates under study, where the system performance with no induced chirp on the DD-MZM, shown in Fig. 3(a), is compared to the case of induced chirp with optimized parameters, reported in Fig. 3(b). KP4 pre-FEC BER limit of 2.4×10^{-4} was considered. As shown, inducing an optimized frequency chirp on the DD-MZM it was possible to extend the maximum system reach from 4 km to 5.5 km for the 100G PAM-4 signals and from 12.5 km to 18 km for the 50G signals, corresponding to an increment of 37.5% and 44%, respectively.

IV. Conclusion

We demonstrated by numerical simulations that by properly inducing a frequency chirp on a dual-drive Mach-Zehnder optical modulator it is possible to enhance the tolerance to chromatic dispersion effects in IM-DD PAM-4 signal transmission at high data rates (50G and 100G per channel). The proposed technique allows to extend the system reach up to more than 40% with no impact on the system complexity, as no additional optoelectronic components or power hungry DSP algorithms are needed. For these reasons, this solution proves to be suitable for application in high-speed intra-data center connectivity, where low cost and low complexity of the optical transceivers are primary concerns.



(a) Reach without Induced Chirp

(b) Reach with Induced Chirp

Fig. 3. BER vs transmission distance without (a) and with (b) an induced chirp on the DD-MZM to mitigate chromatic dispersion effects.

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