Investigation on the Dispersion Tolerance in Dual-drive MZM-based DAC-less Optical PAM4 Transmission

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Abstract: We investigate the chirp characteristics of the two PAM4 generation methods based on dual-drive MZM. Prominent difference in transmission performance between the two methods is experimentally shown for 112Gb/s PAM4 signals when chromatic dispersion exists.

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1. Introduction

4-level pulse amplitude modulation (PAM4) has been adopted as a cost-effective solution for next generation 400G short reach interconnects. For the generation of PAM4 signals in the electrical domain before electrical-to-optical (EO) conversion, a 2-bit digital to analog converter (DAC) is needed and the electrical amplifier is required to have good linearity. Alternatively, we can synthesize the PAM4 signal in the optical domain with two binary electrical signals. This approach has almost no requirement for the linearity and reduces cost. Therefore, PAM4 generation in the optical domain with binary signals, i.e. DAC-less PAM4 generation, has been widely studied and demonstrated in the past few years [1-5]. In [2], a dual-parallel Mach-Zehnder modulator (MZM) is adopted, and two binary signals are applied to the two sub-MZMs. In [3], a segmented MZM is used to generate optical PAM4 signals, with two binary electrical signals applied to the two segments in the Mach-Zehnder interferometer (MZI) arm. Another approach is to directly apply two binary signals to the two arms of one dual-drive MZM (DD-MZM) [4,5]. Compared with the dual-parallel MZM and segmented MZM, the DD-MZM has a lower cost since it has a commercially mature product and contains only one MZI. However, the major issue of using DD-MZM to generate optical PAM4 signals is the inherent frequency chirp, which occurs during the modulation of different data on the two arms, i.e. the DD-MZM no longer works in a push-pull operation.

To the best of our knowledge, the transmission performance in the presence of the frequency chirp in DD-MZM-based optical PAM4 generation has not been studied. In fact, there are two methods to generate PAM4 signals with the DD-MZM. In the first method the peak-to-peak voltage (Vpp) of the upper arm is twice of the lower arm, while in the second method the Vpp of the upper arm is half of the lower arm. In this work we first illustrate that unlike signals in conventional MZM-based systems that present either positive chirp or negative chirp, the PAM4 signals synthesized from a DD-MZM contain a mix of positive chirp and negative chirp. The two methods aforementioned are completely different in the weight of positive chirp and negative chirp. In particular, the first method is dominated by negative chirp with middle eye presenting negative chirp and upper/lower eyes presenting positive chirp, while the second method is the opposite. We conduct 112Gb/s PAM4 transmission experiments using DD-MZM, and show that the BER of the negative chirp dominant method outperforms the positive chirp dominant method by an order of magnitude in the presence of positive chromatic dispersion (CD). Therefore, a proper method should be chosen when CD exists. This result provides an important reference for practical system design of DD-MZM based PAM4 transmission systems.

2. Frequency chirp in DD-MZM-based PAM4 generation

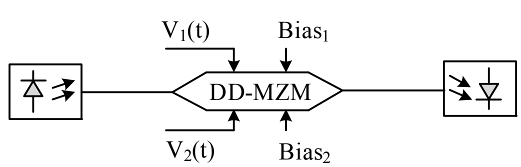

Fig. 1. The basic structure of a DD-MZM.

Fig. 1 shows the basic structure of the DD-MZM and the voltages applied to it. When the DD-MZM is used for intensity modulation (IM), the differential value of the two bias are set as $\frac{V_\pi}{2}$ to make it work on the quadrature point. Generally, the output of the DD-MZM can be expressed as

$$E_{out} = E_{in} \cos\frac{\pi}{2V_\pi}\big(V_1(t) - V_2(t)\big) \cdot \exp\left(j \cdot \frac{\pi}{2V_\pi}\big(V_1(t) + V_2(t)\big)\right) = E_{in} \cdot H_{amp} \cdot H_{phase} \quad (1)$$

In Equation (1), the H_{amp} determines the amplitude of the output and is the main part for IM, whereas the H_{phase} is the phase of the output and causes frequency chirp to IM. When the DD-MZM is in a push-pull operation, $V_1(t)$ and $V_2(t)$ should be balanced, i.e. $V_1(t) = -V_2(t)$. In this case, H_{phase} is a constant, and no frequency chirp occurs when the voltages change. However, in order to generate optical PAM4 signals with two binary signals, $V_1(t)$ and $V_2(t)$ are no longer balanced because $V_1(t)$ and $V_2(t)$ are from different binary data sequences and also have different Vpp. According to Equation (1), it is easy to figure out that there are two methods to generate PAM4 signals with two binary signals:

(i) *method 1*: the Vpp of $V_1(t)$ is two times of $V_2(t)$ as shown in Fig. 2(a).

(ii) *method 2*: the Vpp of $V_1(t)$ is half of $V_2(t)$ as shown in Fig. 2(b).

For simplicity, we assume one binary signal has a voltage swing from -2 to 2, and the other has a voltage swing from -1 to 1. The mapping between the voltages of the two binary signals and the generated PAM4 symbols is illustrated in Fig. 2. For example, in *method 1* according to Equation (1), when $V_1(t) = -2$ and $V_2(t) = 1$, $V_1(t) - V_2(t)$ in the H_{amp} can be -3, which corresponds to Symbol 3 based on the cosine modulation curve in Fig. 2(a).

Next, we characterize the frequency chirp of the two methods. The polarity of chirp is determined by $\Delta f/\Delta I$, in which Δf is the optical frequency change and ΔI is the optical intensity change. When $\Delta f/\Delta I < 0$ negative chirp occurs, and when $\Delta f/\Delta I > 0$ positive chirp occurs, as illustrated in Fig. 2(c). In the DD-MZM-based optical PAM4 generation, based on Equation (1), Δf is related to $\Delta\big(V_1(t) + V_2(t)\big)$, and ΔI is related to $-\Delta\big(V_1(t) - V_2(t)\big)$. Accordingly, the polarity of chirp ($\Delta f/\Delta I$) is shown in Fig. 2 in the mapping between the voltages and the symbol intensity level I. For example, in *method 1*, when the PAM4 symbol changes from 3 to 2 ($\Delta I < 0$), $V_1(t) + V_2(t)$ changes from -1 (-2+1) to -3 (-2-1), which indicates that $\Delta f < 0$. In this case, $\Delta f/\Delta I > 0$ and positive chirp occurs. Similarly, the chirp polarities of all other transient changes are depicted in Fig. 2.

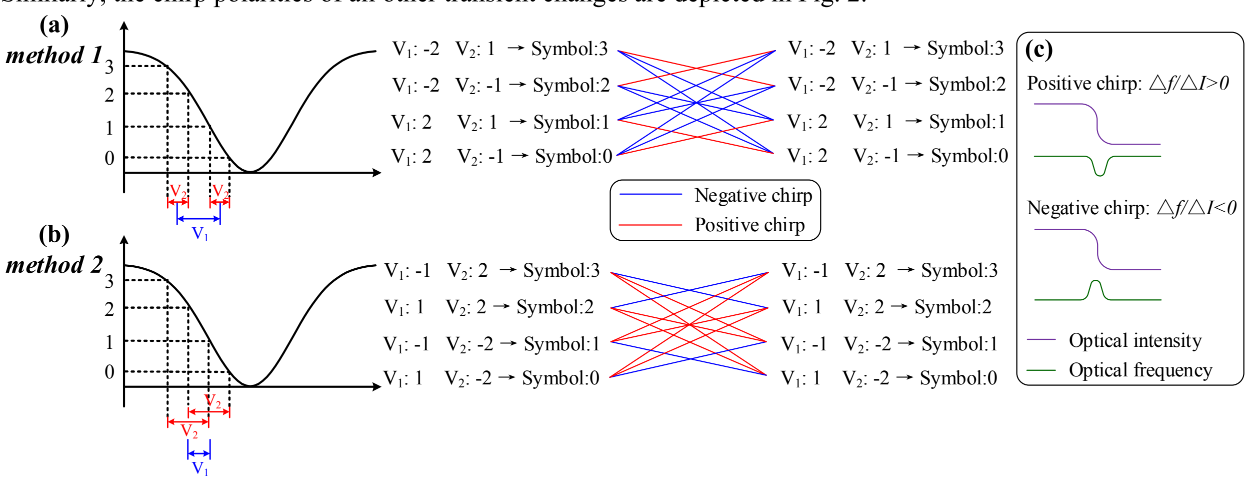

Fig. 2. The modulation curve of DD-MZM and the applied voltages of (a) *method 1* and (b) *method 2*. The chirp polarities during the transient changes of PAM4 signals for (a) *method 1* and (b) *method 2*. (c) Illustration of positive chirp and negative chirp.

From Fig. 2, two major and interesting phenomena can be observed:

(i) In *method 1*, 8 transient changes in PAM4 signals present negative chirp and 4 transient changes presents positive chirp; in *method 2*, 4 transient changes present negative chirp and 8 transient changes presents positive chirp. Therefore, *method 1* is dominated by the negative chirp and *method 2* is dominated by the positive chirp.

(ii) In *method 1*, transient changes in the middle eye present negative chirp while transient changes in upper and lower eyes present positive chirp; In *method 2*, transient changes in the middle eye present positive chirp while transient changes of upper and lower eyes present negative chirp. Since negative and positive chirp induce completely different fiber responses, eye diagrams of the two methods is expected to be completely different when CD is applied. Particularly, when CD is positive, for *method 1*, the middle eye is expected to get larger and the upper/lower eyes are expected to be smaller. For *method 2*, an opposite eye diagram change is expected to be observed.

3. Experiment

Fig. 3(a) plots the experimental setup. In the transmitter side, a C-band DD-MZM (Fujitsu 7937EZ) with a 3dB bandwidth of ~30GHz is used for the investigation. The voltages of the two biases are set to make the DD-MZM operate at the quadrature point. Two binary signals with a bit rate of 56Gb/s are generated from two bit pattern generators (BPG), and amplified by two electrical amplifiers (EA) before applied to the RF ports of the DD-MZM, where the two binary 56 Gb/s signals are synthesized to one 112Gb/s PAM4 signal. The Vpp of the two binary signals are adjusted to match the modulation curve and make the four levels equally spaced. After fiber transmission with a dispersion from 0~17ps/nm, the optical signal is first attenuated by a variable optical attenuator (VOA) and then detected by a PIN. Finally, the detected electrical signal is captured by a real-time oscilloscope (RTO) with a sampling rate of 160GS/s for offline feedforward equalization (FFE) and error counting. In the experiment, the two PAM4 generation methods as aforementioned in Section 2 are studied by adjusting the Vpp of the two binary signals.

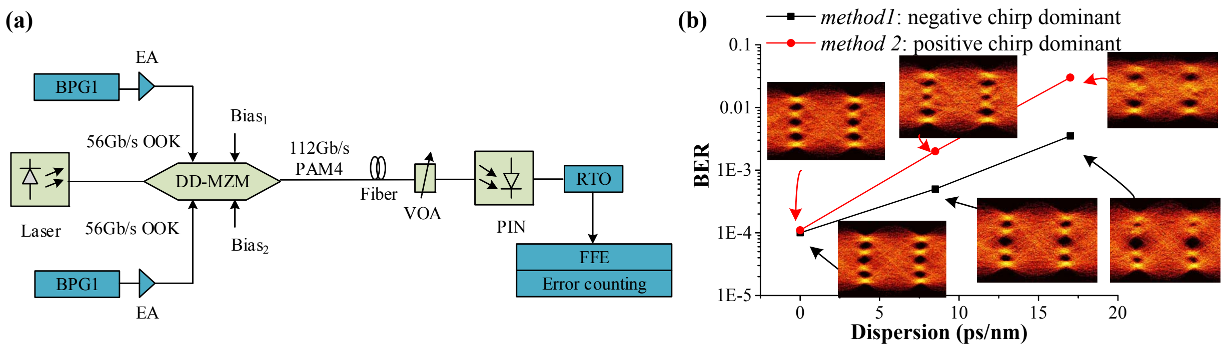

Fig. 3. (a) Experimental setup. (b) BER results.

The experimental results are shown in Fig. 3(b). At first when there is no CD, similar BER performance at ~8e-5 is observed with the two methods. However, with the increase of fiber dispersion, obvious performance distinction between the two methods is observed. For *method 1*, the middle eye occupies the Euclidean distance of the upper/lower eyes with the increase of dispersion. This is because (i) the middle eye in *method 1* mainly manifest negative chirp which enhances the bandwidth of the fiber response in the presence of positive dispersion; (ii) the upper and lower eyes present more positive chirp, which reduces the bandwidth of fiber response. After 17ps/nm dispersion, BER under HD-FEC can still be achieved. In contrast, for *method 2*, upper/lower eyes occupy the Euclidean distance of the middle eye with the increase of dispersion. Since for *method 1* the degradation is shared by two eyes (upper and lower), and for *method 2* the degradation is only applied to one eye (middle), the BER of *method 2* degrades more quickly than *method 1*. The HD-FEC can only be achieved when CD is lower than 8.5ps/nm for *method 2*. According to these results, *method 1* should be chosen in practical deployments. While the results in the experiment are under the positive dispersion condition, results under the negative dispersion is anticipated to be the opposite to what is presented in the above context. To conclude, in dual-drive MZM based optical PAM4 transmissions, *method 1* should be chosen when dispersion is positive and *method 2* should be chosen when dispersion is negative.

Particularly for 400GE O-band edge channels, *method 1* should be chosen for ~1330nm wavelengths which have positive residual dispersion, and *method 2* should be chosen for ~1270nm wavelengths which have negative residual dispersion.

4. Conclusions

In this work, we have investigated the chirp effect of the two PAM4 generation methods based on DD-MZM. Analysis show that PAM4 signals synthesized from DD-MZM is mixed by positive chirp and negative chirp. One method is dominated by negative chirp with middle eye presenting negative chirp and upper/lower eyes presenting positive chirp, which causes degradation of upper/lower eyes in the presence of positive dispersion. The other method is the opposite. We experimentally show that the BER of the negative chirp dominant method outperforms the positive one by an order of magnitude for 112Gb/s PAM4 signals.

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5. References

[1] J. Verbist, et al., “DAC-less and DSP-free PAM-4 Transmitter at 112 Gb/s with Two Parallel……”, ECOC2017, Paper Th.PDP.C.5.
[2] A. Samani, et al., “A Silicon Photonic PAM-4 Modulator Based on Dual-Parallel……”, IEEE Photonics Journal, vol. 8, no. 1, 2016.
[3] D. Patel, et al., “Silicon photonic segmented modulator based electro-optic DAC……”, IEEE Photonics Tech. Letters, vol. 27, no. 23, 2015.
[4] L. Zheng, et al., “Silicon PAM-4 optical modulator driven by two binary electrical signals with……”, Optics Letters, vol. 42, no. 11, 2017.
[5] B. Moeneclaey, et al., “A 64 Gb/s PAM-4 Linear Optical Receiver”, OFC2015, Paper M3C.5.