WHITE PAPER

PAM-4 Transmitter PIC Design Using Segmented-Electrode Mach-Zehnder Modulators

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Introduction

In data center optics, 4-level Pulse Amplitude Modulation (PAM-4) signaling is gradually overtaking Non-Return to Zero (NRZ) signaling. [1-3] Although both signaling schemes use intensity modulation and direct detection, PAM-4 encodes 2 bits into four intensity levels, reducing bandwidth requirements for a given data rate by half. In other words, with PAM-4 signaling, transmission of 40Gbps data rate requires components with 20GHz bandwidth (corresponding to 20GBdps symbol rate).

This paper describes how to design a PAM-4 transmitter photonic integrated circuit (PIC) using a Segmented-Electrode Mach-Zehnder Modulator (SE-MZM), and how to study the impact of manufacturing and packaging variations on overall PIC performance.

SE-MZM-Based PAM-4 Transmitter PIC

Traditionally, in photonic PAM-4 transmitters, an MZM is driven by an electrical digital-to-analog converter (DAC) with an electrical driver, which requires energy-inefficient electronics. Implementations with nested modulators and drivers also exist, but they typically have larger footprints.

As an alternative, we can accomplish a DAC-less design using inherent DAC capabilities of segmented phase-shifters [4]. The longer interaction length in conventional traveling-wave MZMs (TW-MZMs) helps reduce drive voltage due to technology-dependent $V_{\pi}L$. However, longer electrodes result in higher RF losses and mismatch in group velocities between RF and optical signals, which in turn impact modulation bandwidth [5]. The segmented approach offers the advantage of longer interaction lengths without increased loss by shifting the velocity matching to electronic timing circuits to control timing of applied electrical signals to match the optical delay between segments [6].

Figure 1 shows an OptSim Circuit schematic of a PAM-4 transmitter using an SE-MZM made from discrete PIC elements.

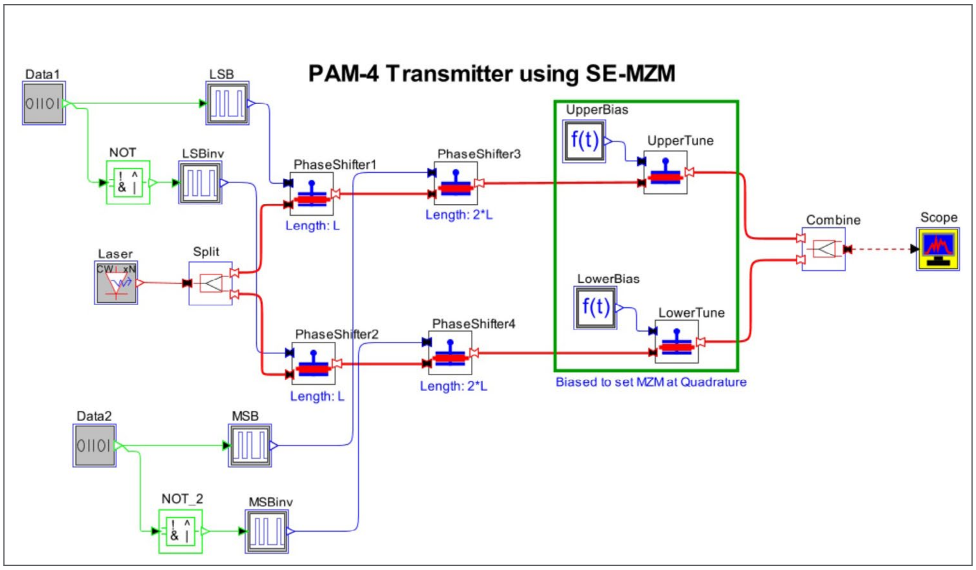

Figure 1: Schematic of a PAM-4 transmitter using SE-MZM

The topology comprises bidirectional PIC elements such as an optical splitter 1x2 and combiner 2x1 with user-defined power ratio, and two pairs of traveling wave optical phase shifters. The phase shifters are used to implement the segmented MZM. The lengths of the phase-shifter are binary-weighted so that each binary word can be applied directly and the number of segments is minimized, which helps with integration. The first segment's length corresponds to 1/3 of the total MZM length; the second segment corresponds to 2/3 of the total MZM length. The 20Gbps bit sequence has already been split into separate bit patterns corresponding to the most- and least-significant bits (MSB and LSB, respectively), with the top driver modulating the first MZM segment using the LSB pattern, and the bottom driver modulating the second MZM segment using the MSB pattern.

Each traveling wave phase shifter has an optical waveguide and a surrounding electrical transmission line that introduces change in the waveguide's refractive index and propagation loss. The interaction between the electrical and optical signals is distributed along the propagation direction. The waveguide's thermal behavior (and hence modulator) is modeled with the derivative of effective index, parameter $V_{\pi}L$, and propagation loss as functions of temperature [7].

Each MZM arm also has a phase tuner near the combiner, which sets the modulator at quadrature. A simple 90-degree phase-shifter model from OptSim Circuit in one of the arms could have also accomplished the same though in a packaged product, external controls for tuning are preferred to account for additional need for tuning due to, for example, factors related to ambient or manufacturing tolerances.

The CW light is modulated by an electrical signal derived from PRBS data followed by an electrical driver. The inverter model provides push-pull electrical bias to one of the electrodes compared to the other. At the output of the SE-MZM PIC, a scope is connected to observe transmitter output.

Figure 2 shows the PAM-4 modulated optical signal (left) and its spectrum (right).

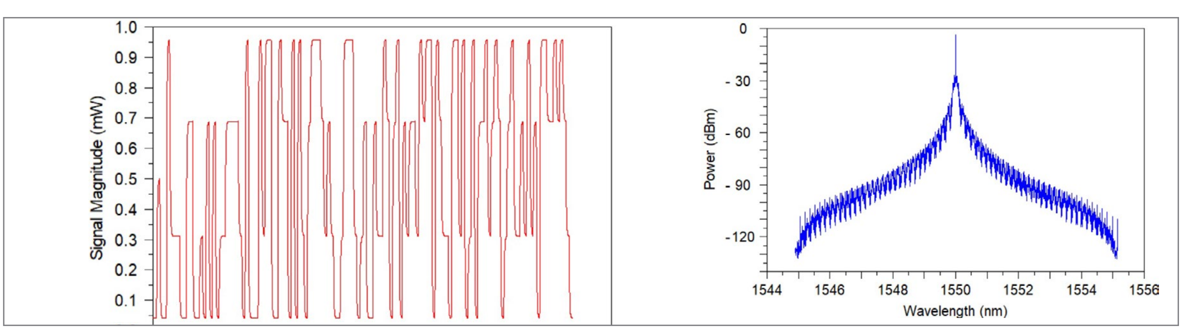

Figure 2: SE-MZM PAM-4 transmitter output signal (left) and spectrum (right)

Figure 3 shows a 4-level PAM-4 optical eye diagram at the output of the transmitter.

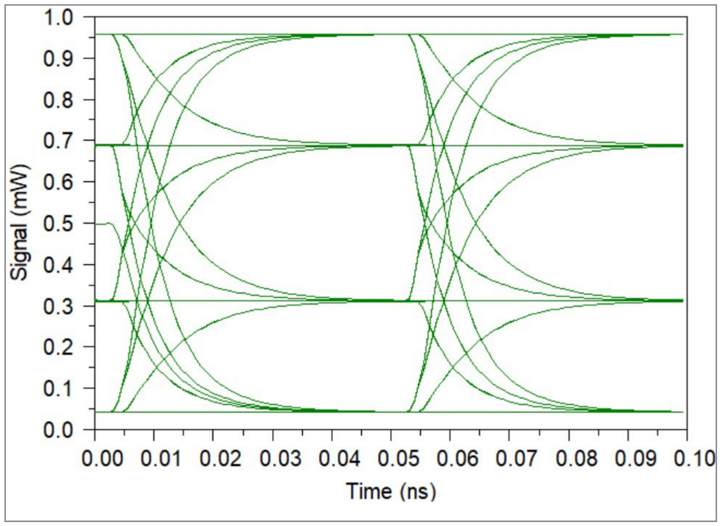

Figure 3: Optical eye diagram at the transmitter output

Now that we understand the design motives and operation of a DAC-less optical PAM-4 transmitter using SE-MZM, we will next use this segmented design concept to build a PAM-2 transmitter to analyze performance with respect to the deviations in segment-to-segment distance, driver time-delay and response time – all of which have direct impact on overall yield of SE-MZM-based high-speed transmitter PICs.

Impact of Inter-Segment Distance Deviations

In the previous section, we designed an optical PAM-4 transmitter PIC using SE-MZM. In SE-MZM, electrodes are split in segments of specific lengths to achieve desired level of amplitude modulation. Whether the phase shifter lengths are binary weighted or thermometer coded [8], the manufacturing process variations can result in deviations in the inter-electrodes, thereby affecting the MZM's bias and bandwidth. OptSim is an excellent platform for Monte Carlo analyses to achieve design for manufacturing (DFM) [9].

In this section, we study the impact of inter-segment deviations in a PAM-2 transmitter using an SE-MZM made from discrete PIC elements in OptSim Circuit. The schematic is shown in Figure 4.

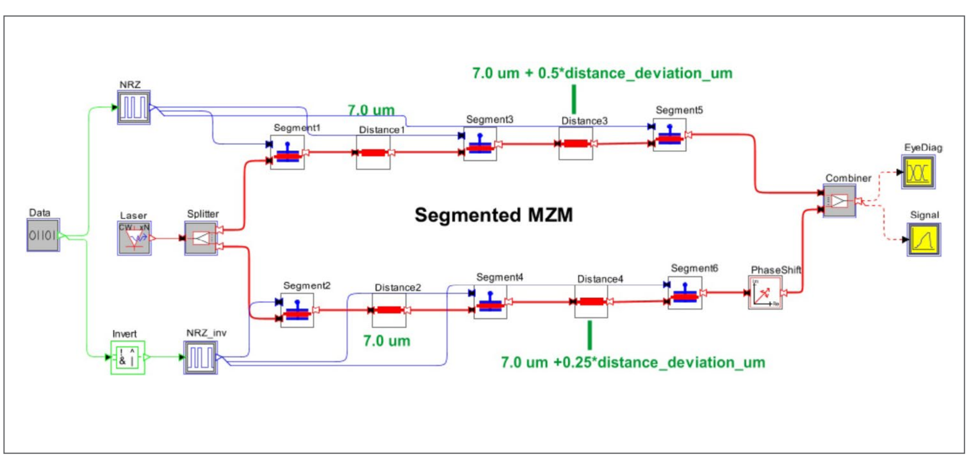

Figure 4: Schematic of a PAM-2 transmitter using SE-MZM

The topology comprises bidirectional PIC elements such as optical splitter 1x2 and combiner 2x1 with user-defined power ratio, and pairs of traveling-wave optical phase shifters. The phase shifters are used to implement the segmented MZM. OptSim Circuit's bidirectional waveguide model connects phase-shifters and implements deviations in separations between the segmented electrodes. A parameter scan is set for distances between the electrode segments. Figure 5 shows the PAM-2 modulated optical eye diagrams.

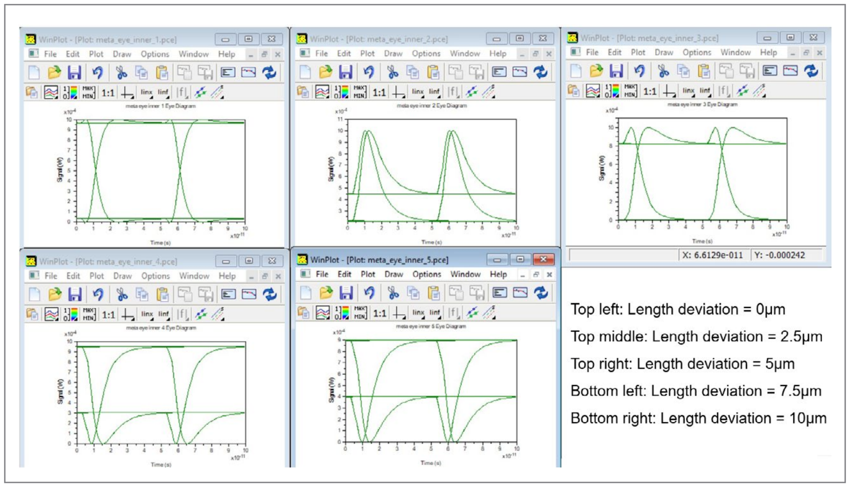

Figure 5: Optical eye diagrams at the transmitter output

The bandwidth narrowing due to deviations in inter-electrode distances is obvious: the higher the deviation, the worse the eye opening.

In the next several sections, we extend this study to analyze performance with respect to the deviations in driver time-delay and response time, both of which have a direct impact on the performance of SE-MZM-based high-speed transmitter PICs.

Impact of Driver Time-Delay Deviations

In the previous section, we studied the impact of deviations in the inter-electrode distances on the transmitter bandwidth. In SE-MZM transmitters, phase shifters are driven by electrical driving circuits. The manufacturing process variations and packaging constraints (such as different lengths of copper traces to electrical pads due to chip placement in a die) can result in electrical timing deviations in driving electrodes, thereby affecting mismatch in RF and optical group velocities and ultimately the bandwidth of the transmitter PIC.

In this section, we study the impact of driver time-delay deviations for an SE-MZM PAM-2 transmitter. The OptSim Circuit schematic is shown in Figure 6.

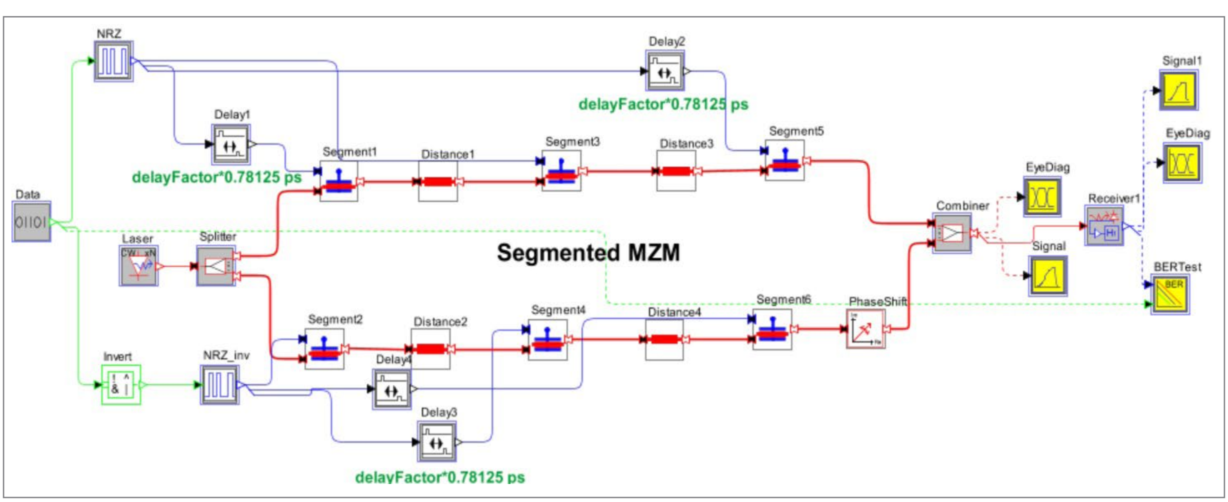

Figure 6: Schematic of a PAM-2 transmitter using SE-MZM

The topology comprises bidirectional PIC elements such as optical splitter 1x2 and combiner 2x1 with user-defined power ratio, and pairs of traveling-wave optical phase shifters. The phase shifters are used to implement the segmented MZM. OptSim Circuit's bidirectional waveguide model connects phase-shifters and implements separations between the segmented electrodes. The electrical time delay block models driver timing delay deviations as integer multiples of sampling interval, which for the design under study is 0.78125ps corresponding to data rate of 20GBd/s sampled at 64 samples per symbol. The lower arm of the MZM uses a discrete 90-degree phase-shifter model from OptSim Circuit to bias the MZM at quadrature.

The CW light is modulated by an electrical signal derived from PRBS data followed by an electrical driver. The inverter model provides push-pull electrical bias to one of the electrodes compared to the other. At the output of the SE-MZM PIC, an eye diagram analyzer and a signal analyzer are connected to observe transmitter outputs. A back-to-back receiver at the SE-MZM PIC's output detects received signal, and the bit error rate (BER) tester is used to estimate driver timing-delay-induced penalties on the BER.

A parameter scan is set for driving delays at segment electrodes as integer multiples of the sampling interval. Figure 7 shows PAM-2 modulated optical eye diagrams with different values of drive delays.

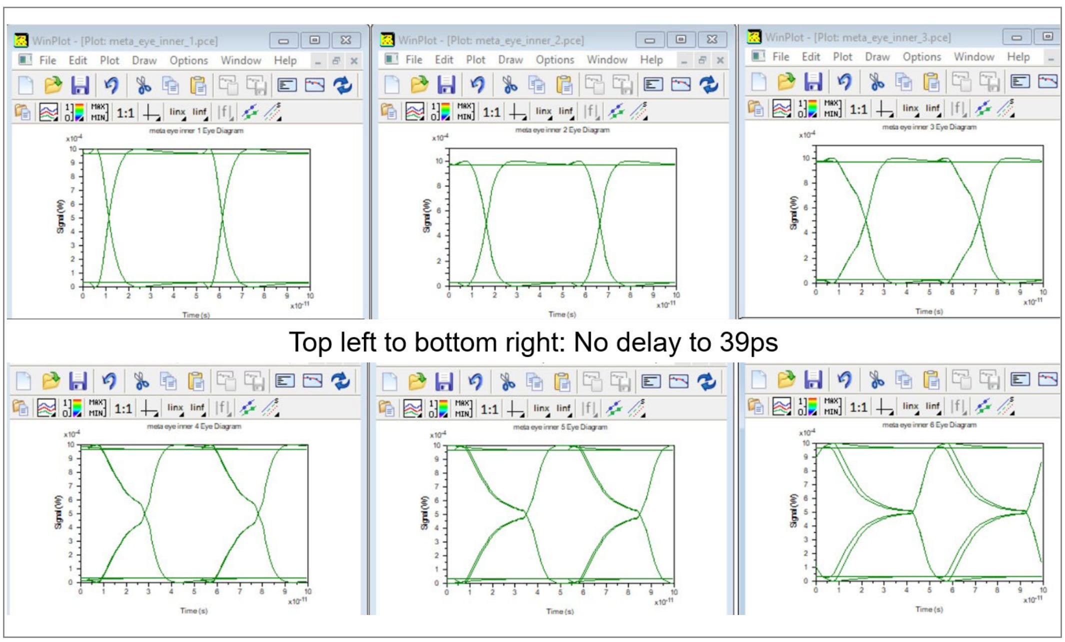

Figure 7: Optical eye diagrams at the transmitter output

The resulting bandwidth penalties can also be visualized as back-to-back BER at the transmitter chip as shown in Fig. 8.

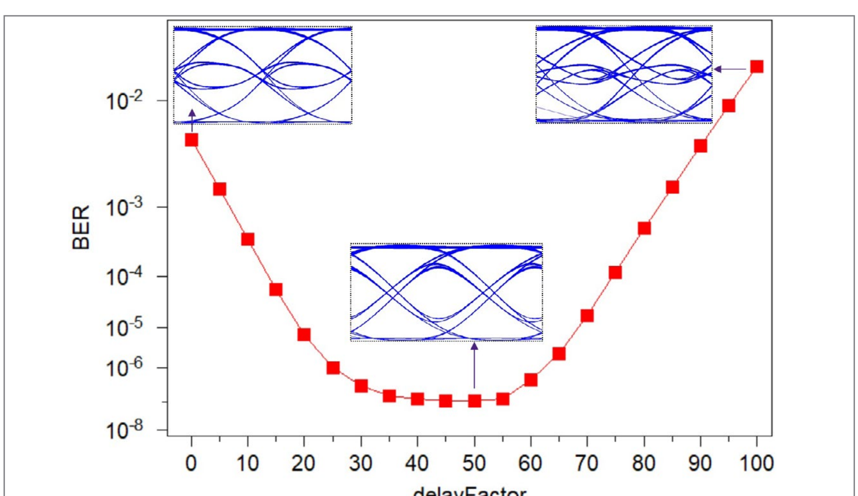

Figure 8: BER as a function of driving time delay

Optimal performance is achieved when optical and RF group velocities match.

The preceding study demonstrated the impact of timing delay deviations due to fabrication tolerances of electrical driver circuitry, as well as different electrode-to-pad RF trace lengths arising from the packaging constraints. This analysis helps designers find optimal trace-lengths to obtain performance within acceptable bounds.

In the next section, we analyze PIC performance with respect to the deviation in electrode response time, which is an important design consideration in SE-MZM-based high-speed transmitter PICs.

Impact of Capacitive Charge and R-C Response Times

Previously, we studied the impact of deviations in the inter-electrode distances and driver circuit's time variations on the bandwidth of an SE-MZM transmitter. In SE-MZMs, the R-C time response of phase shifter electrodes directly impacts bandwidth of the transmitter PIC.

The junction capacitance of the p-n diode and parasitics from packaging both contribute to the capacitive charge and R-C time limitations in a phase shifter. In our study, we lump both effects into the overall R-C response time of the phase shifter. The schematic is shown in Figure 9.

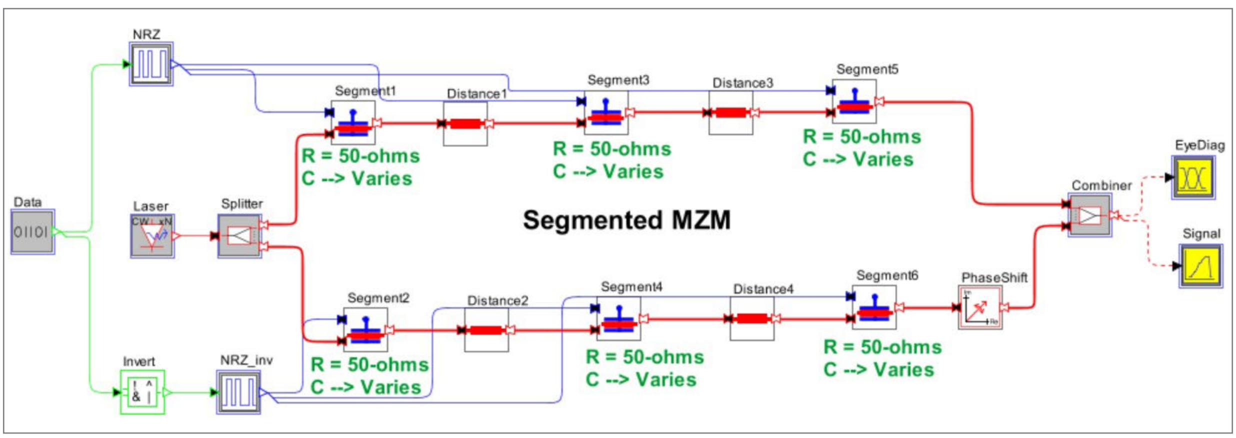

Figure 9: OptSim Circuit schematic of a PAM-2 transmitter using SE-MZM

The topology comprises bidirectional PIC elements such as optical splitter 1x2 and combiner 2x1 with user-defined power ratio, and pairs of traveling-wave optical phase shifters. As shown in Figure 10, the electrical response model of the phase shifter is set to "RC."

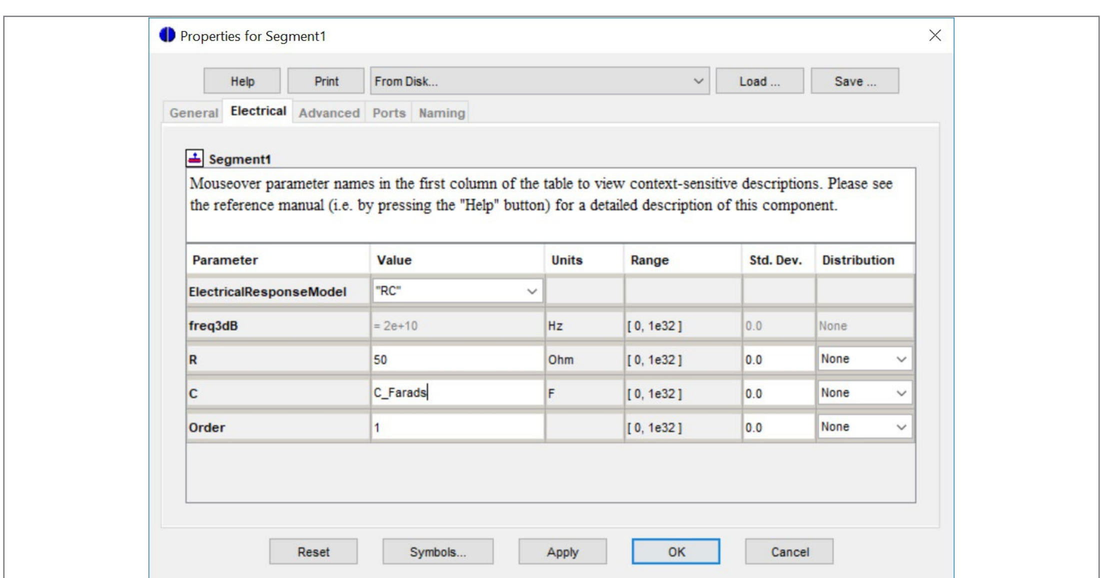

Figure 10: Choice of electrical response model via the parameter window of the phase shifter model

A parameter scan is set for capacitance to model different amounts of capacitive charge and R-C times. Figure 11 shows PAM-2 modulated optical eye diagrams with different values of R-C response.

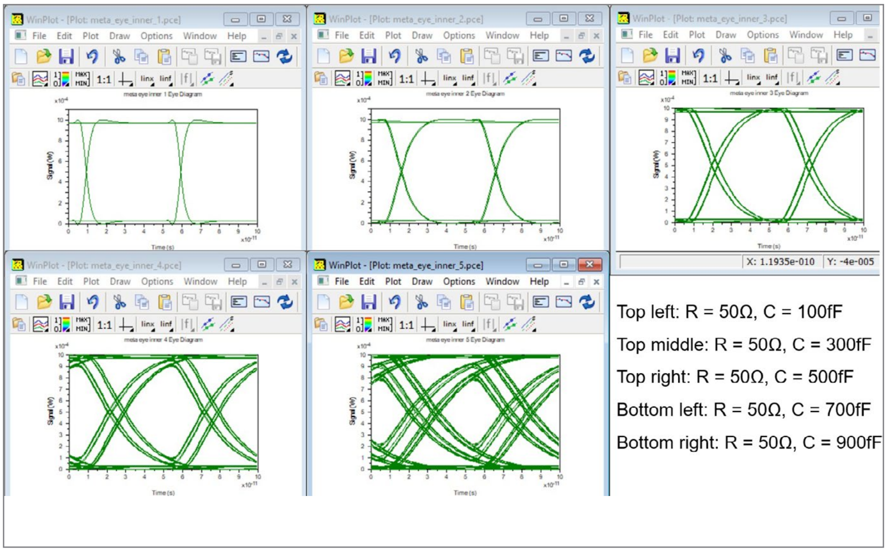

Figure 11: Optical eye diagrams at the transmitter output

The effect of R-C time variations due to the capacitive charging at the p-n junction and the packaging parasitics can be seen in Figure 11. As expected, a higher response time adversely affects modulation speed.

Summary

This paper presents design considerations for SE-MZM based transmitters commonly used for DAC-less, multi-level optical modulation formats. We designed a PAM-4 transmitter for data center interconnect applications in OptSim Circuit and analyzed impairments due to deviations in some of the key design parameters arising from packaging, technology, and manufacturing process variations. OptSim Circuit, an advanced photonic circuit simulation tool, is part of the Synopsys PIC Design Suite. The PIC Design Suite offers photonic-aware physical layout capabilities enabled by support for foundry-specific PDKs. [10]

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