

Design and Simulation of a Mach-Zehnder Modulator with Push-Pull Configuration

Products: RSoft BeamPROP, Multi-Physics Utility,
ADS Photonic Designer
Applications: PICs

Introduction

Before presenting the application note, let us briefly review several fundamental concepts related to the Mach-Zehnder Modulator (MZM).

- What is a Mach-Zehnder modulator?

The Mach-Zehnder modulator is an interferometric device fabricated from materials exhibiting a strong electro-optic effect, such as Silicon, LiNbO₃, GaAs, or InP. Applying electric fields to the modulation arms changes their optical path lengths, resulting in phase modulation. Recombining the two arms with different phase shifts converts phase modulation into intensity modulation.

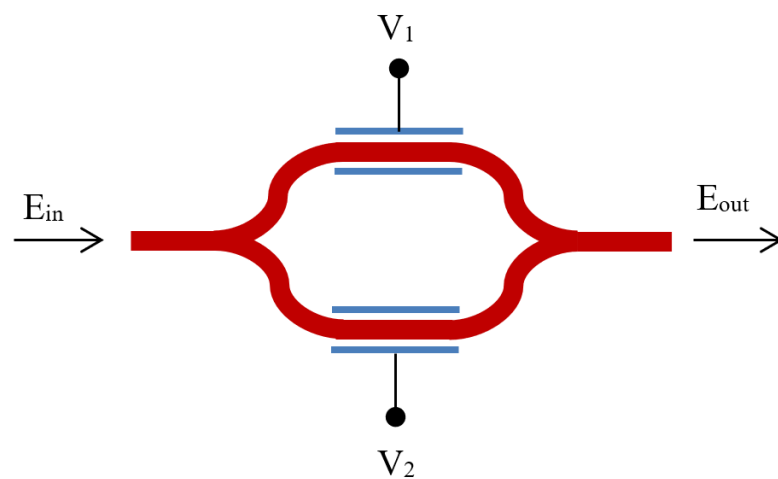


Figure 1. Schematic of a MZM structure with V_1 and V_2 bias voltage applied on both phase-shifter arms

A typical Mach-Zehnder modulator structure is shown in Figure 1. The optical input E_{in} is split into the upper and lower modulator arms that are phase modulated with two phase shifters driven by the electrical signals V_1 and V_2 and then recombined into the optical output E_{out} .

- MZM with symmetric coupler and opposite driving voltages

Coming back to the MZM structure of Figure 1, and assuming that the input optical field is equally split between the upper and lower arms, and that voltages driving the phase shifters are opposite $V_2 = -V_1$, we can obtain the following simplified model equation,

$$E_{out} = \frac{E_{in}}{2} \left(e^{j\frac{\pi V_1}{2V_\pi}} + e^{-j\frac{\pi V_1}{2V_\pi}} \right) = E_{in} \cos\left(\frac{\pi V_1}{2V_\pi}\right).$$

- Why is accurate modeling of MZM critical?

A modulator is one of the most critical and costly components in a high-speed optical transmitter. The bandwidth, footprint (i.e., packaging density) and energy consumption of a modulator – all of which are very critical in today's mega datacenter deployments - depend on a number of design

trade-offs. If the modulator design is suboptimal, system cost and complexity can increase significantly while providing only marginal improvements in performance.

In this application note, we describe the entire design and simulation flow from **RSoft Photonic Device Tools** to **ADS Photonic Designer**. This process leverages:

- **RSoft BeamPROP** and **Multi-Physics Utility** for Y-branch splitter and waveguide phase shifter simulation and optimization
- Custom-PDK Generation Utility for S-parameter data and active phase-shifter model extraction
- ADS Photonic Designer for the creation of MZM, circuit simulation and performance evaluation in an Electro–Optical–Electro (EOE) link

This unified workflow accelerates MZM development, ensures consistency across design stages, and supports scalable Photonic Integrated Circuit (PIC) design.

Workflow Description

The combined use of RSoft utilities and ADS Photonic Designer enables automated creation of custom device libraries and PDK components, effectively bridging device-level simulation and system-level design.

Using RSoft tools, users can:

- Simulate and optimize the Y-branch splitter and active waveguide phase-shifter.
- Extract S-parameter data and active phase-shifter models from device-level simulations.
- Create reusable IP blocks and custom PDK components for PIC design workflows.

When ADS is selected as the target platform, the Custom PDK-Generation utility generates complete S-parameter based component and active phase-shifter model data, including:

- Simulation data
- Schematic symbols
- Layout views

These components can be used directly within the ADS Photonic Designer environment. Figure 2 illustrates the overall workflow for custom PDK generation using the MZM device as an example.

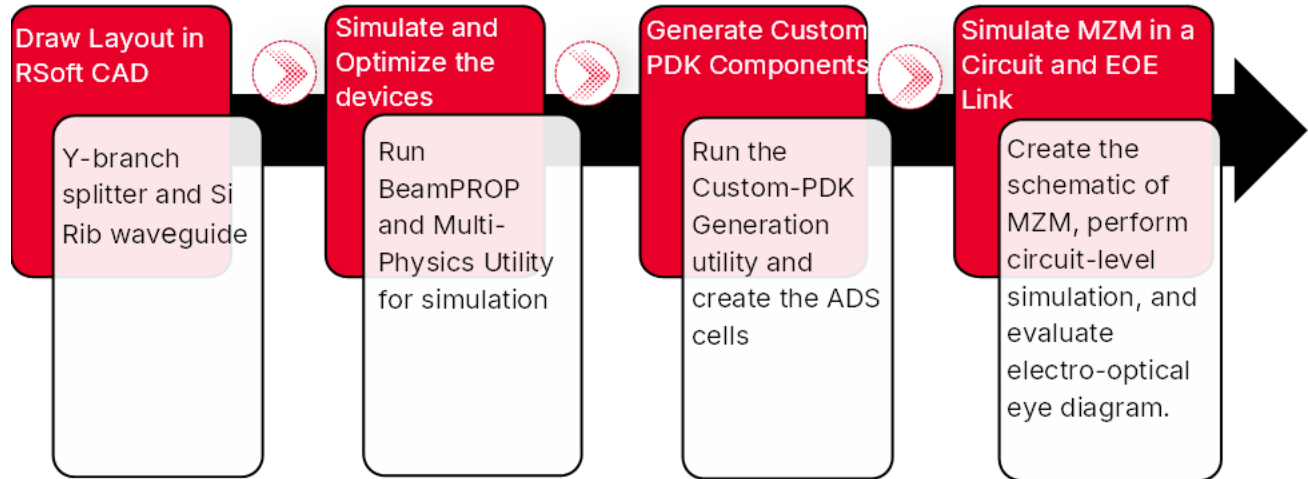


Figure 2. Process flow for custom PDK generation, illustrated using the MZM example.

1: Draw the Layout in RSoft CAD

To simplify the workflow, this example uses the Y-branch splitter and waveguide phase-shifter design files provided with the Custom PDK Generation Utility tutorials. These design files are located at the RSoft installation folder, C:\Keysight\PhotonicSolutions\<Ver.>\RSoft\examples\Utilities\CustomPDK.

For the Y-branch splitter, two S-bend waveguides with a radius of 9.9844 μm are connected to a common input waveguide, forming a conventional Y-branch structure. For the waveguide phase-shifter, a straight Silicon rib waveguide serves as an active phase-shifter, where the waveguide is a P-N junction composed of several sections, each with different doping concentrations set in the Material Editor. Electrodes are placed on both sides of the waveguide to enable electrical biasing.

2: Simulate and Optimize the Devices

The simulation methodology is summarized as follows. The equal power splitting is a design target for the Y-branch splitter. The phase shifter is modeled by solving the optical modes of the waveguide cross-section. The Multi-Physics Utility has been set up to use the Carrier Effects option to compute the index perturbation due to the carriers which will then be used to calculate the effective index of the optical mode. The simulated light propagation result for the optimized Y-branch splitter is shown in Figure 3(a) by using RSoft BeamPROP at an Effective Index Calculation method (EIM), where approximately 41.5% of the optical power is transmitted to each output port. The simulated Neff dependency on wavelength and bias voltages are shown in Figure 3(b), respectively, for the waveguide phase-shifter. These results are subsequently used during the custom PDK generation process.

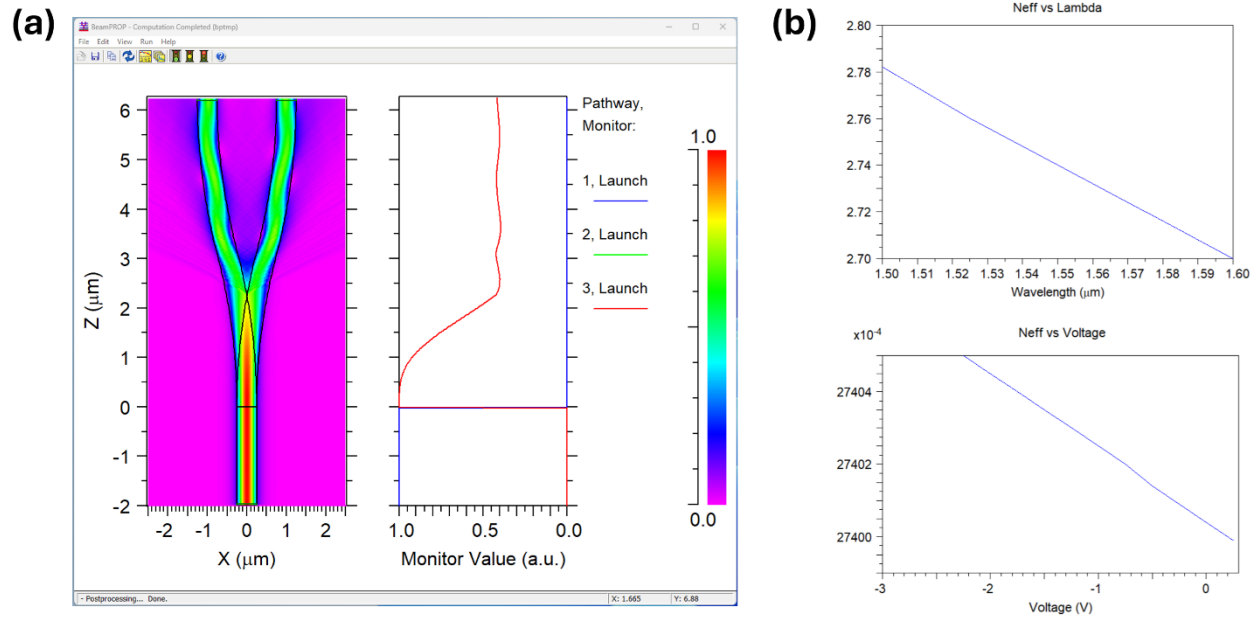


Figure 3. Simulated light propagation result for (a) Y-branch splitter by RSoft BeamPROP and Neff results for (b) phase shifter by RSoft Multi-Physics Utility.

3: Generate Custom PDK Components

Figure 4 illustrates the configuration options for the RSoft Custom-PDK Generation Utility. For this example, the Output Mode is set to "Full PDK", enabling the generation of both S-parameter or phase shifter data and a custom PDK model for use in a target PIC design platform. In the Advanced Options dialog, the Compile Cell option is enabled by default.

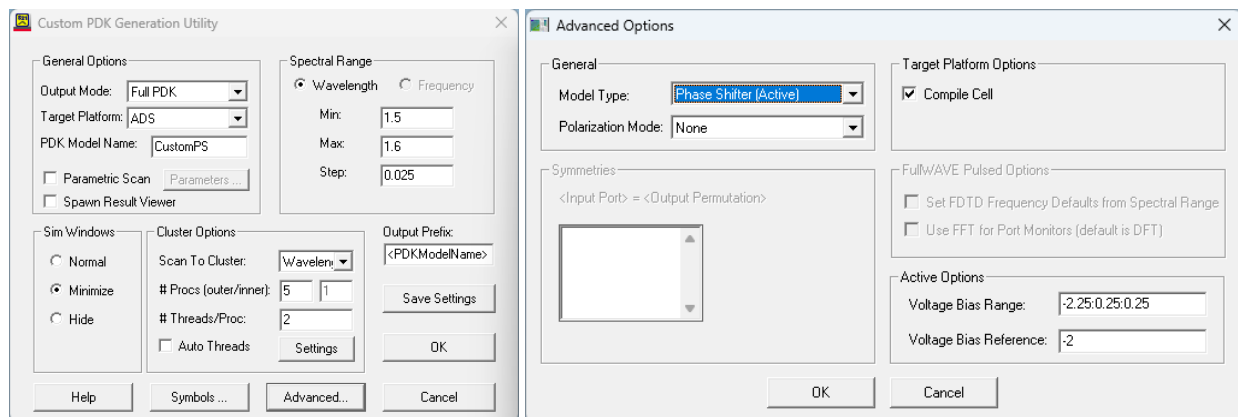


Figure 4. Configuration of the RSoft Custom-PDK-Generation Utility with ADS selected as the target platform.

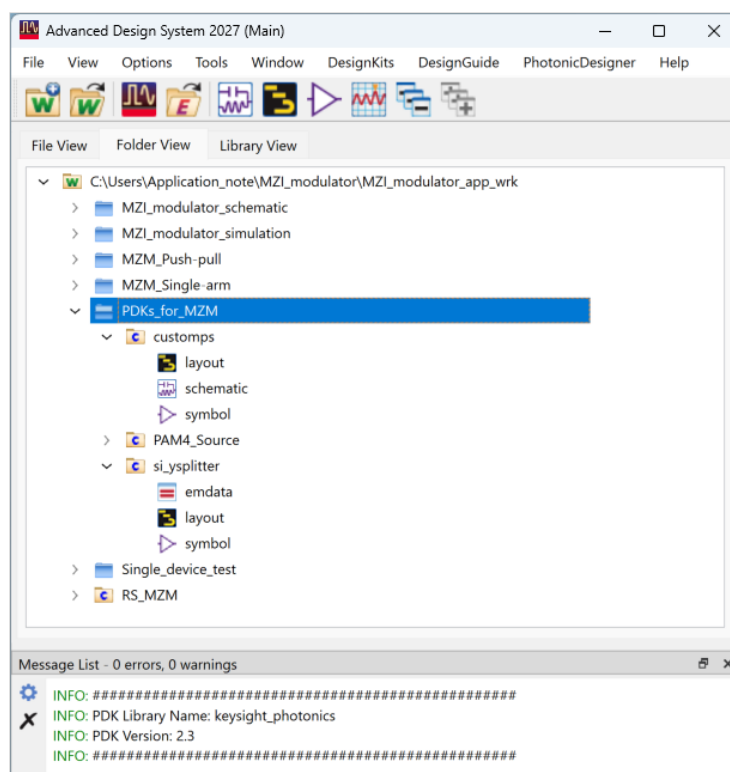


Figure 5. ADS Photonic Designer showing the custom phase-shifter (customps) and Y-branch splitter (si_ysplitter) PDK components in a user-defined library.

The Compile Cell option automates the platform-specific steps required to generate a ready-to-use custom device component. When enabled, the Custom PDK Utility generates the necessary files for the selected target platform and automatically performs any required compilation or post-processing steps. For example, when the target platform is ADS, the Custom PDK Utility automatically runs the ADS cell-generation process, eliminating the need to manually execute `adsgencell` from the command line. Beginning with RSoft 2027, the generated ADS-compatible cell can be copied directly into an ADS library and used without additional processing.

In this application note, ADS is selected as the target platform. For a detailed description of all available options, please refer to the Custom-PDK Generation Utility User Guide. The default Compile Cell option compiles an ADS cell along with its associated views, including schematic, symbol, layout, and emdata, depending on the model types, as shown in Figure 5.

4: Generate and Simulate MZM in a Circuit

The custom phase shifter and the Silicon Y-branch splitter models created above are combined in Keysight ADS Photonic Designer to form a Mach-Zehnder modulator compound component, as shown in Figure 6. A push-pull drive configuration is employed in the schematic.

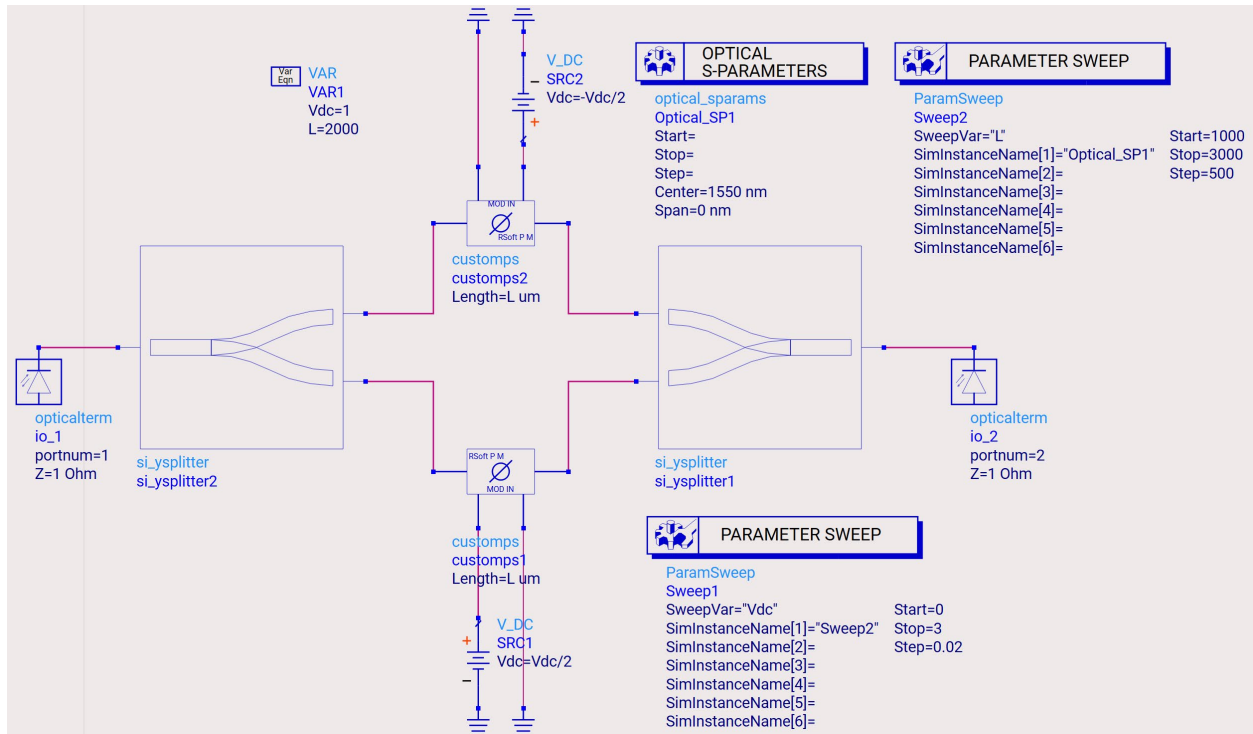


Figure 6. ADS schematic of the MZM compound component after placing and connecting customs and si_ysplitter, adding the optical terminals, and mapping the schematic-level L parameter to the customs Length parameter. Note that the push-pull configuration is utilized in the schematic.

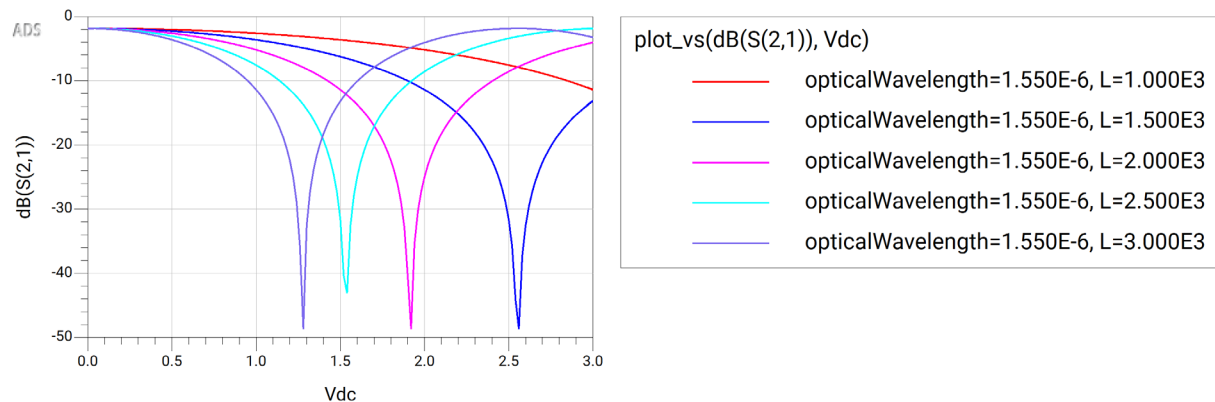


Figure 7. Simulated response at the output port of the Mach-Zehnder modulator dependency on Vdc for various phase-shifter lengths at a fixed working wavelength of 1.550 μm .

Towards finding an optimal quadrature point, the Mach-Zehnder modulator response is simulated with a DC bias sweep for each phase-shifter length at the fixed working wavelength of 1.550 μm , as shown in Figure 8. We can observe 1 mm phase shifter (red) exhibits very weak modulation; 2 mm phase shifter (blue) reaches the extinction point near 1.9 V; 3 mm phase shifter (light blue)

reaches the extinction point near 1.3 V. This behavior is expected because a longer phase shifter produces a larger phase shift for a given drive voltage, due to

$$V_{\pi}L = \text{constant}.$$

Specially, for the 2.5 mm case (cyan curve), the maximum transmission occurs near 0 V and 3 V, and the minimum transmission occurs around 1.5 V. Therefore, the quadrature operating point is located approximately halfway between the maximum and minimum transmission levels,

$$V_{quad} \approx \frac{1.5}{2} \approx 0.75 \text{ V}.$$

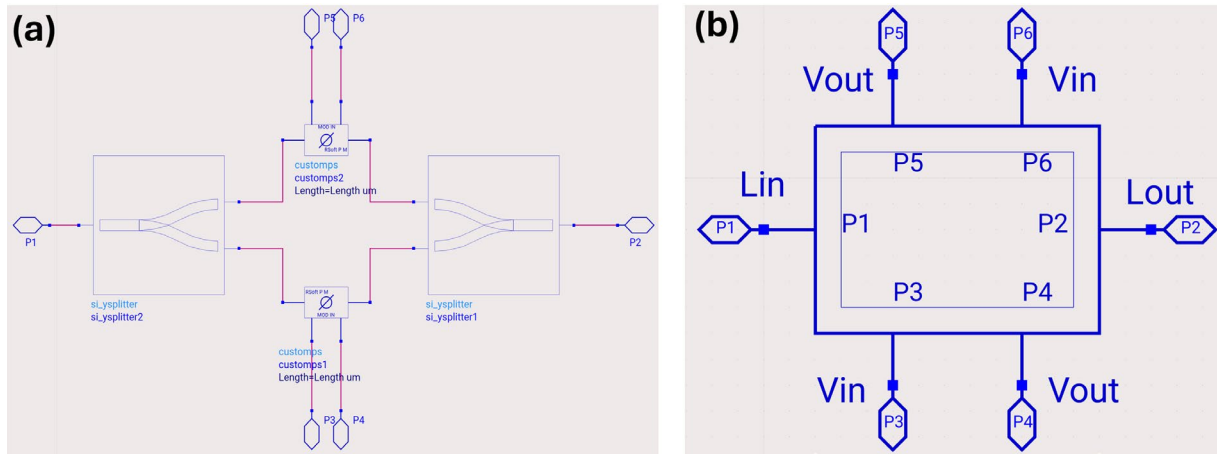


Figure 8. (a) ADS schematic of the MZM by adding the optical and electrical terminals (i.e., P1 to P6), and (b) ADS symbol created for the reusable RS_MZM component.

The completed RS_MZM component can now be tested in ADS. First, a RS_MZM_Push-pull schematic is created to evaluate the optical spectrum and run parameter sweeps over the phase-shifter length and bias voltage, as shown in Figure 9. As expected, the same simulated response at the Lout port of the Mach-Zehnder modulator dependency on Vdc for various phase-shifter lengths at a fixed 1.550 μm wavelength is also achieved (refer to Figure 7). This indicates that the generated RS_MZM component symbol is properly functional.

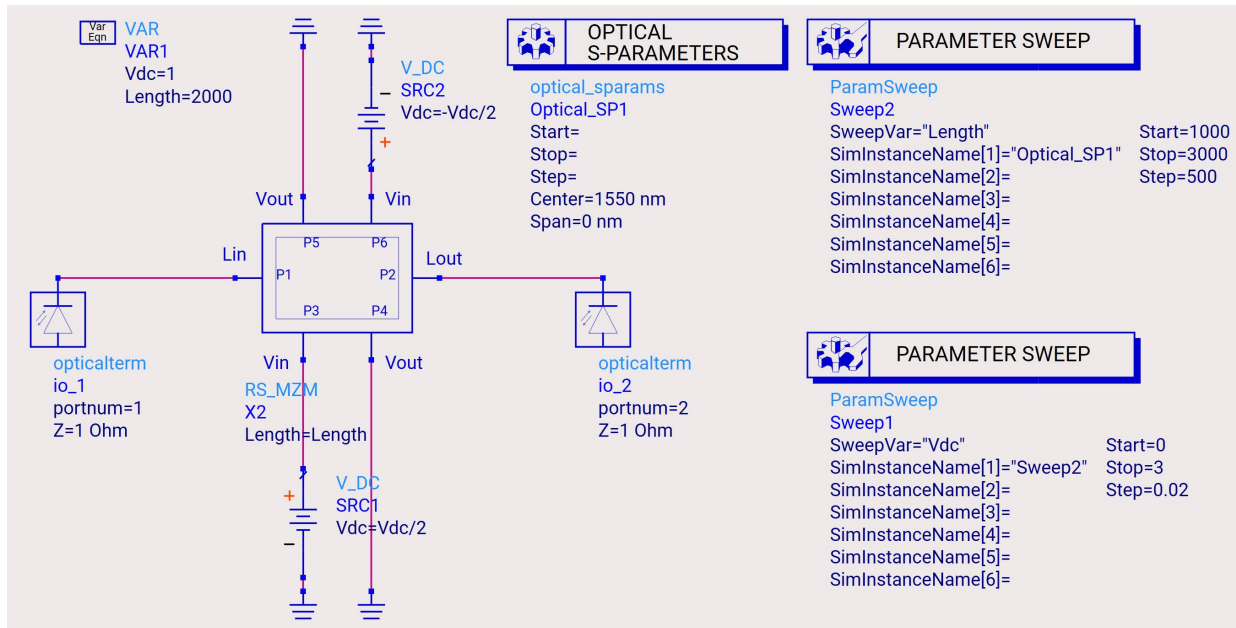


Figure 9. ADS RS_MZM_Push-pull schematic containing the RS_MZM component, optical S-parameter simulation controller, Length and Vdc variables, DC bias source, and parameter-sweep blocks used to evaluate the optical response of the MZM with push-pull configuration.

5: Evaluate Mach-Zehnder Modulator in an EOE Link

The electro-optical performance of the completed RS_MZM component is evaluated using the preconfigured Test_EOE_MZI_Push-pull schematic. The test circuit combines two PAM4 electrical drive signals to implement the push-pull modulation scheme, an optical carrier source, the Mach-Zehnder modulator, optical transmission components, and a photodetector-based receiver. The resulting electrical signal is monitored using an eye-diagram probe to evaluate system-level performance, as shown in Figure 10.

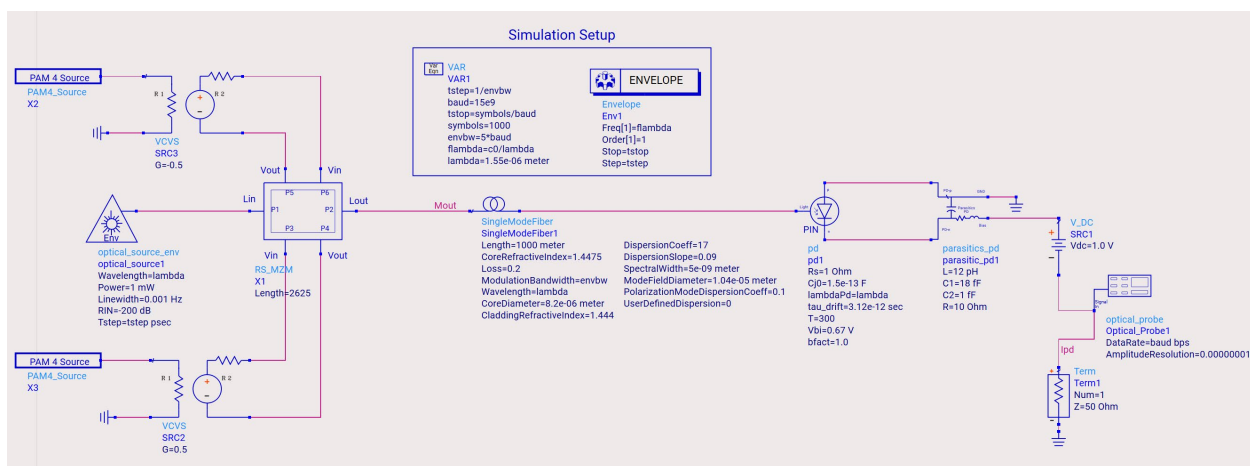


Figure 10. ADS Test_EOE_MZI_Push-pull schematic used to evaluate the electro-optical response of the RS_MZM component in a PAM4-driven test circuit.

The simulation control blocks define the analysis settings, symbol rate, wavelength, and other parameters used for the electro-optical evaluation. The optical carrier wavelength is selected based on the results obtained from the RS_MZM_Push-pull simulations. By examining the simulated response shown in Figure 8, a preliminary phase-shifter length is determined to be 2500 μm .

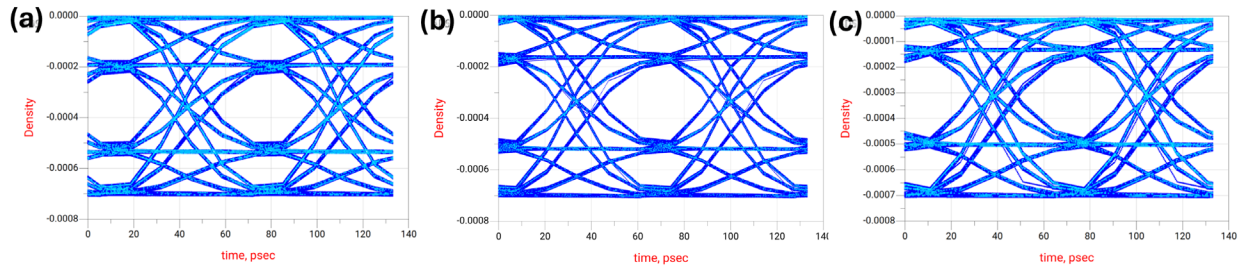


Figure 11. Eye diagrams of the received PAM4 signal generated from the Test_EOE_MZI_Push-pull simulation at the phase-shifter length of (a) 2500 μm , (b) 2625 μm , and (c) 2750 μm .

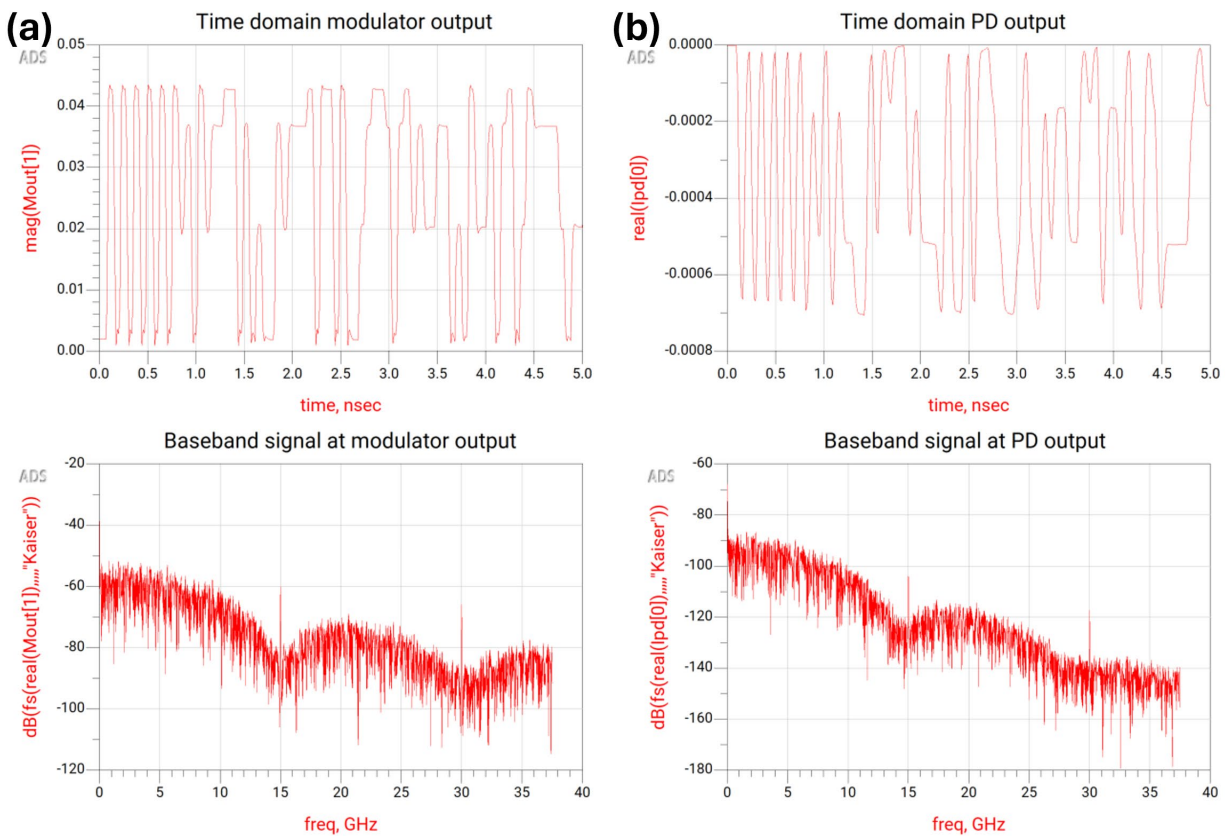


Figure 12. Simulated time-domain and frequency-domain responses of the PAM4-driven MZM-based photonic system with an optimized phase-shifter length of 2625 μm . The plots present (a) the modulated optical signal and baseband signal at the MZM output and (b) the detected electrical signal and baseband signal at the photodetector (PD) output in both the time and frequency domains.

The eye diagram provides a visual representation of the received PAM4 waveform after transmission through the electro-optical link. The opening of the eye indicates the separation between signal levels and can be used to assess the quality of the modulation and overall system performance. To determine the optimum push-pull phase-shifter length, the eye diagram performance is monitored through the scanning of phase-shifter length from 2000 μm to 3000 μm with a spacing of 125 μm . Based on visual inspection of the eye diagrams in Figure 10, The 2500 μm case produces a well-opened eye, the 2625 μm case provides the best overall performance, and the 2750 μm case appears slightly over-modulated.

The time-domain and frequency-domain responses can be examined to verify the electro-optical behavior of the Mach-Zehnder modulator and receiver chain. For the modulator output, Figure 11 (a) shows the magnitude of the optical signal at the MZM output and demonstrates how the electrical PAM-4 signal modulates the optical carrier. For the photodetector output, Figure 11 (b) shows the detected electrical signal after optical-to-electrical conversion and reflects the combined effects of modulator bandwidth, fiber, and photodetector response.

Conclusion

This application note demonstrates an efficient workflow for designing and evaluating a Silicon Mach-Zehnder modulator with a push-pull configuration using RSoft BeamPROP, Multi-Physics Utility, and ADS Photonic Designer. The workflow enables automated device modeling, extraction of S-parameter data and active phase-shifter models, and seamless integration into circuit-level and system-level simulations. Multiple simulation approaches, including S-parameter analysis for bias characterization and envelope simulation for complete EOE link verification, are employed throughout the design flow. The results show how a custom MZM can be characterized, converted into reusable PDK components, and integrated into a high-speed optical communication link with a PIN photodetector, enabling accurate evaluation of operating conditions, modulation performance, and signal integrity.

Example Files

<https://support.keysight.com/KeysightdCX/s/knowledge-article-detail?keyid=Supporting-files-Design-Simulation-MZM-Push-Pull-Configuration>

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