Modeling and Simulation of Silicon Photonics Systems in SystemVerilog & *XMODEL*

Prof. Jaeha Kim

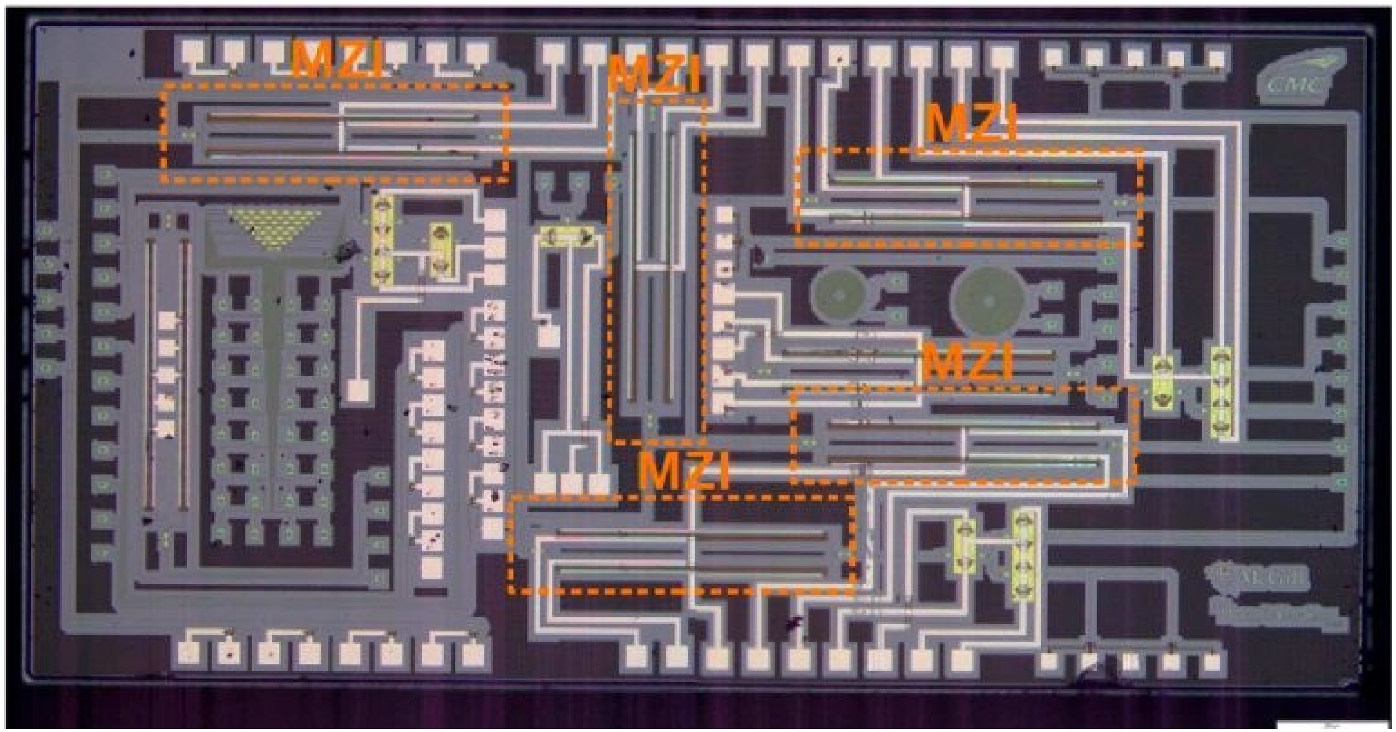
Seoul National University & Scientific Analog, Inc.

CEDA/CASS/SSCS Joint Session on Silicon Photonics

ASP-DAC 2025

Silicon Photonics

- Integration of photonic and electronic components to realize dense, high-bandwidth I/Os with low power



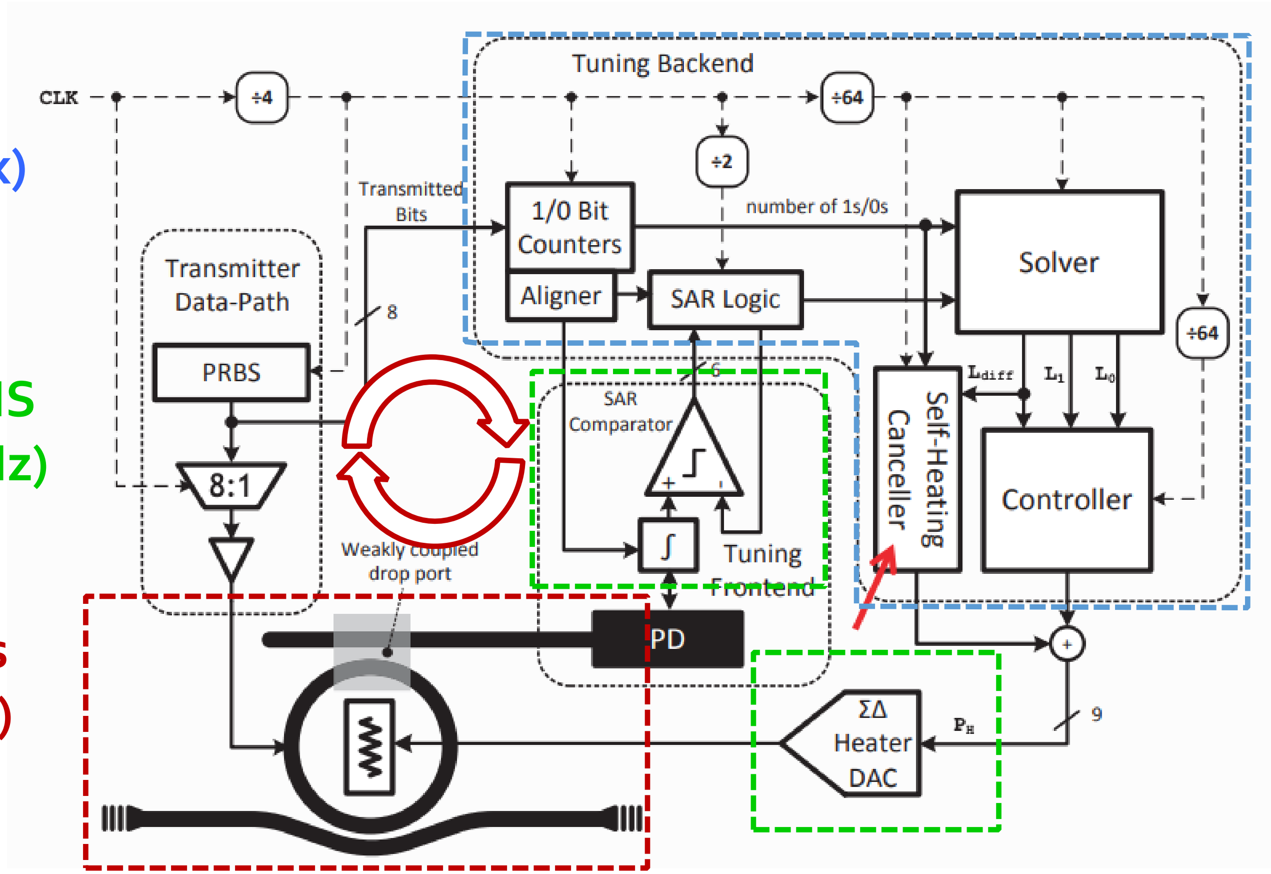
Silicon photonics switch IC based on Mach-Zehnder interferometers (MZI)
[F. G. de Magalhaes, et al., "Silicon Photonic Interconnects: Minimizing the Controller Latency" GLSVLSI, 2018]

Challenge with Verifying SiPh Systems

Digital (Complex)

Analog/MS (~1~10GHz)

Photonics (~100THz)



C. Sun, et al., "A 45nm SOI Monolithic Photonics Chip-to-Chip Link with Bit-Statistics-Based Resonant Mirroring Thermal Tuning, VLSI Symp. 2015.

Goal: Model SiPh in SystemVerilog

- Want to run efficient simulation of silicon photonics, analog, and digital electronics in ***one unified platform***
  - Can't verify the system by simulating each of them separately

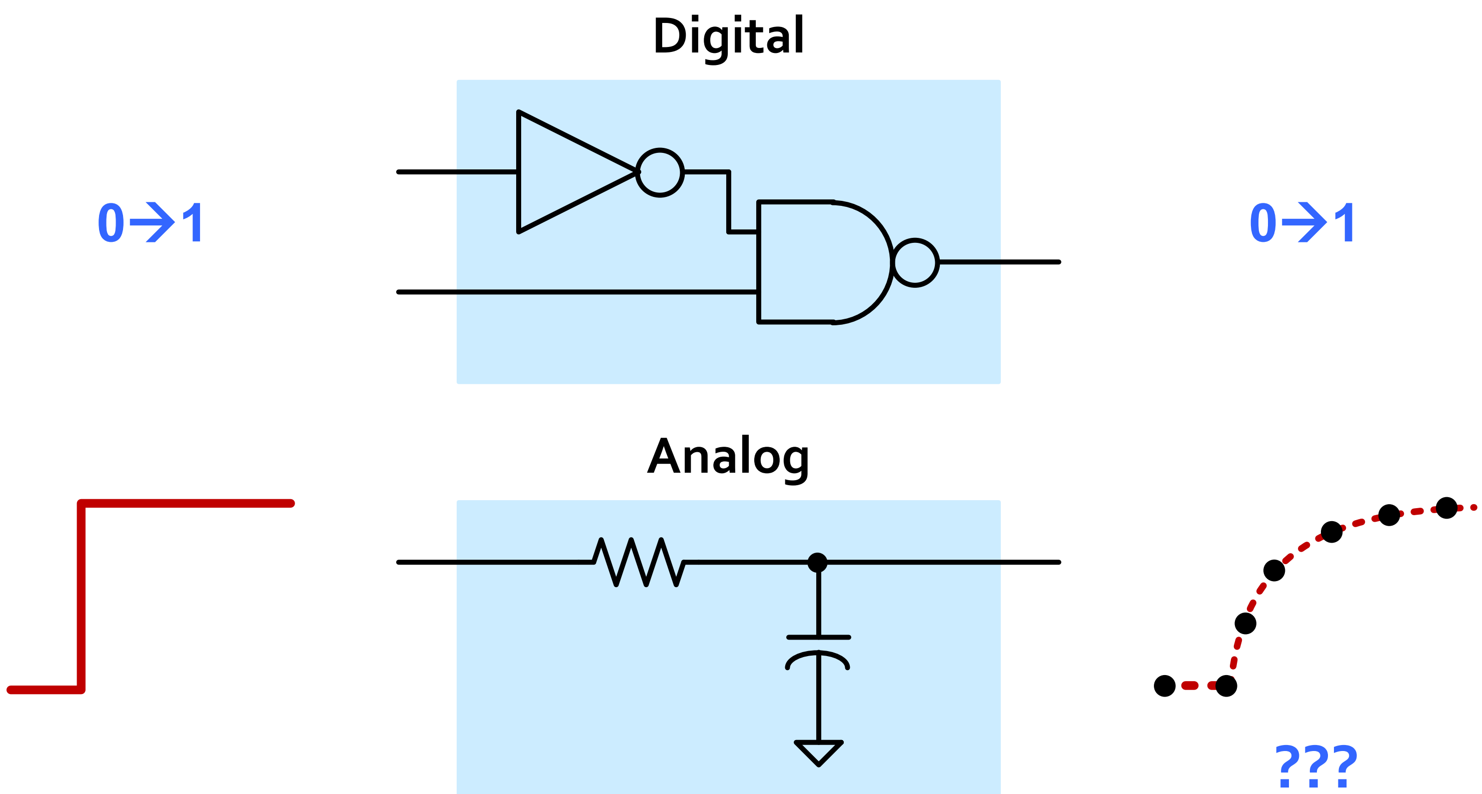
- Want that platform to be ***SystemVerilog***
  - The established platform for verifying most chips (UVM)
  - Validated digital models can be directly synthesized

XMODEL by Scientific Analog

- A plug-in extension that enables ***fast and accurate analog/mixed-signal*** simulation in ***SystemVerilog***
  - ***Event-driven***: 10~100x faster than Real-Number Verilog
  - ***Analog***: supporting both functional and circuit-level models
  - ***SystemVerilog***: enabling analog verification in UVM

Event-Driven Simulation of Analog

- How do we extend the Verilog's event-driven algorithm to simulating analog circuits?

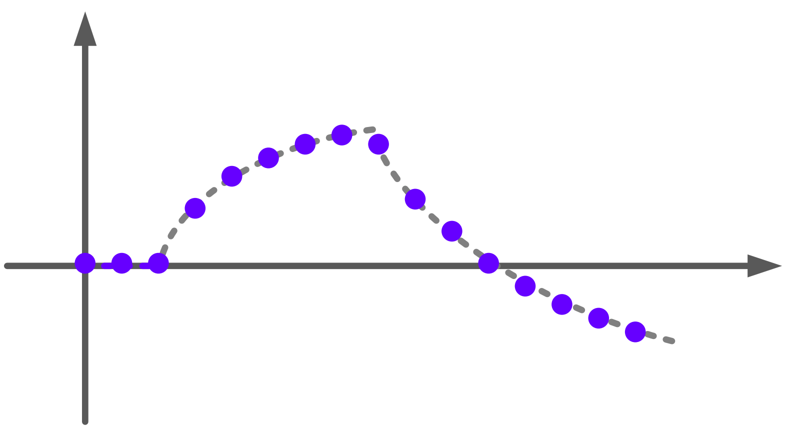


Expressing Analog Signals

- *XMODEL* expresses analog signals in functional forms instead of using a series of time-value pairs:

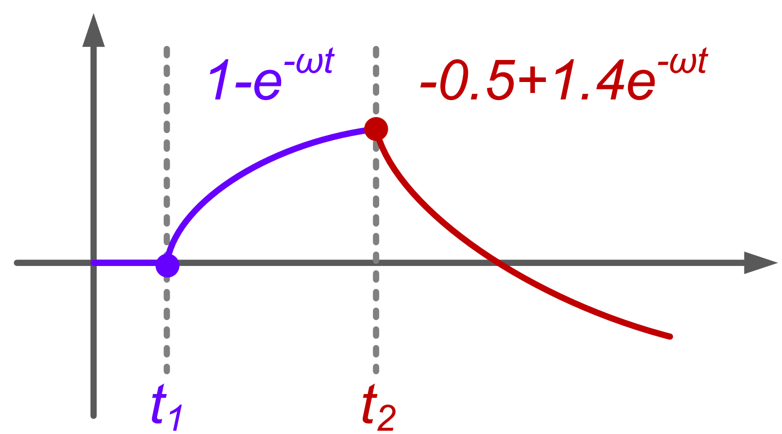
$$x(t) = \sum_i c_i t^{m_i} e^{-a_i t}$$

SPICE



Accuracy relies on fine time step

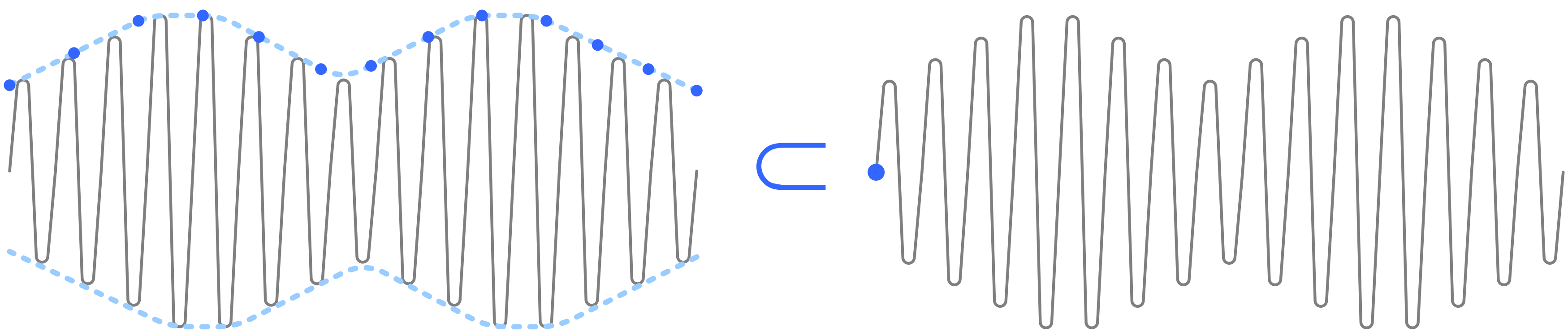
XMODEL



Events occur only when the coefficients are updated

Expressing Optical Waves

Baseband Equivalent | ***XMODEL***



$$x(t) = c(t) \cdot e^{j\omega_0 t}$$

complex

$$x(t) = \sum_i c_i t^{m_i} e^{-a_i t}$$

complex

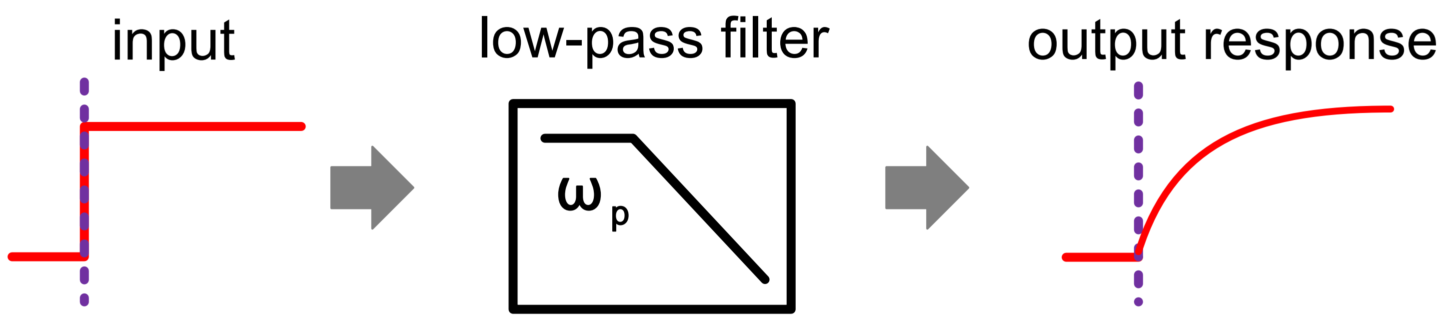
- *XMODEL* can express optical waves with fewer events!
- Even when multiple wavelength signals are mixed

XMODEL's Event-Driven Simulation

- With the signals transformed into Laplace s-domain:

$$x(t) = \sum_i c_i t^{m_i - 1} e^{-a_i t} u(t) \xrightarrow{\mathcal{L}} X(s) = \sum_i \frac{b_i}{(s + a_i)^{m_i}}$$

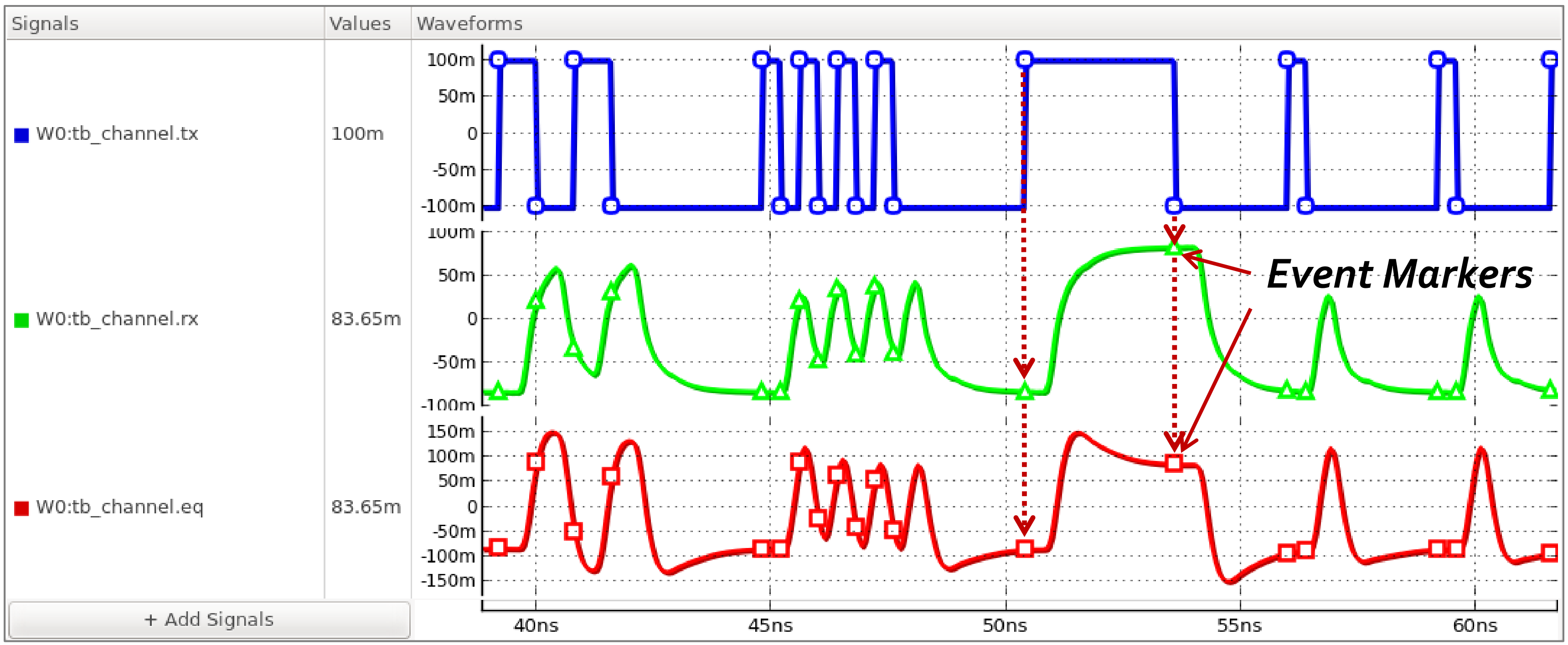
- The response of a system can be computed in an event-driven manner without time-step integration:



$$\frac{1}{s} \times \frac{\omega_p}{\omega_p + s} = \frac{1}{s} - \frac{1}{\omega_p + s}$$

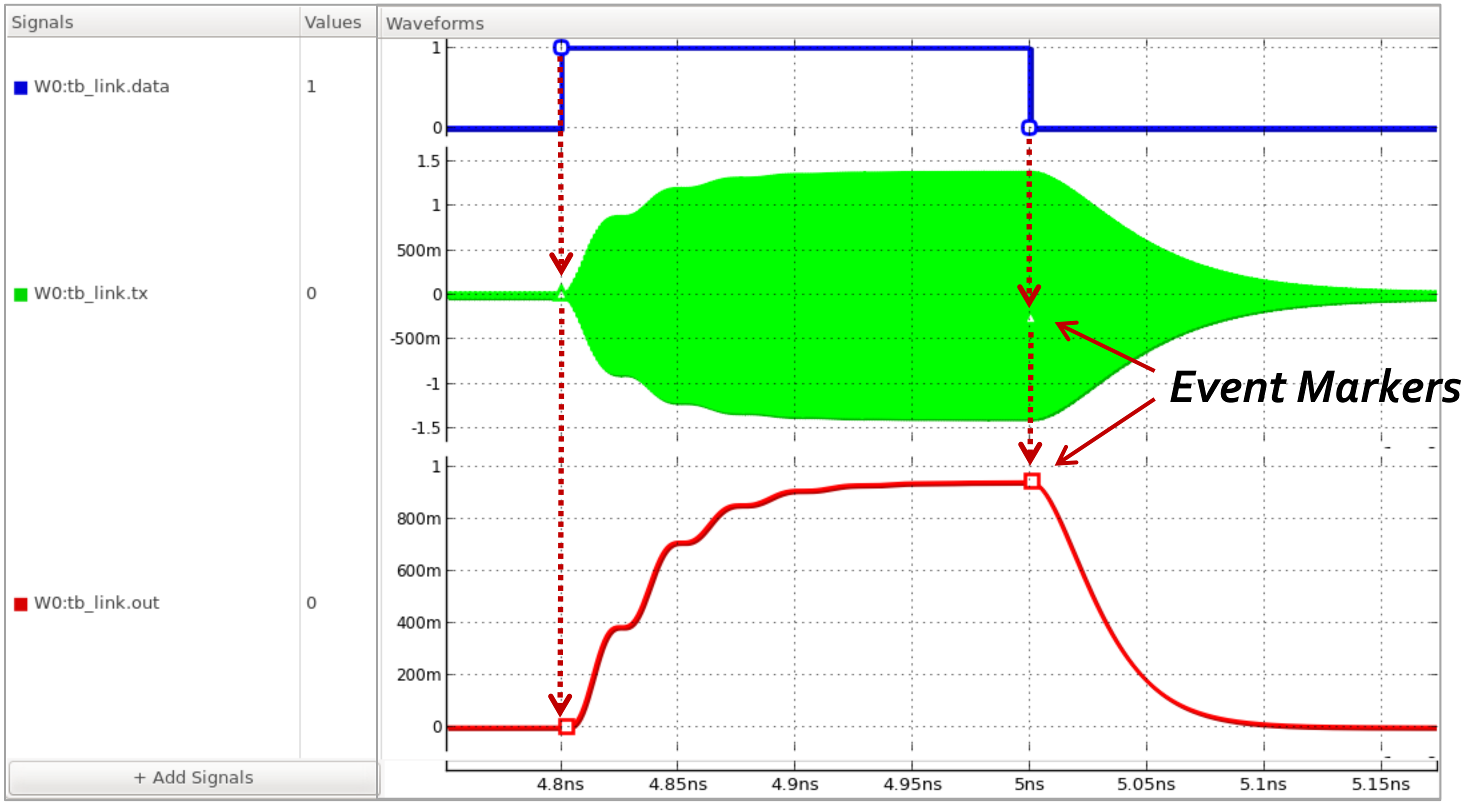
Simulating an Electrical Transceiver

- *XMODEL* successfully extends the Verilog's event-driven algorithm to analog circuits!



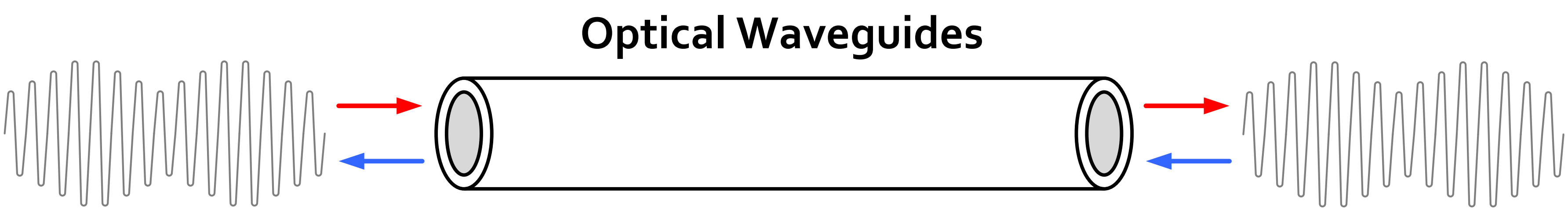
Simulating an Optical Transceiver

- And also to silicon photonics systems communicating by modulating ~200THz signals!



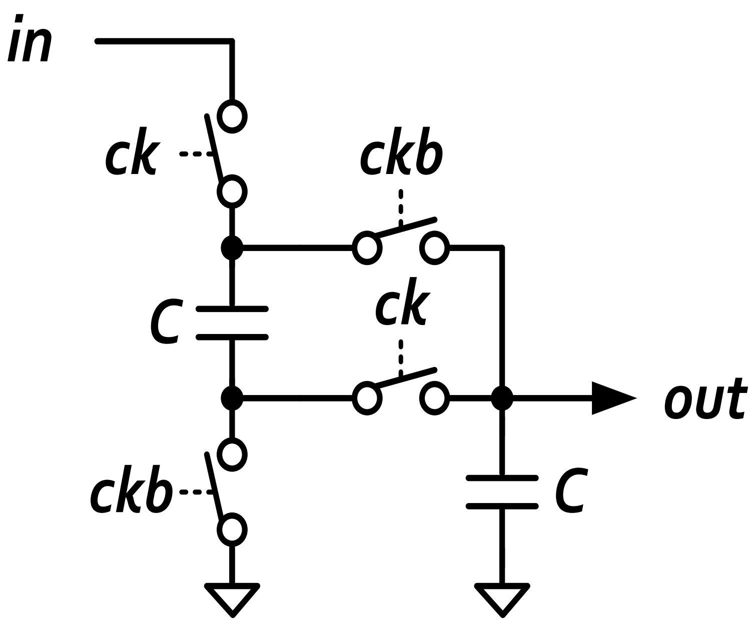
Modeling Optical Waveguides

- Optical waves can propagate in both directions, couple to other waveguides, and get reflected at the ends
- Not a typical phenomenon modeled by SystemVerilog



Circuit-Level Modeling (CLM)

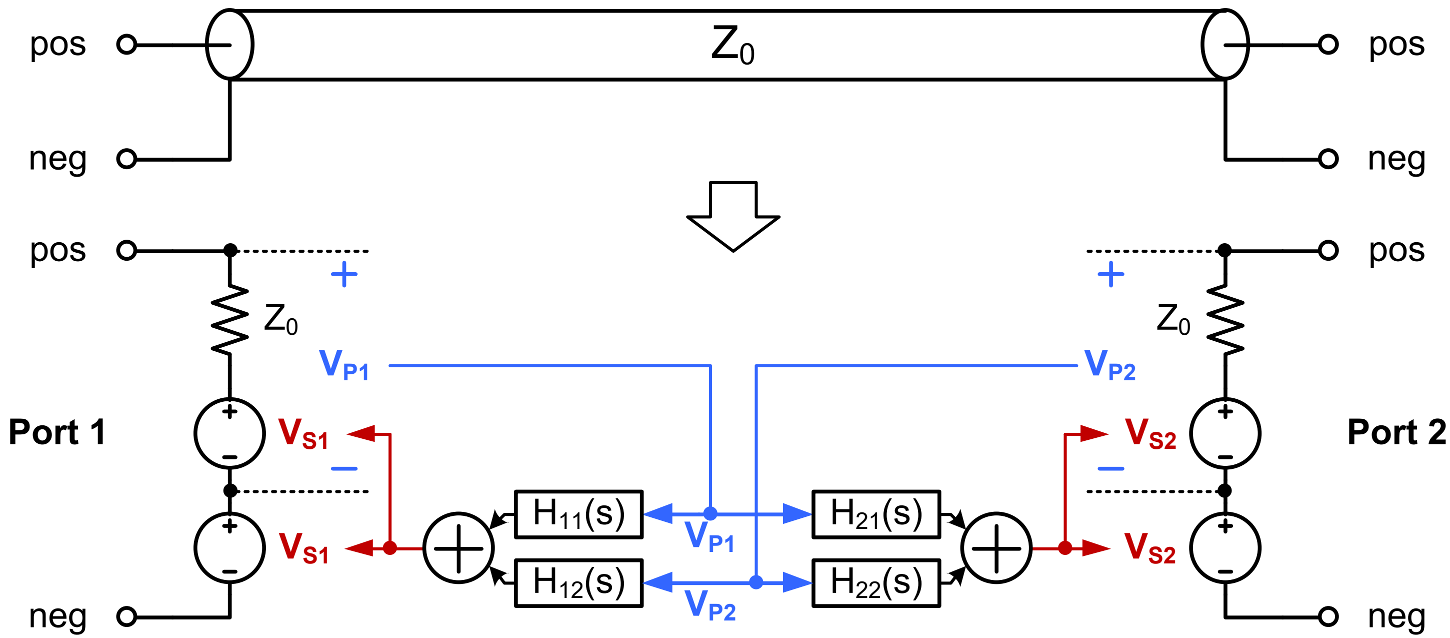
- With *XMODEL*, you can simulate circuit-level models by listing the circuit primitives directly in SystemVerilog
  - Solving V & I; yet still fast with event-driven simulation!



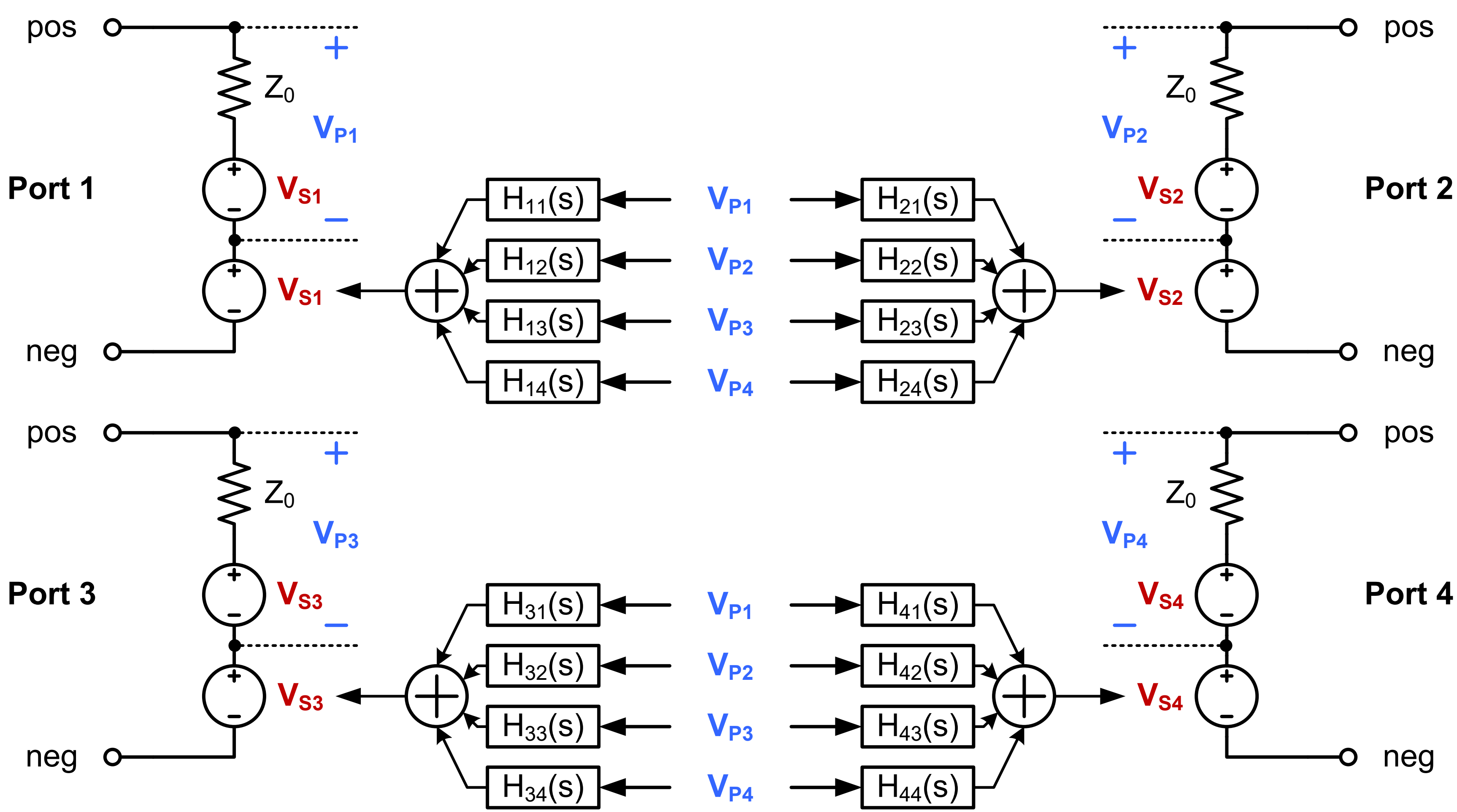

```
module sc_converter(
        input xreal in,
        output xreal out,
        input xbit ck, ckb
);
xreal       n1, n2;

switch      sw1(.pos(in), .neg(n1), .ctrl(ck));
switch      sw2(.pos(n1), .neg(out), .ctrl(ckb));
switch      sw3(.pos(n2), .neg(out), .ctrl(ck));
switch      sw4(.pos(n2), .neg(`ground), .ctrl(ckb));

capacitor   #(.C(1e-12)) C1(.pos(n1), .neg(n2));
capacitor   #(.C(1e-12)) C2(.pos(n2), .neg(`ground));

endmodule
```

Modeling Waveguides

- Waveguides can be modeled using a combination of circuit elements and signal-flow elements
  - Circuits at ports model the reflections due to Z-mismatch
  - $H_{ij}(s)$ can model the delay and frequency-dependent TF



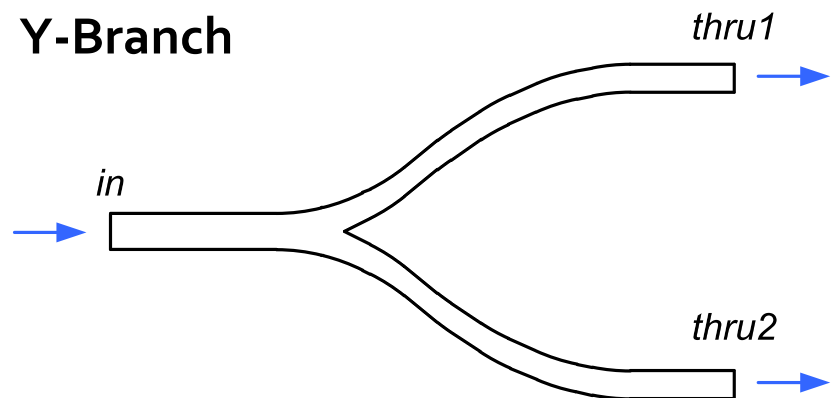
Modeling Multi-port Waveguides



Modeling Y-Branch and Dir. Coupler

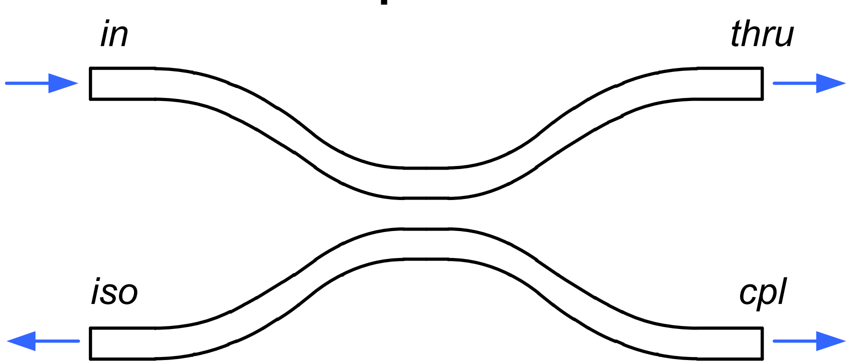
- You can model various optical elements by defining their port-to-port transfer functions H_{ij}

Y-Branch



H_{ij}	*in*	*thru1*	*thru2*
in	0	$\frac{1}{\sqrt{2}}e^{-sT_D}$	$\frac{1}{\sqrt{2}}e^{-sT_D}$
thru1	$\frac{1}{\sqrt{2}}e^{-sT_D}$	0	0
thru2	$\frac{1}{\sqrt{2}}e^{-sT_D}$	0	0

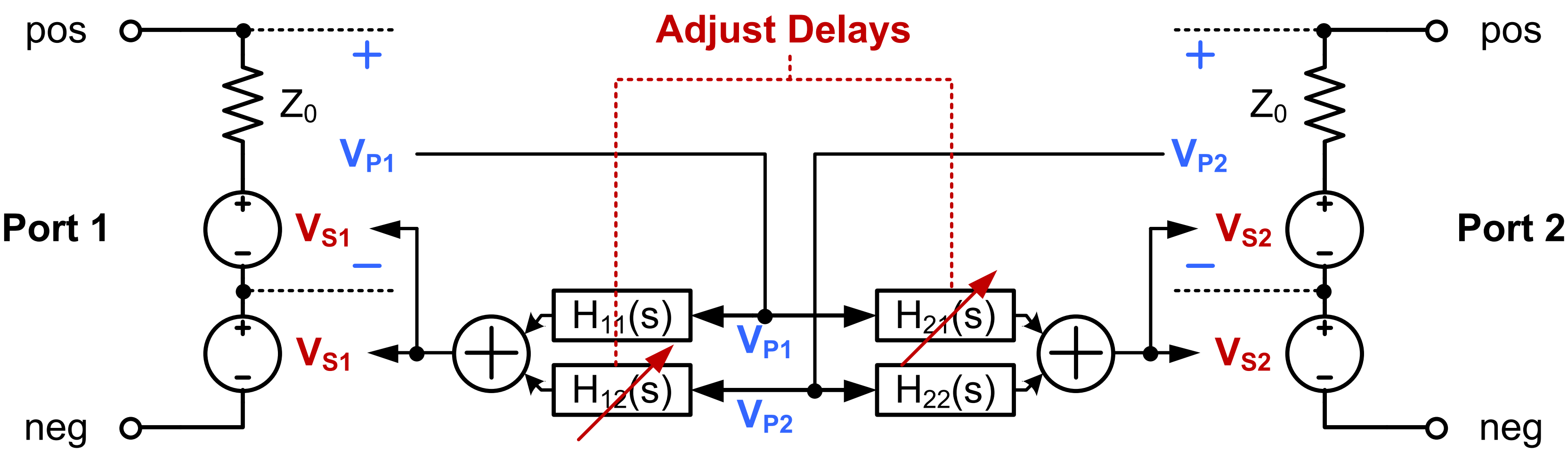
Directional Coupler



H_{ij}	*in*	*thru*	*cpl*	*iso*
in	0	τe^{-sT_D}	$\kappa e^{-j\frac{\pi}{2}-sT_D}$	0
thru	τe^{-sT_D}	0	0	$\kappa e^{-j\frac{\pi}{2}-sT_D}$
cpl	$\kappa e^{-j\frac{\pi}{2}-sT_D}$	0	0	τe^{-sT_D}
iso	0	$\kappa e^{-j\frac{\pi}{2}-sT_D}$	τe^{-sT_D}	0

Modeling Phase Shifters

- Phase shifters are just another optical waveguides
  - Vary the delays of $H_{21}(s)$ and $H_{12}(s)$ with the control input
  - In SystemVerilog, schedule the events with variable delay

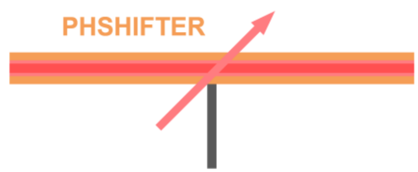


XMODEL Primitives for Si Photonics

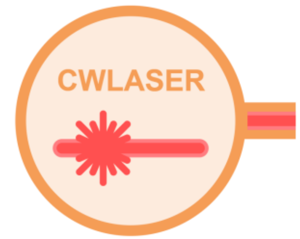
- *XMODEL* offers primitives for basic photonic elements

siph_waveguide

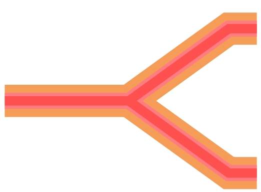
siph_phshifter



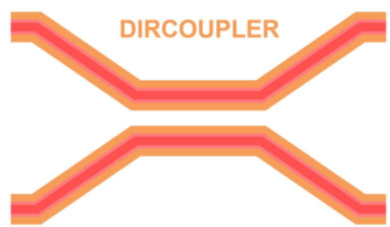
siph_cwlaser



siph_ybranch



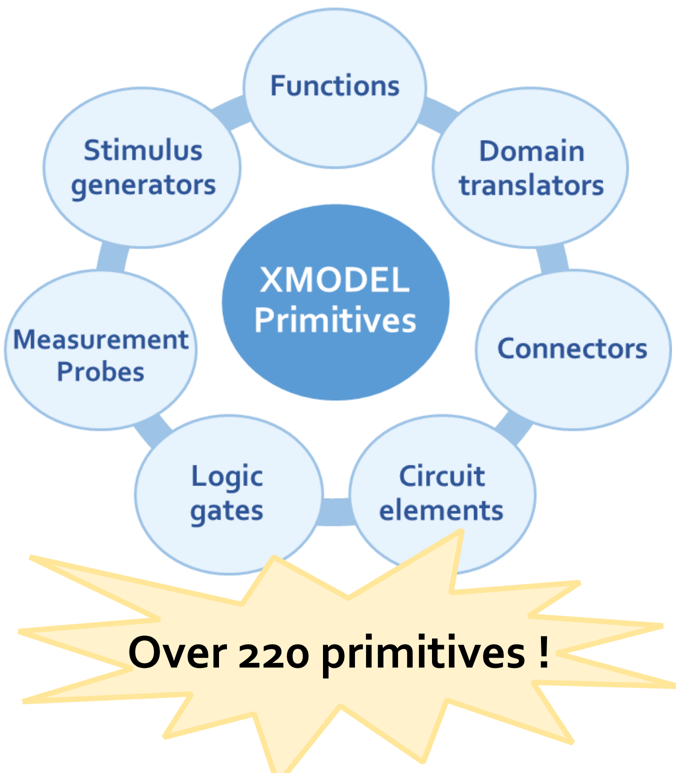
siph_dircoupler



siph_phdetector

Build Models with *XMODEL* Primitives

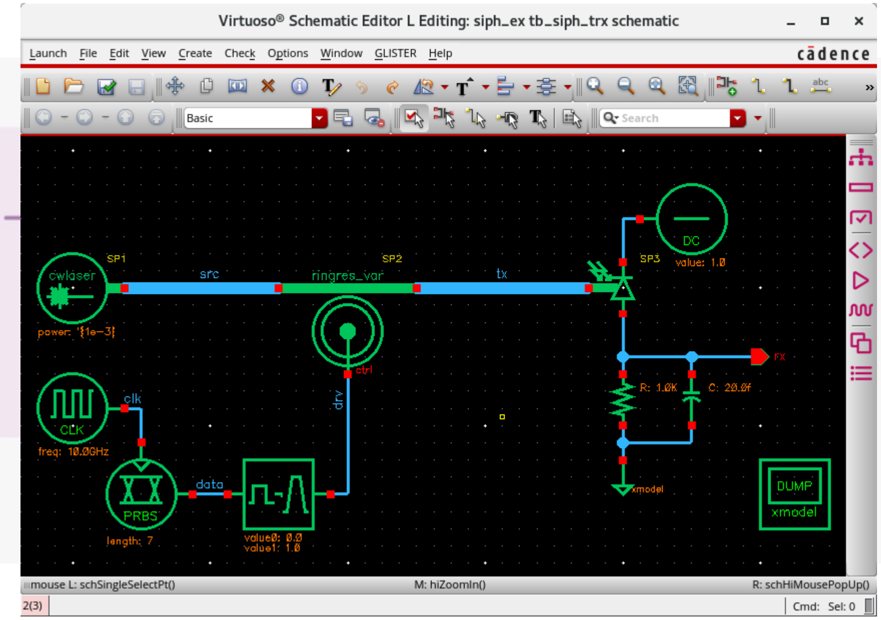
- You can also model your analog circuits by putting together ***XMODEL*** primitives as building blocks



Functions	Filters	Data conversion / comparison	Sampling, selection, and delay
add	filter	transition	sample
multiply	filter_var	slice	select
scale	filter_fir	compare	delay
pwl_func	filter_disc	dac	delay_var
poly_func	integ	adc	buffer
sin_func	integ_mod		
exp_func	deriv		
limit			
power			

GLISTER: Build Top-Down Models

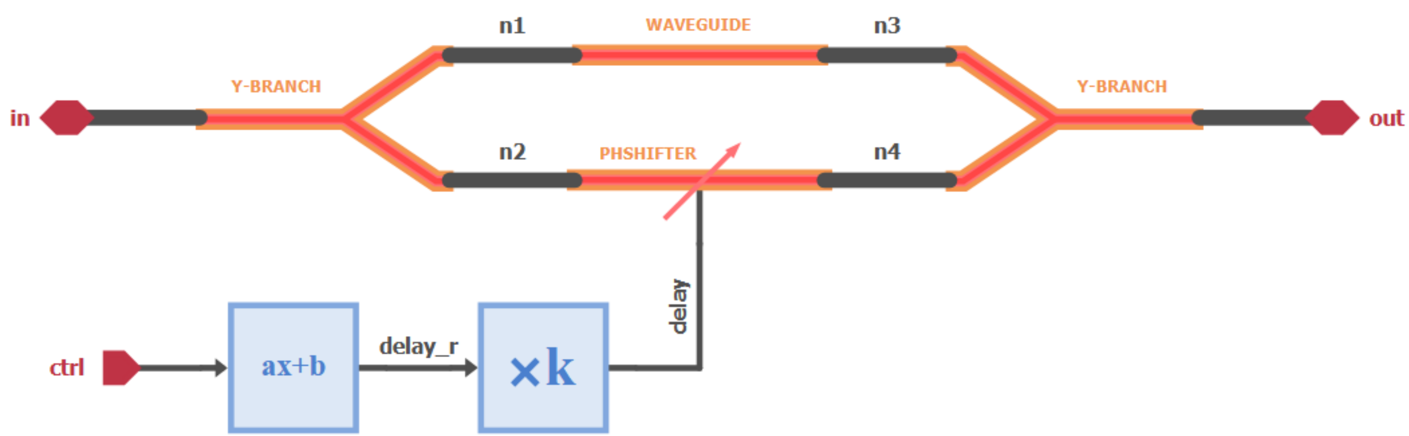
- ***GLISTER*** is a graphical modeling interface integrated into schematic editors (e.g. Cadence Virtuoso)
- Simply place the *XMODEL* primitives on a schematic and connect them with wires; no coding is necessary!




```
module tb_siph_trx (
    `output_xreal rx
);

// signal declarations
xbit clk;
xbit data;
xreal drv;
xreal net6;
xreal src;
xreal tx;

// instance declarations
siph_cwlaser #(.wavelength('{1.55e-06}), .power('{0.001})) SP1 (.out(src));
transition #(.value0(0.0), .value1(1)) XP6 (.out(drv), .in(data));
dc_gen #(.value(1)) XP0 (.out(net6));
siph_phdetector #(.R('{1})) SP3 (.neg(rx), .pos(net6), .in(tx));
siph_ringres_var #(.oplength_cpl(3.875e-05), .oplength_ring(0.000155), .
gain_thru(0.99), .gain_cpl(0.14), .gain_ring(0.99), .gain_mod(0.0002)) SP2
(.ctrl(drv), .in(src), .thru(tx));
capacitor #(.C(2e-14)) R1 (.neg(`ground), .pos(rx));
resistor #(.R(1000)) R0 (.neg(`ground), .pos(rx));
clk_gen #(.freq(1e+10), .init_phase(0.0)) XP2 (.out(clk));
prbs_gen #(.length(7)) XP1 (.trig(clk), .out(data));

// inline dump statements
initial begin
    $xmodel_dumpfile("xmodel.jez");
    $xmodel_dumpvars("level=0");
end

endmodule   // tb_siph_trx
```

Modeling Mach-Zehnder Modulators

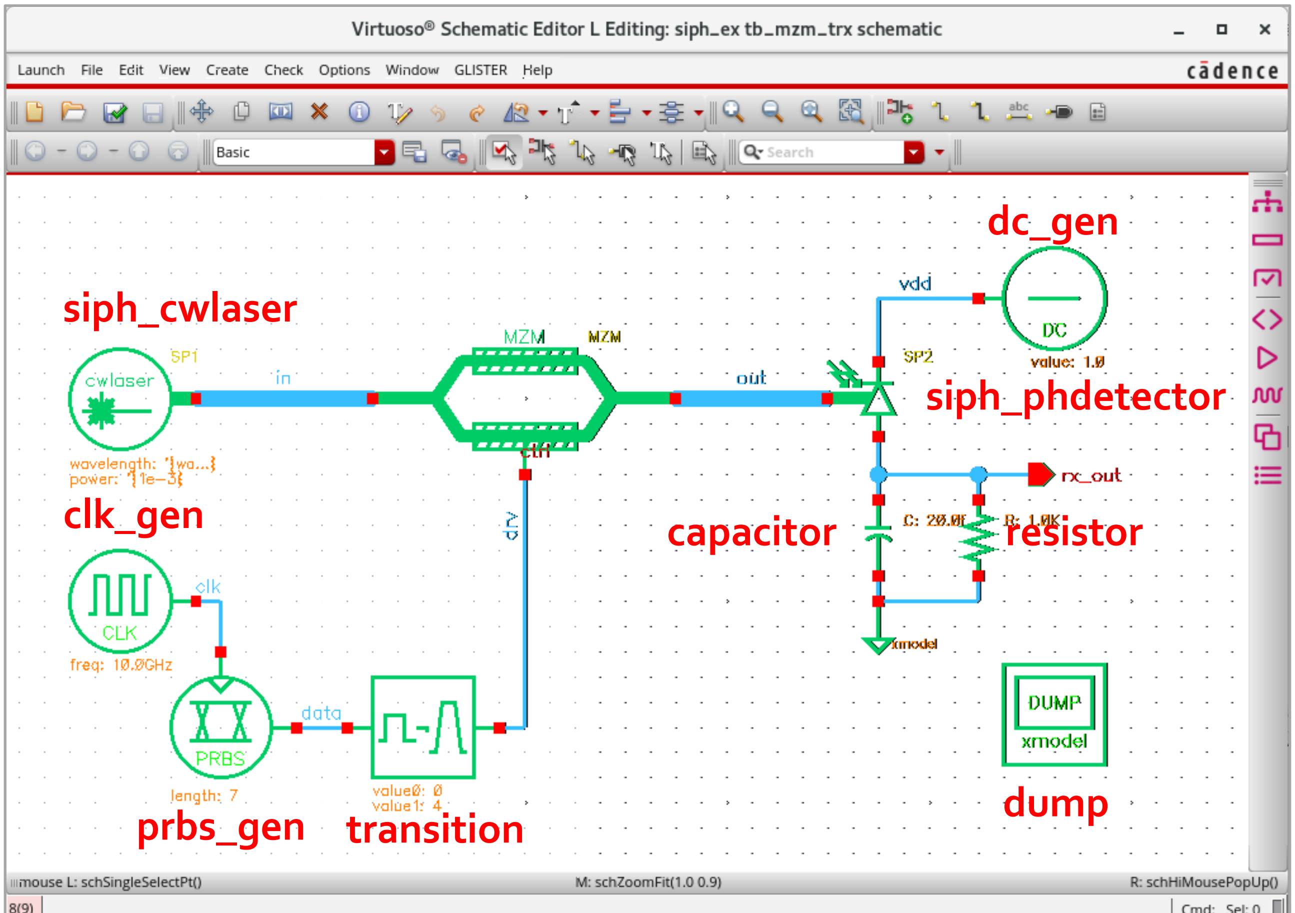
- MZM modulates the transfer gain by varying the interference between two paths
- Can be modeled using the Y-branch, waveguide, phase shifter primitives of *XMODEL*



Adjusts delay with the 'ctrl' input

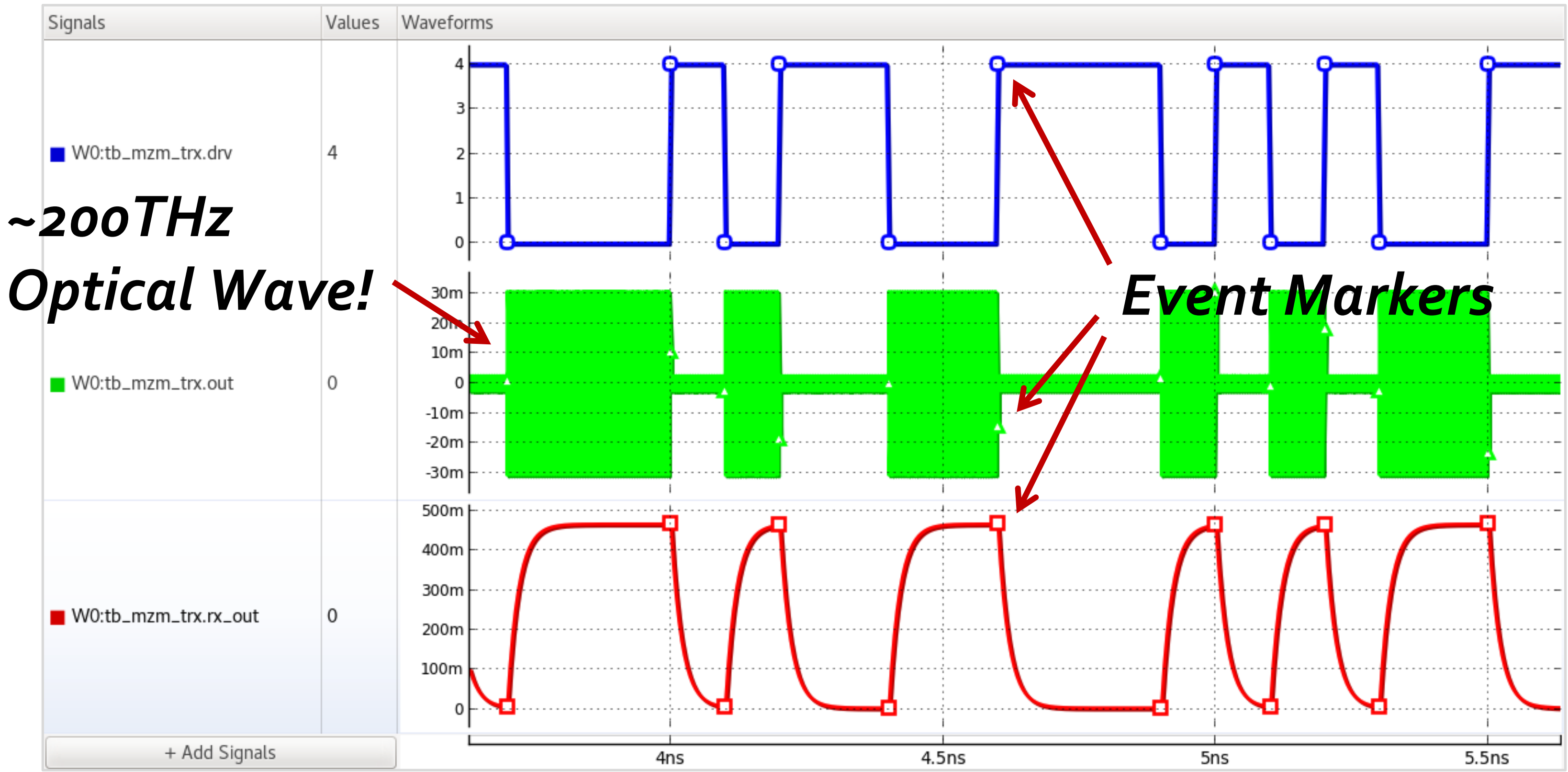
Simulating MZM-based Transceiver

- With a testbench described using *XMODEL* primitives



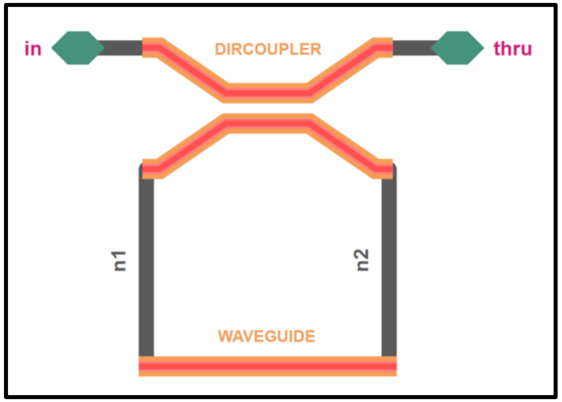
Simulated Waveforms

- Data is transmitted by modulating the optical power
- The low number of events makes the simulation fast

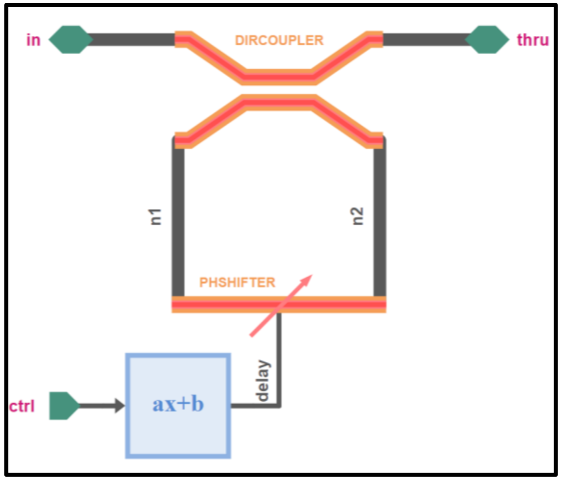


Problem in Modeling Ring Resonators

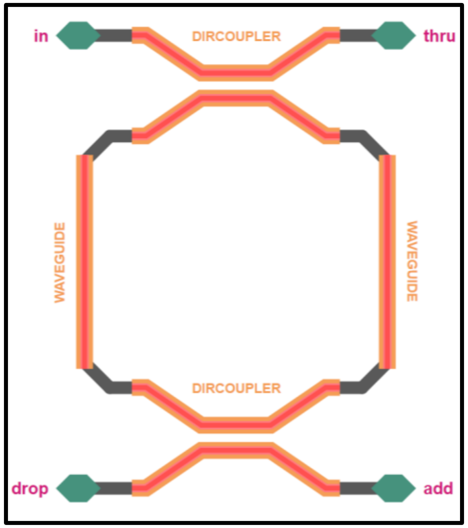
- When you form a ring using the basic SiPh primitives, you will form a loop propagating events indefinitely
  - Causing slow simulation speeds



Ring resonator



Ring modulator

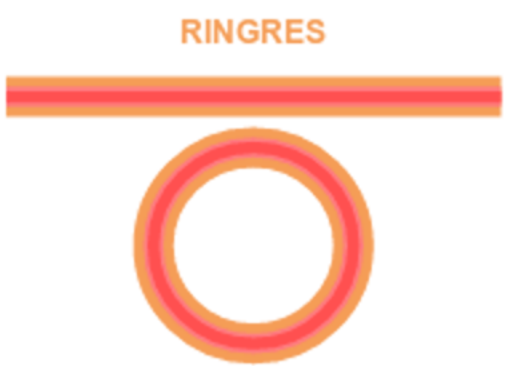


Ring filter

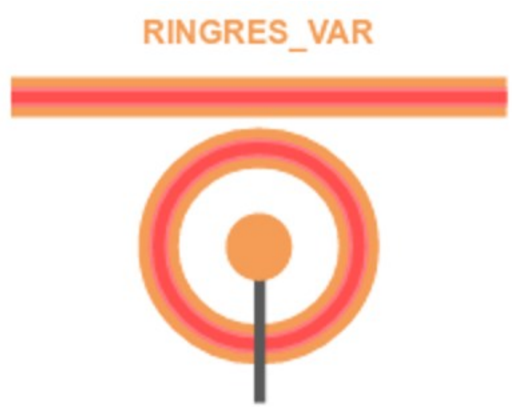
SiPh Primitives for Ring Resonators

- We can model these ring-based elements as multi-port waveguides with their port-to-port transfer functions
  - And avoid the propagation of events inside the rings

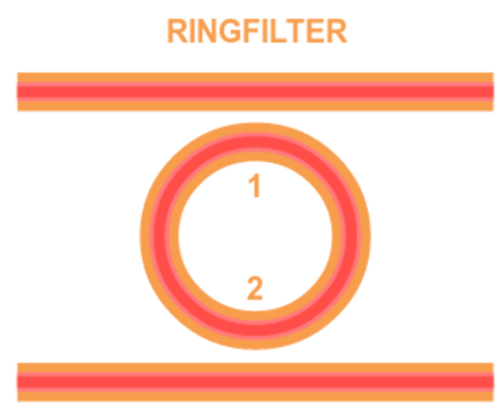
siph_ringres



siph_ringres_var



siph_ringfilter



Approximating Port-to-Port TFs

- Some TFs don't fit into canonical forms due to delays
- They can be approximated as a sum of canonical TFs

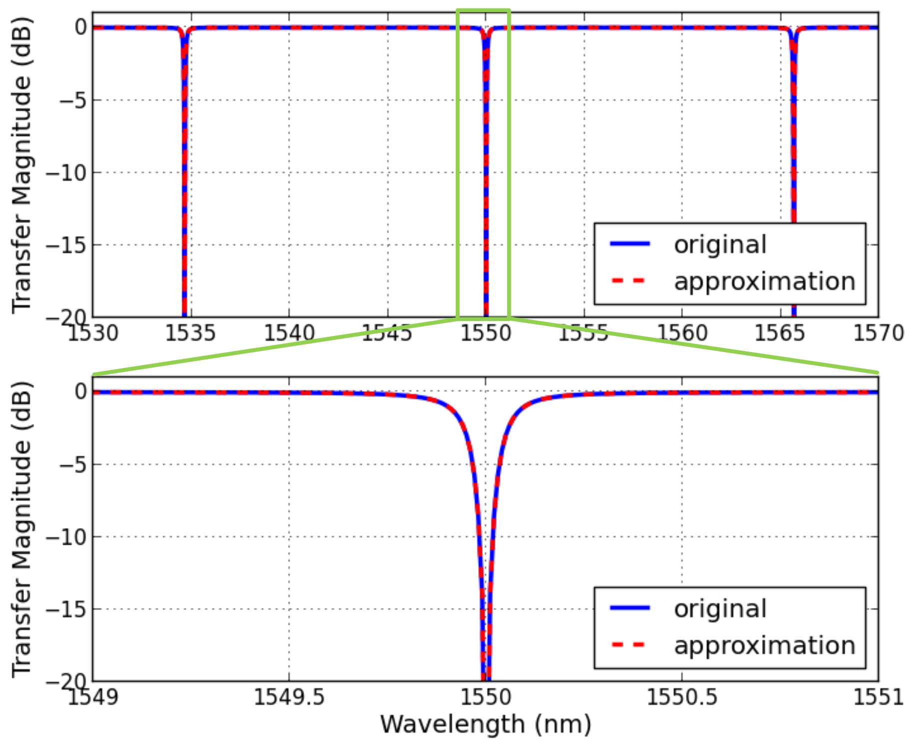
Ring Resonator:

$$H(s) = \frac{\tau - \alpha(\tau^2 + \kappa^2)\boxed{e^{-sT_R}}}{1 - \alpha\tau\boxed{e^{-sT_R}}} e^{-sT_D}$$

Bilinear Transformation

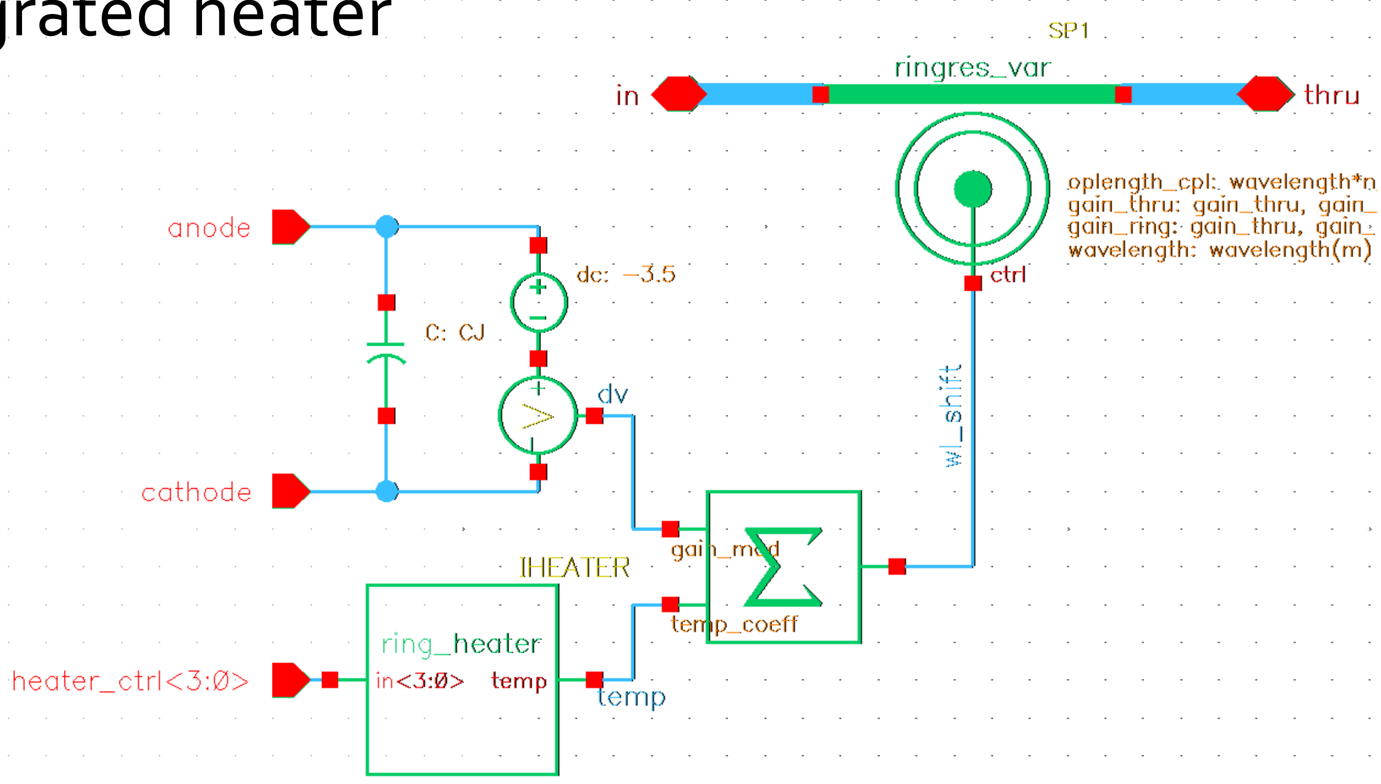
$$H(s) \approx \sum_n K_n \frac{1 + sT_{n,1}}{1 + sT_{n,2}} e^{-sT_D}$$

Bandstop filter having a notch at n-th resonant frequency



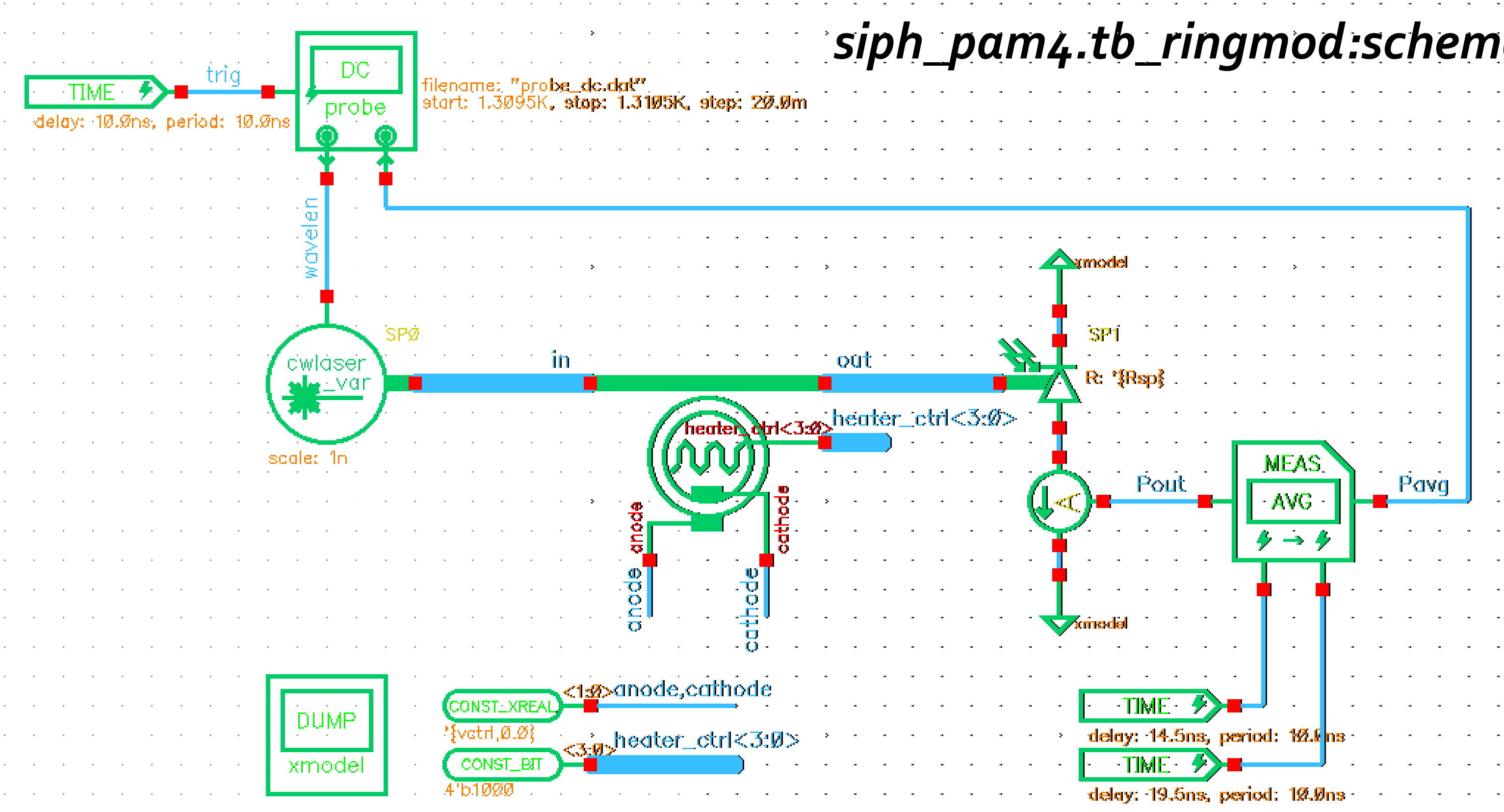
Modeling Micro Ring Modulator (MRM)

- The control terminals may have finite impedance (C_J)
- May also model temperature sensitivity and/or integrated heater



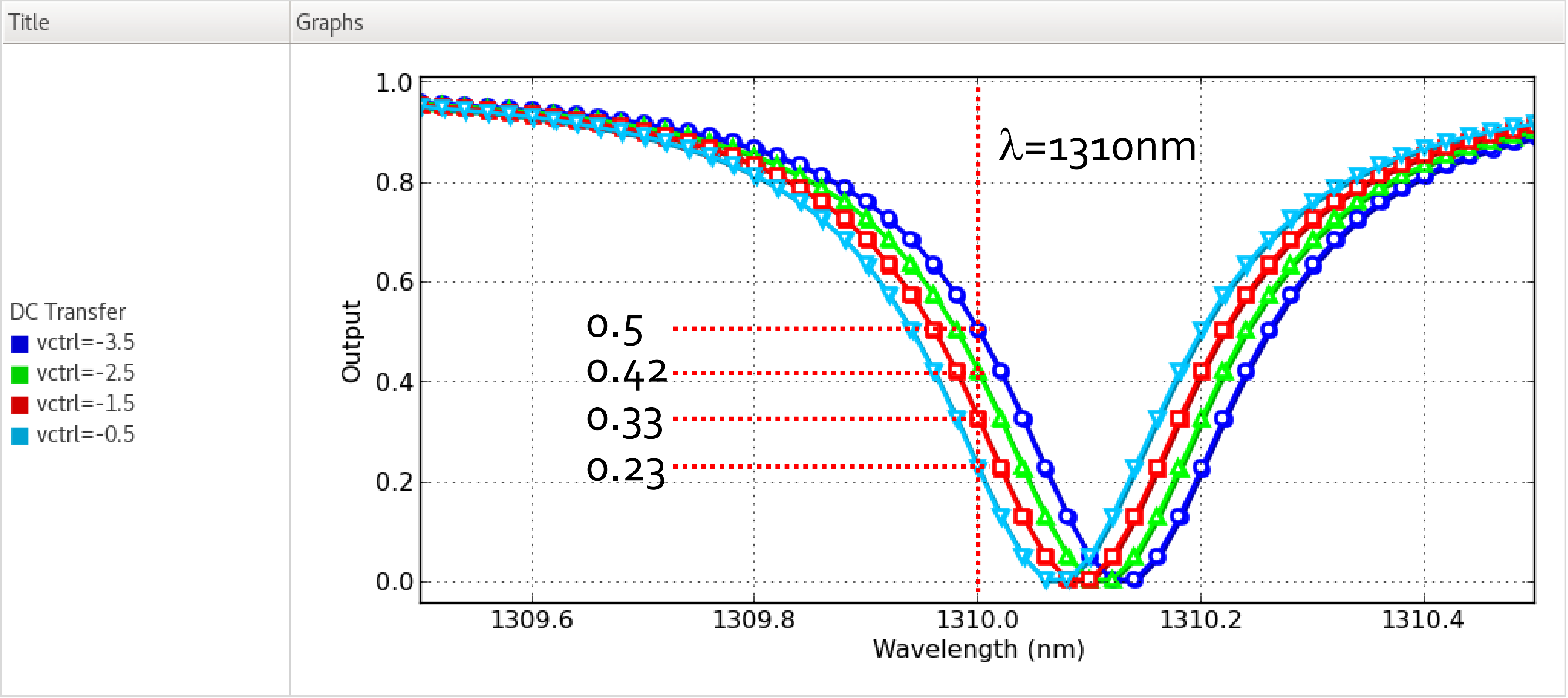
Simulating MRM Characteristics

- We can simulate the MRM's transfer characteristics by sweeping the wavelength and measuring output power



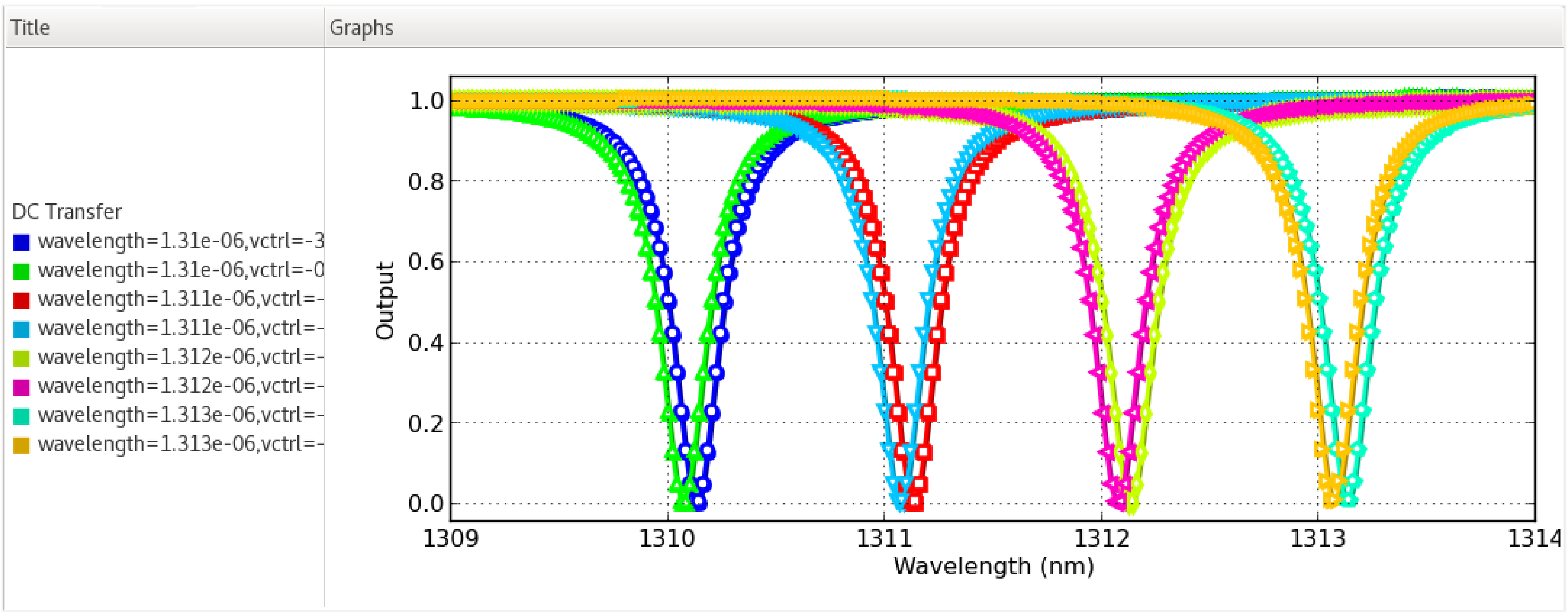
Simulated Results

- Varying the round-trip delay of the ring changes the resonance frequency and modulates the output power



MRM for WDM

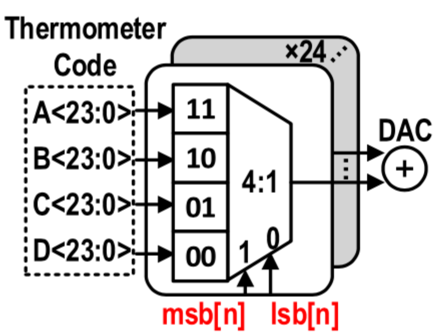
- Checking crosstalk between MRMs with resonances at 1310, 1311, 1312 and 1313nm

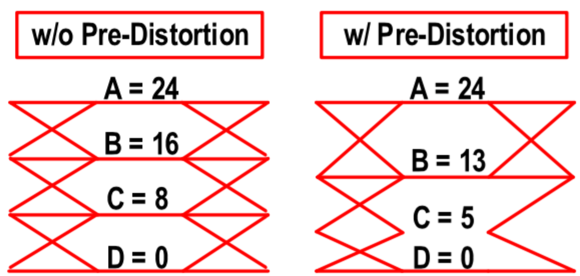


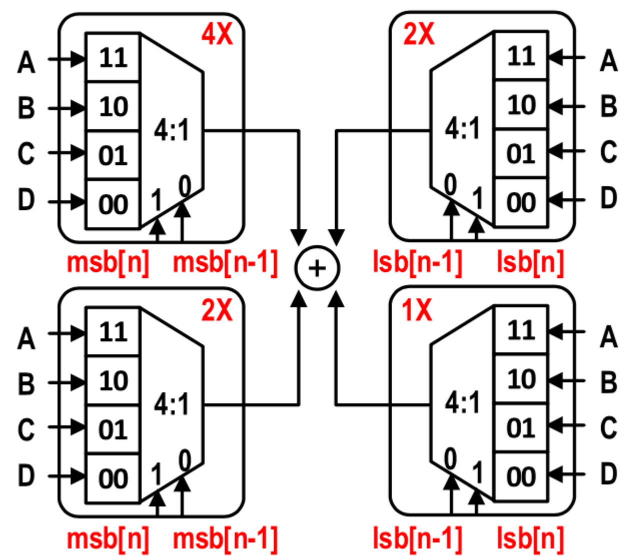
Predistortion and Equalization

- Predistortion (PD) compensates errors in PAM4 levels
- Equalization (EQ) compensates freq.-dependent loss

- A look-up table (LUT)-based implementation:



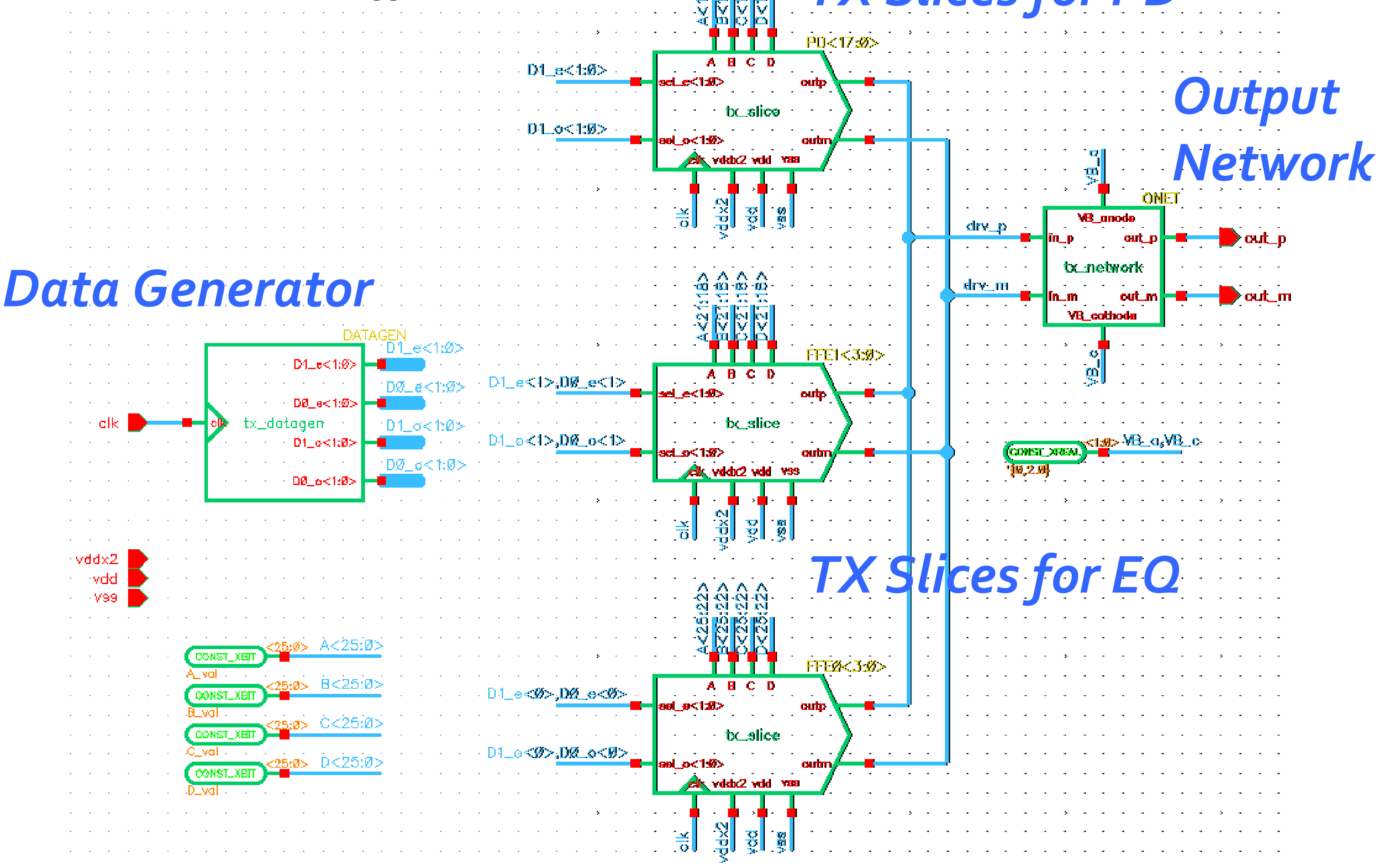




[H. Li, et al., JSSC 01/2021]

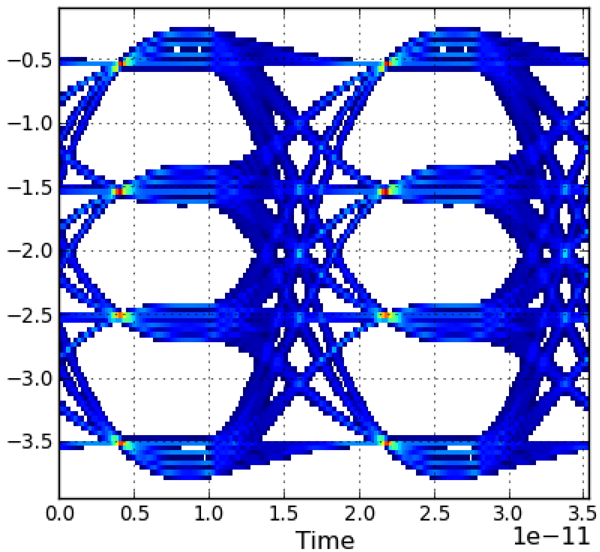
PAM4 TX with PD and FFE

siph_pam4. tx_pam4_ffe:schematic

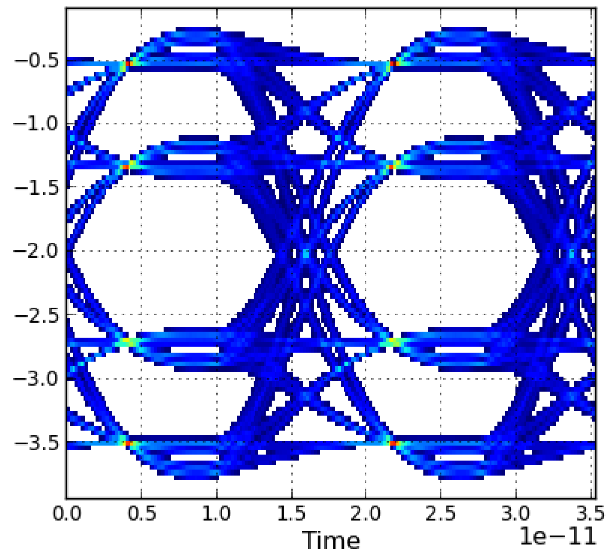


Simulated Eye Diagrams

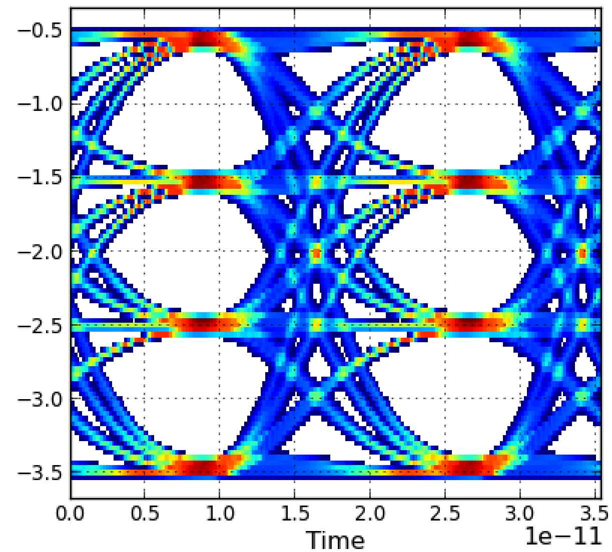
without PD & EQ



with PD



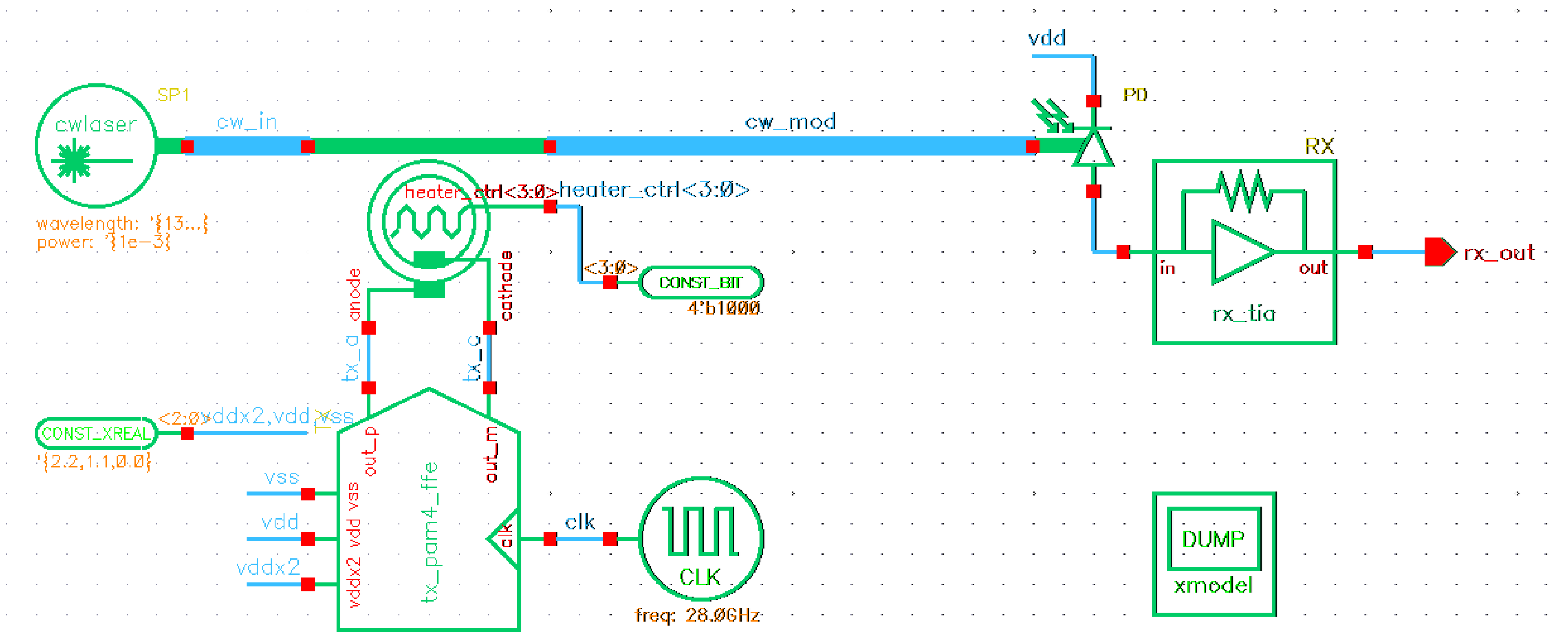
with EQ



siph_pam4. tx_pam4_ffe:tb_run

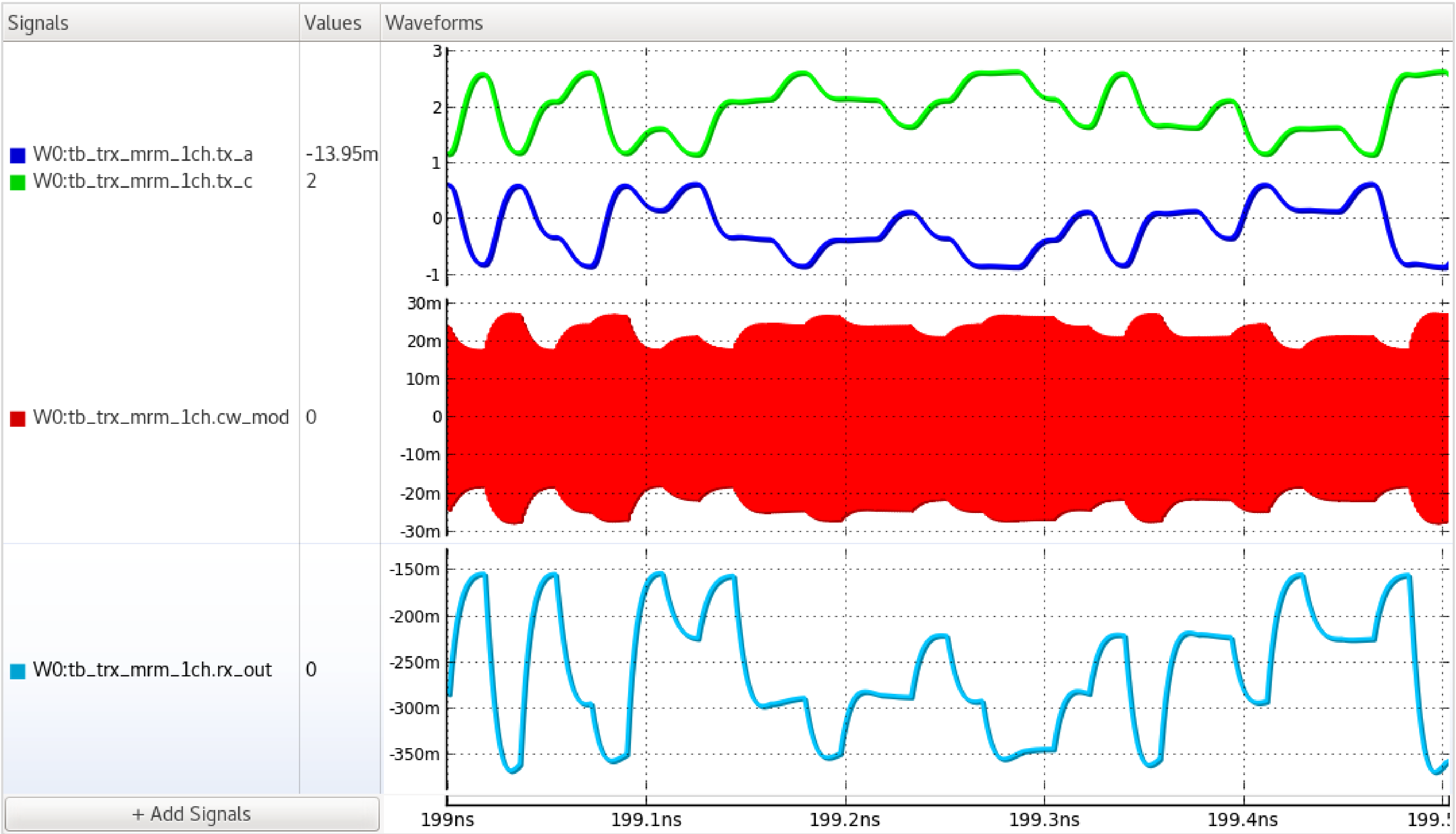
Simulating MRM Transceiver

- Driving MRM with PAM4 TX and receiving with TIA



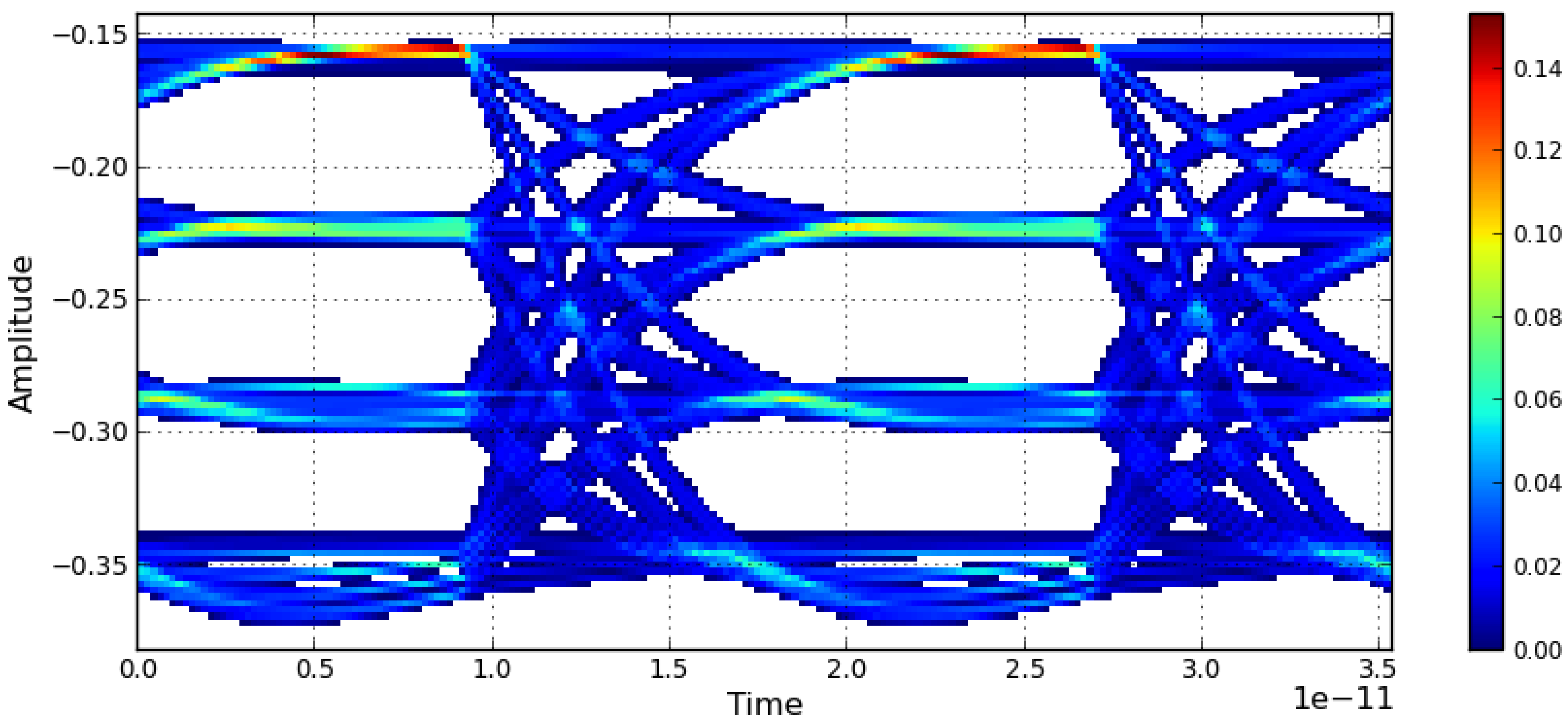
siph_pam4.tb_trx_mrm_1ch:schematic

Simulated Waveforms

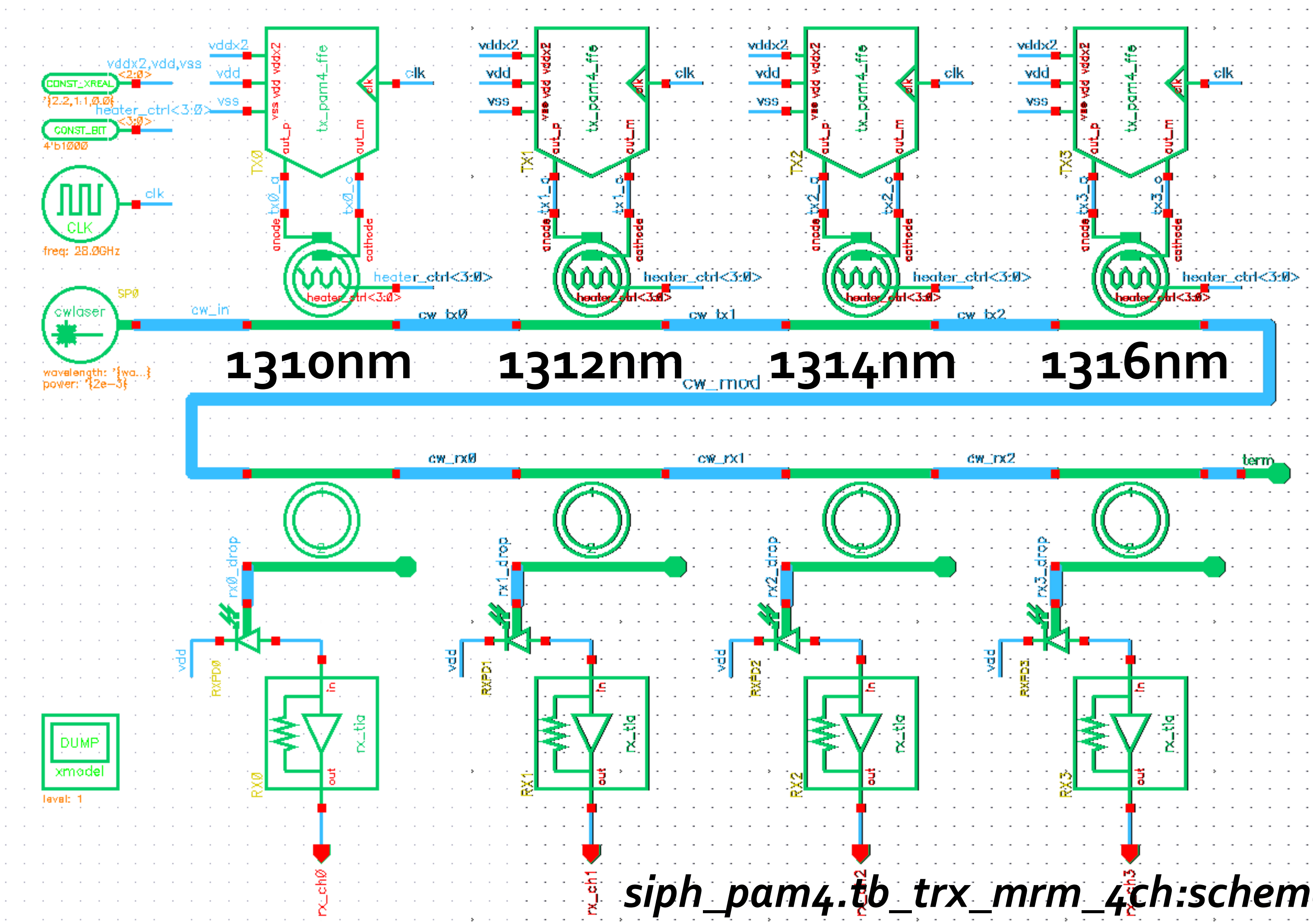


Simulated Eye Diagram

- Eye diagram of the RX TIA output

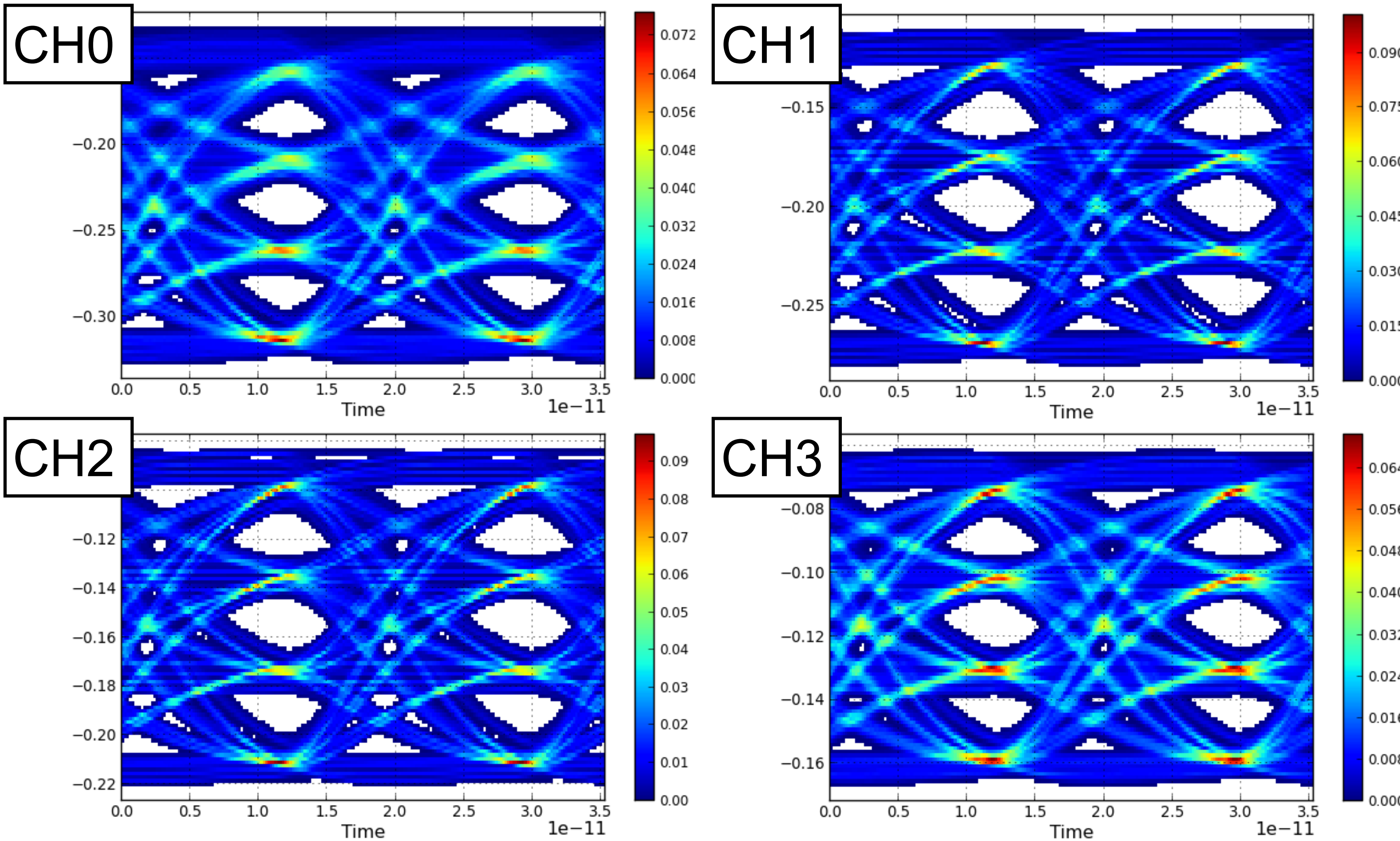


4-Channel WDM Transceiver



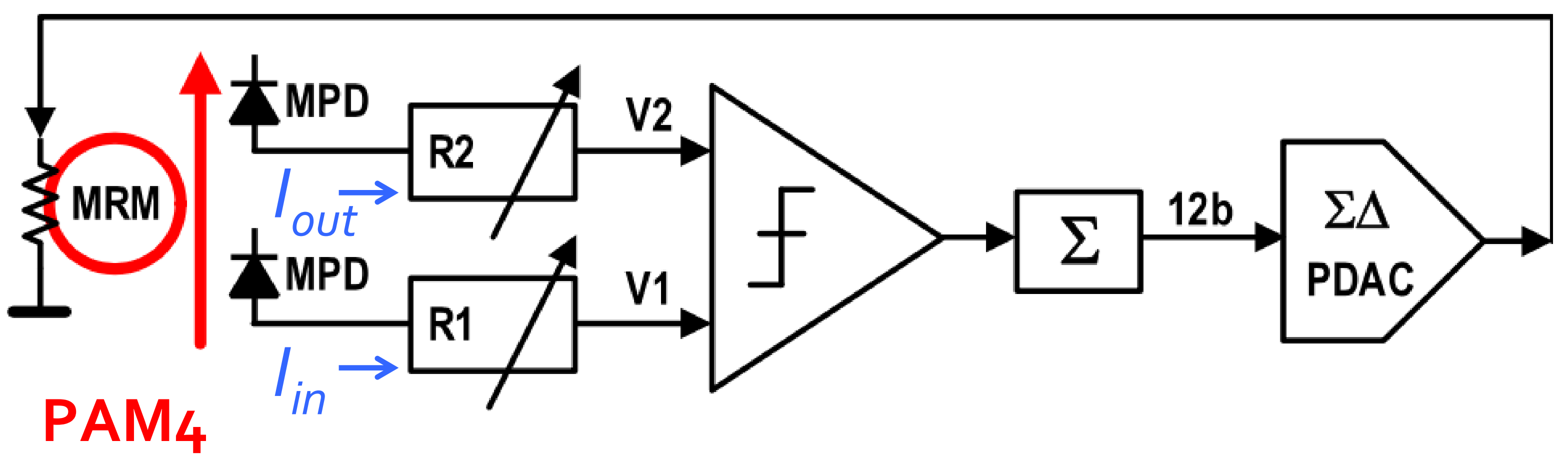
siph_pam4.tb_trx_mrm_4ch:schematic

4-Channel WDM Eye Diagrams



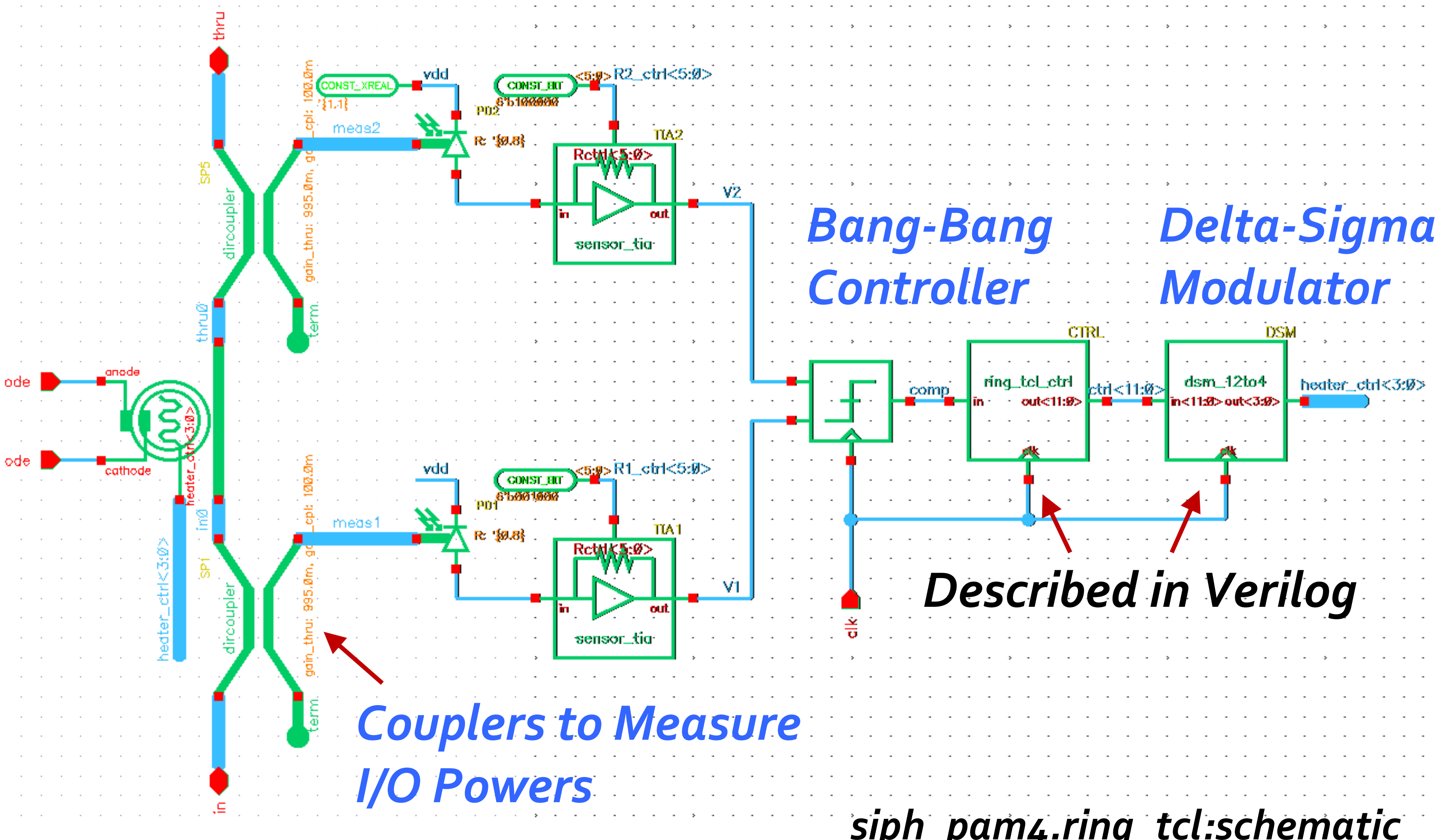
MRM Thermal Control Loop (TCL)

- Closed-loop control of MRM temperature with an integrated heater
  - Adjust temperature so that V1=V2 → I_{out}/I_{in} = R1/R2
  - MRM loss at detuning is set by the ratio R1/R2

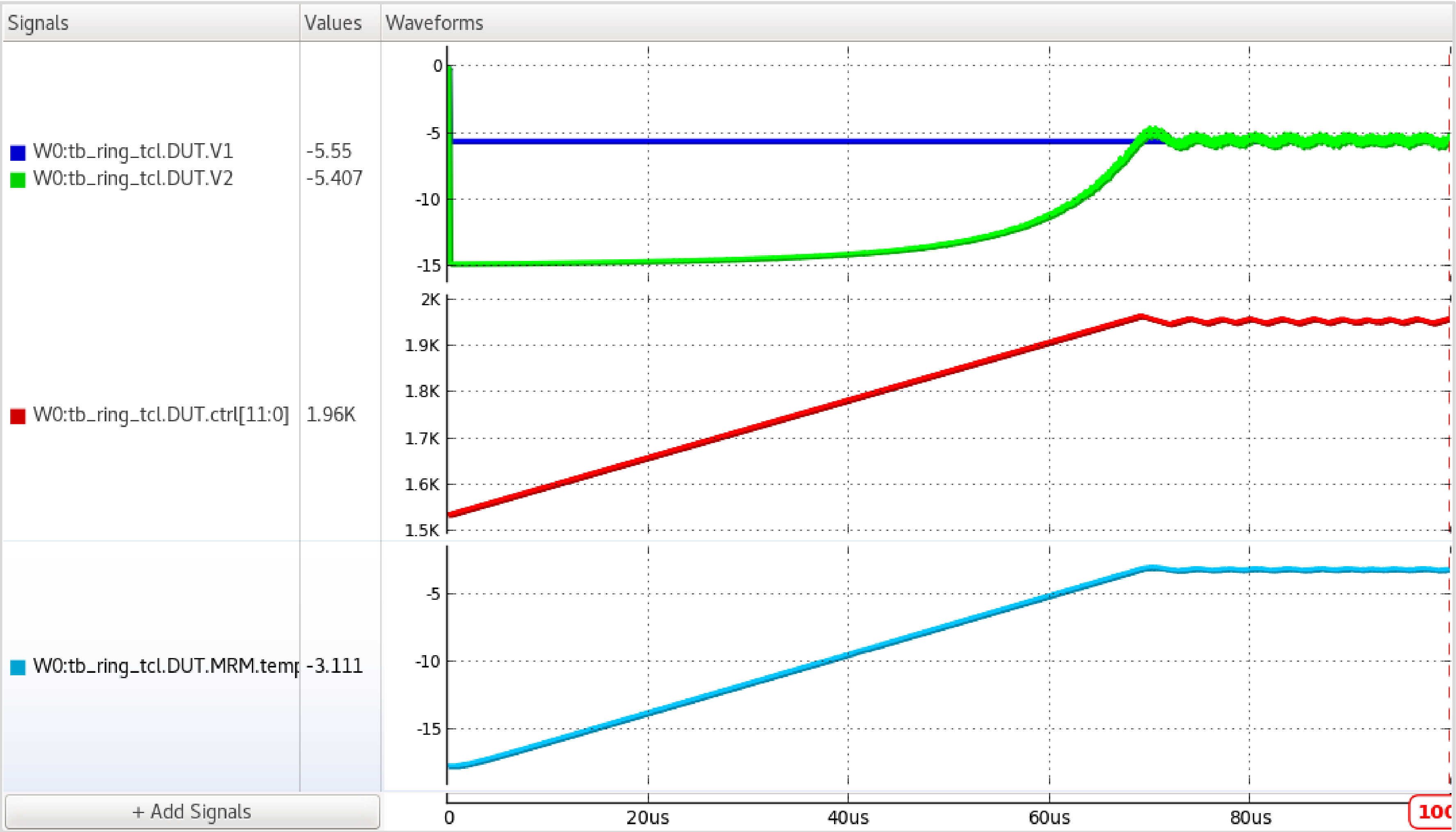


[H. Li, et al., JSSC 01/2021]

Modeling MRM TCL



Simulated Results



Summary

- Presented ways to extend the *XMODEL*'s event-driven simulation approach to silicon photonic systems
  - Expressing optical waves in equation forms
  - Modeling optical waveguides as transmission lines
  - Approximating TFs of ring resonator elements

- Demonstrated that we can model & simulate:
  - 4-channel wavelength-division multiplexing (WDM)
  - PAM4 MRM-based transceiver with PD and EQ
  - Thermal control loops for MRMs