Modeling of Si Rib and Photonic Crystal Mach-Zehnder Modulators for Electro-Optic Co-Simulation up to 64 Gbaud

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Background

Challenge

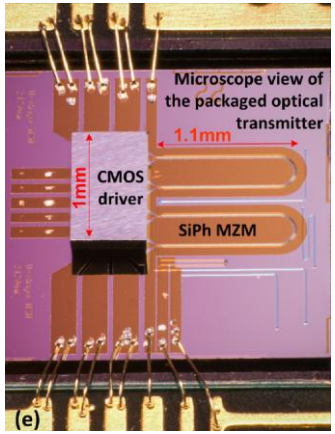
Huge data traffic for cloud services
High power consumption of interconnects

Beyond 400G

50–100-Gbaud modulation with a power of <300 mW
(Including Drivers)

Electro-Optic Hybrid Integrated Si Transmitters

Soton Univ. ’20



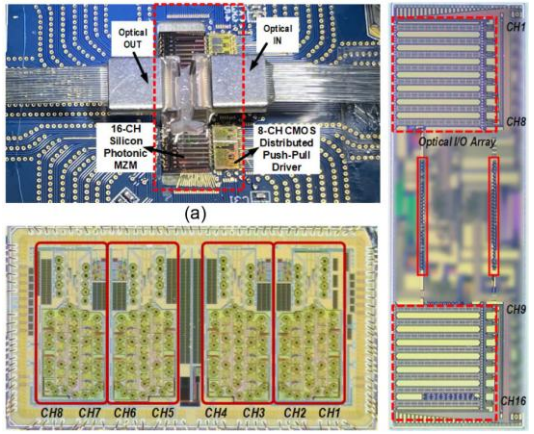
100-Gbps NRZ
203 mW/ch

STMicroelectronics ’20



53-Gbps PAM4 × 4ch
290 mW/ch

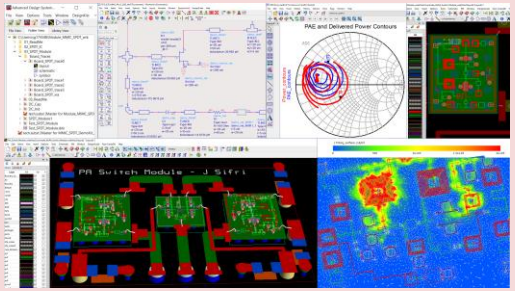
Peking Univ. ’23



50-Gbps NRZ × 16ch
268 mW/ch

Transceiver Design Flow

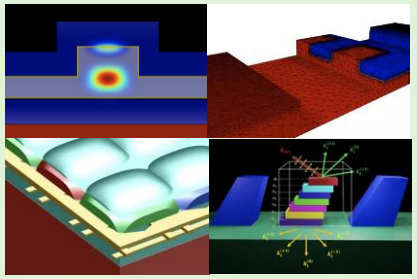
Electronics



© Keysight Technologies, Inc.

- HSPICE
- Spectre
- ADS
- etc…

Photonics



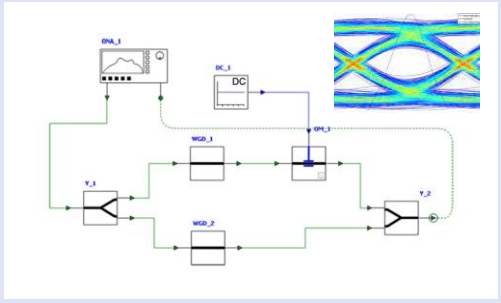
© Ansys, Inc.

- Lumerical
- Rsoft
- OptDesigner
- etc…

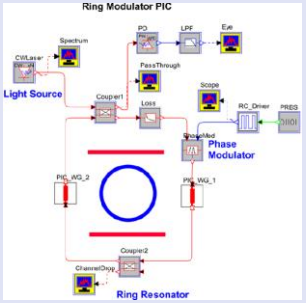
S-parameters

Models

Block Level Simulation



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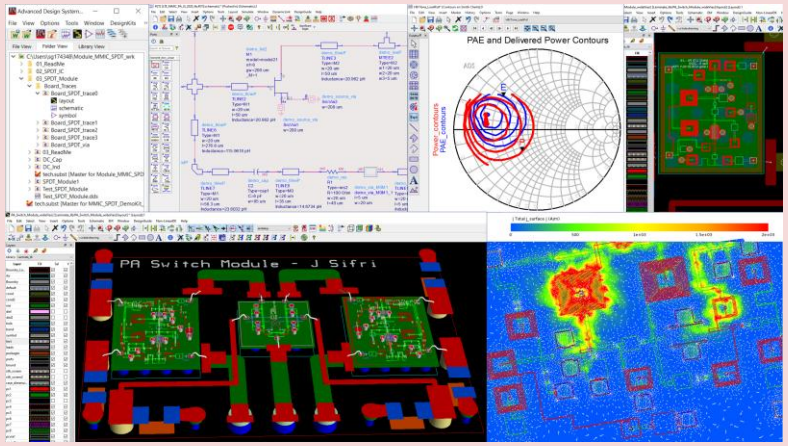
© Synopsys, Inc.

- Lumerical Interconnect
- OptSim Circuit
- OptiSpice
- MATLAB Simulink
- etc…

There is a barrier between electronics and photonics

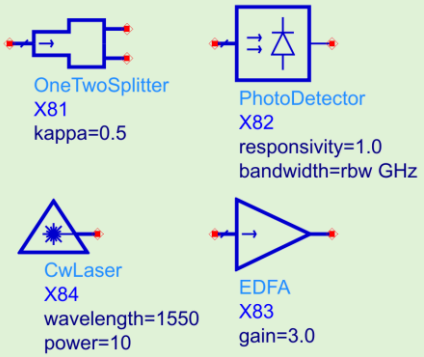
Verilog-A Modeling Approach

Electronics Simulators



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Photonics (Verilog-A PDKs)




```
`include "constants.vams"
`include "disciplines.vams"

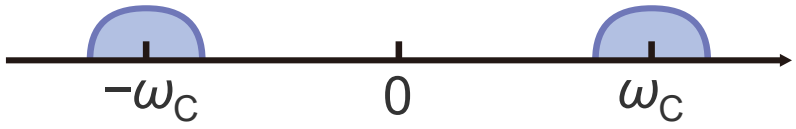
module Waveguide(in, out);
    input [0:1] in;
    output [0:1] out;
    optical [0:1] in, out,
```

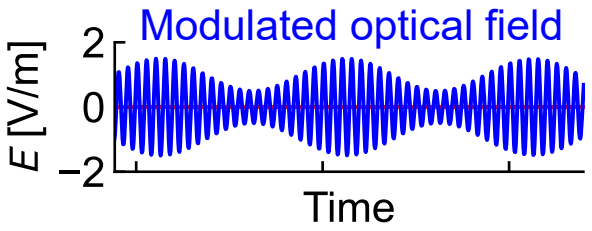
- Verilog-A
  - Analog circuit (or device) modeling language
  - Used in many electronic circuit simulators
- Photonics device models in electronics simulators
  - Allows for co-design and co-optimization

Verilog-A Model Overview

C. Sorace-Agaskar, *et al.*, *Opt. Express*, vol. 23, no. 21, pp. 27180–27203, Oct. 2015.

Real Signal

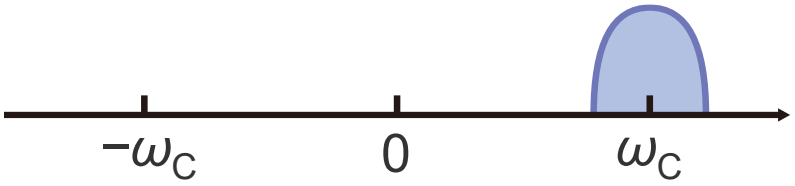


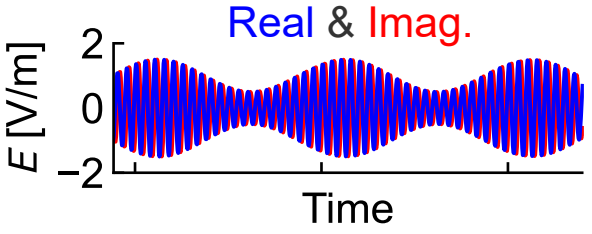


× Difficult to compute instantaneous amplitude and phase

× Optical frequency ω_C is too high (≈300 THz) for circuit simulation

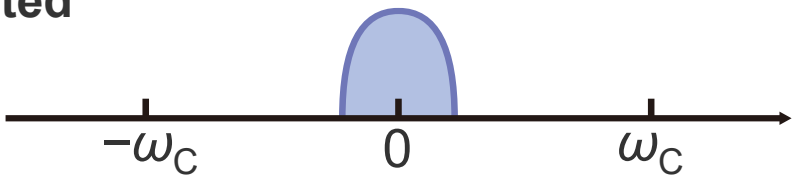
Analytic Signal

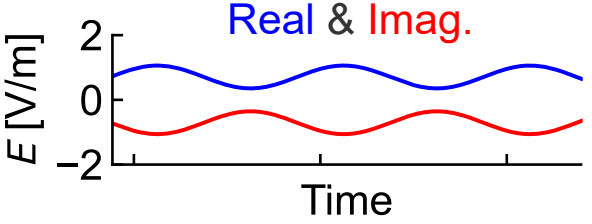




✓ Simple handling of amplitude and phase like $A(t)e^{j(\omega_C t+\theta(t))}$

Frequency Shifted Analytic Signal

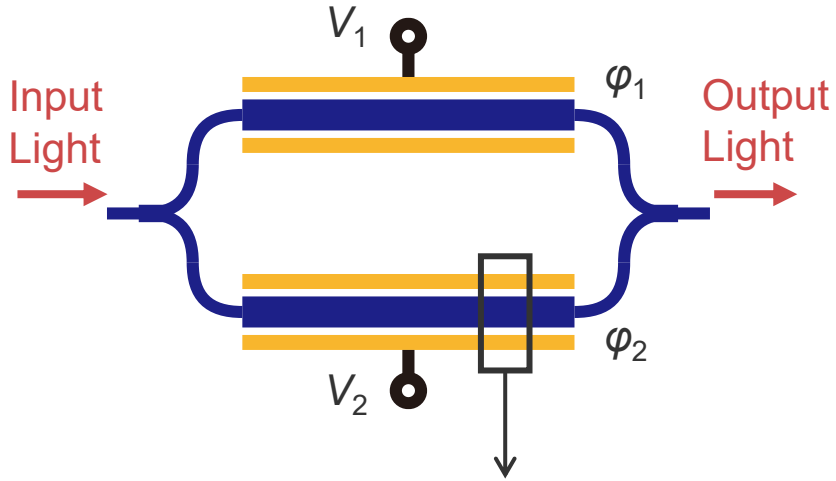


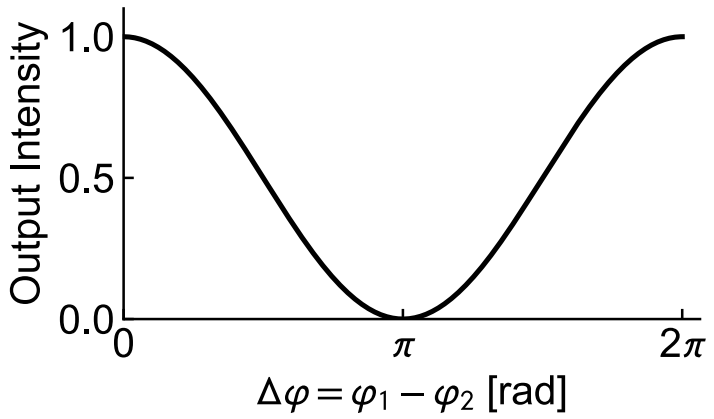


✓ Reduces simulation time steps

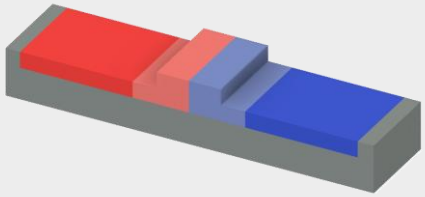
Si Mach-Zehnder Modulator

Modulators convert electrical signals to light intensity

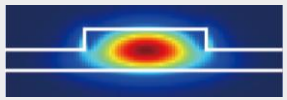




Rib Waveguide

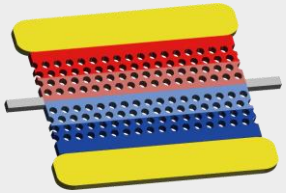


Cross Section

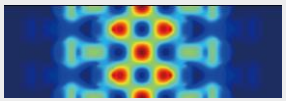


✓Commercial products

Photonic Crystal Waveguide (PCW)



Top View

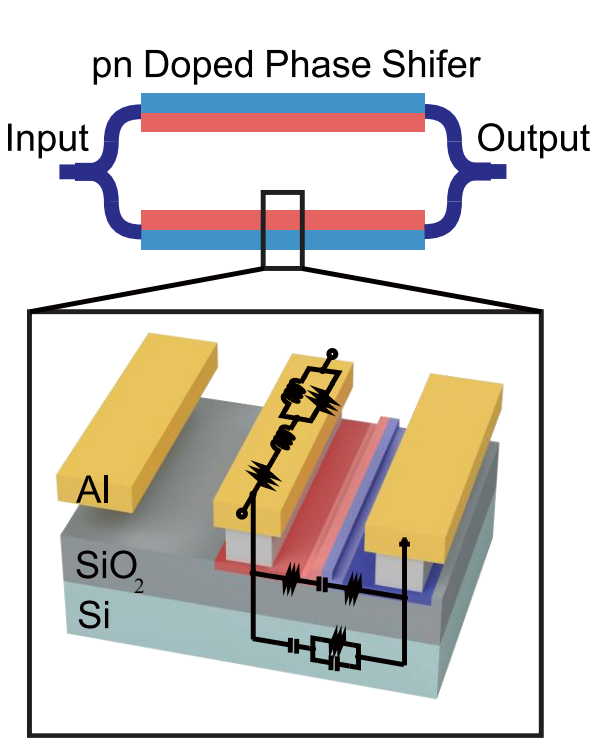


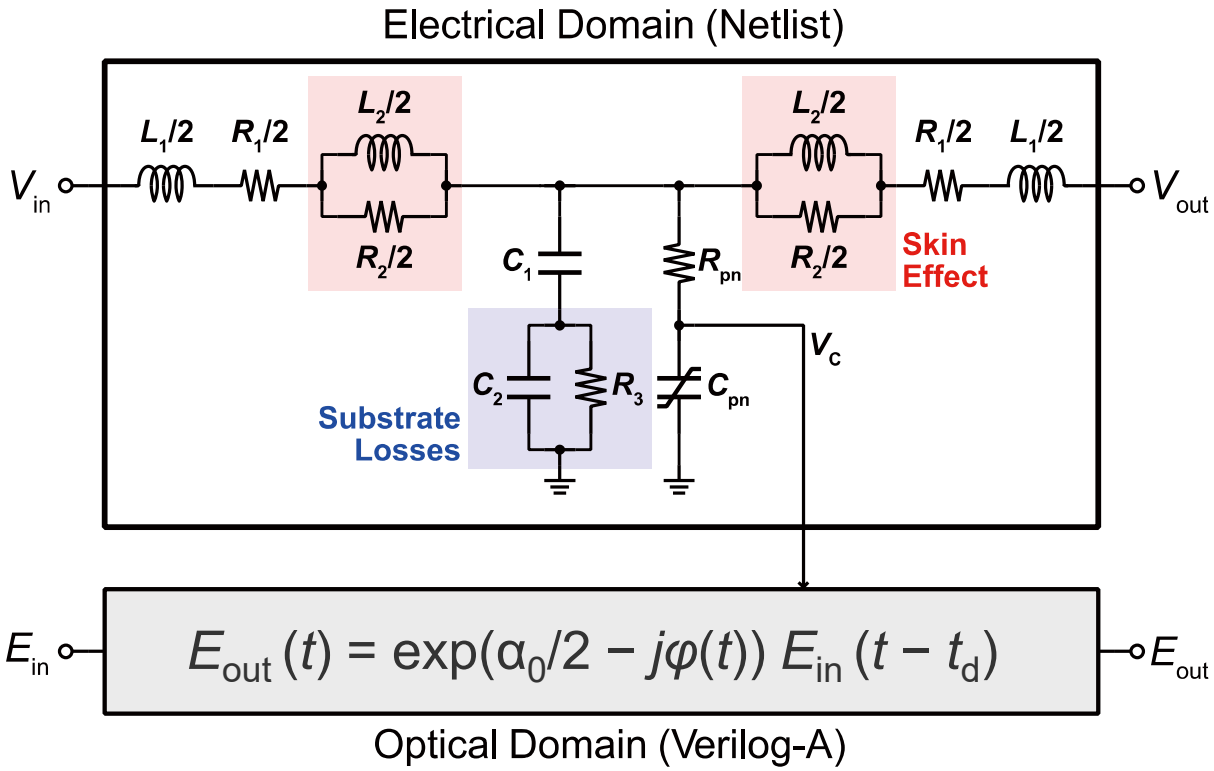
✓Efficient due to slow light effect

High-frequency (> 25 Gbaud) Verilog-A model is still missing

This work: Accurate RF modeling of Si rib and PCW modulators

Proposed Model Schematic

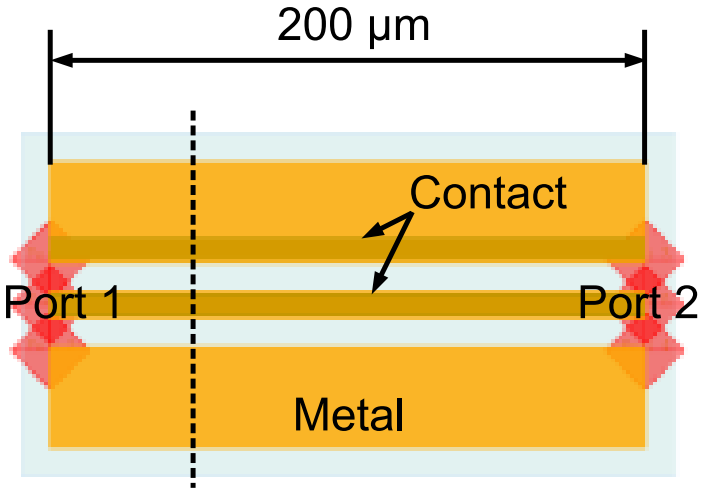


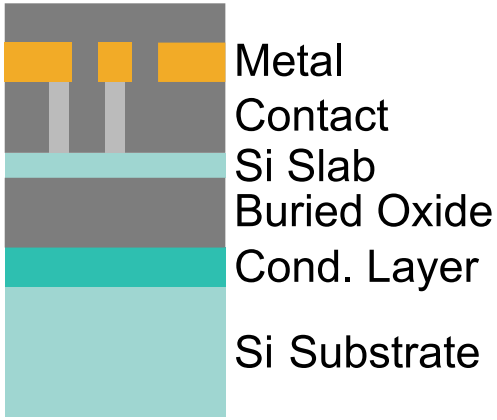


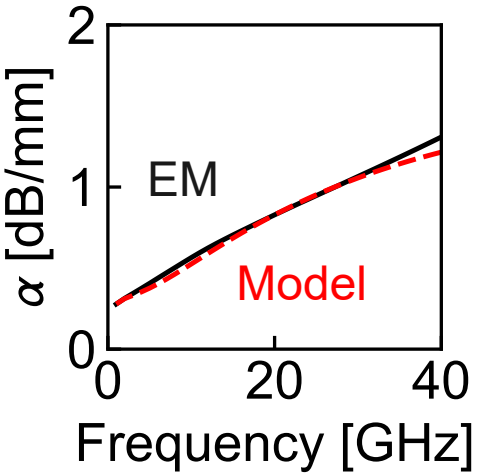
- Distributed circuit model
  - Provides the phase mismatch between RF and optical pulses
  - Provides the RF propagation losses (skin effect and substrate losses)
- Fitting parameters: L_1, L_2, R_1, R_2, C_1, C_2, R_3, R_{pn}, $C_{pn}(V)$, $n_{eq}(V)$, n_g

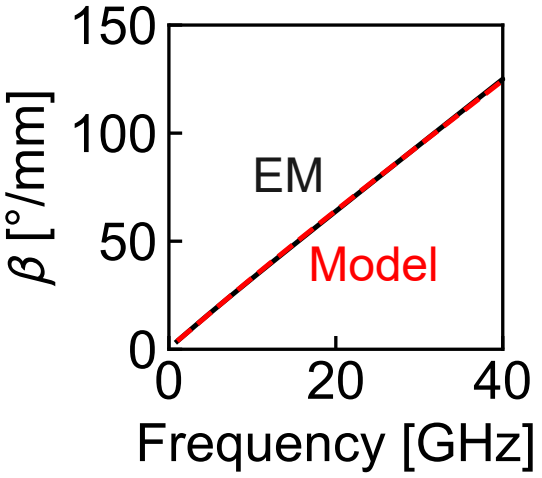
Electrode Extraction

- EM simulation with Keysight Momentum
- Electrodes only (not include pn junction)









2-port S-parameters

↓

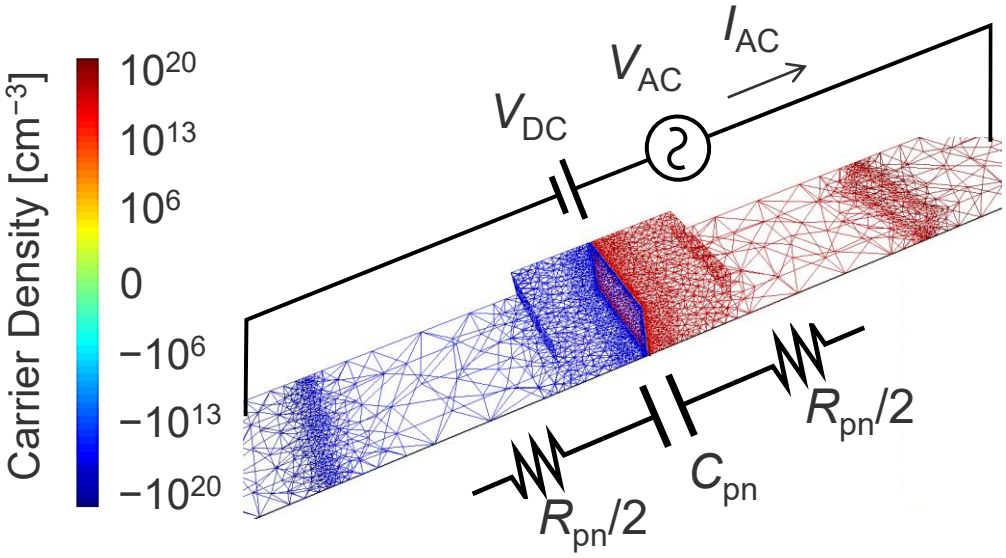
Impedance Z_0 and propagation constant $\gamma = \alpha + j\beta$

↓ Fitting

$L_1, L_2, R_1, R_2, C_1, C_2, R_3$

RC Time Constant

Small signal AC analysis using Lumerical CHARGE



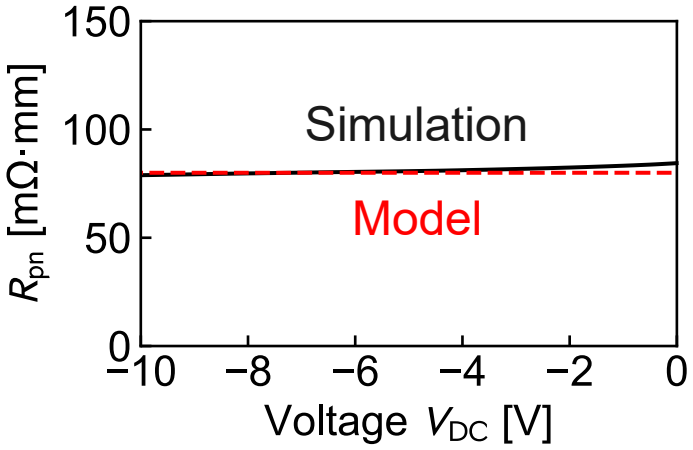
Calculate Z_{pn} for various V_{DC}

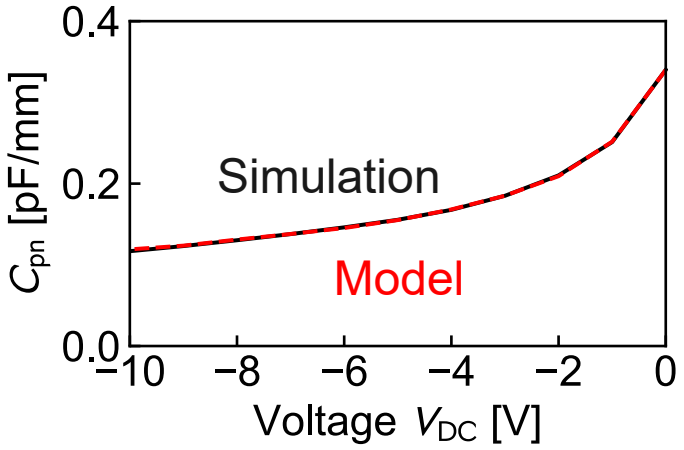
↓

R_{pn} = real (Z_{pn})
C_{pn} = 1 / ω | imag(Z_{pn}) |

↓ Fitting

$C_{pn}(V) = C_6V^6 + C_5V^5 + \ldots + C_0$

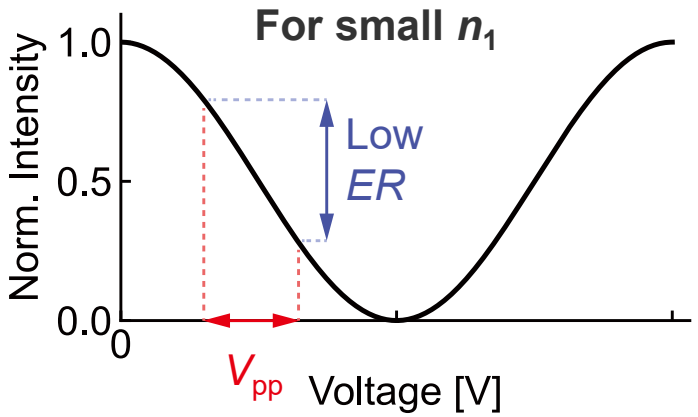


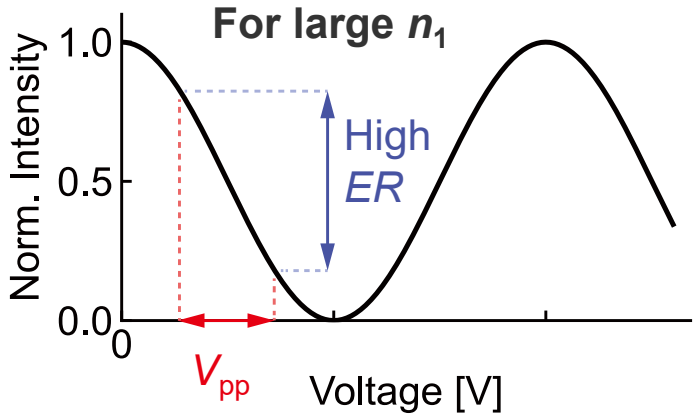


Modulation Efficiency

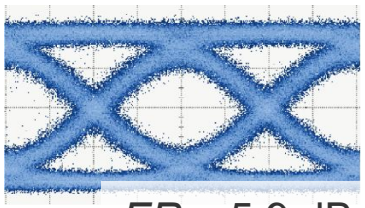
Modal equivalent index: $n_{eq}(V) = n_0 + n_1 V$

- n_0 was calculated using mode simulation (ex. Lumerical MODE)
- n_1 was determined from the *ER* of measured eye



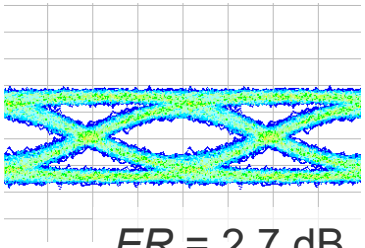


Measurement



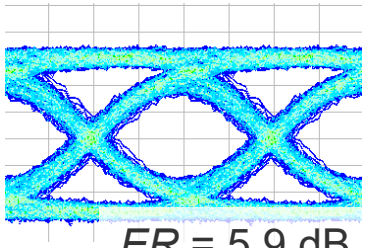
ER = 5.9 dB

Too small n_1



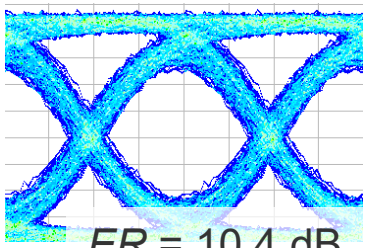
ER = 2.7 dB

Optimal n_1



ER = 5.9 dB

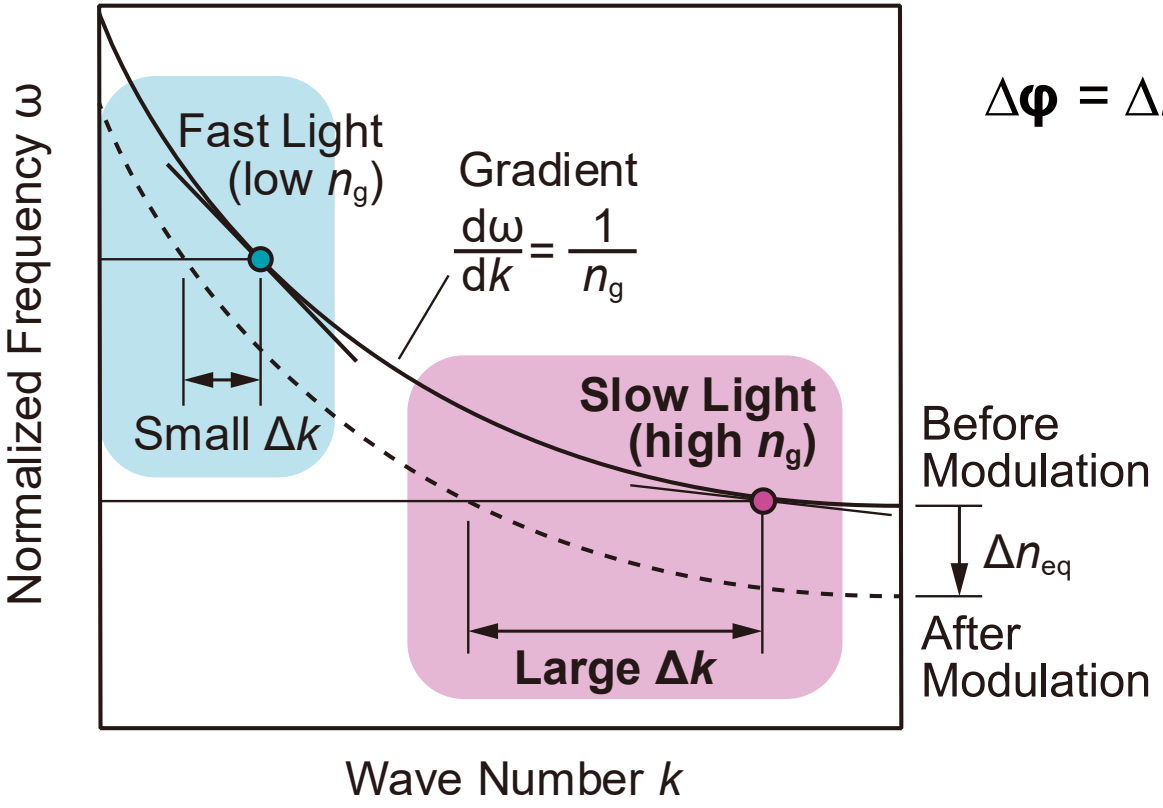
Too large n_1



ER = 10.4 dB

Slow Light Effect

Modulation efficiency of a PCW phase shifter ∝ group index n_g



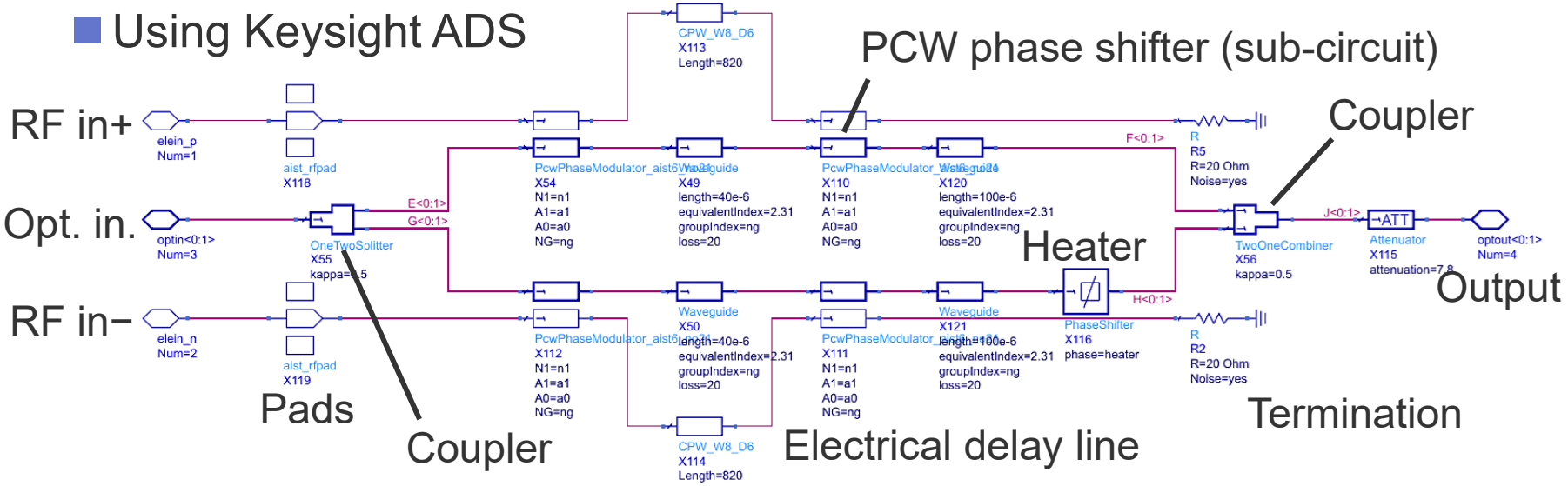
$$\Delta\varphi = \Delta kL = k_0 \boldsymbol{n_g} \zeta \frac{\Delta n_{eq}}{n_{eq}} L$$

$$\left[\zeta \equiv \frac{n_{eq}}{\omega_b} \frac{d\omega_b}{dn_{eq}} \right]$$

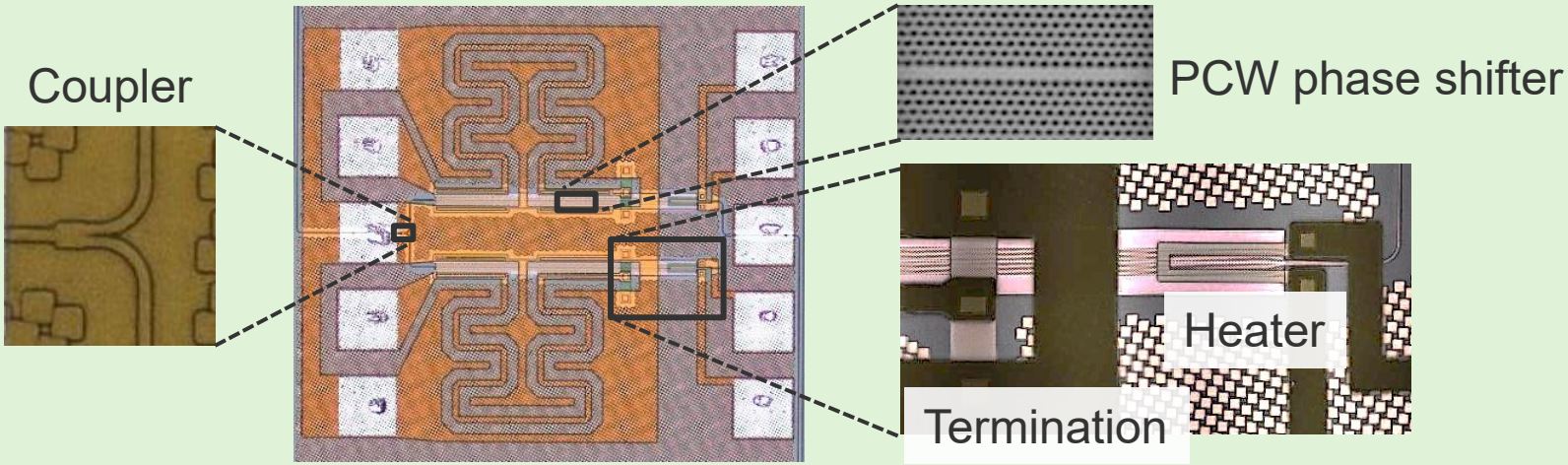
Verilog-A model equation of a PCW phase shifter: $n_{eq}(V) = n_0 + \boldsymbol{n_g} n_1 V$

Full Simulation Schematic

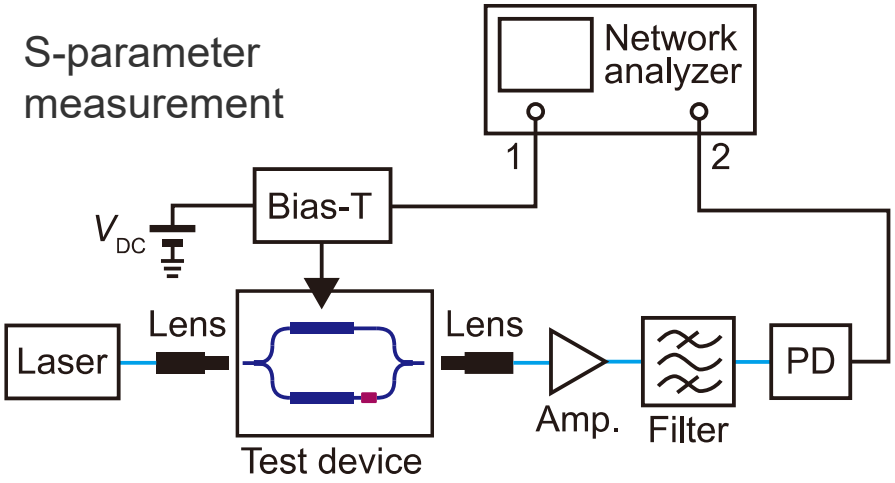
- Using Keysight ADS

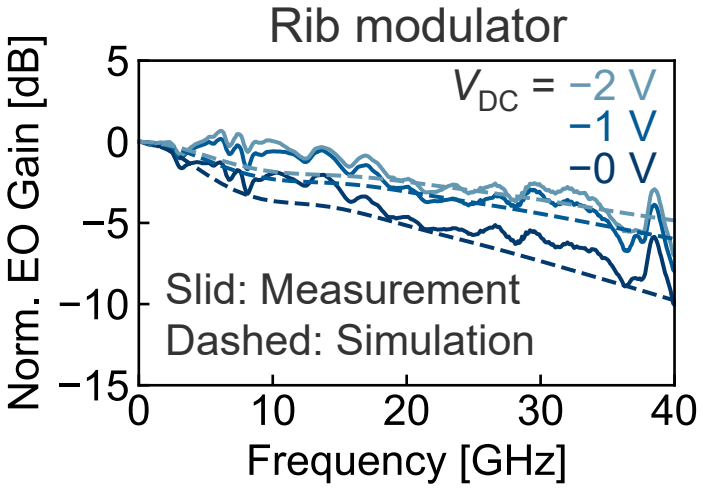


Simulation schematic corresponds perfectly to the actual device

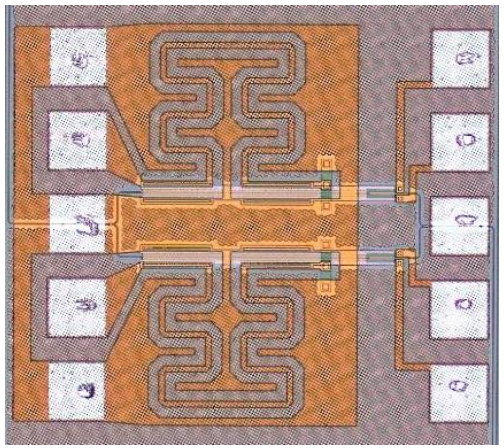


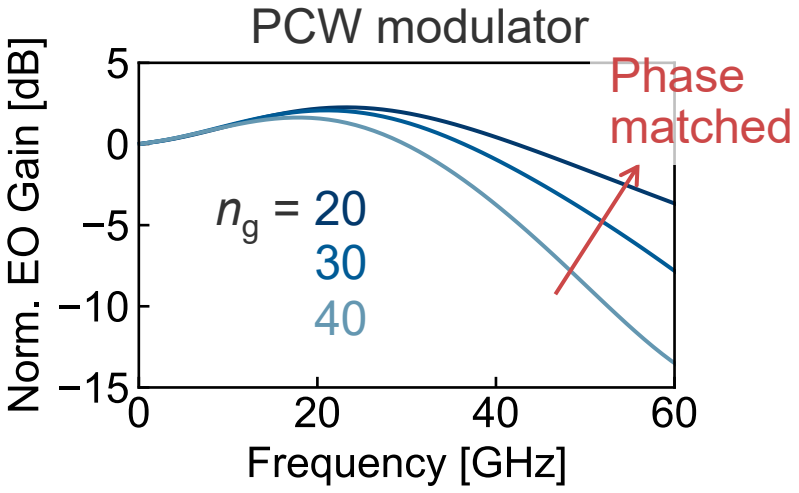
Result - Frequency Response





Simulation agreed well with the measurement up to 40 GHz



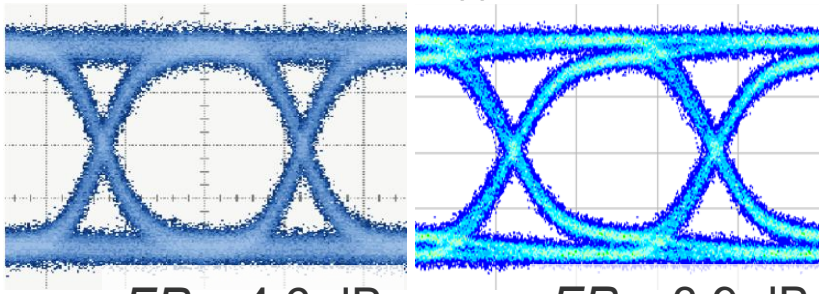


For PCW modulators, simulation can estimate n_g dependency

Eye Diagram (Rib Modulator)

Measurement Simulation

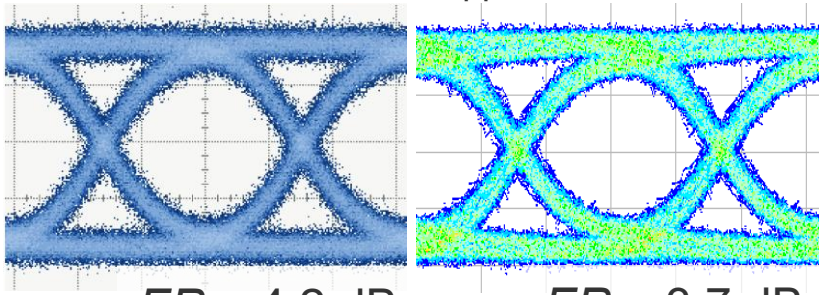
20 Gbps, V_{pp} = 2 V



ER = 4.6 dB *ER* = 3.9 dB

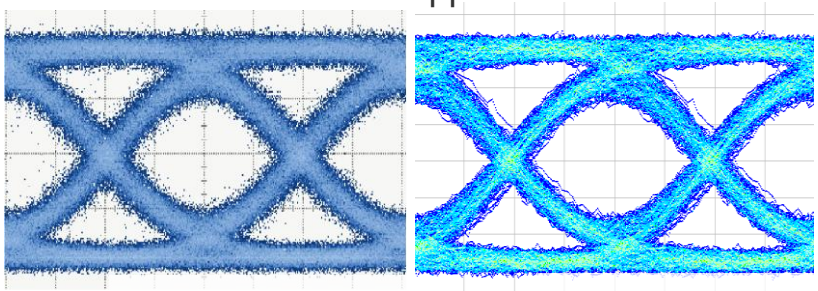
Measurement Simulation

32 Gbps, V_{pp} = 2 V



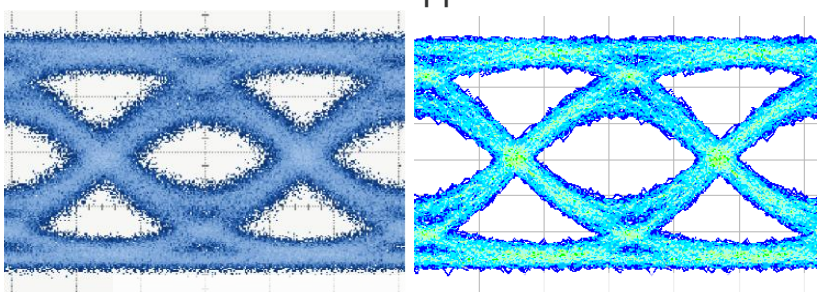
ER = 4.2 dB *ER* = 3.7 dB

50 Gbps, V_{pp} = 3.5 V



ER = 5.9 dB *ER* = 5.9 dB

64 Gbps, V_{pp} = 3.5 V

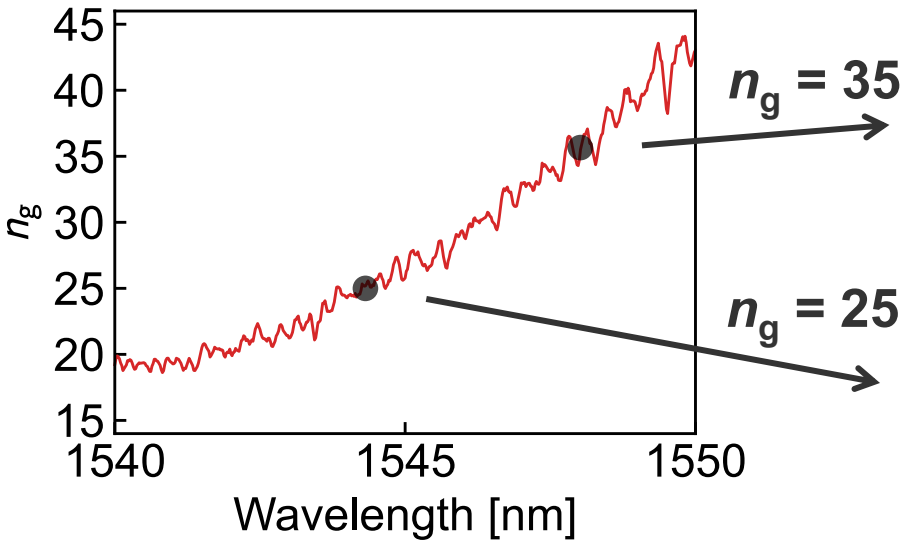


ER = 5.0 dB *ER* = 5.2 dB

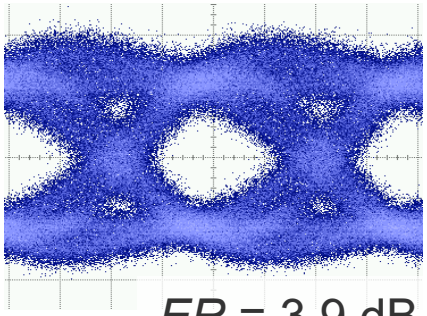
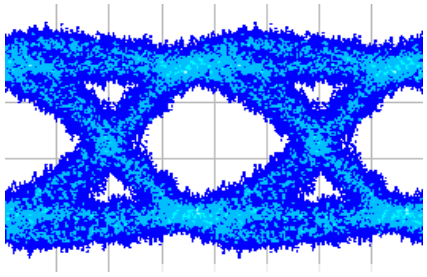
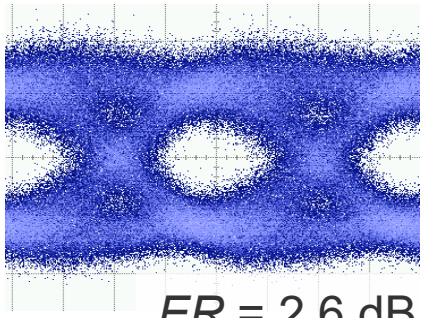
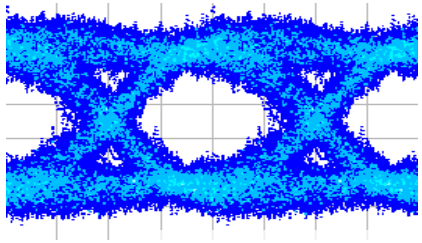
The error of *ER* was less than 1 dB up to 64 Gbps

Eye Diagram (PCW Modulator)

n_g dependence of *ER* was measured at different wavelengths



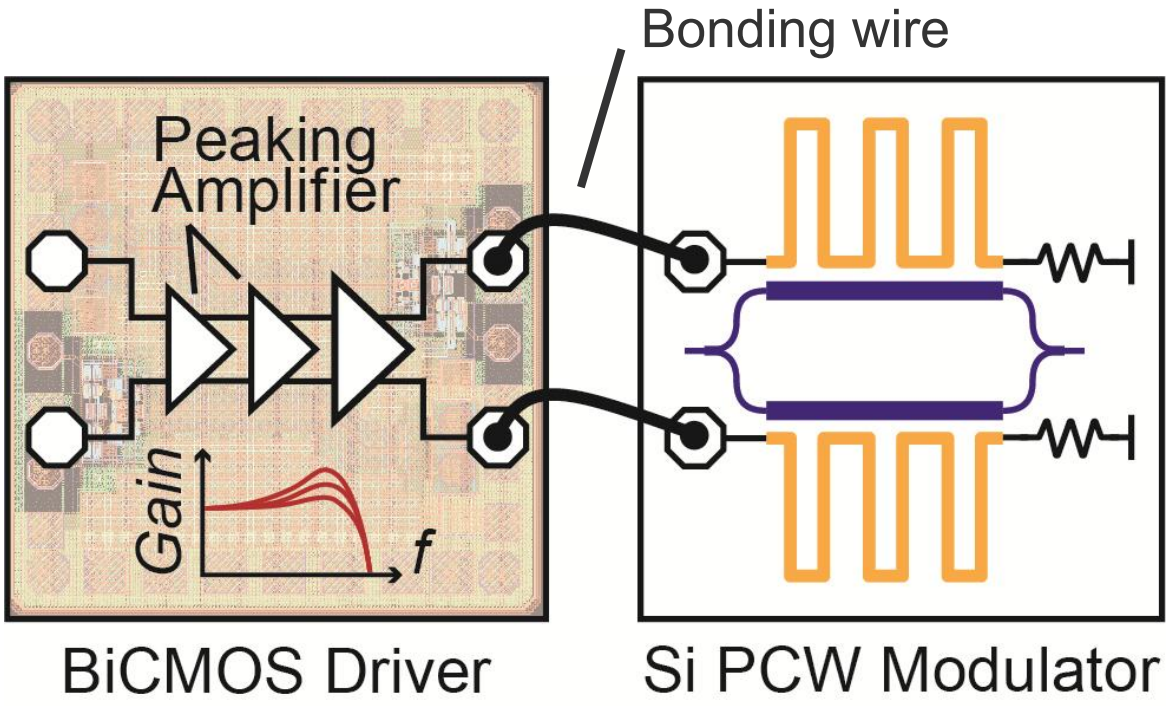
50 Gbps, V_{pp} = 3.5 V

Measurement	Simulation
	
ER = 3.9 dB	*ER* = 3.7 dB
	
ER = 2.6 dB	*ER* = 2.7 dB

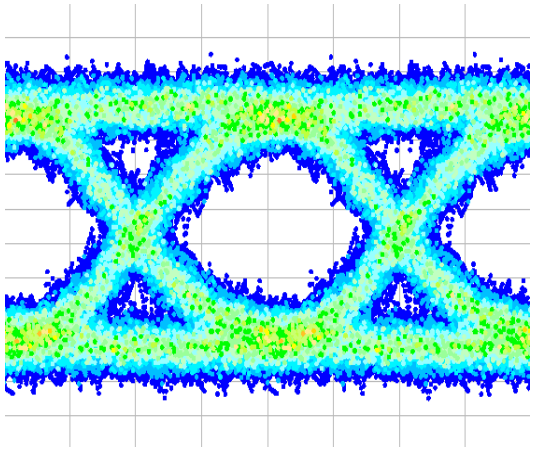
Model accurately predicted *ER* improvements due to slow light effect

EO Co-Simulation

- Hybrid integration of a SiGe BiCMOS driver and Si PCW modulator
- BiCMOS device models were provided from a foundry



Optical Out., **50 Gbps**



ER = 3.5 dB

Co-simulation predicted the overall performance

Conclusion

Purpose

- Remove the barrier between electronics and photonics
- Verilog-A modeling of Si optical modulators at high frequencies

Result

- Accurate model including propagation loss and slow light effect
- Good agreement between measurement and simulation up to 64 Gbaud

Conclusion

Verilog-A modeling approach is effective for the state-of-the-art EO co-design beyond 50 Gbaud

Future work: Process variation modeling for yield analysis