A Simulation Tool Development Roadmap to Support a Scalable Silicon Photonics Design Ecosystem

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Outline

Introduction

Overview of design flows and where simulation is required

Review current status and needs

- Component design and optimization
- Compact model library (CML) generation for PDKs
- Photonic integrated circuit simulation

Roadmap

Conclusions

Introduction

Silicon photonics offers many opportunities

edX course | Silicon Photonics Design, Fabrication and Data Analysis

- Scalable
  - high-index contrast -> compact
  - a variety of devices -> high functionality
- Low cost & high volume
  - CMOS manufacturing facility
- Many applications
  - optical interconnects (data centers, telecom, HPC, …)
  - sensing (biological, chemical, …)

Circuit complexity continues to increase

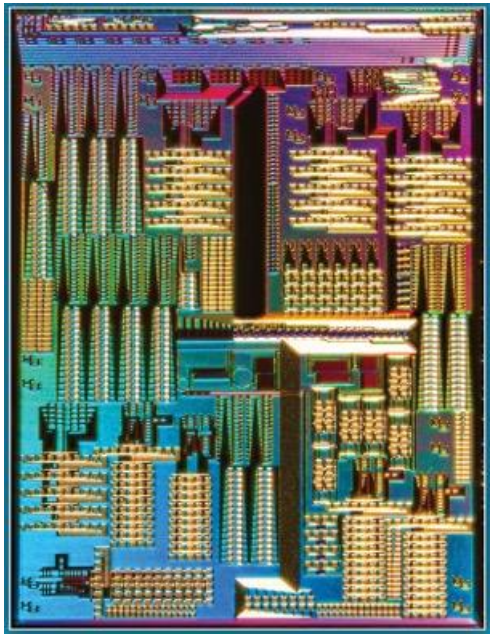
- Full design flow solutions are emerging
  - EDA tools + photonic simulation technologies
- Silicon photonic process design kits (PDKs) are emerging

Introduction

Fabless model and foundry

- Multi-project wafer (MPW) services
- Wide range of reliable components available
- Packaging
- Prototyping
- Path to mass production

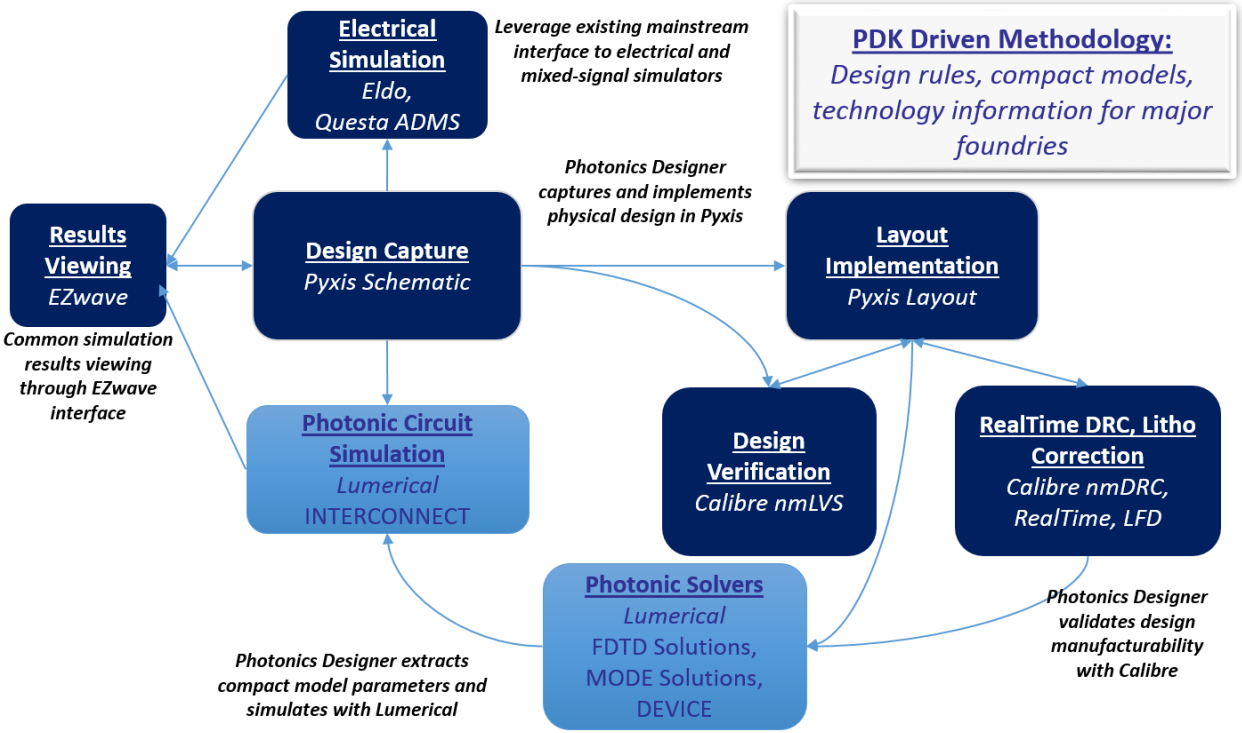
Book: Silicon Photonics Design



SiEPIC-IME chip, including active components such as modulators

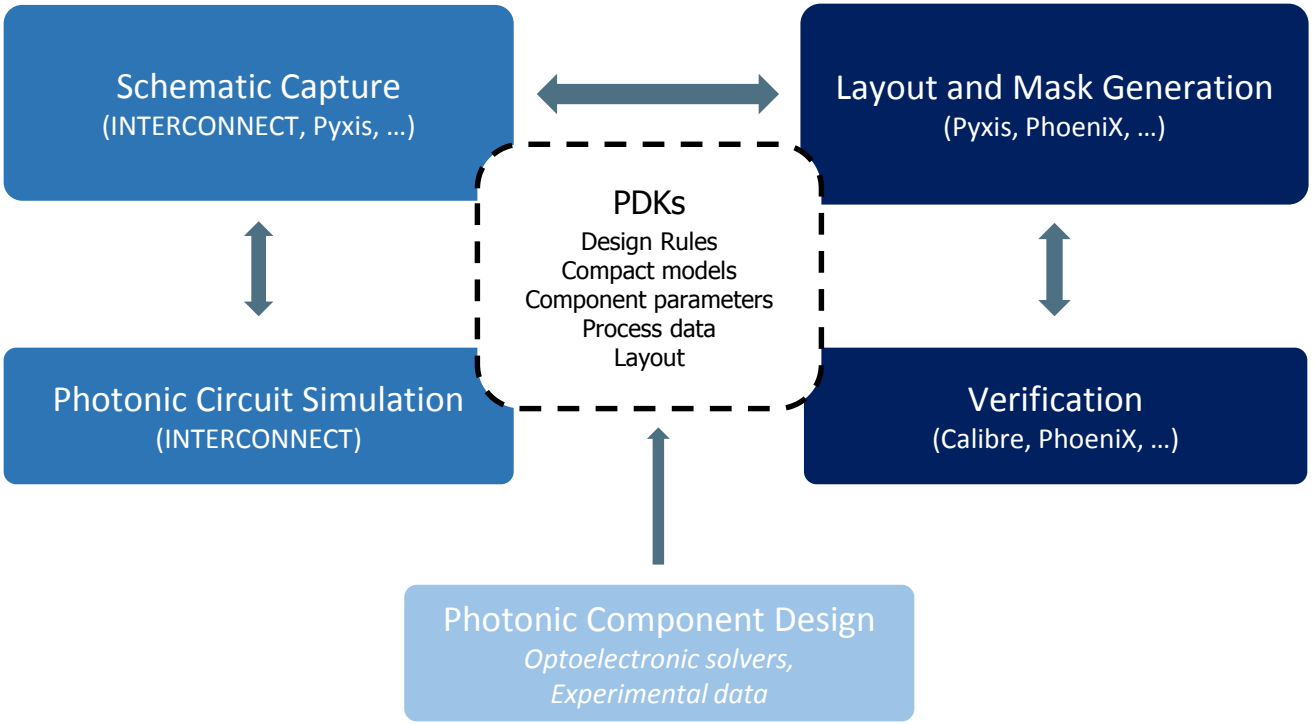
Design Flows

Many advanced design flows are being developed



Pond et al., "A complete design flow for silicon photonics", Photonics Europe 2014

Design Flows and Simulation



Simulation Areas

Component design and optimization

- Design and optimize a component for desired performance

Compact model library generation for PDKs

- Build compact model for component
- Calibrate against experimental results
- Inform with simulation results

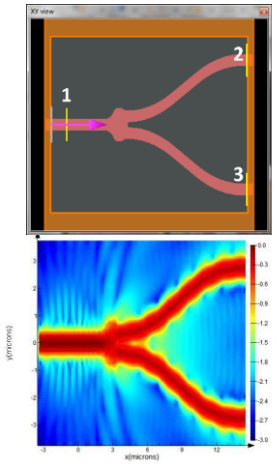
Photonic integrated circuit simulation

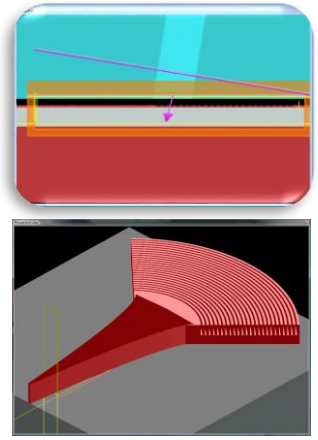
- Build complex circuits based on known components with validated compact models

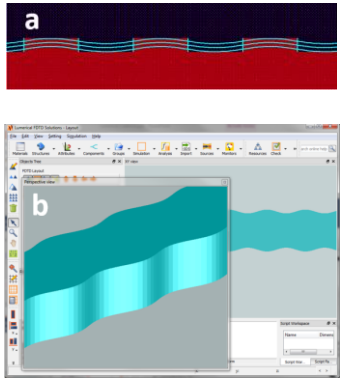
Component Design/optimization

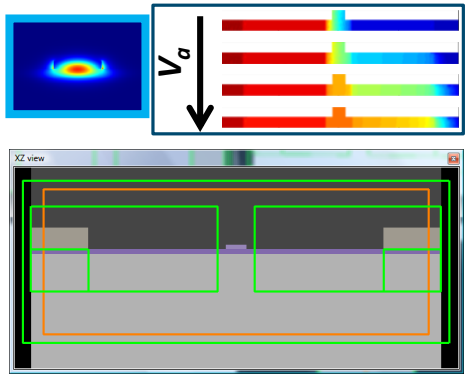
Component design tools are relatively mature

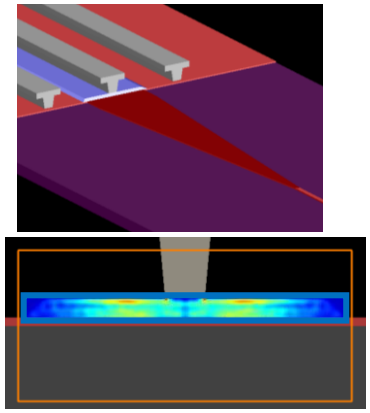
- Physics-based solvers:
  - Optical: solving Maxwell's equations, e.g., FDE, FDTD, EME…
  - Electrical: solving drift-diffusion and Poisson's equations









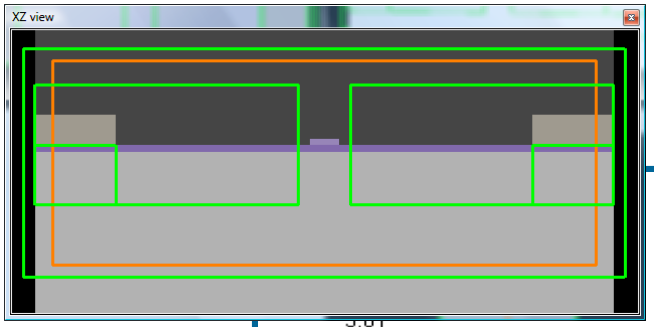


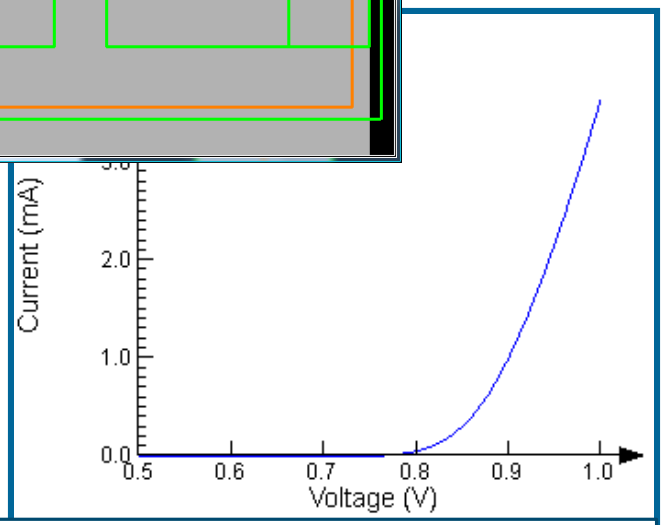
Component Design/optimization

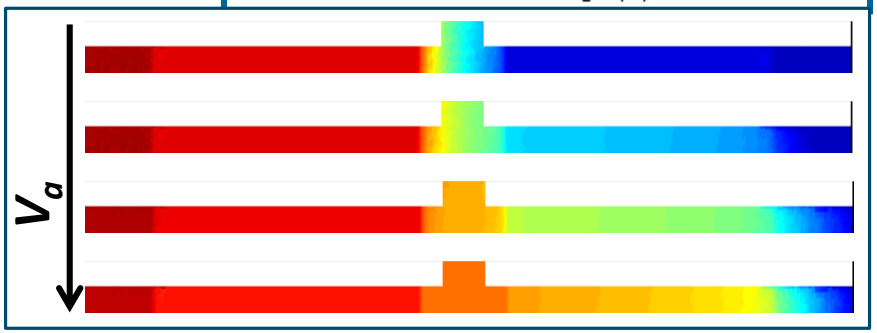
There are still key areas for improvement and ongoing development

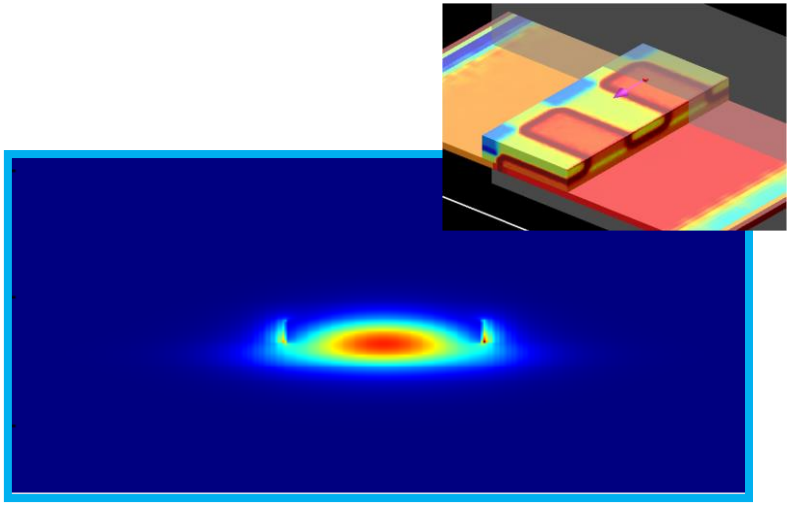
- Increasing need for multi-physics solvers
  - E.g. opto-electronic, thermal effects, strain, …
- Must keep up with new materials and technologies
  - Graphene
- Process aware optimization and design centering

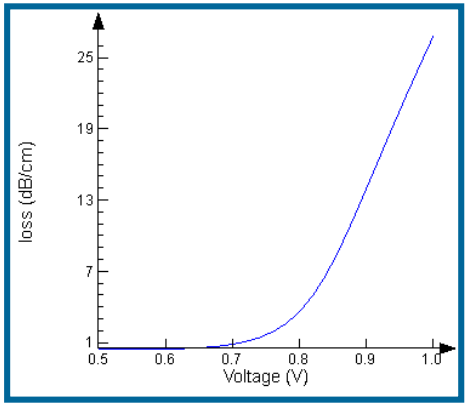
Multiphysics

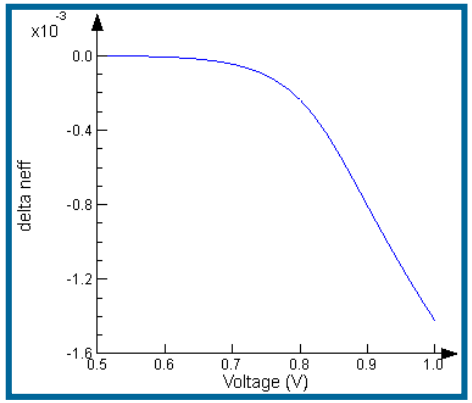




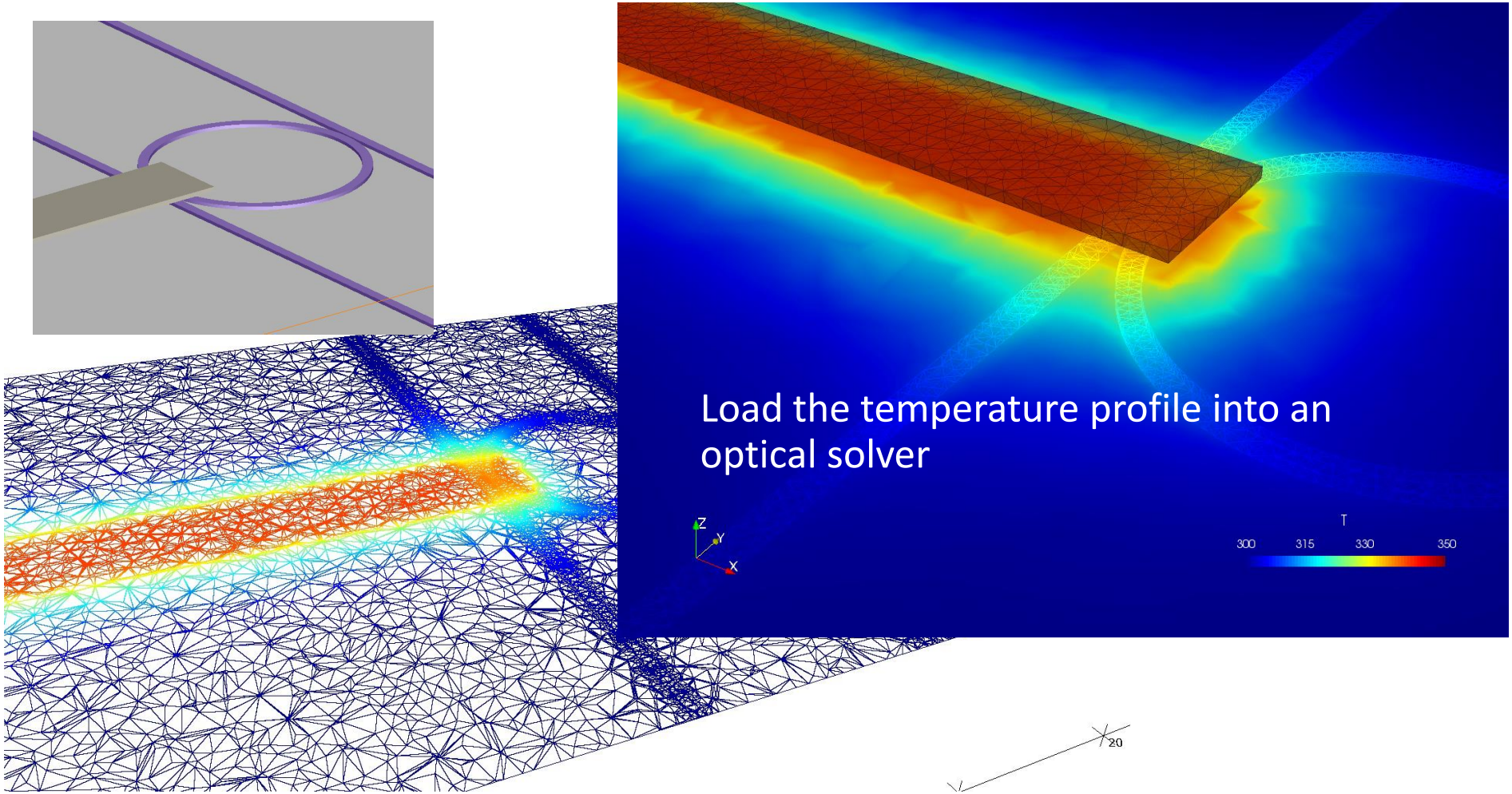






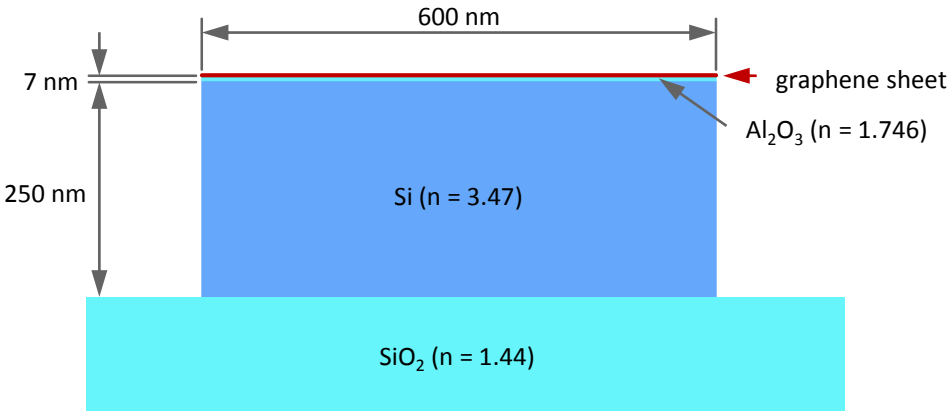


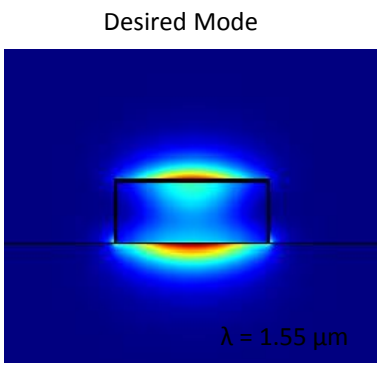
Multiphysics - Thermal



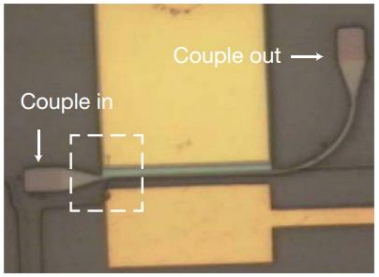
New Materials and Technologies

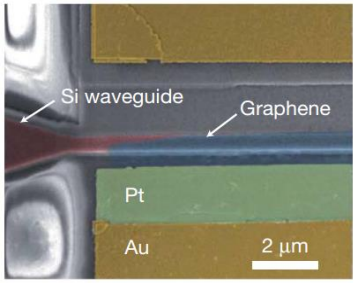
Graphene modulator





- Chemical potential of the graphene layer can be tuned using a voltage source



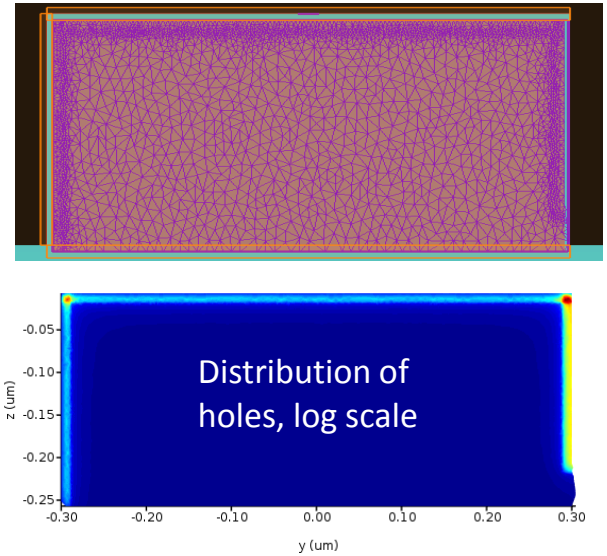


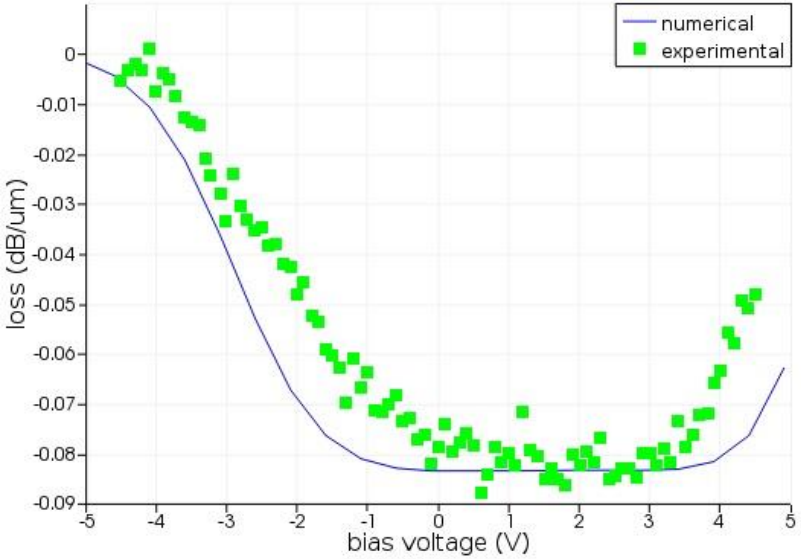
M. Liu, X. Yin, E. Ulin-Avila, B. Geng, T. Zentgraf, L. Ju, F. Wang and X. Zhang , "A graphene-based broadband optical modulator", *Nature Letters*, vol. 474, pp. 64-67, 2011.

Graphene Modulator

We can combine **optical and electrical simulation** results

- Electron-hole distribution in Si (depends on bias voltage)
- Relationship between bias voltage and chemical potential





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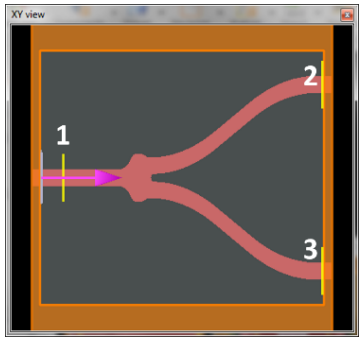
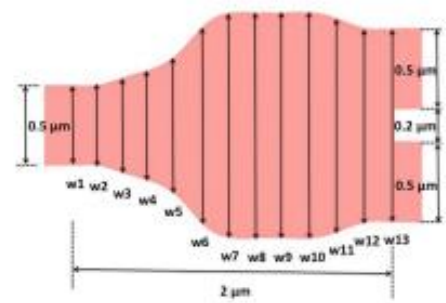
Optimization

Dramatic improvements can be obtained by optimization

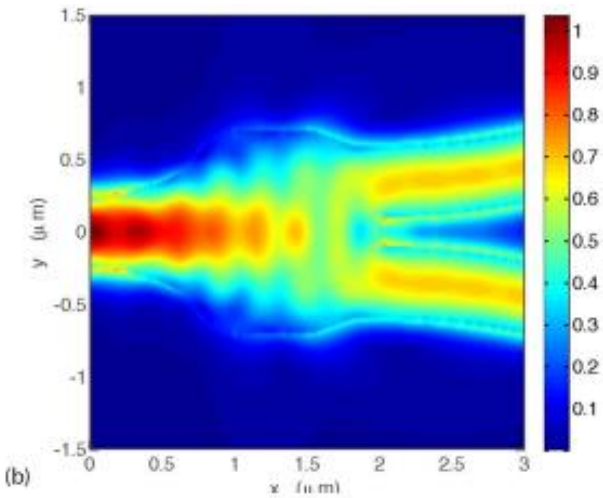
In 2011, Yi Zhang, et al., designed a y-splitter with 0.28 ± 0.02 dB IL

- Used Particle Swarm Optimization (PSO) and FDTD simulation





(a)



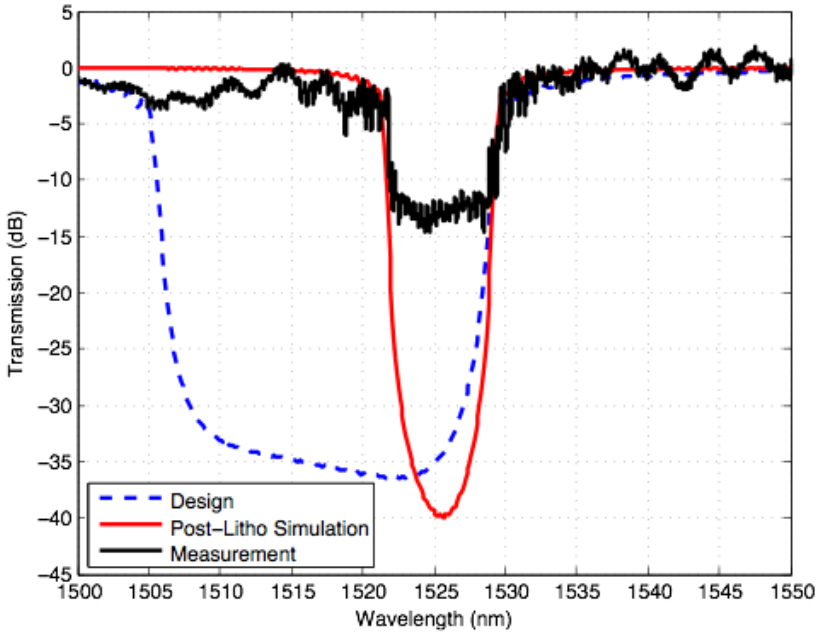
(b)

Zhang, Y., Yang, S., Eu-Jin Lim, A., Lo, G-Q., Galland, C., Baehr-Jones, T., and Hochberg, M., "A compact and low loss Y-junction for submicron silicon waveguide," Optics Express 21, 1310-1316 (2013).

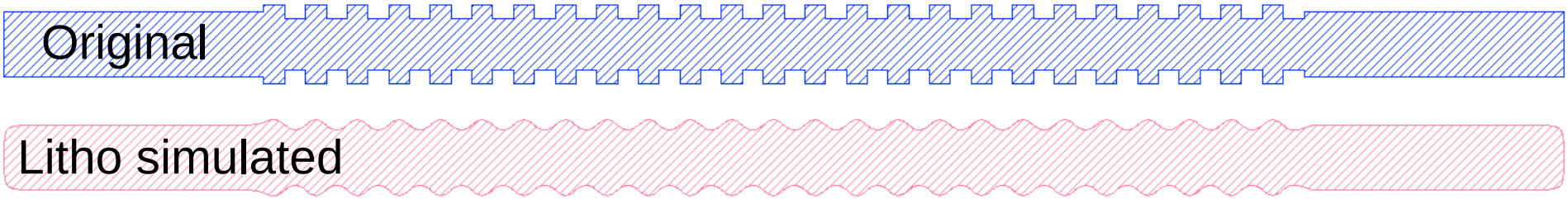
Lithography

Comparison for a Bragg grating designed with 40 nm square corrugations

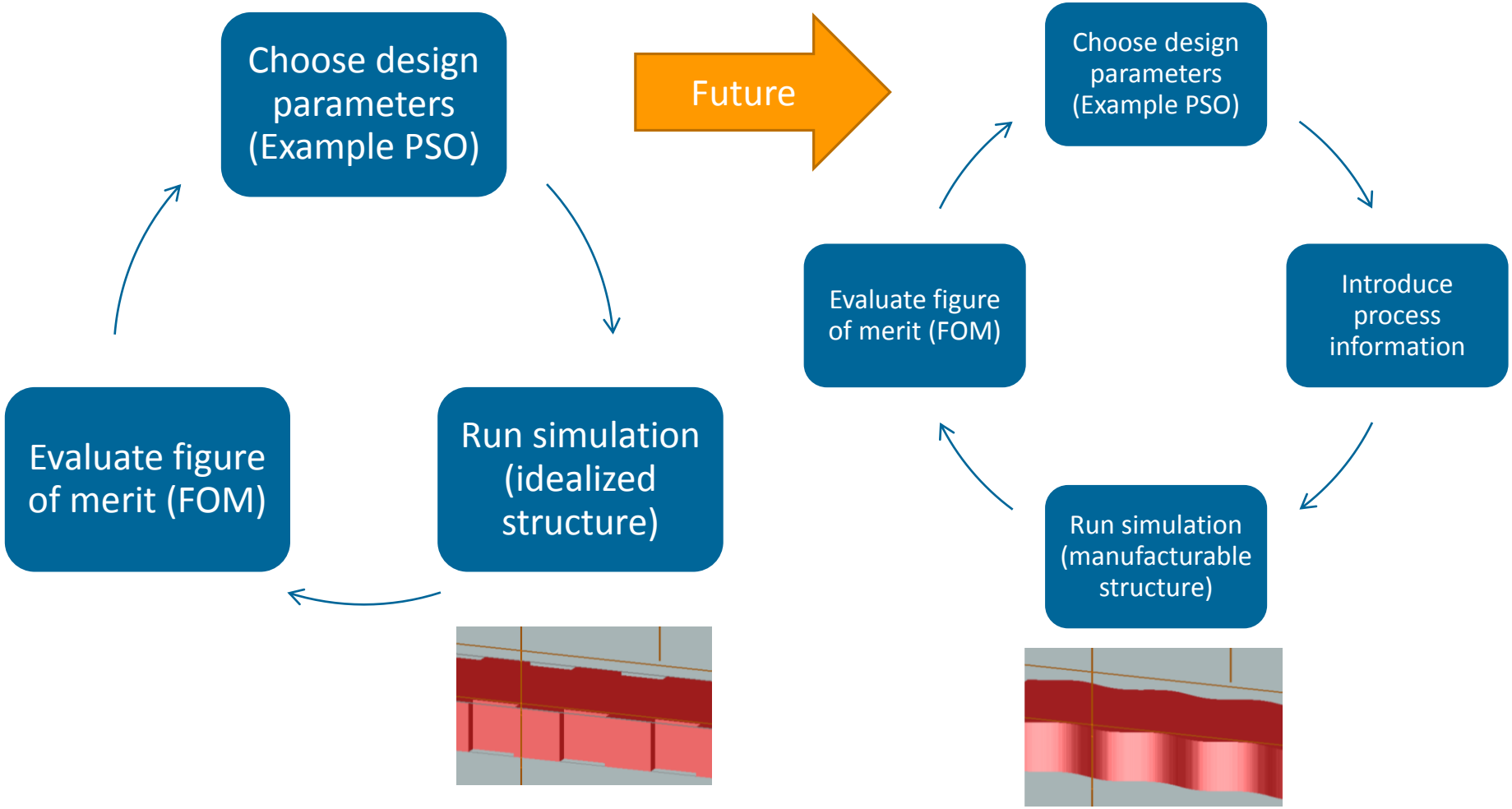
Litho + FDTD Solutions simulations match experimental Bragg bandwidth



Xu Wang, et al., "Lithography Simulation for the Fabrication of Silicon Photonic Devices with Deep-Ultraviolet Lithography", IEEE GFP, 2012



Process Aware Optimization

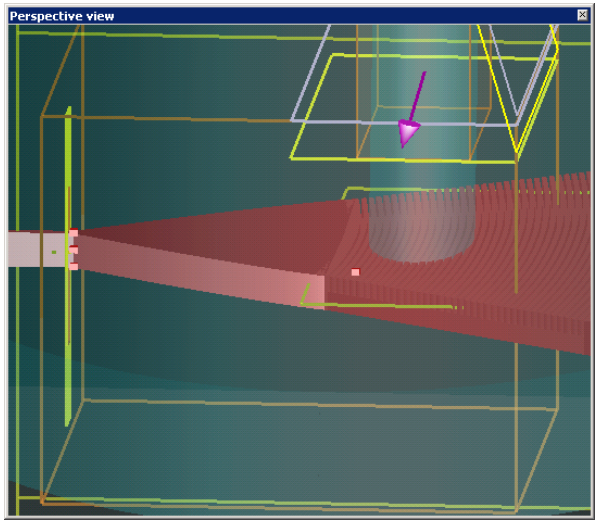


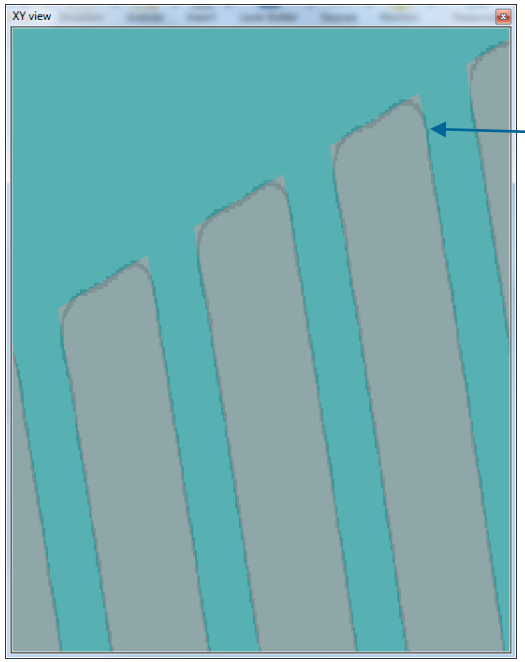
Process Aware Optimization

Could extend to a variety of devices

Could extend the concept to other process information

- Sidewall roughness, angle, etc.





Outline shows litho simulated design

Yield Optimization

Ultimately we want to introduce **design centering** concepts

- Map out the device sensitivity to choose the design that can meet specifications with the maximum possible yield
- The best performing device is not necessarily the best choice

CML Development

Compact model libraries (CML) must be

- Calibrated to measurements
- Packaged for distribution

Good progress has been made

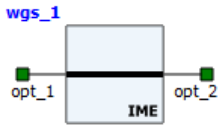
- Recent announcement of IME CML

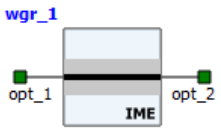
Remaining issues

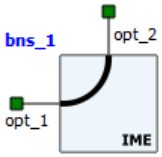
- Ongoing migration to design intent based parameters
- CML infrastructure
  - Ongoing integration within the larger design flows, 3rd party tools and PDKs
  - Version control
- Knowledge of statistical variations of components due to manufacturing imperfections

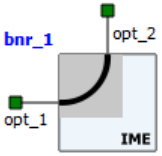
IME CML

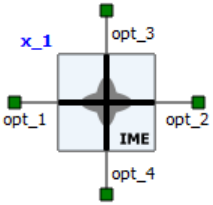
Waveguides



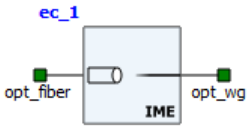


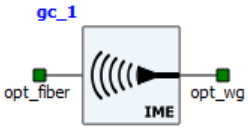


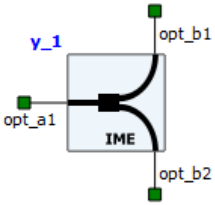


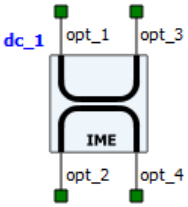


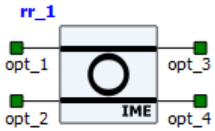
Other Passives



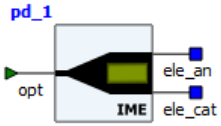


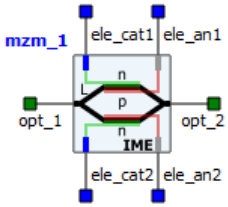


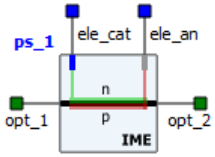


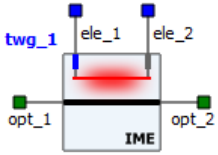


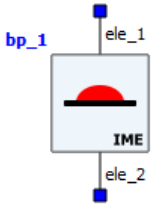
Actives





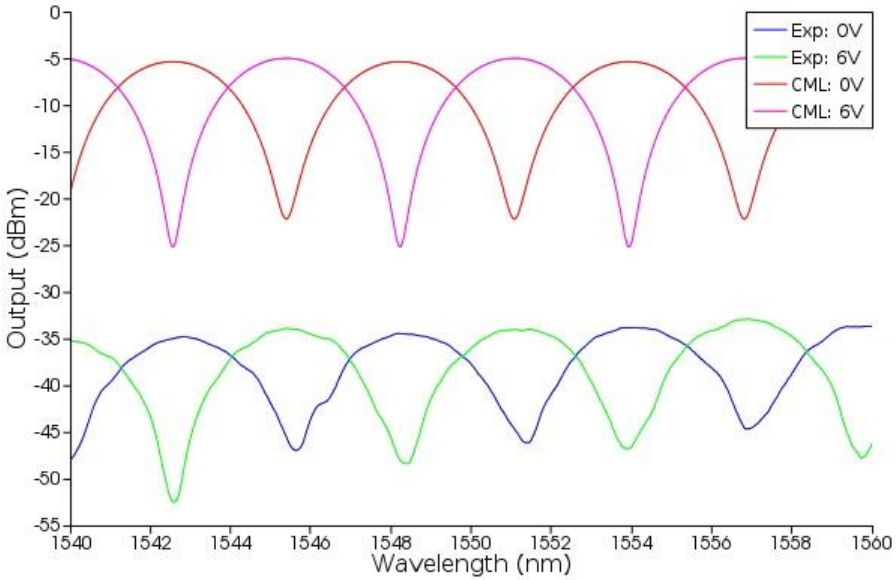






CML Generation

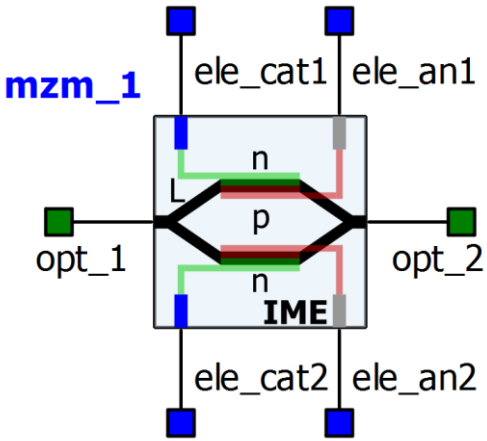
IME Mach-Zehnder Modulator



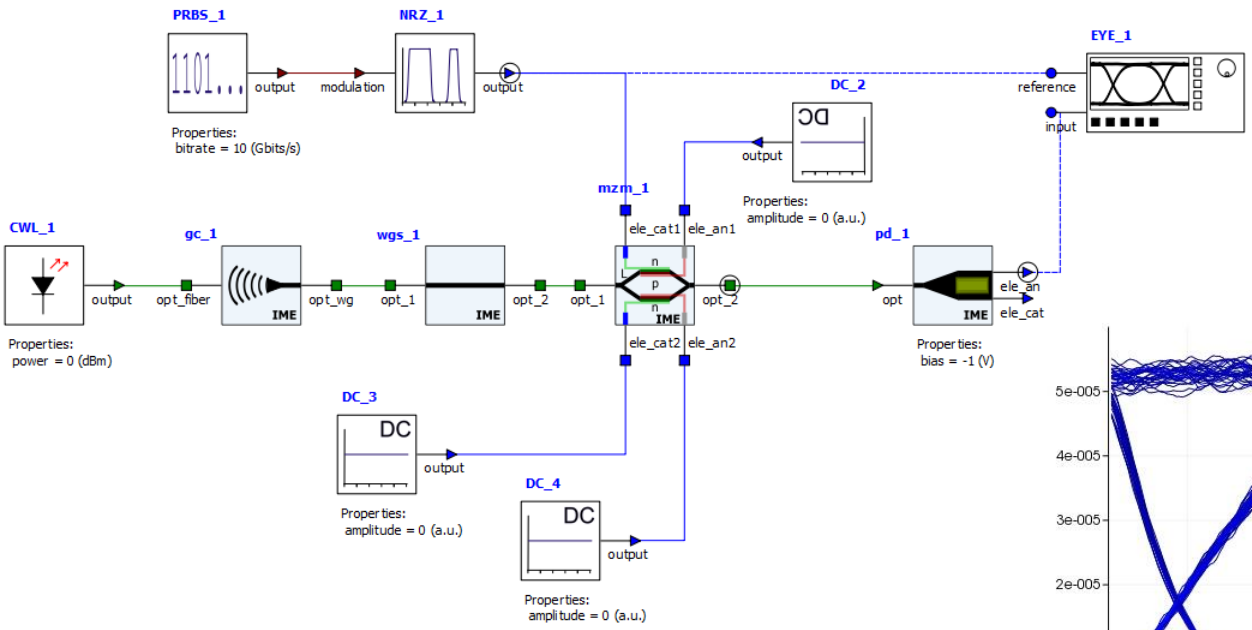
simulation

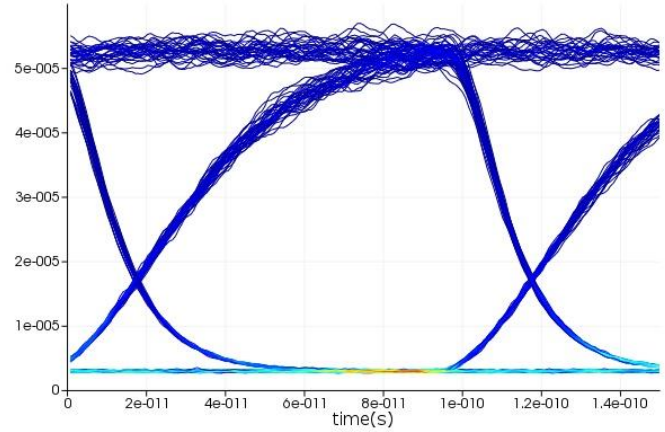
vs.

experiments



Example Circuit Using the CML





Circuit and System Simulation

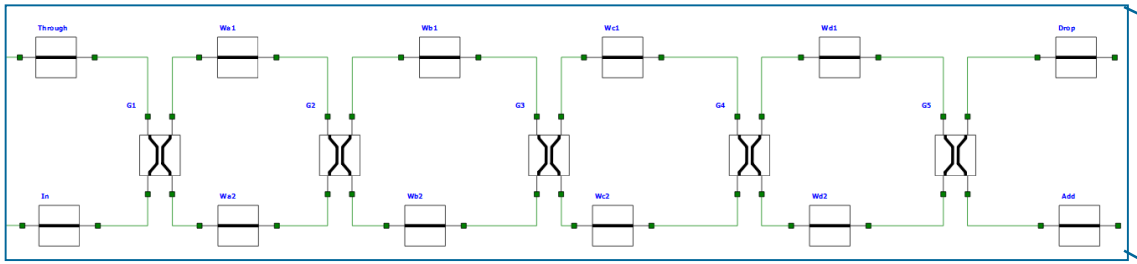
General Photonic circuit simulation challenges

- Complex nature of optical signals
- Both electrical and optical signals are required
- No standardized behavioral models exist
- Frequency and time domain simulation are necessary

Additional challenges and needs

- Improved statistical analysis for correlated and uncorrelated variations
- Thermal variations across the chip
- Co-simulation with electronic circuit/system simulation
- Need for advanced compact models such as lasers

Statistical Analysis of Yield



Waveguide width:
500 (nm) ± 10 (nm)
Waveguide height:
220 (nm) ± 10 (nm)

Edit yield analysis

Configuration

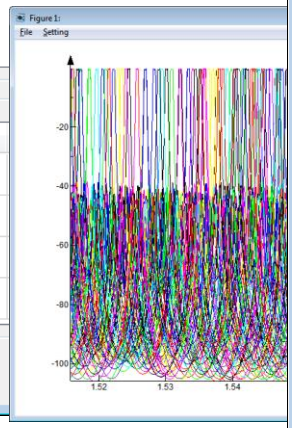
Number of trials: 500

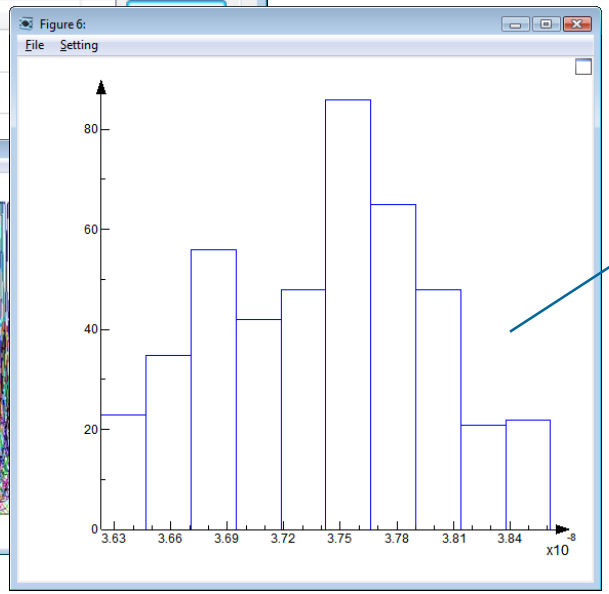
Properties

Name	Parameter	Description
width	::Root Element::waveguide...	Gaussian (mean = 5e-07, std. dev. = 2e-08)
heigth	::Root Element::waveguide...	Gaussian (mean = 2.2e-07, std. dev. = 2e-08)

Results

Name	Result	Estimation
FSR	::Root Element::...	false
gain	::Root Element::...	false
transmission	::Root Element::...	false
band	::Root Element::...	false





Coupling coefficients
Effective index
Group index
vs.
Waveguide width
Waveguide height

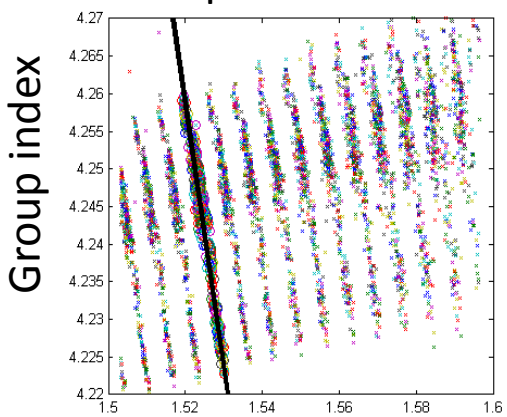
Free spectral range:
37.5 ± 0.5 (nm)
4.65 ± 0.07 (THz)
Bandwidth:
0.47 ± 0.05 (nm)
57 ± 6.7 (GHz)

Statistical Analysis

Example:

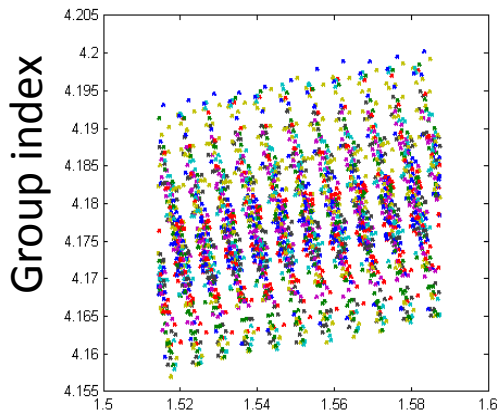
- Create ring resonator compact model by running a series of component level simulations with different variations of thickness and width
- Simulate statistical variations in group index and resonant wavelength with INTERCONNECT

Experimental



Resonant wavelength (μm)

Simulated



Resonant wavelength (μm)

5nm rms waveguide width variation, 1nm rms Si thickness variation

Chrostowski, L., Wang, X., Flueckiger, J., Wu, Y., Torres, M.A.G., Wang, Y., and Talebi Fard, S., "Impact of Fabrication Non-Uniformity on Chip-Scale Silicon Photonic Integrated Circuits," Optical Fiber Conference (2014).

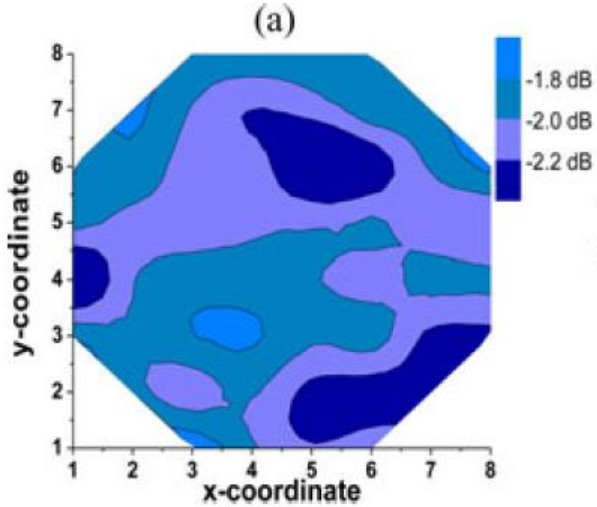
IME Components

Excellent waveguide loss uniformity

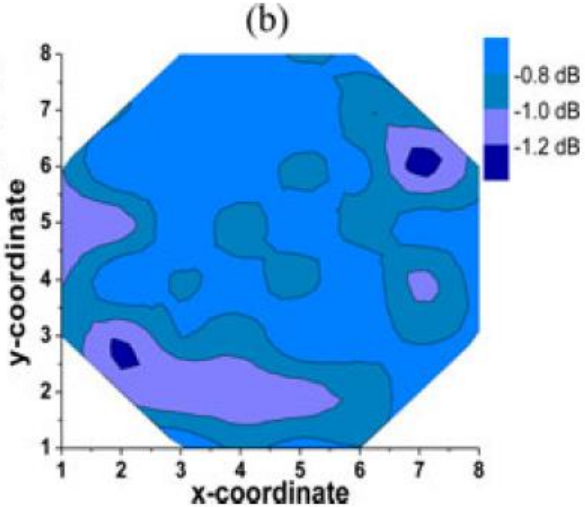
Clearly there is a correlation based on relative waveguide position

- We must account for this in the yield analysis

Strip waveguide: ~2 dB/cm



Rib waveguide: ~0.8 dB/cm

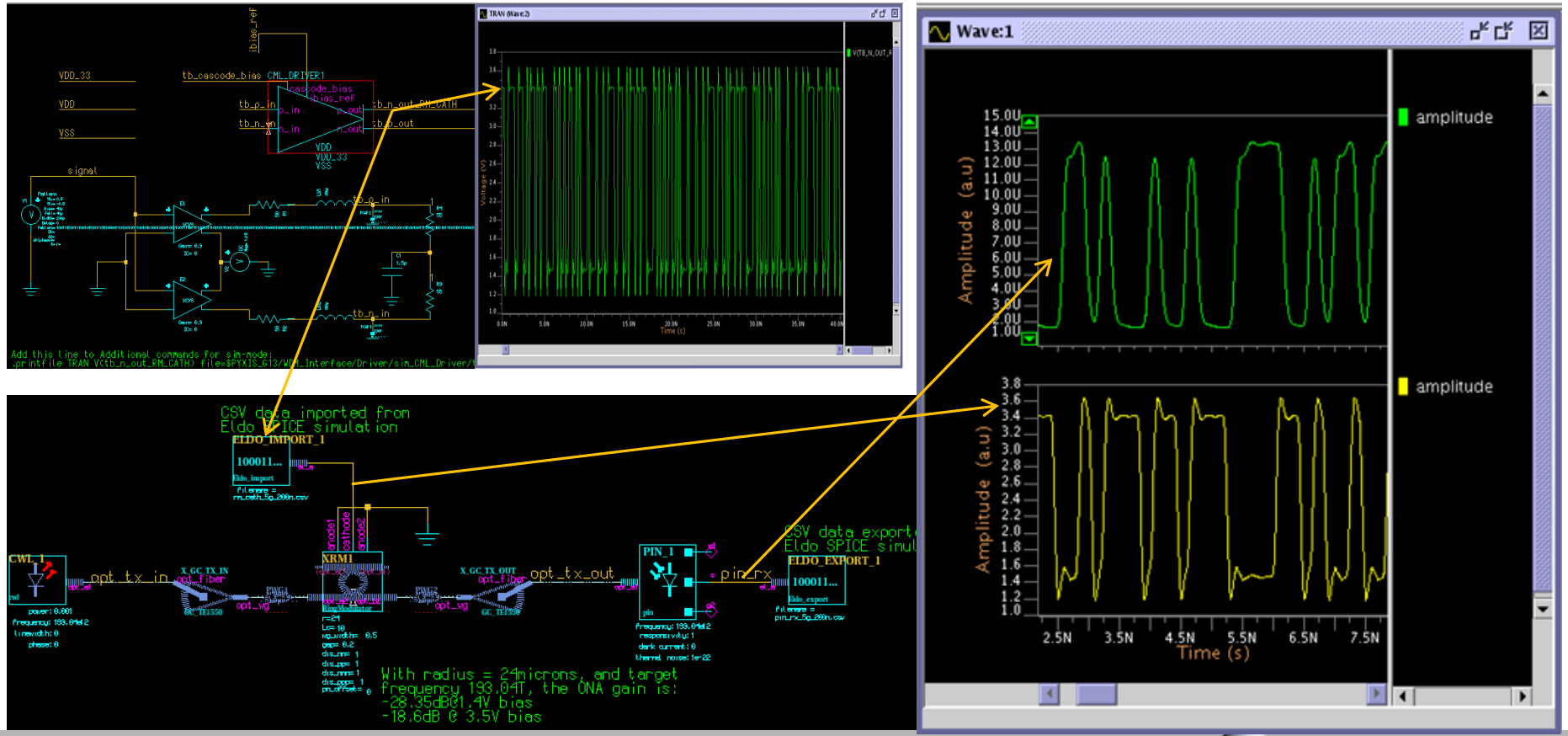


Andy Eu-Jin Lim, et al., "Review of Silicon Photonics Foundry Efforts", JSTQE vol. 20, no. 4, 2014.

Electrical Co-simulation

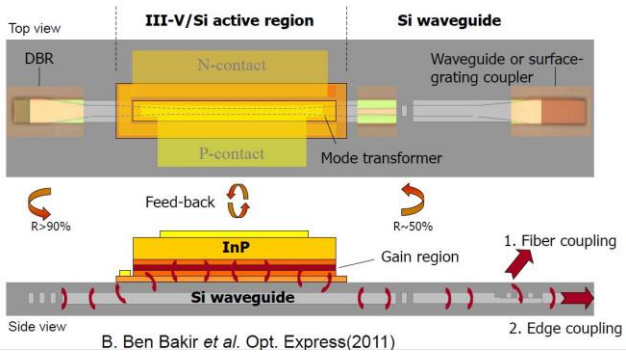
System level time domain simulation using waveform exchange

- What is required beyond this and how will it be done?



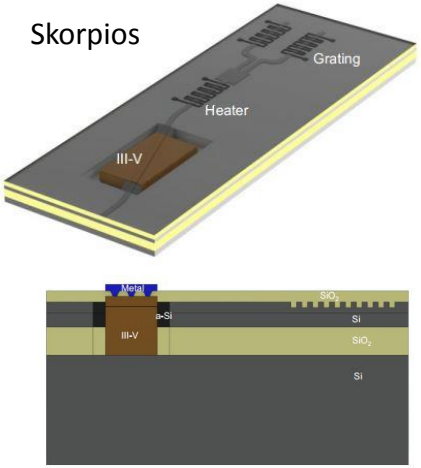
Advanced Compact Models

CEA-LETI

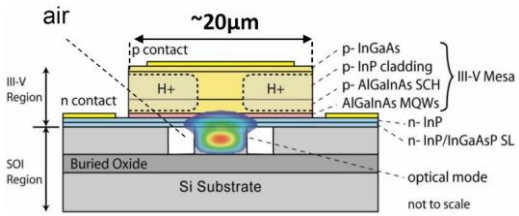


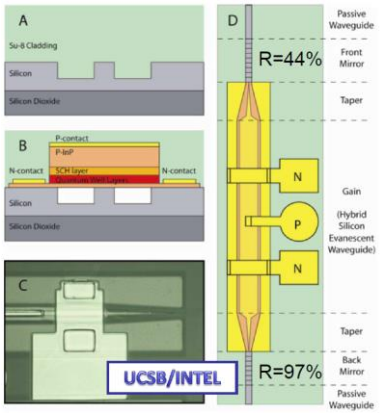
B. Ben Bakir *et al.* Opt. Express(2011)

Skorpios



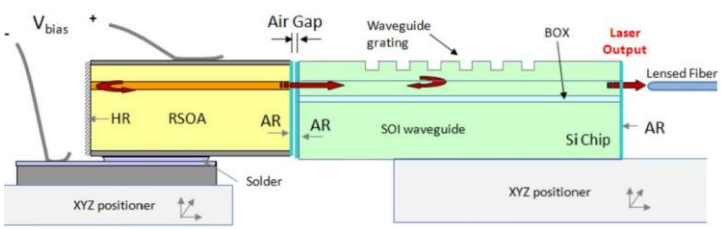
UCSB Intel Aurrion

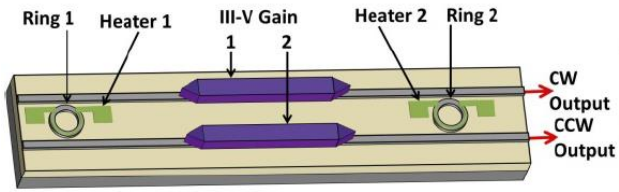




A. W. Fang *et al.* IEEE PTL(2008).

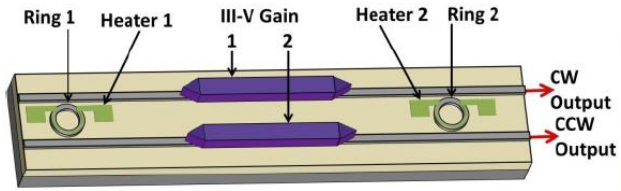
Kotura



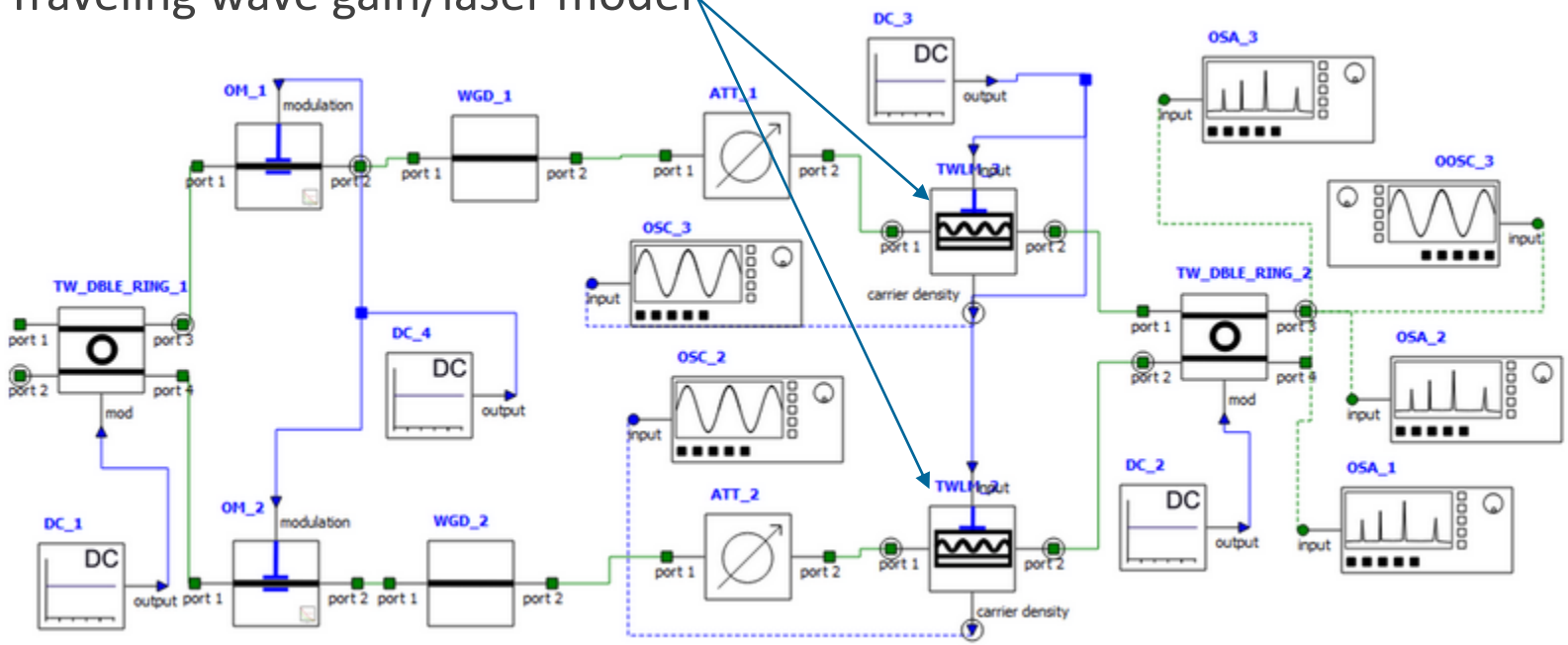


J. C. Hulme, J. K. Doylend, J. E. Bowers, "Widely tunable Vernier ring laser on hybrid Silicon", Optics Express, Vol. 21, No. 17, 19722, 2013

Advanced Compact Models



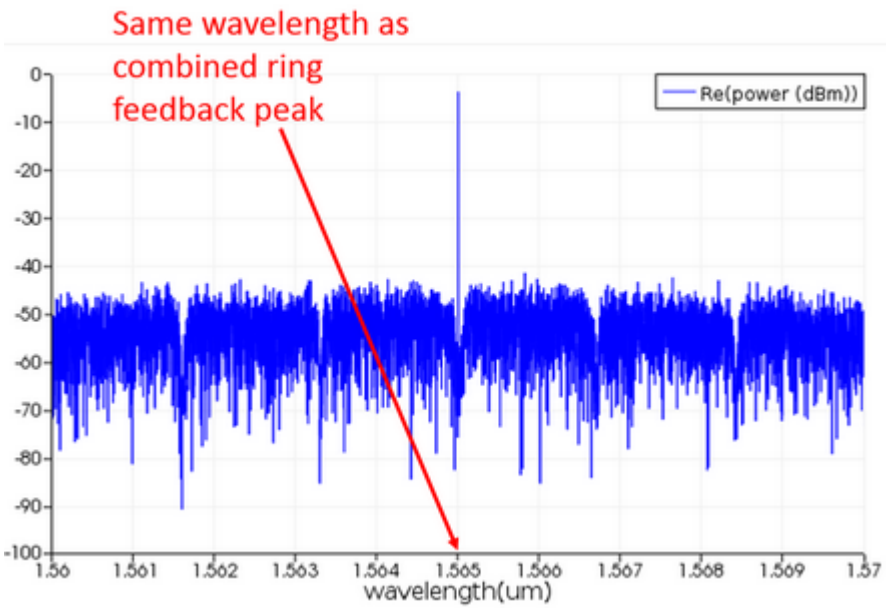
Traveling wave gain/laser model

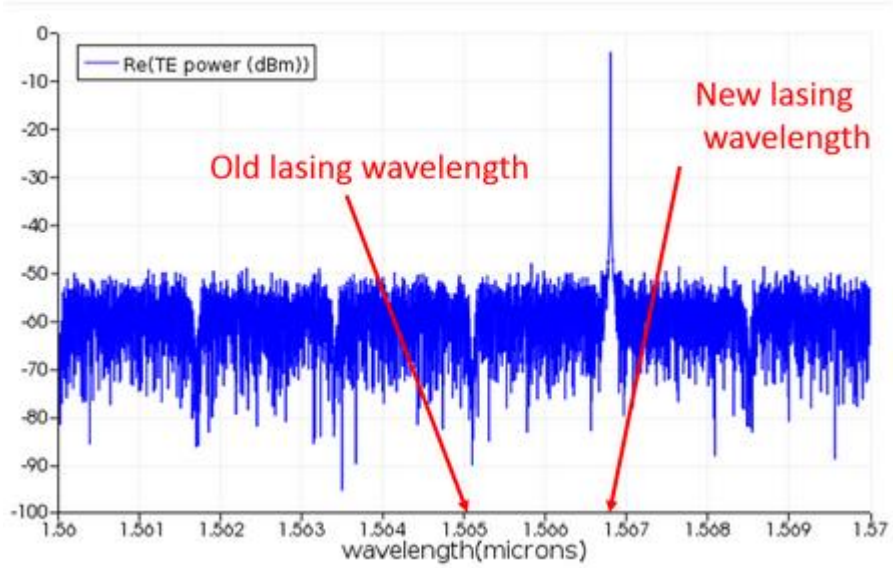


J. C. Hulme, J. K. Doylend, J. E. Bowers, “Widely tunable Vernier ring laser on hybrid Silicon”, Optics Express, Vol. 21, No. 17, 19722, 2013

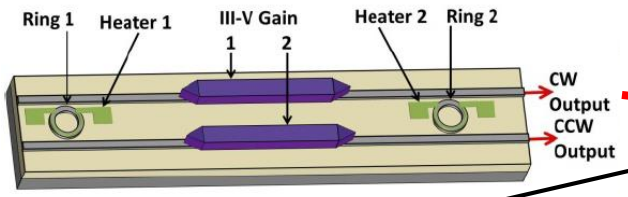
Advanced Compact Models

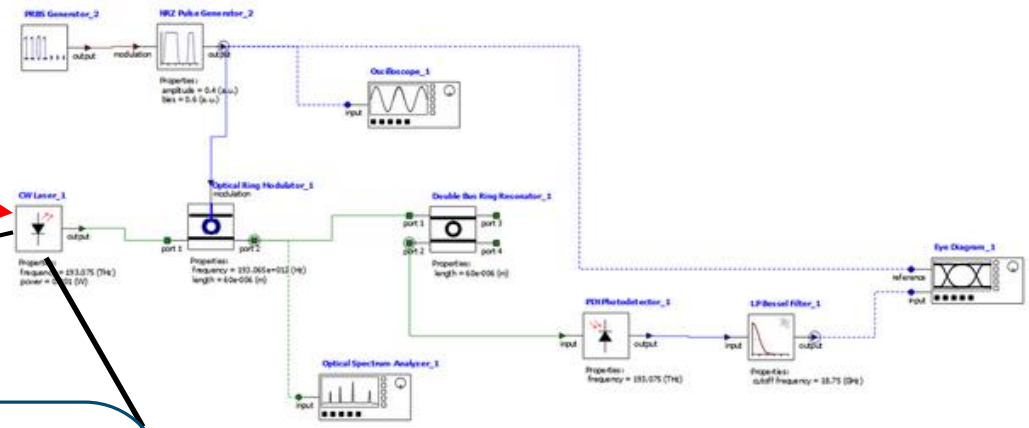
Traveling wave laser

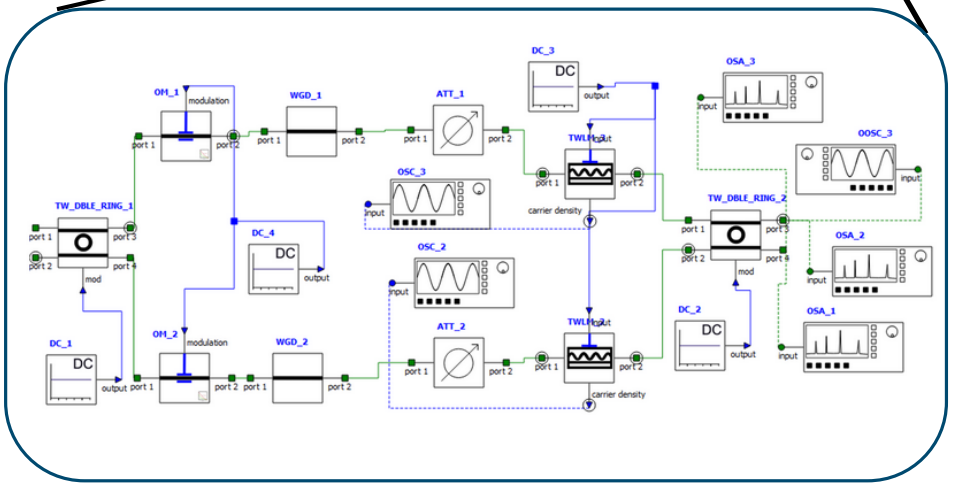




Hybrid Laser Integration into PIC







Hierarchical design for complex models

Roadmap

Component design and optimization

Area	Current	0-12 months	1-3 years
Multi-physics	Electro-optical	Thermal/electro-thermal	Ongoing
New materials and technologies	Graphene	Improved electrical and thermal graphene models	Depends on what you throw at us!
Design for manufacturing	FDTD based optical/lithography effects	Optimization including photo-lithography simulation	Design centering

Roadmap

Compact model library generation for PDKs

Area	Current	0-12 months	1-3 years
Migration to design intent parameters	Good progress	Ongoing	Ongoing
CML infrastructure	CML publishing and IP protection capabilities	Version control, CML validation and improved interoperability with 3rd party tools	
More validated CMLs	IME	…	…

Roadmap

Photonic integrated circuit simulation

Area	Current	0-12 months	1-3 years
Thermal effects	Limited	Component temperature	…
Advanced statistical analysis	Yield calculations based on randomized parameters within chosen statistical distributions	Layout dependent effects	Full statistical analysis based on process-specific, correlated and uncorrelated variations, all stored within CML
Electrical co-simulation	Waveform exchange	To be determined	Possibly several methods, depending on system
Advanced compact models	Dynamic ring modulator, travelling wave modulator, traveling wave laser model	Enhanced laser model	As required

Conclusions

Design flows have made tremendous advances in recent years

Simulation is critical for several aspects of PIC design

- Component design and optimization
- CML generation for PDKs
- Photonic integrated circuit (and system) simulation

We have a simulation tool development roadmap to support a scalable silicon photonics design ecosystem

We gratefully acknowledge the contributions of our software vendor partners, foundry partners, and customers in helping us to formulate this vision

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