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

- 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

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

Schematic Capture (INTERCONNECT, Pyxis, ...)

Photonic Circuit Simulation (INTERCONNECT)

PDKs
Design Rules
Compact models
Component parameters
Process data
Layout

Verification (Calibre, PhoeniX, ...)

Layout and Mask Generation (Pyxis, PhoeniX, ...)

Photonic Component Design
Optoelectronic solvers,
Experimental data
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
Load the temperature profile into an optical solver
New Materials and Technologies

Graphene modulator

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

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

Optimization

Dramatic improvements can be obtained by optimization

In 2011, Yi Zhang, et al., designed a y-splitter with $0.28 \pm 0.02$ dB IL
- Used Particle Swarm Optimization (PSO) and FDTD simulation

Lithography

Comparison for a Bragg grating designed with 40 nm square corrugations

Litho + FDTD Solutions simulations match experimental Bragg bandwidth

Process Aware Optimization

Choose design parameters (Example PSO)

Run simulation (idealized structure)

Evaluate figure of merit (FOM)

Introduce process information

Choose design parameters (Example PSO)

Run simulation (manufacturable structure)

Evaluate figure of merit (FOM)

Future
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)

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

**Free spectral range**: 37.5 ± 0.5 (nm)
- **Gain**: 4.65 ± 0.07 (THz)
- **Bandwidth**: 0.47 ± 0.05 (nm)
- **Transmission**: 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.

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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

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

Skorpios

UCSB Intel Aurrian

Kotura

Advanced Compact Models

Traveling wave gain/laser model

Advanced Compact Models

Traveling wave laser
Hybrid Laser Integration into PIC

Hierarchical design for complex models
Roadmap

Component design and optimization

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

**Compact model library generation for PDKs**

<table>
<thead>
<tr>
<th>Area</th>
<th>Current</th>
<th>0-12 months</th>
<th>1-3 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Migration to design intent parameters</td>
<td>Good progress</td>
<td>Ongoing</td>
<td>Ongoing</td>
</tr>
<tr>
<td>CML infrastructure</td>
<td>CML publishing and IP protection capabilities</td>
<td>Version control, CML validation and improved interoperability with 3rd party tools</td>
<td></td>
</tr>
<tr>
<td>More validated CMLs</td>
<td>IME</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
# Roadmap

## Photonic integrated circuit simulation

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

Questions? support@lumerical.com
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