How to Simulate and Optimize Integrated Optical Components

Lumerical Solutions, Inc.
Outline

- Introduction
- Integrated optics for on-chip communication
  - Impact on simulation
- Simulating planar devices
- Simulation steps
- Demonstration examples
- Examples from guest expert Dr. Lukas Chrostowski
- Simulation tips
- Building an optical integrated circuit
- Questions and Answers
Introduction

We simulate light interacting with wavelength scale structures.

MODE Solutions

FDTD Solutions
Why is integrated optics important?

- “Today, optics is a niche technology. Tomorrow, it's the mainstream of every chip that we build.”
  - Patrick Gelsinger, Sr. Vice President, Intel

- “With optical communications embedded into the processor chips, the prospect of building power-efficient computer systems with performance at the Exaflop level is one step closer to reality.”
  - Dr. T.C. Chen, vice president, Science and Technology, IBM Research
**Integrated optics**

Why simulate?

- Simulation gives the opportunity to cheaply and quickly test ideas, optimize designs and solve problems
  - Expensive and time-consuming to build prototypes
  - Design optimization is challenging and results are not always intuitive
Integrated optics

What do we want to calculate?

- We need to extract the important parameters of individual elements
  - Passive waveguides: effective index, dispersion, bend loss
  - Couplers: coupling efficiency, reflection
  - Fiber I/O: insertion loss, reflection
  - Filters: transfer functions, quality factors, FSR
  - Active waveguides: effective index vs voltage
  - Photodiodes: quantum efficiency
  - ...  

- The properties of optical integrated circuits
  - S-matrix analysis
  - Impulse response
  - Eye diagrams
  - ...
Planar integrated optics

- How do we simulate planar waveguide devices?
  - **MODE Solutions** (design)
    - Eigenmode solver
    - Eigenmode decomposition and propagation (unidirectional)
    - 2.5D Propagator (omnidirectional in the plane)
  - **FDTD Solutions** (verification and final design)

- How do we simulate opto-electronic integrated circuits?
  - **Lumerical INTERCONNECT**
    - Coming soon...
Collapse the z dimension based on the vertical mode profiles
2.5D Propagator in MODE Solutions

Time to solve real problems on an X5550 workstation (2009)

<table>
<thead>
<tr>
<th>Simulation type</th>
<th>Memory</th>
<th>Min mesh size (nm) dx:dy:dz</th>
<th>Volume (μm³)</th>
<th>Processing time (16 cores used)</th>
<th>λ (μm)</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crossover (3D FDTD)</td>
<td>3.8 GB</td>
<td>40</td>
<td>46x16x1.2 =883.2</td>
<td>24 minutes (16 cores)</td>
<td>1.4-1.8</td>
<td>Si, glass</td>
</tr>
<tr>
<td>Crossover (2.5D Propagator)</td>
<td>50 MB</td>
<td>40:40:1</td>
<td>46x16x2 =1472</td>
<td>25 seconds (16 cores)</td>
<td>1.4-1.8</td>
<td>Si, glass</td>
</tr>
</tbody>
</table>

2.5D Propagator

3D FDTD

![Graph showing transmission vs. wavelength]
Simulation steps

- Parameterization of your design
- Simulation
  - Eigensolver
  - 2.5D Propagator
  - FDTD
- Analysis of results and parameter extraction
- Optimization

- We will demonstrate with 2 examples
  - Ring resonator
  - Grating coupler
Ring resonator
Parameterization of the design

- Parameterize the ring resonator
  - Create properties appropriate for your device
  - Use the scripted parameterization
  - Import from GDSII if necessary
Parameterization of your design

- Parameterization can include position of sources and monitors
  - Any group can set properties of the children

```python
1 select("ring_resonator");
2 set("radius", radius);
3 set("base_width", width);
4 set("gap", gap);
5
6 select("PROP");
7 set("y span", 2*radius+4e-6);
8
9 select("through");
10 set("y", radius+gap+width);
11
12 select("drop");
13 set("y", -(radius+gap+width));
```
Parameterization of your design

- Essential for
  - Reproducibility
  - Easy parameter sweeps
  - Optimization

- Lumerical’s hierarchical group layout and script based parameterization makes almost anything possible

- It is worth the initial investment!
Ring resonator

- With the eigenmode solver we can quickly calculate
  - Effective index, group index, coupling length
  - Waveguide is 400nm x 180nm in SOI
- This allows us to quickly choose physical parameters
  - Ring radius, straight coupling length, waveguide spacing
- To meet certain target specifications at 1550nm
  - Channel spacing = 1.6nm
  - Free spectral range (FSR) = 25.6nm
  - Quality factor (Q) = 2000
**Ring resonator design**

- Eigenmode solver analysis gives
  - Group index at 1550nm
  - Coupling length of waveguides

  ![Symmetric mode (Ey)](image1)
  ![Anti-Symmetric mode (Ey)](image2)

  \[ \Delta n \approx 0.11 \]

- Conclusion for our target specifications
  - Simple ring of radius 3.1 microns
Ring resonator

- Demo and results
  - Eigensolver
  - MODE 5 Propagator
  - 3D FDTD
  - Theory (Design)
Parameter extraction

- Extracting parameters can be done in several ways
  - Fit results to parameterized equation
    - Excellent if parameterized equation is used in next steps
  - Direct extraction of desired quantities
    - Example, Drop(\( \lambda \)), Through(\( \lambda \))
    - Excellent if transfer function is used in next steps
  - Extraction of complex transfer function
    - Only has a meaning when associated with a particular waveguide mode
    - Get amplitude AND phase information
      - Gives total transmission AND group delay/dispersion
    - Relatively easy for single mode waveguides
    - In multimode systems, it must be done with an overlap analysis
Grating coupler

- Input coupler
- Output coupler
Grating coupler, example results

- Can calculate near fields

- Far field angular distribution vs wavelength
Grating coupler, example results

- Parameter sweeps of input beam position
Concurrent computing

- Optimization and parameter sweep require many simulations
- Send them to many different workstations
  - Each workstation can run in distributed computing mode, using all cores

N computers means you can get your optimization or parameter sweep results N times faster!
Grating coupler, optimization demo

- Set position of beam to -5.5 microns
- Optimize pitch and fill factor to maximize transmission at 1550nm
Examples

- Guest expert
  - Dr. Lukas Chrostowski from the University of British Columbia
- Helpful links
  - http://www.mina.ubc.ca/lukasc
  - http://mina.ubc.ca/eece584
  - http://depts.washington.edu/uwopsis/
- Email
  - lukasc@ece.ubc.ca
Simulation tips

- Use a coarse mesh (large values of $dx$)
  - Use conformal meshing
  - Use mesh grading if a fine mesh is required in a particular region
  - **Always make any fine mesh simulations the last step!**

- For planar propagation
  - Design with MODE Propagator and Eigensolver
  - Use FDTD to verify

- Multi-wavelength calculations
  - Check material fits!
  - Fit material data with MCM to avoid incorrect waveguide dispersion calculations

- Periodic structures for high Q filters
  - Match mesh with the structure periodicity

- Reduce memory and simulation time
  - Store only necessary data to keep file sizes smaller
  - Remove movie monitors for faster simulations
Tip: Use a coarse mesh

- Memory scales as $dx^3$
- Simulation time scales as $dx^4$
- Example convergence tests from CMOS image sensors
Tip: Conformal meshing

Potential problems with finite sized mesh

- Devices can be extremely sensitive to certain dimensions
- Can we define dimensions to better than the mesh size?
  - Yes
  - Conformal meshing
Building an optical integrated circuit

- Physical devices must be abstracted into elements that can be modeled based on parameterized models
  - \( S \) matrices
  - Modal propagation data
- The optical circuit can then be simulated
- Example with MZI
MZI example

- We extract parameters
  - Waveguide
    - Effective index, group delay, dispersion, mode profiles
  - Bends and couplers
    - S matrices
  - **Active waveguide**
    - Extract $n_{\text{eff}}$ and loss vs applied voltage
Active waveguide

- 2D Electrical modeling of active waveguide

- Poly-Si

- Oxide

- Buried oxide

- p-epi Si (2x10^{17} cm^{-3})

- p++

- 450nm

- 200nm

- 200nm

- 200nm

- 200nm

- 50nm
Active waveguide

- Calculate hole-density accumulation
Active waveguide

- Calculate change in refractive index across the waveguide
- Re-solve for modes (most accurate) or use perturbative approach
Active waveguide

- Calculate change in effective index and loss as a function of applied voltage
Building an optical integrated circuit

- Use extracted parameters and curves in MZI element
Building an optical integrated circuit

- Calculate the eye diagram of the device
# Challenges and solutions

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Solutions and best practices</th>
</tr>
</thead>
<tbody>
<tr>
<td>High index contrast, wavelength scale devices</td>
<td>Full vectorial 3D Maxwell solvers</td>
</tr>
</tbody>
</table>
| Simulation methodology                        | “Think before you simulate”  
• Setup simulation methodology to calculate the desired results  
• Are these results you can directly compare to experiment? |
| Complex 3D geometries                         | Parameterize designs                                                                          |
| Simulation time and memory                    | • Choose the right algorithm  
  • Eigensolver, 2.5D Propagator, 2D FDTD, Eigenmode propagation for initial design  
  • 3D FDTD for verification  
  • Use coarse mesh size where possible  
    • Always for initial simulations  
    • Do convergence testing of mesh size last  
  • Advanced meshing  
    • Use non-uniform meshing  
    • Use conformal meshing  
  • Use distributed parallel computation to take advantage of modern hardware  
  • Reduce unnecessary computational and file size requirements  
  • Store only necessary data |
## Challenges and solutions

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| Opto-electronic modeling                                                   | Combine optical and electrical modeling  
|                                                                             |  • Bring optical generation rate into electrical models  
|                                                                             |  • Bring free carrier information into optical models  
|                                                                             |  • Contact us for assistance and advice on these calculations                                                                                              |
| Parameter extraction                                                       | Careful analysis of each element  
|                                                                             |  • Is phase information important?                                                                                                                         |
| Multi-wavelength simulations                                               | Time domain gives broadband results  
|                                                                             |  • Highly dispersive materials require multi-pole material models  
|                                                                             |  • Use multi-pole material models to avoid discontinuities in dispersion                                                                                  |
| Optimization and parameter sweeps                                         |  • Using a global search algorithm that significantly reduces the number of simulations required  
|                                                                             |  • Use concurrent computing to use all your available computer resources optimally                                                                      |
| Modeling of large, multi-mode waveguide-based opto-electronic system       | Lumerical INTERCONNECT, coming soon!                                                                                                                       |
Conclusion

- Lumerical provides a suite of physics-based solvers for almost all integrated optical components
  - Eigensolver
  - Eigenmode propagation
  - 2.5D Propagator
  - FDTD
- These solvers make it easy to follow best practices
- Used in combination with upcoming INTERCONNECT
  - Can simulate optical integrated circuits
## Question and Answer

<table>
<thead>
<tr>
<th>Dr. James Pond</th>
<th>Dr. Guilin Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTO</td>
<td>Senior R&amp;D Scientist</td>
</tr>
<tr>
<td><a href="mailto:jpond.support@lumerical.com">jpond.support@lumerical.com</a></td>
<td><a href="mailto:gsun.support@lumerical.com">gsun.support@lumerical.com</a></td>
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<table>
<thead>
<tr>
<th>Chris Kopetski</th>
<th>Dr. Mitsunori Kawano</th>
</tr>
</thead>
<tbody>
<tr>
<td>Director of Technical Services</td>
<td>Technical Sales Engineer</td>
</tr>
<tr>
<td><a href="mailto:ckopetski.support@lumerical.com">ckopetski.support@lumerical.com</a></td>
<td><a href="mailto:mkawano.support@lumerical.com">mkawano.support@lumerical.com</a></td>
</tr>
</tbody>
</table>

Sales inquiries
sales@lumerical.com

Sales representatives (other regions)
http://www.lumerical.com/company/representatives.html

Free, 30 day trial at www.lumerical.com
Appendix 1

- Simulation tip details
Tip: Multi-wavelength calculations (time domain)

- FDTD and the 2.5D Propagator is appealing because we can obtain the entire spectrum from 1 simulation

- Challenges
  - Dispersive material models
  - Incident angle changes with wavelength
    - Careful with input couplers!
  - Incident mode profile changes with wavelength
    - Can work around this with some care
Tip: Multi-wavelength calculations (time domain)

- Dispersive materials
  - Well-known frequency domain relationship

\[
\vec{D}(\omega) = \varepsilon(\omega)\vec{E}(\omega)
\]

- FDTD is a time domain technique: relationship?

\[
\vec{D}(t) = \varepsilon(t) \ast \vec{E}(t) = \int_{0}^{t} \vec{E}(t')\varepsilon(t - t')dt'
\]
Tip: Multi-wavelength calculations (time domain)

- Lumerical’s Multi-Coefficient Model (MCM) can solve for materials with arbitrary dispersion such as Si, GaAs, or Ge or the effective material used in the 2.5D Propagator.
- You may sometimes need to adjust the advanced fit settings to get the fit quality you require.
Tip: Multi-wavelength calculations (frequency domain)

- We must be careful when using experimental material data and calculating dispersion with the frequency domain eigenmode solver.
- Discontinuities in experimental data will lead to artificial dispersion peaks.

[Graph showing dispersion curve for Si (Silicon) - Palik]
Tip: Multi-wavelength calculations (frequency domain)

- Solution is to fit the experimental data using Lumerical’s MCM
- This fits the data with an analytical expansion that has continuous derivatives
- Note that it will introduce a small amount of loss
  - This has a negligible impact on dispersion calculation
Appendix 2

- Additional examples
Grating couplers

3D grating couplers
Grating couplers

3D grating couplers

![Image of 3D grating couplers](image)
Waveguides and waveguide bends

Singlemode/multimode, effective index and modal fields

Only one mode with $n_{\text{eff}} > n_{\text{substrate}}$
Waveguide is singlemode
Waveguides and waveguide bends

Dispersion of mode

Figure 1: Effective Index

Figure 2: Group Velocity (m/s)

Figure 3: Dispersion (ps/nm/km)
Waveguides and waveguide bends

Bending loss

- What is the loss for sharp bends (1.5 $\mu$m radius)

Overlap mismatch
Radiation loss in bent section
Waveguides and waveguide bends

Bending loss

- What is the loss for sharp bends (1.5 μm radius)

Overlap mismatch
Radiation loss in bent section
Waveguides and waveguide bends

- **Overlap mismatch**
  - \(-10 \times \log_{10}(0.985806) = 0.06 \text{ dB}\)
  - 2 interfaces = 0.12 dB

Calculate all three contributions with MODE Solutions
Waveguides and waveguide bends

Calculate all three contributions with MODE Solutions

- Radiation loss
  - $0.0037793 \text{ dB/}\mu\text{m}$
  - Bend length: $1.5\mu\text{m} \times \pi/2$
  - $0.01 \text{ dB total}$

- Most significant contribution is the overlap mismatch
Waveguides and waveguide bends

Can we shift the waveguides to improve the design?
Waveguides and waveguide bends

Can we shift the waveguides to improve the design?

- A 20 nm shift in waveguide position can reduce the overlap mismatch losses to
  \[ -10 \times \log_{10}(0.994072) = 0.026 \text{ dB} \]

- Total bend loss of
  \[ 2 \times 0.026 \text{ dB} + 0.01 \text{ dB} = 0.062 \text{ dB} \]
  - Compared to 0.13 dB in original design
# Integrated optics in SOI, 3D FDTD

## Time to solve real problems on an X5550 workstation (2009)

<table>
<thead>
<tr>
<th>Simulation type</th>
<th>Memory (MB)</th>
<th>Min mesh size (nm) dx:dy:dz</th>
<th>Volume (μm³)</th>
<th>Single processing time (min)</th>
<th>Parallel processing time (min)</th>
<th>λ (μm)</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>crossover</td>
<td>3800</td>
<td>40</td>
<td>46x16x1.2 = 883.2</td>
<td>188</td>
<td>24</td>
<td>1.4-1.8</td>
<td>Si, glass</td>
</tr>
<tr>
<td>3D grating coupler</td>
<td>4600</td>
<td>37</td>
<td>20x20x1 = 400</td>
<td>100</td>
<td>17</td>
<td>1.3-1.6</td>
<td>Si, glass</td>
</tr>
<tr>
<td>Ring resonator</td>
<td>850</td>
<td>25:10:17</td>
<td>16x5x1.2 = 96</td>
<td>195</td>
<td>30.5</td>
<td>1.55</td>
<td>Si, glass</td>
</tr>
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</table>
Much of the design can be accomplished with the eigenmode decomposition build into the “propagate” command.