Webinar: Efficient Design of Integrated Photonic Circuits

Pierre Wahl, Luceda Photonics
Frank Demming-Janssen, CST GmbH
Why integrated photonics?

- While fiber optics are used in long range data communications since the late 1970s, interconnects in the datacenter is still mostly “electric”

- Data transfer bandwidth between and within microchips becomes increasingly important to progress in computer technology

- The idea of Photonic Integrated Circuits (PICs) is, to use optical interconnects ON the chip which will improve speed and decrease power consumption

Cisco: predicted 5x increase in data traffic between by 2015-2020

Data Centers are projected to use 73 billion kWh annually

Introduzione alla Photonica del Silicio

La photonica del silicio è lo studio e l'applicazione di sistemi fotonici che utilizzano il silicio come mezzo ottico.

Si tratta di una tecnologia che consente il trasferimento di informazioni tramite ultrasuoni, permettendo una velocità di trasmissione superiore a quella delle linee di comunicazione basate su fibre ottiche.

La photonica del silicio offre molteplici vantaggi, come la riduzione del consumo energetico, la riduzione dei costi e la possibilità di creare dispositivi minuti e portatili.

L'immagine mostra un esempio di applicazione della photonica del silicio, con un'analisi di campo elettrico e un diagramma che illustrano le caratteristiche fisiche del sistema.
Introduction to Silicon Photonics

Silicon photonics is the study and application of photonic systems which use silicon as an optical medium.

Silicon photonic devices can be made using existing semiconductor fabrication techniques.

Since silicon is already used as the substrate for most integrated circuits, it is possible to create hybrid devices in which the optical and electronic components are integrated onto a single microchip.
This Webinar

Pierre Wahl: Addressing the key challenges of integrated photonics design teams

Frank Demming-Janssen: Design of Silicon Photonics Devices in CST STUDIO SUITE
Design of Silicon Photonics Devices in CST STUDIO SUITE®

Frank Demming-Janssen
Basic Technology – Dielectric Slab Waveguides

Low Index Cladding (Air, SiO₂...)  
High Index Core (Si)  
Low Index Substrate SiO₂

TE Modes

TM Mode
Building Blocks for PICs

Couplers & Power Dividers
Building Blocks for PICs

Crossings

Terminations
Building Blocks for PICs

Grating Couplers
Time or Frequency Domain?

Novel concept for ultracompact polarization splitter-rotator based on silicon nanowires
Daoxin Dai and John E. Bowers
May 2011 / Vol. 19, No. 11 / OPTICS EXPRESS 10940

- PICs can be very large ~1,000 wavelengths!
Time or Frequency Domain?

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A Plasmonic based Ultracompact Polarization Beam Splitter on Silicon-on-Insulator Waveguides
Qilong Tan, Xuguang Huang, Wen Zhou & Kun Yang
Nature SCIENTIFIC REPORTS | 3 : 2206 | DOI: 10.1038/srep02206

- PICs can be very large ~1,000 wavelengths!
- FEM-FD often prohibitively large
- FIT-TD has a much lower memory footprint
- For some models FEM still superior
Simulation Considerations
Material and Port Modeling

- Silicon shows material dispersion in the IR

![Graph showing refractive index vs wavelength for silicon in the infrared range. The graph displays a downward trend in refractive index with increasing wavelength.]
Material and Port Modeling

- Silicon shows material dispersion in the IR
- Mode Patter of Silicon Wires is also frequency depended (dispersive)
Material and Port Modeling

- Silicon shows material dispersion in the IR
- Mode Patter of Silicon Wires is also frequency depended (dispersive)
- **Question:** is it required to take into account the material and mode dispersion for PIC devices
- **Answer:** Check Mode propagation const.
  - Numbers of merit: $n_{\text{eff}}$ and $n_g$

\[
 n_{\text{eff}} = \frac{c_0}{v_p} \quad n_g = \frac{c_0}{v_g} = n_{\text{eff}} - \lambda \frac{dn_{\text{eff}}}{d\lambda}
\]
Material and Port Modeling

- FD & TD Solver have broadband material models & port operators
Material and Port Modeling

- FD & TD Solver have broadband material models & port operators
- with direct access to $n_{eff}$ and $n_g$

$n_{eff}$ and $n_g$ of a 450 x 220 nm$^2$ Si wire on a SiO$_2$ substrate
Material and Port Modeling

- FD & TD Solver have broadband material models & port operators
- with direct access to $n_{eff}$ and $n_g$

**dispersive vs. non dispersive Silicon**

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*Image of plots showing the comparison between dispersive and non-dispersive Silicon.*
Components Examples
Polarization Beam Splitter – Simulation Strategy

Novel ultra-short and ultra-broadband polarization beam splitter based on a bent directional coupler
Daoxin Dai* and John E Bowers,
OPTICS EXPRESS 18614, Vol. 19, No. 19 (2011)
Polarization Beam Splitter – Simulation Strategy

TE-Mode

TM-Mode
Polarization Beam Splitter – Simulation Strategy

Matching Condition in Coupler Region:
OPL1 = OPL2

\[ OPL = n_{\text{eff}2}k_0R_2\theta = n_{\text{eff}1}k_0R_1\theta \]

\[ \rightarrow n_{\text{eff}2}R_2 = n_{\text{eff}1}R_1 \]
Polarization Beam Splitter – Simulation Strategy

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- For each \( w_1, R_1 \) and gap width an corresponding \( w_2 \) is fixed
- Numbers of free parameters for coupling optimization is reduced
Grating Couplers – Simulation Strategy

back reflector

grating
Grating Coupler – Simulation Strategy

Suggested Design Strategy

Optimize a 2D model of the structure first

Create and simulate the full structure in 3D
Schematic Drawing of the 2D Grating Coupler

Geometric Parameters:

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>p</td>
<td>420</td>
<td>Periodicity</td>
</tr>
<tr>
<td>gw</td>
<td>210</td>
<td>Width of the gratings</td>
</tr>
<tr>
<td>gth</td>
<td>100</td>
<td>Height of the gratings</td>
</tr>
<tr>
<td>mth</td>
<td>140</td>
<td>Thickness of AlCu</td>
</tr>
<tr>
<td>sth</td>
<td>480</td>
<td>Thickness of SiO2 (bottom)</td>
</tr>
<tr>
<td>cth</td>
<td>1405</td>
<td>Thickness of SiO2 (top)</td>
</tr>
</tbody>
</table>

If unknown, the user may employ a global optimizer to find these values.
2D Results: Power Flow and Efficiency

<table>
<thead>
<tr>
<th>Result name</th>
<th>Type</th>
<th>Template name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power absorbed by port</td>
<td>0D</td>
<td>Mix Template Results</td>
<td>0.003390462602</td>
</tr>
<tr>
<td>Power in unperturbed beam</td>
<td>0D</td>
<td>Mix Template Results</td>
<td>0.0005411446106</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0D</td>
<td>Mix Template Results</td>
<td><strong>0.626535424</strong></td>
</tr>
</tbody>
</table>

Close agreement with efficiency reported in reference (59%) = 63%
Full 3D Model

The structure is excited with a Gaussian beam from the top.

Output power is recorded at the waveguide position.

View from bottom:
Full 3D Results

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</tr>
</thead>
<tbody>
<tr>
<td>Power absorbed by port</td>
<td>0D</td>
<td>Mix Template Results</td>
<td>0.331297146</td>
</tr>
<tr>
<td>Power in unperturbed beam</td>
<td>0D</td>
<td>Mix Template Results</td>
<td>0.8992455284</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0D</td>
<td>Mix Template Results</td>
<td>0.3684167845</td>
</tr>
</tbody>
</table>

The model features 500M mesh cells (1 symmetry plane) and requires less than 40 GB of RAM.

Easily fits on a single workstation with 4xK40 GPUs.

3D Efficiency is lower than in 2D model, but still good. Further improvements possible, e.g. by optimizing grating angle.
Ultra-compact high order ring resonator filters using submicron silicon photonic wires for on-chip optical interconnects

Fengnian Xia*, Mike Rooks, Lidija Sekaric, and Yurii Vlasov
IBM Thomas J. Watson Research Center Yorktown Heights, NY 10598
Vol. 15, No. 19 / OPTICS EXPRESS 11934
Results 3 Ring Resonator FULL 3D Simulation

- Full 3D Simulation possible
- …but slow
- Solution → divide & conquer
Ring Resonator Filter – Simulation Strategy

Fig. 3. Scanning electron micrograph (SEM) images of fabricated optical filters with 5 ring resonators.
Results 3 Ring Resonator in DS Circuit Simulator
Comparison DS-Circuit vs. Full Wave

- Full 3D: 3h on dual GPU system per port
- DS circuit model: 30 min on laptop for full S-matrix
DS – Results Ring Resonator Filter Circuit

- Full 3D: 1d on dual GPU system per port
- DS circuit model: 1h on laptop full S-matrix

Runtimes
MMI – Simulation Strategy
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- Replace center part by multi mode transmission line
- Use “analytical“ line length with numerical simulated propagation constant
- FAST Parameter sweep on MMI length!!
MMI – Simulation Strategy

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MMI – Simulation Strategy

- Sweep of length
Coupler – Simulation Strategy
Coupler – Simulation Strategy

- Sweep of length

- Replace center part by multi mode transmission line

- Use “analytical” line length with numerical simulated propagation constant

- FAST Parameter sweep on coupler length!!
Wrap-Up

CST Studio Suite offers a variety of „special features“ for silicon photonics simulations

- Broadband port operators with direct access to mode parameters
- Broadband material models
- ...

TD Solver with GPU acceleration allows simulation very large 3D models

.. but often a smart simulation approach using also advanced circuit simulation capabilities are more promising without compromising on accuracy
Waveguide Crossing – Simulation Strategy

Low-loss, low-cross-talk crossings for silicon-on-insulator nanophotonic waveguides
Wim Bogaerts,* Pieter Dumon, Dries Van Thourhout, and Roel Baets
Ghent University - IMEC, Department of Information Technology, Photonics Research Group,
October 1, 2007 / Vol. 32, No. 19 / OPTICS LETTERS
Waveguide Crossing – Simulation Strategy
Waveguide Crossing

S2,1 vs width at 1.56 \( \mu \text{m} \)

Averaged E-Field vs width at 1.56 \( \mu \text{m} \)
IPKISS-CST LINK

- IPKISS is an integrated photonics designer’s tool to perform circuit design, layout & simulation of integrated photonic devices.
IPKISS-CST LINK

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- IPKISS is an integrated photonics design tool to perform Circuit design, Layout & Simulation of integrated Photonic Devices.
IPKISS-CST LINK

- A full integrate photonics design requires much more than just 3D
- IPKISS is an integrated photonics designers tool to perform Circuit design, Layout & Simulation of integrated Photonic Devices
- CST provides accurate & fast 3D Simulation engine for IPKISS
IPKISS-CST LINK

IPKISS Layout

Use model circuit simulations

CST Model

Import model in IPKISS

CST Simulation

Extract S-Parameters