Photonic components for signal routing in optical networks on chip

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OUTLINES

- Progress in silicon based technology
- Why rapid development of the Integration of Photonics networks on chip?
- 1D PBG devices for wavelength division multiplexing applications on photonic networks on chip
- 2D PBG devices for wavelength routing in photonic networks on chip
- Conclusions
Why Silicon Photonic Technology?

- Silicon can be considered the workhorse of the semiconductor industry

- Due to its abundance and versatility the silicon can be regarded as a dominant platform for the microelectronic fabrication

- Crystalline silicon photonic waveguides are capable of transporting wavelength-parallel optical data with terabit per second data rates across the entire chip

- Silicon waveguides can be bent, crossed and coupled, creating regions where the optical signal can be passed from one waveguide to another one
Why Optical Interconnects?

The recent (i.e. since 2006) advances in:

- Massive fabrication of silicon photonic devices
- Integration of silicon photonic devices in CMOS electronic circuits

photonic technology practical for a new generation of NoCs.

Advantages of photonic NoCs:

- High transmission bandwidth
- Low power consumption
- Low latency
Integration of Photonic Networks on chip - NoC

SUPERCOMPUTING BOARD

DRAM

CMP stack

Photonic Network

Memory

CMP Chip MultiProcessor

Photonic Building Blocks

Photonic NoC

High speed Modulators

10 – 40 Gb/s


SWITCH MATRIX for the signal routing all over the network

Basic elements: Switches, filters, etc.

Periodic effective refractive index by varying the waveguide width $w$
1D PBG WAVEGUIDE

Bragg Wavelength

\[ \lambda_B = 2(n_{\text{eff}1}l_1 + n_{\text{eff}2}l_2) \]

PBG: \( \Delta\lambda \approx 300 \text{ nm} \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Bragg wavelength</td>
<td>1.55 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Si core refractive index</td>
<td>3.477</td>
</tr>
<tr>
<td>SiO(_2) substrate and cladding refractive index</td>
<td>1.444</td>
</tr>
<tr>
<td>Waveguide depth ( d )</td>
<td>200 nm</td>
</tr>
<tr>
<td>Width of the first layer ( w_1 )</td>
<td>500 nm</td>
</tr>
<tr>
<td>Width of the second layer ( w_2 )</td>
<td>260 nm</td>
</tr>
<tr>
<td>Length of the first layer ( l_1 )</td>
<td>180 nm</td>
</tr>
<tr>
<td>Length of the second layer ( l_2 )</td>
<td>0.180 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Number of layers ( N )</td>
<td>32</td>
</tr>
</tbody>
</table>
1D PBG WAVEGUIDE with 1 DEFECT

\[ L_d = 2l_2 = 0.360 \, \mu m \]
1 channel

\[ L_d = 10 \, \mu m \]
6 channels
1D PBG WAVEGUIDE with 1 DEFECT

Defect length variation

- Number of channels vs. defect length [µm]
- FSR [nm] vs. defect length [µm]
- Channel bandwidth [nm] vs. defect length [µm]
1D PBG WAVEGUIDE with 2 DEFECTS

Defect position index \( m \)

Transmittance \( T \)

Wavelength \( \lambda \) [\( \mu \text{m} \)]

- \( m=2 \)
- \( m=4 \)
- \( m=8 \)

Wavelength \( \lambda \) [\( \mu \text{m} \)]

Defect position index \( m \)
BINOMIAL DISTRIBUTION of DEFECTS

2 BINOMIAL DEFECTS

\[ L_d = 2l_2 = 0.360 \, \mu m \quad 1 \text{ channel} \]

<table>
<thead>
<tr>
<th>Channel bandwidth [nm]</th>
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<tbody>
<tr>
<td>1 defect</td>
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<tr>
<td>2 binomial defects</td>
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</table>
BINOMIAL DISTRIBUTION of 2 DEFECTS

$L_d=10 \, \mu m$

6 channels

<table>
<thead>
<tr>
<th></th>
<th>FSR [nm]</th>
<th>Channel bandwidth [nm]</th>
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</thead>
<tbody>
<tr>
<td>1 defect</td>
<td>43.9</td>
<td>7.4</td>
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<tr>
<td>2 binomial defects</td>
<td>44.2</td>
<td>12.6</td>
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</tbody>
</table>
Photonic Crystals for the Optical Interconnects

We need:

- waveguides
- resonators
- bends
- crossings
NoC Components in Photonic Crystals

Broadband Crossing $\lambda = 1.35 \, \mu\text{m} - 1.6 \, \mu\text{m}$

FDTD Simulations

Input at South port $\rightarrow$ Output at North port

W and E are isolated

Maximum attenuation $A = -0.75 \, \text{dB}$ at $\lambda = 1.571 \, \mu\text{m}$
NoC Components in Photonic Crystals

1x2 Photonic Crystal Ring Resonator Switch

- OFF resonance $\lambda_1$
  - Input South → Output North

- ON resonance $\lambda_2$
  - Input South → Output East

Transmittance vs. Wavelength

Graph showing transmittance against wavelength for two resonances $\lambda_1$ and $\lambda_2$.
NoC Components in Photonic Crystals

4x4 Photonic Crystal Ring Resonator Switch Matrix

<table>
<thead>
<tr>
<th>INPUT</th>
<th>W</th>
<th>N</th>
<th>E</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>–</td>
<td>λ₃</td>
<td>λ₂</td>
<td>λ₁</td>
</tr>
<tr>
<td>N</td>
<td>λ₁</td>
<td>–</td>
<td>λ₃</td>
<td>λ₂</td>
</tr>
<tr>
<td>E</td>
<td>λ₂</td>
<td>λ₁</td>
<td>–</td>
<td>λ₃</td>
</tr>
<tr>
<td>S</td>
<td>λ₃</td>
<td>λ₂</td>
<td>λ₁</td>
<td>–</td>
</tr>
</tbody>
</table>

Wavelength [um]

Transmittance

<table>
<thead>
<tr>
<th>wavelength [um]</th>
<th>λ₁</th>
<th>λ₂</th>
<th>λ₃</th>
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<tbody>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.49</td>
<td>0.1</td>
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<td>0</td>
</tr>
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<td>0</td>
<td>0</td>
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<tr>
<td>1.51</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1.52</td>
<td>0</td>
<td>0</td>
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<tr>
<td>1.53</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
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<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1.55</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Silicon components make possible the optical interconnects on chip.

Photonic crystals on silicon integrated on NoC: to perform all the operations of the conventional silicon components, but with more compact sizes.

1D PBG multi-wavelength filters: the Newton binomial distribution of defects allow flat transmission channels with larger bandwidth.

2D PhCs for the wavelength routing in photonic networks on chip