Predictions of CMOS Compatible On–Chip Optical Interconnect

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Agenda

- Introduction
- On-chip CMOS optical data paths
- Optical interconnect vs. electrical interconnect
- Conclusions
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- Introduction
- On-chip CMOS optical data paths
- Optical interconnect vs. electrical interconnect
- Conclusions
Multiple design criteria should be considered in the interconnect design process
Optical Interconnect

- Cost-effective
- CMOS-compatible
- High speed
- Compact
On-Chip Optical Interconnect

When and in what situation is optical interconnect better than electrical interconnect?
Agenda

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- On-chip CMOS optical data path
- Optical interconnect vs. electrical interconnect
- Conclusions
On–Chip Optical Interconnect Data Path

Laser → Optical Modulator → Waveguide → Photo Detector → Amplifier

On-Chip

Driver → Electrical Logic Cell

Electrical Logic Cell
# Modulators – Choice of Structures

<table>
<thead>
<tr>
<th>Optical Structure</th>
<th>Electrical Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach-Zehnder</td>
<td>p-i-n diode</td>
</tr>
<tr>
<td>Microresonator</td>
<td>MOS capacitor</td>
</tr>
</tbody>
</table>
P-i-n Diode: Microresonator

- Size (20 µm)
- Power consumption (mWs)
- CMOS compatible
- Speed (injection-based)

MOS Capacitor : Mach-Zehnder

- Speed (1 GHz and up)
- CMOS compatible
- Size (10 mm)
- Power consumption (watts)

Proposed Modulator Model

- High speed
- CMOS compatible
- Compact size
- Low power
Model of Modulator Driver

- Optical modulator is modeled as a lumped capacitor
- A series of tapered buffers used to drive $C_M$
- The size of the buffers is optimized for minimum delay
Si waveguide
- Consumes Si resources
- High refractive index ~ 3.5
  - Narrower waveguide
  - Slower light speed

Polymer waveguide
- Additional layer
- Low refractive index ~ 1.4
  - Wider waveguide
  - Faster light speed
Optical receiver is composed of a photodector and an amplifier circuit
Photodetector

- **Material:** Ge or SiGe
  - Longer wavelength absorption window
    - Compatible with CMOS

- **Structure:** Metal-semiconductor-metal (MSM)
  - High speed
  - Easy to fabricate
  - Reasonable quantum efficiency
Photodetector Optimization

- Response time
  - \( T_r = \sqrt{\tau_{tr}^2 + \tau_{RC}^2} \)
  - Transit time
  - \( RC \) response time

- Expected size
  - In ten years
    - 5 \( \mu \)m x 5 \( \mu \)m
  - Limited by the optical mode size

Amplifier Circuit

- Amplifier is designed to satisfy noise and bandwidth requirements *
  - BER: 10^{-15}
  - 3 dB bandwidth: 0.7 x bit rate (NRZ)

• Introduction
• On-chip CMOS optical data path
• Optical interconnect vs. electrical interconnect
• Conclusions
Electrical Interconnects with Repeaters

- Electrical interconnects are modeled as $RLC$ transmission lines
- Three dimensions of freedom
  - Interconnect width
  - Number of repeaters
  - Size of repeaters
Minimum Delay of Electrical Interconnect

- Scaling has a small effect on the delay of global interconnect with repeaters
  - The minimum achievable delay is constant for advanced technology nodes: 20 ps/mm

\[ L = 0.5 \text{ pF/\mu m} \]

Line spacing = \( W_{\text{min}} \)
## Delay of Optical Interconnect

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<tr>
<td>Technology node</td>
<td>90 nm</td>
<td>65 nm</td>
<td>45 nm</td>
<td>32 nm</td>
<td>22 nm</td>
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<tbody>
<tr>
<td>Modulator driver</td>
<td>83.7</td>
<td>45.8</td>
<td>25.8</td>
<td>16.3</td>
<td>9.5</td>
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<tr>
<td>Modulator</td>
<td>114.0</td>
<td>52.1</td>
<td>30.4</td>
<td>20.0</td>
<td>14.3</td>
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<tr>
<td>Waveguide</td>
<td>46.7</td>
<td>46.7</td>
<td>46.7</td>
<td>46.7</td>
<td>46.7</td>
</tr>
<tr>
<td>Photo-detector</td>
<td>1.4</td>
<td>0.5</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Receiver amplifier</td>
<td>37.5</td>
<td>16.9</td>
<td>10.4</td>
<td>6.9</td>
<td>4.0</td>
</tr>
</tbody>
</table>

| Total optical | 283.3 | 162.0 | 113.6 | 90.2 | 74.7 |

Unit: ps, Length = 10 mm

- Electrical interconnect delay: 20 ps/mm
Power Consumption in Optical Interconnect

- **Assumptions**
  - Input optical power ~ 0.2 mW
  - Power consumption in the optical interconnect is independent of interconnect length
    - Optical power loss in waveguide is ignored

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| Transmitter | 177.5 | 18.4 | 8.6 | 6.0 | 5.0 |
| Receiver | 0.4 | 0.3 | 0.2 | 0.3 | 0.3 |

**Total**

| 177.9 | 18.7 | 8.8 | 6.3 | 5.3 |

Unit: mW
Power-Delay Product (PDP)

Length = 10 mm
Bandwidth Density

- Bandwidth density
  - The ability to transmit data through a unit width
- The maximum bit rate is the clock rate
- Wavelength division multiplexing (WDM)
  - Four additional channels for each new technology node
Critical Length

- Critical length
  - The length beyond which optical interconnect is advantageous over electrical interconnect

![Graph showing normalized critical length against year with 1/3 \( l_{\text{edge}} \)](image)
Agenda

- Introduction
- CMOS compatible on-chip optical data path
- Performance prediction of optical interconnect compared with copper interconnect
- Conclusions
Conclusions

- Predictions of CMOS compatible on-chip optical interconnect are presented
  - Device models are described
  - Delay, power, and bandwidth are analyzed
- Modulator is the key component in an on-chip electro-optical system
- WDM is necessary for improving the bandwidth density of the optical interconnect
- The critical length is about 1/3 of the chip edge length at the 45 nm technology node
Backup
Electrical Structures

\[ \Delta n_{\text{eff}} = \Delta n \ast \sigma \]

\begin{itemize}
  \item **P-i-n diode**
    \begin{itemize}
      \item Uniform injection over large areas, high \( \Delta n_{\text{eff}} \)
      \item Slow (20 ps and higher)
    \end{itemize}
  \item **MOS capacitor**
    \begin{itemize}
      \item Carrier concentration varies in small area.
      \item Very fast
    \end{itemize}
\end{itemize}


Optical Structures

- Mach-Zehnder interferometer
- Destructive interference
  - condition: $\Delta \phi = \pi$
  
  \[ L = \frac{\lambda}{4\Delta n_{\text{eff}}} \]

- Micro-resonator
- Wavelength selective
- Compact


Optical Part: Microresonator

- Compact
- Wavelength selective

Category of Photodetectors

♦ p-n Photodiodes

♦ p-i-n Photodiodes

♦ Metal-semiconductor-metal (MSM)
  – High speed
  – Easy fabrication
  – Reasonable quantum efficiency
Delay and power of an optical receiver

- For MSM interdigitated photodetector, response time is

\[ T_r = (\tau_{tr}^2 + \tau_{RC}^2)^{1/2} \]

- Transit time \( \tau_{tr} = tX/2V, \)
  - \( V: \) carrier drift velocity
  - \( X: \) drift distance corrective coefficient
- RC response time \( \tau_{RC} = 2.2RC \)

Delay is \( T_D = 0.315T_r \)

- Delay is \( T_D = 0.693 / (2 \pi \Delta f) \)
- Power is

\[ \text{Prec} = \left( \frac{W_{TIA}}{W_{min}} \right) I_{dsat0} V_{dd} + \left( I_{bias} V_{dd} + I_{ph} V_{bias} \right)/2 + N_{inv} I_{dsat0} V_{dd} \]
Electro-optical effects in silicon

Electroabsorption

Electrorefraction

Optical modulator – Mach-Zehnder interferometer structure
Optical modulator – Mach-Zehnder interferometer structure

\[ n_0 \]

\[ n_0 + \Delta n \]
Propagation delay – both structures

Blue line: M-Z interferometer

\[ T_{pi} = \frac{L}{c} n_{si} \]

Red line: Microresonator

\[ \Delta t \Delta \Omega \geq \frac{1}{2} \]

\[ \Delta n \]
Microcavity-based modulator (Barrios et. al)

- Size (20 µm)
- Power consumption (mWs)
- CMOS compatible
- Speed (injection-based)
Assumption 1:
Modulator is a sinc mode field can be

\[ E_z(x, y) = \sin\left(\frac{a - x}{2a} \pi\right) \sin\left(\frac{a - y}{2a} \pi\right) \]