Will photonics penetrate into inter-chip and intra-chip communications?

Harm Dorren and Oded Raz
On-chip interconnect networks

Electronic on-chip interconnect network
- Interconnect needs repeaters
- Each repeater receive, buffers and re-transmits every bit
- Higher clock frequencies: more power per repeater and more repeaters

Optical on-chip interconnect network
- No repeaters
- Power independent of distance/ no cross talk, etc

Forecast for 2020
- 10 TFLOP processors
- On-chip I/O ~ 1 byte per flop (Amdahl)
- Power electronic network 10 TFLOPs chip ~ 500 Watts
- ~ 7 pJ/bit or 7 mW/Gb/s
Photonic interconnect network:  
**Receiver**

Transmission path

Typical receiver sensitivity at BER $10^{-9}$

<table>
<thead>
<tr>
<th>Speed</th>
<th>PIN</th>
<th>APD</th>
<th>Power (TIA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 Gb/s</td>
<td>-10 dBm</td>
<td>-</td>
<td>~250 mW</td>
</tr>
<tr>
<td>10 Gb/s</td>
<td>-20 dBm</td>
<td>-25 dBm</td>
<td>~200 mW</td>
</tr>
<tr>
<td>2.5 Gb/s</td>
<td>-25 dBm</td>
<td>-30 dBm</td>
<td>~75 mW</td>
</tr>
</tbody>
</table>
### Photonic interconnect network

*Transmission path*

- **Transmitter**
- **Transmission path**
- **Receiver**

### Typical waveguide losses

<table>
<thead>
<tr>
<th>Material</th>
<th>Typical losses</th>
<th>Bending radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>0.01 dB/cm</td>
<td>500 micrometer</td>
</tr>
<tr>
<td>Etchless silicon</td>
<td>0.3 dB/cm</td>
<td>50 micrometer</td>
</tr>
<tr>
<td>SOI</td>
<td>2.4 dB/cm</td>
<td>5 micrometer</td>
</tr>
<tr>
<td>InP membranes</td>
<td>3 dB/cm</td>
<td>5 micrometer</td>
</tr>
</tbody>
</table>

/Department of Electrical Engineering
Photonic Interconnect network: Option 1: *Off-chip laser and transmitter*

<table>
<thead>
<tr>
<th>Data Rate</th>
<th>Power Laser (mW)</th>
<th>Power Modulator (mW)</th>
<th>Power Modulator Driver (W)</th>
<th>Insertion Losses (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 Gb/s</td>
<td>150</td>
<td>60</td>
<td>5.85</td>
<td>8</td>
</tr>
<tr>
<td>10 Gb/s</td>
<td>150</td>
<td>&lt; 50</td>
<td>3.6</td>
<td>8</td>
</tr>
<tr>
<td>2.5 Gb/s</td>
<td>150</td>
<td>&lt; 50</td>
<td>1~2</td>
<td>8</td>
</tr>
</tbody>
</table>

**Silicon modulators**, MZI or Ring resonator, limited data available, but high losses, and high power!

See Ding and Pan, SLIP 09
Direct modulation

Use microdisk laser (diameter 7.5 micrometer)
Threshold current is ~ 0.1 mA
Power 5 mW (2V, 2.5mAmps)
Optical power in waveguide ~ 50 mW
10 Gb/s wavelength conversion is possible but
direct modulation at high speed never been demonstrated

Devices made by IMEC/Gent (FP7 project HISTORC)
Link and power budget

*40 Gb/s (off-chip laser)*

- Receiver sensitivity (PIN): -10 dbm
- Waveguide losses: 5 dB
- Insertion losses modulator: 8 dB
- Coupling losses: 3 dB
- Required laser power: 6 dbm (4mW)

<table>
<thead>
<tr>
<th>Component</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power laser</td>
<td>150</td>
</tr>
<tr>
<td>Power modulator</td>
<td>60</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>210</strong></td>
</tr>
<tr>
<td><strong>Power modulator driver</strong></td>
<td><strong>5850</strong></td>
</tr>
<tr>
<td><strong>Power TIA Receiver</strong></td>
<td><strong>250</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6100</strong></td>
</tr>
</tbody>
</table>

210 mW (5.25 mW/Gb/s)

6100 mW (153 mW/Gb/s)
Link and power budget

10 Gb/s (off-chip laser)

Receiver sensitivity (APD): -25 dBm
Waveguide losses: 5 dB
Insertion losses modulator: 8 dB
Coupling losses: 3 dB
Required laser power: -9 dbm (0.13 mW)

Power laser: 150 mW
Power modulator: 50 mW
200 mW (20 mW/Gb/s)

Power modulator driver: 3600 mW
Power TIA Receiver: 200 mW
3800 mW (380 mW/Gb/s)
Link and power budget

2.5 Gb/s (off-chip laser)

Receiver sensitivity (APD): -30 dBm
Waveguide losses: 5 dB
Insertion losses modulator: 8 dB
Coupling losses: 3 dB
Required laser power: -14 dBm (0.04 mW)

Power laser: 150 mW
Power modulator: 50 mW
200 mW (80 mW/Gb/s)

Power modulator driver: 1000 mW
Power TIA Receiver: 75 mW
1075 mW (430 mW/Gb/s)
Link and power budget
2.5 Gb/s (direct modulation)

Receiver sensitivity (APD): - 30 dbm
Waveguide losses: 5 dB
Insertion losses modulator: 8 dB
Coupling losses 3 dB
Required laser power -14 dbm (0.04 mW)

<table>
<thead>
<tr>
<th>Component</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power laser</td>
<td>5 mW</td>
</tr>
<tr>
<td>Power modulator</td>
<td>0 mW</td>
</tr>
<tr>
<td></td>
<td>5 mW (2 mW/Gb/s)</td>
</tr>
<tr>
<td>Power modulator driver</td>
<td>0 mW</td>
</tr>
<tr>
<td>Power TIA Receiver:</td>
<td>75 mW</td>
</tr>
<tr>
<td></td>
<td>75 mW (30 mW/Gb/s)</td>
</tr>
</tbody>
</table>
Bandwidth distance product

including driver power

Off-chip laser at 2.5, 10 and 40 Gb/s

Direct modulation at 2.5 Gb/s

Electronic with repeaters (3.5 GHz)
Bandwidth distance product without *driver power*

- Off-chip laser at 2.5, 10 and 40 Gb/s
- Electronic with repeaters (3.5 GHz)
- Direct modulation at 2.5 Gb/s
Conclusions (1)

Off-chip laser
- Sufficient link budget to allow some networking, but, ..... high power dominated by drivers

On-chip laser
- Sufficient power for a single link, but, .... insufficient link budget for a network on a chip
Conclusions (2)

Photonics gives an improved bandwidth distance product:

Bandwidth is limited by electronics, thus photonics only gives distance!!

Need applications with "distance"