Introduction to Silicon Photonics 2: Markets and Technology

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November 11, 2014
Summary—silicon photonics on track

- Silicon photonics **nearing commercialization**
  - Technical advances addressing challenges
  - Critical mass of diverse ecosystem participating
  - Expect new products based on silicon photonics for 100G datacom and DWDM

- Today’s interconnect products is a market entry point

- Silicon photonics is disruptive
  - Plan for the long-term and grab revenues
  - Consider business models
  - Consider new products and markets
    - High integration level and complex solutions
Outline

- The “Anywhereization” Opportunity
  - Internet content provider are spending on datacenters and networking
- Networking gains needed
  - Flatter architecture, more connections, more bandwidth per connection
- Why silicon photonics and what is being offered
  - Potential to scale to high density
- Silicon photonics is low cost: fact or fiction?
  - Answer is not clear cut
- Evidence of progress
  - New products but the disruptive promise of SiPh is not yet evident
ANYWHEREIZATION is... 
...the trend towards being constantly connected. It means access to everything. Anytime. Anywhere.

The possibilities are unlimited. Today you can access the internet from the summit of Mount Everest.

# anywhereization
Data center and connectivity upgrade required

“It really means we need to provide faster systems with more efficient hardware per performance per watt with high efficiency cooling … hopefully at improved cost points to end user”

Source: Cisco
Servers are an easy target as they account for a big fraction of data center cost and power consumption.

Data center cost

- Servers: 45%
- Infrastructure: 25%
- Power draw: 15%
- Network: 15%


Typical breakdown of the data center energy consumption.

Communication Service Providers capex steady with upside from new network builders

ICPs capex fueling demand for datacenters, equipment, and connectivity

Source: Ovum

ICPs: “Internet content & cloud providers”, such as Google, Amazon, Baidu, IBM, Microsoft, etc.
Fixed CSPs: ATT, BT, CT, CU, Comcast, DT, NTT E&W, TWC & Verizon
Data center architectures to support today’s applications requires more connections and higher bandwidth.

Yesterday: Hierarchical 3 tier

Today: Leaf and spine

Flatten network, reduce over-subscription but increase connectivity

Near Future

Low-cost high-bandwidth interconnects needed.

Also driving technology adoption such as silicon photonics for interconnects.
Higher connectivity and bandwidth needed for all data center connections

<table>
<thead>
<tr>
<th></th>
<th>Short (&lt;1km)</th>
<th>Medium (1 to 40km)</th>
<th>Long (&gt;40km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supports</td>
<td>Server to switch, switch to switch</td>
<td>Switch to switch, DC to DC, DC to POP</td>
<td>DC to DC, DC to POP</td>
</tr>
<tr>
<td>Environment</td>
<td>Fiber rich</td>
<td>Mostly fiber rich</td>
<td>Fiber scarce</td>
</tr>
<tr>
<td>Fiber and laser</td>
<td>Multimode and VCSEL</td>
<td>Single fiber, single laser</td>
<td>Tunable laser</td>
</tr>
<tr>
<td>To support transmission above 10G</td>
<td><strong>Active optical cables</strong></td>
<td><strong>Multiple wavelength for 100G</strong></td>
<td><strong>Narrow linewidth laser for coherent</strong></td>
</tr>
<tr>
<td>Scaling approaches</td>
<td>Arrays, data rate</td>
<td>Wavelength, data rate, complex modulation</td>
<td>Wavelength, data rate, transmission spectrum</td>
</tr>
<tr>
<td>Issues</td>
<td>Distance limitations</td>
<td>High cost and power consumption</td>
<td>Approaching fiber carrying capacity</td>
</tr>
</tbody>
</table>

Solutions are technology agnostic. Best solution wins!
Why silicon photonics and what is being offered?

**Silicon photonics definition:** processing and/or manipulating light in a silicon medium (silicon on insulator). The light source is **NOT** in silicon.
SiPh is an attractive connectivity option due to the POTENTIAL of higher density, lower power, and lower cost.

<table>
<thead>
<tr>
<th>Company</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aurrion</td>
<td>Lower cost, lower power and higher density</td>
</tr>
<tr>
<td>Intel</td>
<td>One solution for all connectivity</td>
</tr>
</tbody>
</table>
| Luxtera | Leverage as much as possible from the integrating electronics industry  
  • Power consumption reduction |
| Mellanox | 100G optics in QSFP28 package |
| Skorpios Technologies | Reduce optics cost |
| Ovum   | Support 100G medium distance demand |

Comments from Open Server Summit 2013
Various approaches discussed in 2013
Distance inferred by the problem and/or solutions introduced

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<tbody>
<tr>
<td>Cisco Systems</td>
<td>Server disaggregation</td>
<td></td>
<td></td>
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<tr>
<td>Aurrion</td>
<td></td>
<td><strong>Uncooled</strong> WDM laser arrays,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>modulators, photodiodes, etc</td>
<td></td>
</tr>
<tr>
<td>Intel Corp.</td>
<td>Server disaggregation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luxtera</td>
<td>Active Optical Cable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mellanox Technologies</td>
<td></td>
<td><strong>Parallel single mode and</strong></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td><strong>Uncooled</strong> <strong>WDM lasers</strong></td>
<td></td>
</tr>
<tr>
<td>Skorpios Technologies</td>
<td></td>
<td><strong>CWDM laser array, modulators, etc.</strong> for QSFP28</td>
<td><strong>Uncooled</strong> tunable external cavity laser for coherent</td>
</tr>
</tbody>
</table>
Scalability is a key silicon photonics feature

Demand for higher bandwidth between and inside the datacenter will require unprecedented levels of integration

Silicon photonics scaling is in early stages
Silicon photonics is low cost: Fact or fiction?
Wafer-scale testing helps keep cost down

- **Wafer testing**
  - Strength is that it can yield the die for optical performance and for low-speed electrical requirements.
  - Weakness is that grating couplers are wavelength and fabrication sensitive. Data analysis can be complex.

- **Grating couplers must be designed into wafer to test optics**

- **Add optical fiber assembly alignment stage to prober, then can measure almost anything**
  - Insertion loss over wavelength, polarization, etc.
  - Measure over temperature

- **Electrical testing straightforward**
  - Dark current of photo-diode, V-I curves of modulator, resistance, etc.

- **Cannot measure high-speed performance, but when optical and low-speed electrical are good then chip is good**

Note: InP can be wafer tested, but it is not typically done.
Silicon photonics also supports lower cost packaging

- BGA packages are really available only in SiPh
  - InP is too fragile for thermo-compression bonding
- Silicon photonics is easy to make self-hermetic
- Can do lots of integration at wafer level in silicon photonics, reducing packages

Expect bigger savings to come from packaging technologies
But active alignment is needed for single mode fiber attachment, one of the highest packaging cost

<table>
<thead>
<tr>
<th></th>
<th>Silicon Photonics</th>
<th>Indium Phosphide</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design and tools</td>
<td>↔</td>
<td>↔</td>
<td>Single mode device</td>
</tr>
<tr>
<td>Tape out and mask</td>
<td>↑</td>
<td></td>
<td>CMOS mask very expensive</td>
</tr>
<tr>
<td>Material cost</td>
<td></td>
<td>↑</td>
<td>Substrate cost is small</td>
</tr>
<tr>
<td>^Processing cost</td>
<td></td>
<td>↑↑↑</td>
<td>Comparable cost per wafer, but more dies for SiP***</td>
</tr>
<tr>
<td><strong>Packaging</strong></td>
<td>↔</td>
<td>↔</td>
<td><strong>Expensive, both single mode</strong></td>
</tr>
<tr>
<td>Testing final device</td>
<td>↑</td>
<td></td>
<td>Maturity issue for SiPh</td>
</tr>
<tr>
<td>Yield</td>
<td></td>
<td>↑</td>
<td>InP can have yield issues?</td>
</tr>
<tr>
<td>Printed circuit board</td>
<td>↔</td>
<td>↔</td>
<td>Advantage to SiPh??</td>
</tr>
<tr>
<td>Capital equipment</td>
<td></td>
<td>↑</td>
<td>CMOS fabs are expensive, but</td>
</tr>
<tr>
<td>Other**</td>
<td></td>
<td>↑</td>
<td>Maturity, IP, license for SiPh</td>
</tr>
</tbody>
</table>

* SiP hermetic?, **(Laser, maturity, IP, license); ***Relative device size unclear

Legend: Comparable cost ↔; Higher cost ↑; Much higher cost ↑↑↑

No clear evidence of lower cost for SiPh
Evidence of progress since Open Server Summit 2013
Disaggregated server and optical technologies have progressed since last year

<table>
<thead>
<tr>
<th>distance</th>
<th>what</th>
<th>2013 Status</th>
<th>2014 ytd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cisco</td>
<td><strong>Disaggregated server</strong></td>
<td></td>
<td>Introduced its Unified Computing System Modular Server</td>
</tr>
<tr>
<td>Aurrion</td>
<td>Medium, long Uncooled Tunable laser, modulators, Pd</td>
<td>developing</td>
<td></td>
</tr>
<tr>
<td>Intel</td>
<td>short multimode Developing—fiber, connectors, Optical PCIe</td>
<td>Developing; IDF showing applications</td>
<td></td>
</tr>
<tr>
<td>Luxtera</td>
<td>Short and medium Shipping (Molex) 4x10G AOC</td>
<td>Developing</td>
<td>Developing</td>
</tr>
<tr>
<td>Mellanox</td>
<td>Medium Flip chip bonded laser and tunable laser</td>
<td>developing</td>
<td>100G in QSFP28 demo</td>
</tr>
<tr>
<td>Skorpios</td>
<td>Long and medium Tunable laser developing</td>
<td>Demos</td>
<td>Demonstrated micro ITLA for coherent and QSFP28 CWDM</td>
</tr>
<tr>
<td>Acacia Communications</td>
<td>Long Single SiPh chip transceiver</td>
<td></td>
<td>Generally available</td>
</tr>
<tr>
<td>Finisar</td>
<td>Medium <strong>Demonstrated 50G SiPh transceiver</strong></td>
<td></td>
<td>Demonstration with STMicroelectronics</td>
</tr>
</tbody>
</table>

*Note: HP’s Moonshot, Facebook’s Open Compute, and Dell are also looking at modular server
Disaggregated server to improve data center cooling

Segment Cooling

High speed interconnects, low latency

Source: adopted from Cisco
New SiPh product became generally available in September 2014

Single-chip 100G SiPh transceiver

Transmitter and receiver integrated together to save significant packaging cost and size

Package includes linear drivers and TIAs
Total power < 4.5W
Conclusion

- Anywhereization driving new datacenter architectures
  - Internet content provider spending fueling market growth
- Connectivity and high bandwidth are key elements to the leaf and spine networking architecture and to the disaggregated server
- Silicon photonics scalability potential is very attractive
  - 100G is SiPh market entry point
    - Expect clearer advantages for transmission beyond 100G
- Evidence that silicon photonics is lower cost still unclear
- New products slowly emerging
  - Cisco’s disaggregated server
  - Acacia’s single chip coherent transceiver

The disruptive promise of silicon photonics is not yet evident.
Elsevier has commissioned us to write a market focused book on the outlook for silicon photonics in the next decade. It will be written and submitted in 2015. Daryl Inniss and Roy Rubenstein are authors.

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