Silicon Microphotonics Roadmap
Status and Outcomes

CTR
technology supply chain
research = options
development = choices
manufacturing = cost reduction
MIT Microphotonics Center Industry Consortium

MIT Microphotonics Center
Prof. Lionel Kimerling, Director

Microphotonics Industry Consortium
Consortium Executive Committee
Chair, Richard Grzybowski, Corning

Administration
Ms. Lisa Sinclair
CTR and Consortium

Communications Technology Roadmap
Prof. Lionel Kimerling, Director

CTR III Technology Working Groups
- Scaling Limits and Energy
- Copper Interconnect Scalability
- Short Reach Optical Interconnects for Computing
- System Optimization
  open architecture system design rules
  communication interfaces

MphC Industry Consortium Chairs:
CTR I (Bruce Wallace, Nortel)
CTR II (Jerry Bautista, Intel)
CTR III (Richard Grzybowski, Corning)

28 Supporting Companies
102 Participating Organizations

- Research and roadmap review meetings
- Twice-monthly technology briefs
- Independent and collaborative R&D
- On-site / remote access to MIT seminars
- Poster session access to graduate students and post-docs
- 7 Roadmap Organizations: ITRS; iNEMI; OIDA; OITDA and AIST (Japan); MONA and EPIC (Europe)
The Evolution of the Roadmap

- **CTR I (2000-2005) Survival**
  - Identify industry trends and areas for product development.
    - *Electronic-Photonic Synergy - Integration - Standardization - Cross-market Platforms*

- **CTR II (2005-2009) Performance**
  - Identify market opportunities for high volume and electronic-photonic convergence.
    - *Cost – Power Efficiency – Bandwidth Density*

- **CTR III (Annual Releases) Scalability**
  - *Energy – Copper – Interconnection - Systems*
1. Photonics technology will be driven by electronic-photonic convergence and short (<1km) reach interconnection. This direction will ignite a major shift in the leadership of the optical component industry from information transmission (telecom) to information processing (computing, imaging).

2. E-P convergence will require a standard platform and infrastructure for high volume production.

3. E-P convergence will drive higher performance and new functionality in both analog and digital signal processing.

4. The competence required for these new directions does not exist within any one company or business sector.

3. The relevant technology supply chain can benefit from precompetitive coordination through the MIT Microphotonics Center Industry Consortium.
Business: Cross-Market Platforms
The Telecom Revenue Dynamic

Forecast Demand for Broadband

New Optical Network Build

Costs

BW x D

R&D to Reduce Costs

R&D to Improve Performance

Transceiver Sales

Transceiver Revenue

POTS vs performance scaling
Network Build lifecycle?
Technology obsolescence?

Total Broadband Demand

Revenue

Time (Year)

800 M

600 M

400 M

200 M

0

800

600

400

200

0

Time (Year)

legacy
dominance

build
complete

Speerschneider, Kelic, MIT

Microphotonics Center

communications technology roadmap
## Standardization vs. Proliferation

### Technologies

- Differentiation to preserve market share
- Loss of economies of scale

### Silicon Microphotonics is a standard platform
- further supplier consolidation
- fewer transceiver variants
- lower cost
- higher volume production
- single standard for
  - telecom/datacom
  - computing
  - imaging

### Optical Transceiver Variants

<table>
<thead>
<tr>
<th>3</th>
<th>Application</th>
<th>SAN, LAN, WAN/MAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Bit Rate</td>
<td>0.155 Gb/s, 0.622 Gb/s, 1 Gb/s, 2.5 Gb/s, 10 Gb/s</td>
</tr>
<tr>
<td>3</td>
<td>Wavelength</td>
<td>850 nm, 1310 nm, 1550 nm</td>
</tr>
<tr>
<td>4</td>
<td>Reach</td>
<td>SR, IR-1, IR-2, LR</td>
</tr>
<tr>
<td>×6</td>
<td>Form Factor</td>
<td>SFF, SFP, GBIC, XFP, MSA, Other</td>
</tr>
</tbody>
</table>

| 1080 | Approx. number of logical exclusions |
| 500  |
| 580  |

The “Death Spiral” Dynamic
Proliferation vs. Standardization

Standardization expands TAM and stimulates a learning curve for performance/cost scaling.
Photonics Economics

- Cannot wait for upturn in investment in telecom: 10-15 yr ‘network build’ intervals
- Currently too many firms in the industry
- Standardization and consolidation will decrease cost and price.
- The industry problem is that components have a low cost-share of the final product.
- Need to develop *new demand drivers* that will shift out the demand curve.

J. Hausman, MIT (2005)
1. The emergence of broadband Communications as a commodity has facilitated a migration of component technology focus from Telecommunications to distributed Information Processing.

2. Scalability to higher communication bandwidths is a major issue at all levels of the interconnection hierarchy: networks, systems, boxes, boards, modules and chips.

3. The key communication technology performance metrics
   i) cost ($/Gbps)
   ii) power efficiency (mW/Gbps)
   iii) bandwidth density (Gbps/cm² or Gbps/cm)

4. The competence required for these new directions does not exist within any one company or business sector.
CTR II: Business Environment

- The O-E-O interface is the critical focal point for solutions to communication cost.
- The single channel data rate will likely standardize at 10 to 25Gbps due to EMI and density/complexity limits of electronics.
- Optical interconnects will be multimode in the near term and will migrate to a single mode, WDM standard in the long term (~2016).
- The defining attributes for markets will be COST, system density, power consumption, cable management, EMI shielding, heat management. Technical and reliability issues have been well demonstrated in telecom applications.
Key Barriers to Adoption

- cost
- lack of universally accepted infrastructure
- fragmentation of market opportunities
- additional capital investment required
- risk, both at the corporate and personal level, presented by implementing a new technology
- acceptance of electrical interconnects, even though the ability of electrical transport to meet future requirements is self-limited

Volume threshold for cost competitive, CMOS photonic solutions is ~1M units/yr.
CTRII: Silicon Microphotonics

- The transceiver is the near term driver for silicon microphotonics.
- Silicon is the only material platform capable of supporting a standard cross-market, high-volume transceiver in the long term.
- Initial optical cabling applications will be multimode; but board, module and chip level interconnection will be single mode.
- A WDM standard of 20Gb/s per channel will optimize the tradeoff between power efficiency and aggregate bandwidth density.
- An independent optical power supply will be the dominant architecture in the near term.
Data Center Interconnection

System Design Targets

- **Power efficiency:** 5mW/Gbps
- **Cost** of bandwidth should decrease by 25%/yr.
  - target cost < $1/Gbps
- **Improved system density:** Gbps/cm²
- **Improved cable management:** I/O, HPC clusters
- **Thermal management:** less airflow obstruction
- **EMI:** reduced shielding costs

T Morris, Hewlett Packard

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Key drivers for optical interconnection

Power efficiency – Cost – Bandwidth density – Heat - EMI
CTR II: Interconnection and Packaging

- Optical pins will be needed within the next decade to address EMI and pin count issues.
- Packaging cost must decrease as it supports an exponential increase in off-chip bandwidth with time.
- **WDM will be necessary to meet off-chip bandwidth needs by 2020, single-mode, long wavelength (1300-1600 nm) will be the standard.**
- **The BGA platform must be viable for both electronics and photonics.**
- **For large volume commercial applications, transceiver chips will stand alone from signal processing chips during the next decade; and they will become monolithically integrated thereafter for chip-to-chip.**
MIT Converged E-P Chip Package

BGA electronic + edge optical pin

Single-mode fiber with 0.25 mm pitch
Up to 80 WDM optical pins per edge for a 2 cm × 2 cm chip
CTR III: Scaling Information Technology

- 5 Exabytes (billion gigabytes) to 2000AD
  + 487 Exabytes 2000-2009AD
  + 2500 Exabytes/yr by 2012

- By 2020 the energy utilized by IT traffic will exceed 10% of the total electrical power generation in developed countries.

- A single optical fiber with multilevel quadrature and polarization modulation, can transmit the entire 492 Exabytes of 2009 human knowledge in two minutes.

cost – energy - bandwidth density
**CTR III: Scaling Limits and Energy**

*Released June 2010  (Alan Benner, IBM)*

- **Smart interconnection** that configures/optimizes
  - data rate, point-to-point and broadcast communication, routing
  - wire delay, contention, wire energy
- **New architectures** and **standards**
  - shift from hierarchical electronic to agile optical solutions
- **Migration from maximum-size to density scaling**
  - Mid-board transceivers improve performance/cost
  - HPC optical interconnect performance targets for 2012
    - 25mW/Gbps; 200Gbps/cm²; $1/Gbps; and $10^7 optical interconnects/machine; optical cables for L> 5 cm.
Scaling Limits for Copper Interconnects

CTR III: released October, 2011 (Dick Otte, Promex)
Short Reach Optical Interconnection
Released May 2013  (Roe Hemenway, Corning)

- A higher-speed I/O generation emerges every ~3.5 years.
- Interfaces are standardized and optimized for a specific functionality in the compute environment (PC, laptop, server, etc.).
- Board level optical interconnects are emerging
  - Both VCSEL and Silicon photonics are viable
  - 10G for consumer and Nx(2x25) G for HPC
- Driven by BW density, power
- Lower cost through better integration and cost
- Mature high density low cost connectors are emerging
- Primary challenge for optimized design and ubiquity is manufacturing integration
Monolithic, chip-level photonic integration: solution to cost, energy bandwidth density.
Why Microphotonic Integrated Systems?

- Data Rate is increasing.
  - Electrical links are loss-limited at high data rate.
  - \([\text{Data rate} \times \text{distance}]\) is the Figure of Merit.
- Photonic links are displacing electrical.
  - As \(L\) decreases, photonic interconnects trend to a higher fraction of the interconnect count of a system.
- High unit volumes: new manufacturing paradigm
  - Telecom: 10k-100k units/yr; discrete
  - Datacom/Compute: >1M units/yr; integration

*Microphotonics: performance + manufacturing*
Telecom: Long Haul Fiber Capacity

Essiambre, et.al., IEEE Breakthroughs In Photonics 2012
Datacom: Technology Transitions

- Today: transition to 10Gbps links
- 2014: 20Gbps at 3-5m
- 2017: board-level photonics
- Application-based determinants
  - communication: reach and BW density
  - computation: energy and latency

*New system design metric: cost-per-function*

Reach and BW density will drive transition to photonics. 
*Path*: ‘Good enough’ photonics with high performance electronics.
Electronic-Photonic Synergy

A Graded Transition

- AOCs: be like ‘electronics’
  - backward compatibility; high data rate; high power
- Parallel MM cables
  - VCSEL-based transceivers; high data rate; electronics for signal integrity; moderate power
  - entry of ‘good enough photonics’
- WDM waveguide on chip
  - disruptive BW density solution: low data rate; electronics for signal integrity; lowest power
  - disruptive, synergistic E-P architecture
The Technology Transition is Happening Now
Molex Silicon Photonics Transceiver
In Jan. 2013, Intel announced a collaboration with Facebook on a new disaggregated, rack-scale server architecture that enables independent upgrading of compute, network and storage subsystems.

The disaggregated rack architecture includes Intel’s new photonic architecture, based on high-bandwidth, 100Gbps Intel® Silicon Photonics Technology, that enables fewer cables, increased bandwidth, farther reach and extreme power efficiency compared to today’s copper based interconnects.
## Electronic/Photonic Convergence in Silicon

<table>
<thead>
<tr>
<th></th>
<th>1990</th>
<th>2000</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PHOTONICS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component</td>
<td>Fiber, Lasers, Detectors</td>
<td>MUX, EDFA</td>
<td>100Gb/s Ethernet, &gt;1Gb/s I/O, Tb/s Transceiver</td>
<td>Microphotonic ICs and ASICs</td>
<td>Pervasive Microphotonic ICs</td>
</tr>
<tr>
<td>Function</td>
<td>ETDM</td>
<td>DWDM</td>
<td>Inter-rack Chip-Chip</td>
<td>Backplane PWB</td>
<td>Pervasive edge functionality</td>
</tr>
<tr>
<td>Target Application</td>
<td>WAN</td>
<td>WAN</td>
<td>Access HPC, Data Center, Automotive, Consumer Devices</td>
<td>1Gb/s Access 10Tb/s WAN Optical Router</td>
<td>Transparent Network</td>
</tr>
<tr>
<td>Package</td>
<td>Fiber</td>
<td>Fiber pigtail</td>
<td>AOC, Optical Engine</td>
<td>E-P Chip Stack</td>
<td>Optical I/O Pins</td>
</tr>
<tr>
<td><strong>ELECTRONICS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology</td>
<td>IC: Al/SiO₂</td>
<td>IC: Cu/SiO₂</td>
<td>Hybrid Flip Chip, Hybrid Bonded</td>
<td>CMOS Optical Plane</td>
<td>Monolithic E-P processing</td>
</tr>
<tr>
<td>Function</td>
<td>DRAM, SRAM, μProc</td>
<td>DSP, μProc</td>
<td>Parallel Processing, Spectral Efficiency</td>
<td>Global Optical Control</td>
<td>Analog/Digital Functionality</td>
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<tr>
<td>Constraint</td>
<td>Yield</td>
<td>Shrink</td>
<td>E-P Packaging, E-P Test Reliability</td>
<td>E-P CAD</td>
<td></td>
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