 Photonics in the Package for Extreme Scalability in Heterogeneous Systems

**Faculty:** Ali Adibi

**Students:** TBD
Outline

- Goals & Objectives
- Prior Work
- Technical Approach
- Results & Key Accomplishments
- Comparison with Prior Art
- Schedule
- Summary
Goals and Objectives

- **Goal**: Develop an ultrafast monolithic optical link for optical interconnection between chiplets in module using individually modulated comb signals in the hybrid Si/SiN/III-V material platform.

- **Vision**: Combine wide bandwidth, fast dynamics, and robustness of optical frequency combs with fast low-power modulation techniques in miniaturized CMOS-compatible integrated nanophotonic structures to form optical links on a single substrate with ultra-high data rates.

- **Major Building Blocks**: The proposed research builds on extensive developments in 1) high-quality hybrid CMOS-compatible material and device platforms and novel techniques for realization of low-power high-speed modulators, 2) realization of wideband frequency combs in CMOS-compatible platforms, 3) state-of-the-art glass interposer packaging technology at PRC.

- **Enabling Technology**: The proposed platform addresses the major interconnection needs of system on package (SoP) while providing potential solutions for chip-to-chip, board-to-board, and rack-to-rack in terms of data rate, power consumption, and bit density.
Prior Work: Application of Si Photonics

- Optical links and interconnects
- Computing, Lidar, sensing
- Trends
  - Size and density
  - Power efficiency
  - Bandwidth and speed
  - Cost

---

**Prior Work: Application of Si Photonics**

- Optical links and interconnects
- Computing, Lidar, sensing
- Trends
  - Size and density
  - Power efficiency
  - Bandwidth and speed
  - Cost

---

**Si photonics market forecast (US$ million)**

- Silicon Photonics for Data Centers
- Silicon Photonics for Novel Applications

---

**Si photonics market forecast**

Silicon Photonics for Data Centers and Other Applications 2016, October 2016, Yale Développement

- Si photonics for data centers
- Si photonics for novel applications

---

**Transmission density**

- Si photonics for data centers
- Si photonics for novel applications

---

**Si photonics market forecast (US$ million)**

- Silicon Photonics for Data Centers
- Silicon Photonics for Novel Applications

---

**Si photonics market forecast**

Silicon Photonics for Data Centers and Other Applications 2016, October 2016, Yale Développement

- Si photonics for data centers
- Si photonics for novel applications

---

**Transmission density**

- Si photonics for data centers
- Si photonics for novel applications

---

**Si photonics market forecast (US$ million)**

- Silicon Photonics for Data Centers
- Silicon Photonics for Novel Applications

---

**Si photonics market forecast**

Silicon Photonics for Data Centers and Other Applications 2016, October 2016, Yale Développement

- Si photonics for data centers
- Si photonics for novel applications

---

**Transmission density**

- Si photonics for data centers
- Si photonics for novel applications

---

**Si photonics market forecast (US$ million)**

- Silicon Photonics for Data Centers
- Silicon Photonics for Novel Applications

---

**Si photonics market forecast**

Silicon Photonics for Data Centers and Other Applications 2016, October 2016, Yale Développement

- Si photonics for data centers
- Si photonics for novel applications

---

**Transmission density**

- Si photonics for data centers
- Si photonics for novel applications

---

**Si photonics market forecast (US$ million)**

- Silicon Photonics for Data Centers
- Silicon Photonics for Novel Applications

---

**Si photonics market forecast**

Silicon Photonics for Data Centers and Other Applications 2016, October 2016, Yale Développement

- Si photonics for data centers
- Si photonics for novel applications
Optical Interconnects

- **Challenge:** Interconnection accounts for a large portion of power consumption in data centers and multi-core processors

- Need for lower power, higher speed communications and higher information density
  - Low power, high-speed modulators
  - Low-power, fast switching for signal routers

www-03.ibm.com/ibm/history

https://computing.llnl.gov/tutorials
Optical Interconnect: Requirements

- I/O Bandwidth density $>> 11$ Pbps/cm$^2$
- High-capacity optical router
- Modulation
  - Operation voltage $< 1$V
  - Power consumption $1-10$ fJ/bit
  - Speed $> 50$GHz
  - Multiplexing through WDM
- Optical routers
  - Wideband tuning for channel switching
  - Fast ($< 10$ ns) for packet switching

Optical interconnection for Data centers

Optical interconnection for multi-core processors

Terascale, 80 cores
Intel Polaris 2007
Si Photonic Interconnect


Zhang et al., $8 \times 8 \times 40$ Gbps fully integrated silicon photonic network on chip, *Optica* (2016)

Large enhancements in the performance of the nanophotonic devices are required to meet the requirements for next-generation optical interconnects.
WDM Source: Optical Frequency Combs

- Ultrashort optical pulse train
- Four-wave mixing principle
- Advantages:
  - High degree of coherence
  - Uniform spacing between adjacent lines (defined by the free-spectral range of the resonator)
  - CMOS-compatible fabrication

Ultrafast Heterogeneously Integrated Optical Link

- Comb generation in SiN microresonator
- Adiabatic coupling into Si
- Microresonator add-drop filters simultaneously select and modulate each comb line
- The proposed modulating schemes can be employed for low-power/high-speed performance
### Broadband On-chip Optical Interconnect

<table>
<thead>
<tr>
<th></th>
<th>Expected Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Communication bandwidth</strong></td>
<td>5-10 Tbps / waveguide (80-160 DWDM channels)</td>
</tr>
<tr>
<td><strong>Optical bandwidth</strong></td>
<td>&gt; 100 nm (O-band or C&amp;L band)</td>
</tr>
<tr>
<td><strong>Latency</strong></td>
<td>1-10 ns</td>
</tr>
<tr>
<td><strong>Power Consumption</strong></td>
<td>&lt;1 fJ/bit</td>
</tr>
<tr>
<td><strong>Size (Each modulator)</strong></td>
<td>&lt; 50 µm²</td>
</tr>
</tbody>
</table>
Technical Approach

- Using an optical frequency comb source and filtering/modulating its individual tones using an array of Si microring resonators
- Comb generation in SiN, modulation in Si, and lasing, SOA, and detection in III-V
- Operation wavelength: around 1300 (bandwidth: 40 nm); 100-200 comb lines with 25-50 Gbps modulators for a 5 Tbps modulated signal (or port)
- Future goals: 1) increasing the modulation efficiency/speed to achieve a 10 Tbps port; 2) use multi-ports for ultra-high data rates (e.g., ten 10 Tbps ports for 100 Tbps)
Technical Approach: Photonic-electronic System-on-Package for Ultra-high-speed and Low-power Interconnection

- Bonding III-V layer to the Si/SiN hybrid platform to form a complete photonic subsystem; tapered waveguide couplers for coupling light between different layers (including BCB glass)
- Integration with CMOS electronics using PRC’s glass packaging technology
- Optical I/O through coupling glass waveguides to fibers

Builds on initial proposal submitted to Intel, Oct ‘19
Results & Key Accomplishments: Hybrid Platforms

- Realization of several hybrid material platforms (e.g., double-layer Si, Si-on-SiN, SiC-on-SiN) with world-record performance
- Demonstration of several CMOS-compatible device architectures for ultra-fast low-power modulation, routing, and switching

![Highly efficient layer-to-layer coupling](image)

**Q_{intrinsic} \approx 3 \times 10^6**
Results & Key Accomplishments: High-performance Devices

Reconfigurable photonic subsystems: High-order system for reconfigurable filters and MIMO signal processing

Fast modulator and switch devices based on depletion-mode PN junction and carrier accumulation in multi-layer silicon on isolator (SOI) devices

Low-power and wide-band tunable reconfigurable photonic devices based on thermal and electro-static tuning.

Hybrid Si/SiN material platform and devices: Enables low-loss and low-nonlinearity systems

Adibi’s group has developed several high-performance material platform, device technology, and subsystems that can be used for millimeter-wave communication
Comparison with the State-of-the-art: Photonic vs. Electronic Interconnects

**Electronic**

- **NVLink 2.0**
  - 8 Line @ 50 Gbps
  - 2mm size port
  - 200 Gbps/mm
  - 2-8 pJ/bit
  - 25-100 Gbps/mm/(pJ/bit)

- **Board-to-board**
  - 2 PJ/bit @ 10 cm
  - 50 Gbps/line
  - 0.2 mm wire pitch
  - ~500 Gbps/mm/(pJ/bit)

**Photonic**

- **DWDM**
  - 50 Gbps/Wavelength
  - 50-100 fJ/bit
  - (Modulator share < 5fJ)
  - 100 - 200 wavelengths (O-band)
  - 250 µm fiber pitch
  - $2 \times 10^5$-$8 \times 10^5$ Gbps/mm/(pJ/bit)

- **On-chip**
  - 0.1 PJ/bit @ 10 cm
  - 50 Gbps/line
  - < 0.01 mm waveguide pitch
  - 100 wavelengths/waveguide
  - ~$5 \times 10^6$ Gbps/mm/(pJ/bit)
Comparison with the State-of-the-art: Photonic vs. Electronic Interconnects

- Chip
  - Electronics: ~40 fJ/bit @ 1 mm
  - Photonic: ~2 pJ/bit @ 10 cm

- Board
  - NVlink 2

- Rack
  - Finisar SR4 QSFP
  - DARPA PIPES
  - Ayar Lab TeraPHYc
Summary

- We have demonstrated a variety of CMOS-compatible platforms with devices showing world-record performance.
- The key elements of this research, including high-speed modulators and WDM filters along with dispersion engineering form comb generation have been achieved.

If funded:

- **Year 1 milestones** include the demonstration of the comb signal in a hybrid SiN/Si platform, realization of the Si-based modulator/filter WDM network, and demonstration of the glass-based packaging technology for the proposed chips.
- **Year 2 milestones** include integration of III-V lasers, optical comb generation, and Si-based WDM network along with the necessary packaging technology to form the first single-port multi-channel comb-based WDM transceiver.