Large-Scale Silicon Photonic Switches

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Outline

• Optical switches for data centers
  – Why do we need it?
  – What’s available now?
  – What’s needed in the future?

• Silicon photonic switch
  – Is it a game changer?
  – How does it scale?

• Silicon photonic MEMS switches
  – 64x64 switch on 1-cm² chip
  – Technology scaling

• Discussion about packaging needs

• Summary
Challenges in Datacenter Networks

- Link rate continues to increase (40G, 100G, 400G, ..)
- Cannot rely on continual scaling of CMOS
  - Switch bandwidth-portcount limited by thermal issue, die size, pin count
- Optical switching can facilitate scaling out datacenters
  - Reduce number of hops, transceivers, power consumption
  - Critical issues: switching time, arbitration, cost, power consumption, scalability
Hybrid Data Center Networks
Example (1): REACToR (UCSD)

- Optical circuit network
  - High bandwidth,
  - Bufferless TDMA network
  - Tx when circuit connects

- Electrical packet switch networks:
  - Low bandwidth, small packets
  - Buffered all the way
  - Tx all the time

- Implementation:
  - Using Nistica MEMS WSS
  - 30 us reconfiguration time

- Performance
  - 10G EPS + 100G OCS $\approx$ 100G EPS

Hybrid Data Center Networks
Example (2): Elastic WDM Switches (UCSB)

- Adding an layer of optical switches between spine and leaf greatly expand the scale of network (number of servers)
- Can be space switch or wavelength switch
- Wavelength routing also investigated by many other groups (Columbia, UCD, Nagoya U, NTT, ..)

Commercially Available Switches

3D (Free-Space) Switch
- Calient: 320x320
- Polatis: 384x384
  + High port count
  + Low loss: < 3 dB
  - Slow (10 to 25 ms)
  - High cost ( $100’s /port)

2D (Integrated) Switch
- NTTElectronics: 16x16 (commercial)
  32x32 (publication)
  - Limited port count
  - Higher loss: 5 dB
  - Slow (3 ms)
  + Low cost (~ $10’s /port ?)
  + Fully integrated
Scaling of Optical Switches: 2D vs 3D

- **3D switch uses** $2N$ analog mirrors
  - Complex control

- **2D switch uses** $\sim N^2$ digital switching elements
  - but simple control
  - Monolithic integration

**Si photonics can be a game changer**
- High integration density
- Tight bending radius

Largest (commercially available) Switch:
- **3D MEMS**: 320x320 (< 3dB)
- **2D PLC**: 32x32 (6.6 dB)
32x32 Non-Blocking PILOSS Switch (AIST, Japan)

- Switch on 11x25 mm²
- Path-independent insertion loss (PILOSS) architecture
- Multi-stage topology: each NL switch has N stages
- On-chip loss: 15.8 dB

A Different Approach for High Radix Switch

Traditional Approach:
Active Crossbar + EO (or Thermo) Switching
• Many cascaded 2x2 elements
• Lossy in both Bar and Cross states
• High cumulative loss
  (~ 0.5\cdot N dB for N\times N)
• Largest switch demonstrated: 32\times 32 with 16dB on-chip loss

Berkeley Approach:
Passive Crossbar + MEMS Switching
• Single stage switching
• Nearly zero loss in BAR state
• No cumulative loss
• Largest switch demonstrated: 64\times 64 with < 4dB on-chip loss
• Sub-microsecond switching time
MEMS-Actuated
Vertical Adiabatic Coupler Switch

- Nearly zero loss at OFF state
- Extremely high ON/OFF ratio (60 dB)
- Broadband operation: > 300nm
  - Covers S, C, L bands

Calculated Transfer Curve
Scalability of 2D Si Photonic Switches

<table>
<thead>
<tr>
<th>NxN Switch</th>
<th>Number of Switches</th>
<th>Number of Crossing</th>
</tr>
</thead>
<tbody>
<tr>
<td>PILOSS</td>
<td>N</td>
<td>N-1</td>
</tr>
<tr>
<td>Switch-Select</td>
<td>$2 \log_2 N$</td>
<td>$(N-1)^2$</td>
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<tr>
<td>Passive Matrix</td>
<td>1</td>
<td>2N-1</td>
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</tbody>
</table>

Assumption:
0.25 dB/switch
0.005 dB/crossing

- On-chip loss < 1.25 dB possible for 100x100 Si Photonic 2D MEMS Switch
MEMS Crossbar Switch: Experimental Implementation

64x64 switch

1x1 cm² die

IMI Crossing

OFF State

Drop Ports

Drop Ports

In Ports

Bus Waveguide

MEMS-Actuated Adiabatic Coupler

Low-Loss Crossing
Switch Performance

Digital Switching

- Extremely energy efficient
  - No dc power consumption, like CMOS
  - Low switching energy: \(10 \text{ pJ per switching}\)

On-Chip Loss

- Resonance Frequency: \(0.71 \text{ MHz}\)
  - \((a)\) (b) (c) 
  - \((d)\) (e)

Loss per Cell Switching Loss

- Time: \(0.28 \mu s - 0.91 \mu s\)

Improvement

- \(3.7 \text{ dB}\)

B. Bell Lab, 8x8
AIST, 8x8
AIST, 32x32
UCB, 50x50
UCB, 50x50
1000x

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Broadband Operation

- Measured bandwidth > 120 nm (limited by range of tunable laser)
- Simulated bandwidth > 300 nm
Switch Packaging

64 Channel Fiber Array
PCB Test Board
Wire bond
Silicon Photonic MEMS Switch
Interposer

AIN Interposer
Si Photonic MEMS Switch (Flip-chip bonded)

Packaging performed at Tyndall Institute
System-Level Testing of Packaged Si Photonic MEMS Switch

Test performed at UCSD (George Papen Group)
Summary of Si Photonic Switches

- Highly scalable matrix switch
- 64x64 switch integrated on 1 cm$^2$ die
  - Largest integrated switch in any technology
- Lowest on-chip loss (3.7 dB, or 0.05 dB/port)
- Sub-microsecond switching time
- Scalable to 100’s of ports

- T. J. Seok, N. Quack, S. Han, R. S. Muller, and M. C. Wu, *Optica*, p. 64, Jan. 2016.
- S. Han, T. J. Seok, N. Quack, B.-W. Yoo, and M. C. Wu, *Optica*, p. 370, Apr. 2015.

Bronze Medal, 2015 Collegiate Inventors Competition

Tyndall Packaging

64x64 switch

1x1 cm$^2$ die

Bench-Top Probing

Bronze Medal, 2015 Collegiate Inventors Competition
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Additional Slides
Current and Emerging Optical Space Switches

<table>
<thead>
<tr>
<th>Switching Time (second)</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1,000</th>
<th>10,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>ns</td>
<td>s</td>
<td>ms</td>
<td>us</td>
<td>us</td>
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Cost Per Port ($)

- **3D MEMS**
- **Silicon Photonics**
- **64x64 SiPh Switch (UC Berkeley)**
- **320x320 3D MEMS (Calient)**

- **AIST, Huawei**
- **Calient**
- **Thermo-Optic**
- **3D MEMS**
- **UCB SiPh MEMS**
- **SJTU Electro-Optic SiPh**
- **AIST, Huawei**
- **Calient**
- **Thermo-Optic**
- **3D MEMS**
- **UCB SiPh MEMS**
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**Radix (Port Count)**
Wavelength-Domain Switches/Router

- Array waveguide grating router (AWGR) with tunable lasers
- Microrings with fixed or tunable lasers
- (subjects of many papers in this conference)


A. S. P. Khope, A. A. M. Saleh, J. E. Bowers, and R. C. Alferness, 2016 IEEE Optical Interconnects Conference (OI)