Silicon-Photonic Clos Networks for Global On-Chip Communication

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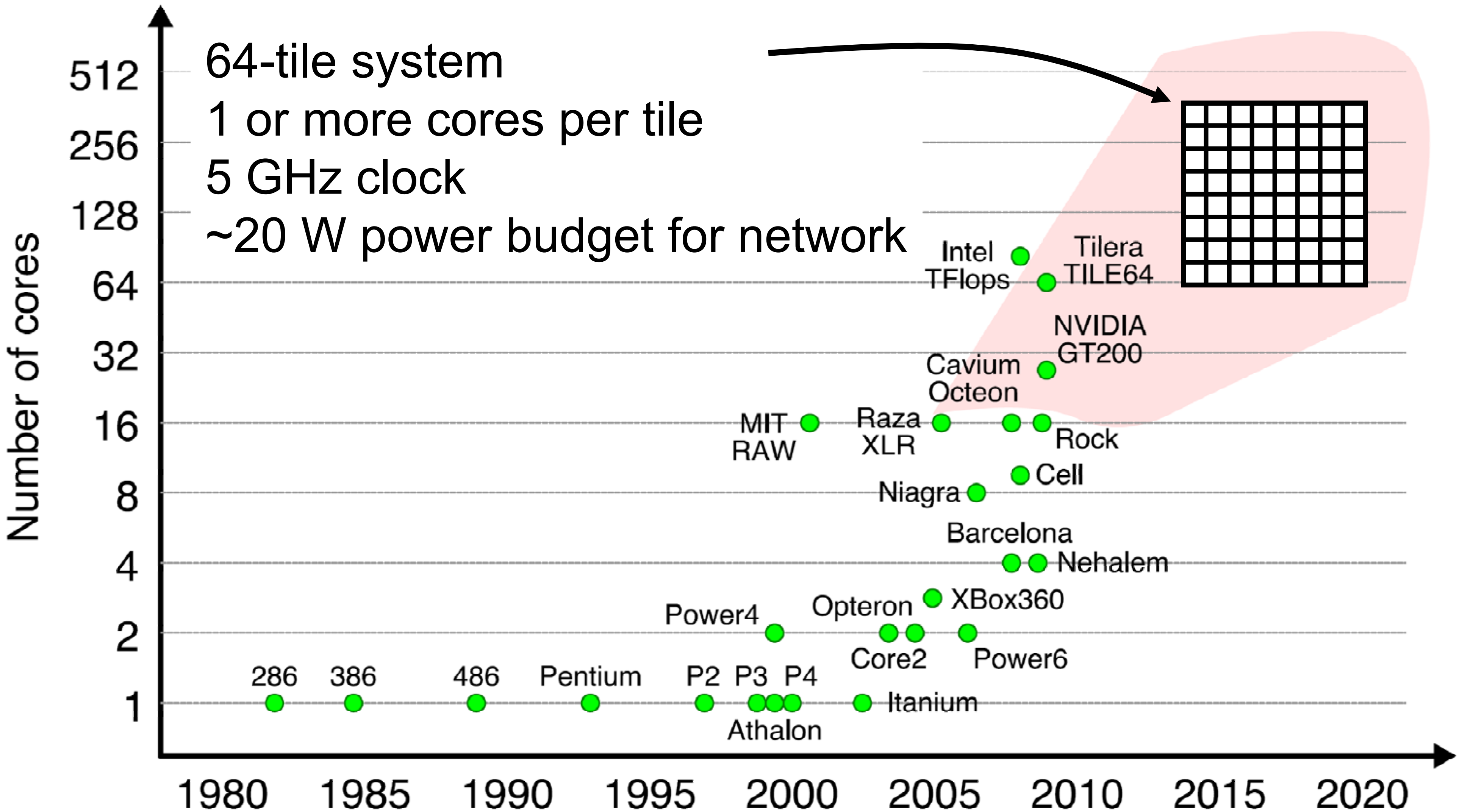
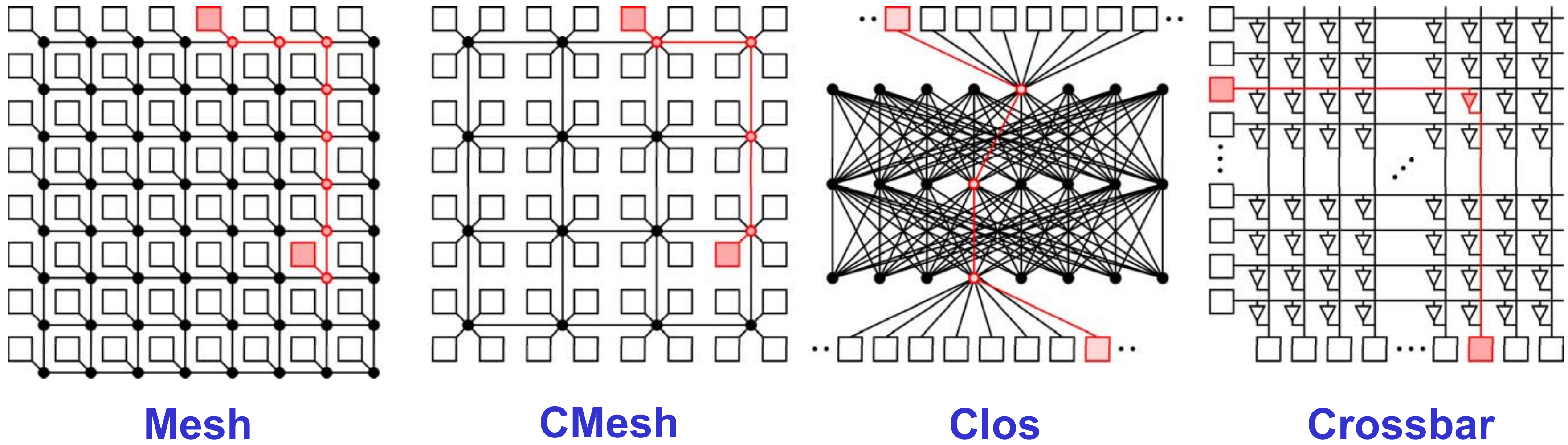
HPEC 2009

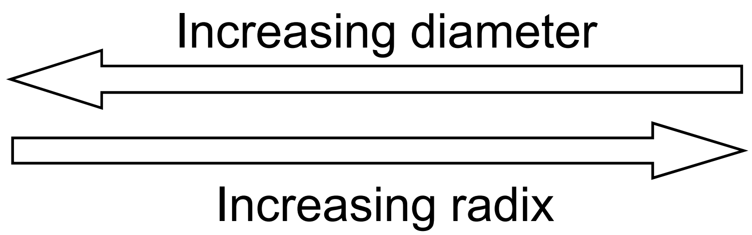
Our target manycore system

64-tile system
1 or more cores per tile
5 GHz clock
~20 W power budget for network



On-chip network topology spectrum





Shorter wires

- Low area
- Low latency
- Low power dissipation

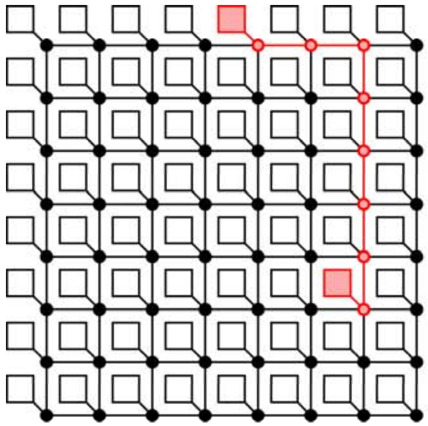
Difficult to map applications

Longer wires

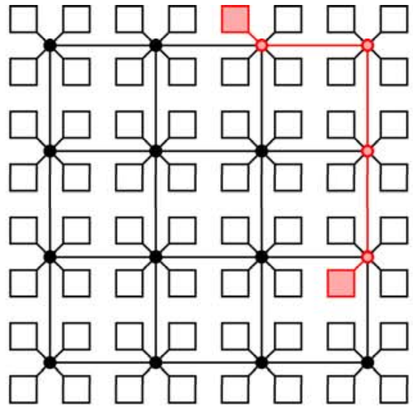
- High area
- High latency
- High power dissipation

Easier to map applications

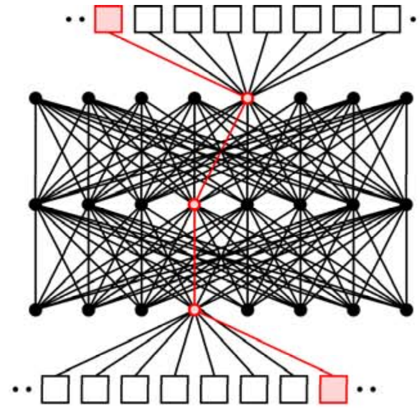
Landscape of on-chip photonic networks



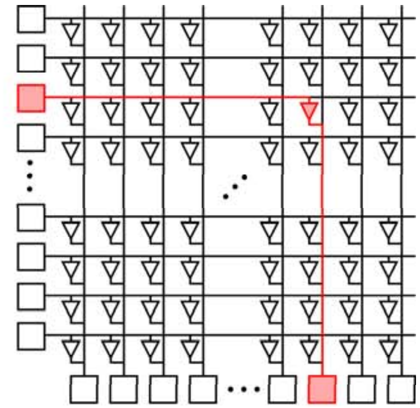
Mesh



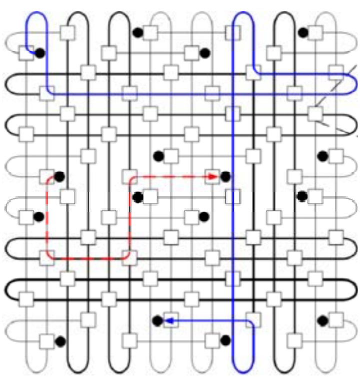
CMesh



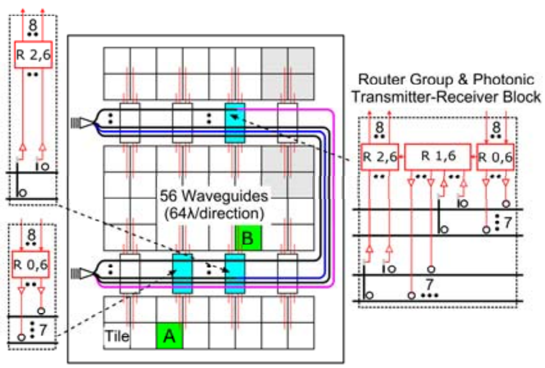
Clos



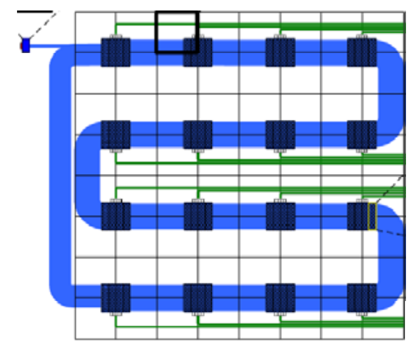
Crossbar



[Shacham'07]
[Petracca'08]

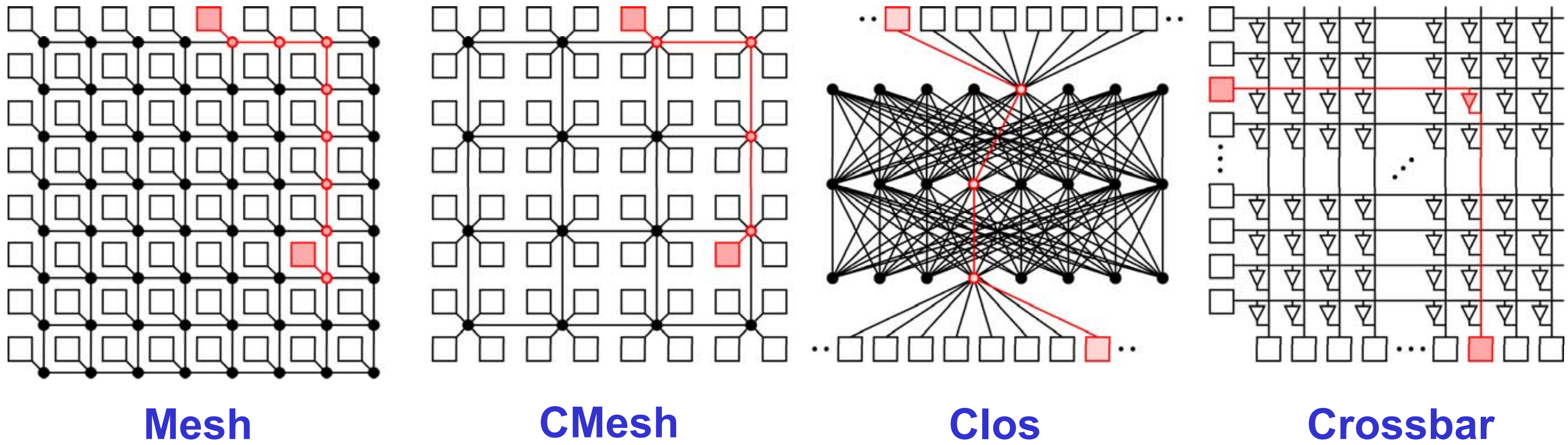


[This work]
[Pan'09]



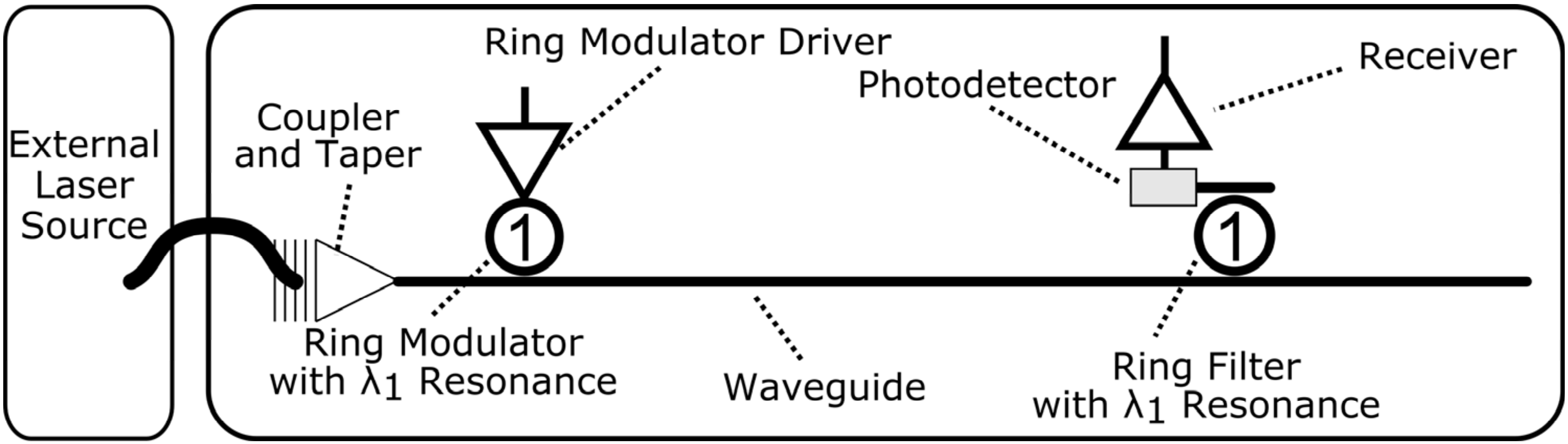
[Vantrease'08]
[Psota'07]
[Kirman'06]

Outline

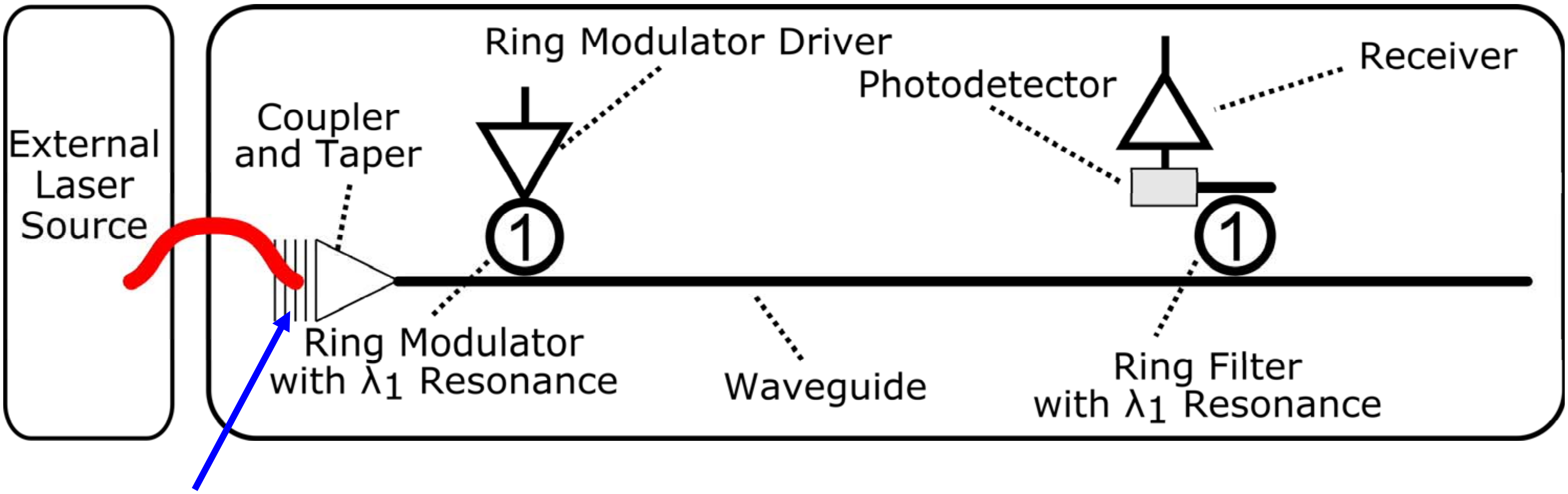


- Photonic interconnect technology
- Photonic networks
- Electrical vs Photonic networks

Photonic technology – Silicon photonic link

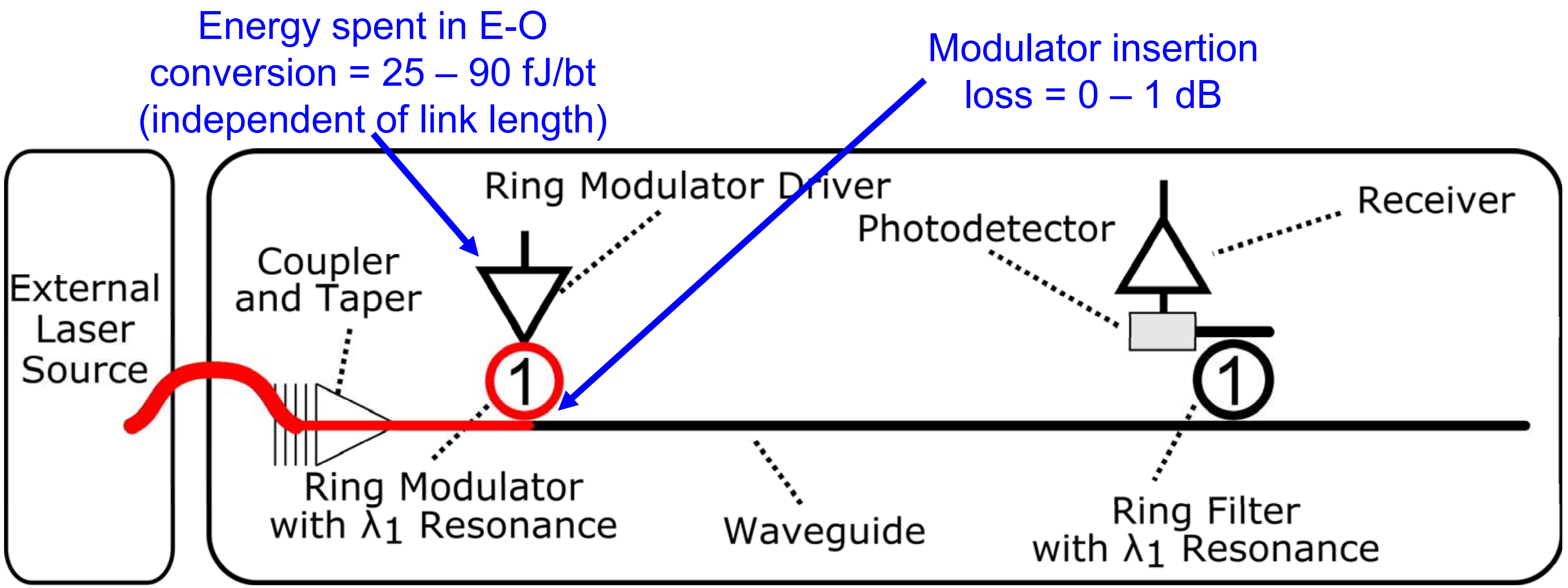


Silicon photonic link – Coupler

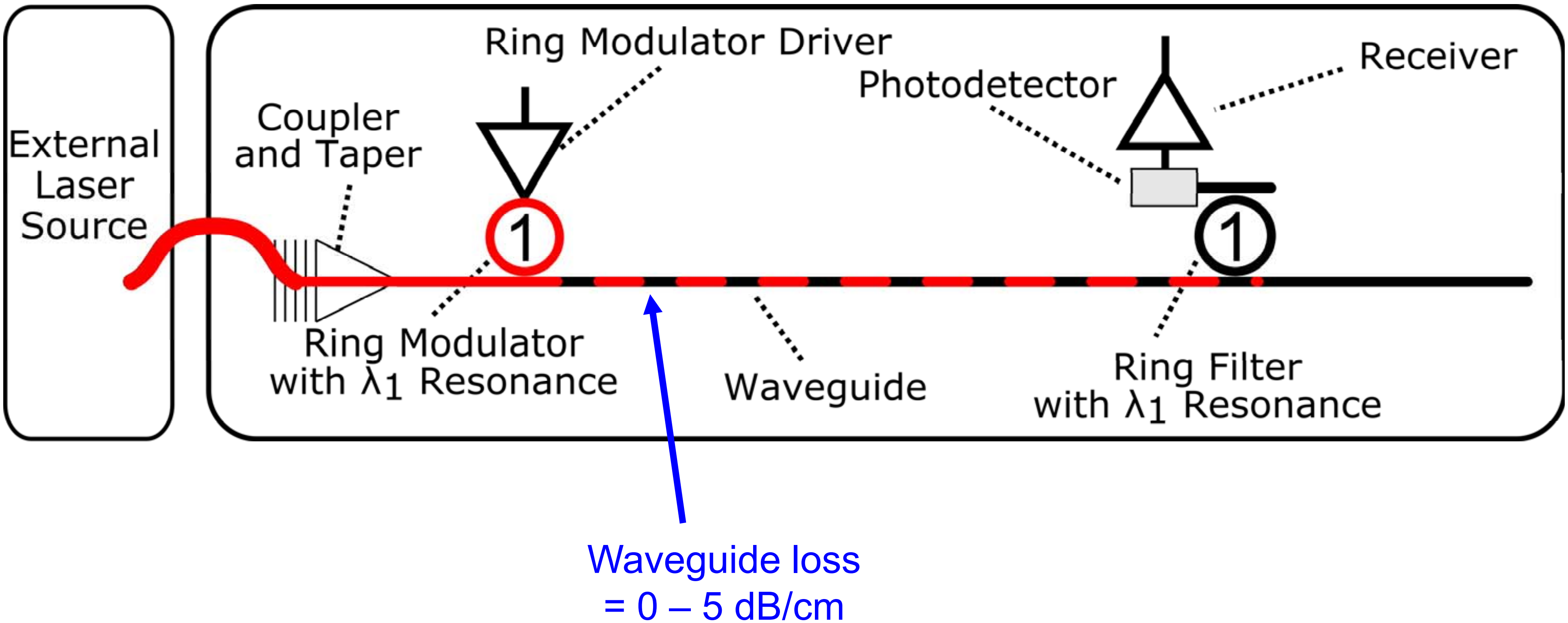


Coupler loss = 1 dB

Silicon photonic link – Ring modulator



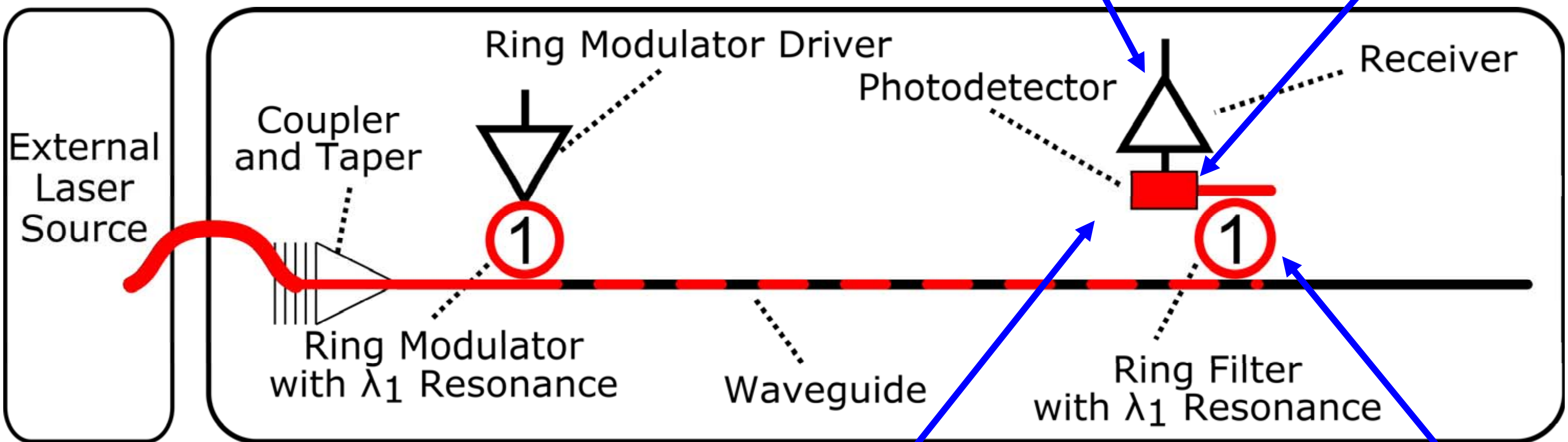
Silicon photonic link – Waveguide



Silicon photonic link – Ring filter, photodetector

Energy spent in O-E conversion = 25 - 60 fJ/bt (independent of link length)

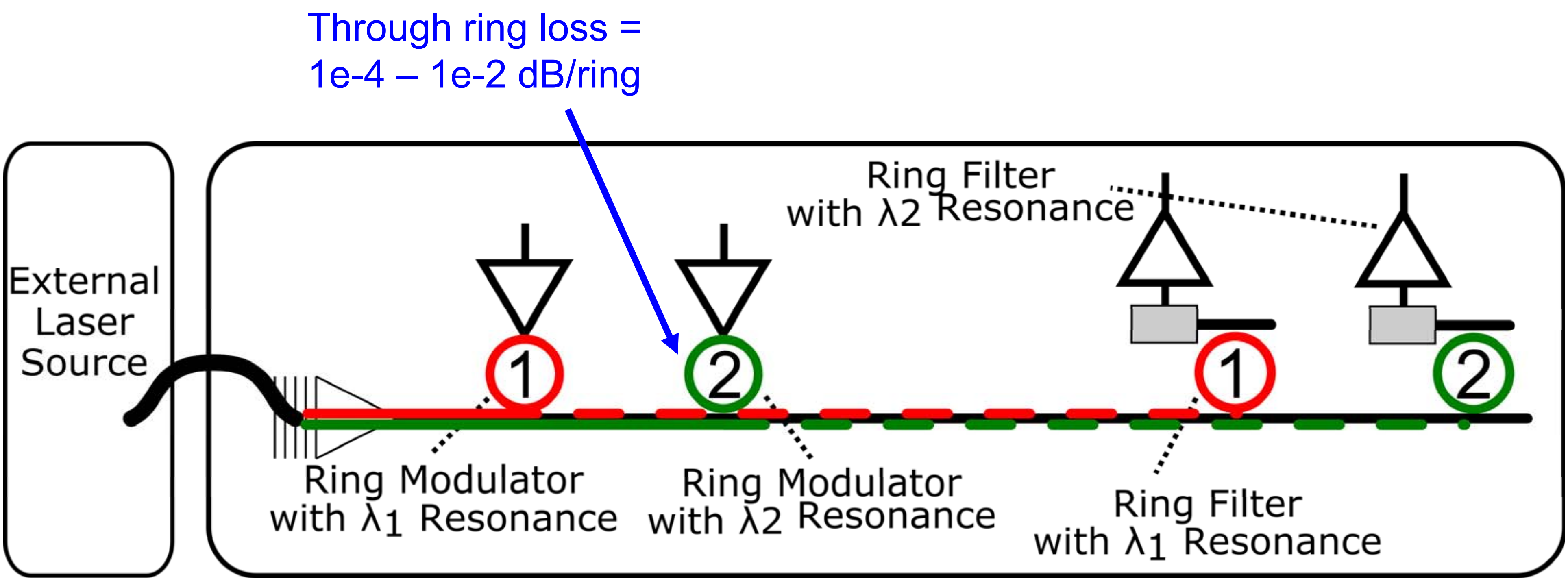
Photodetector loss = 0.1 dB



Receiver sensitivity = -20 dBm

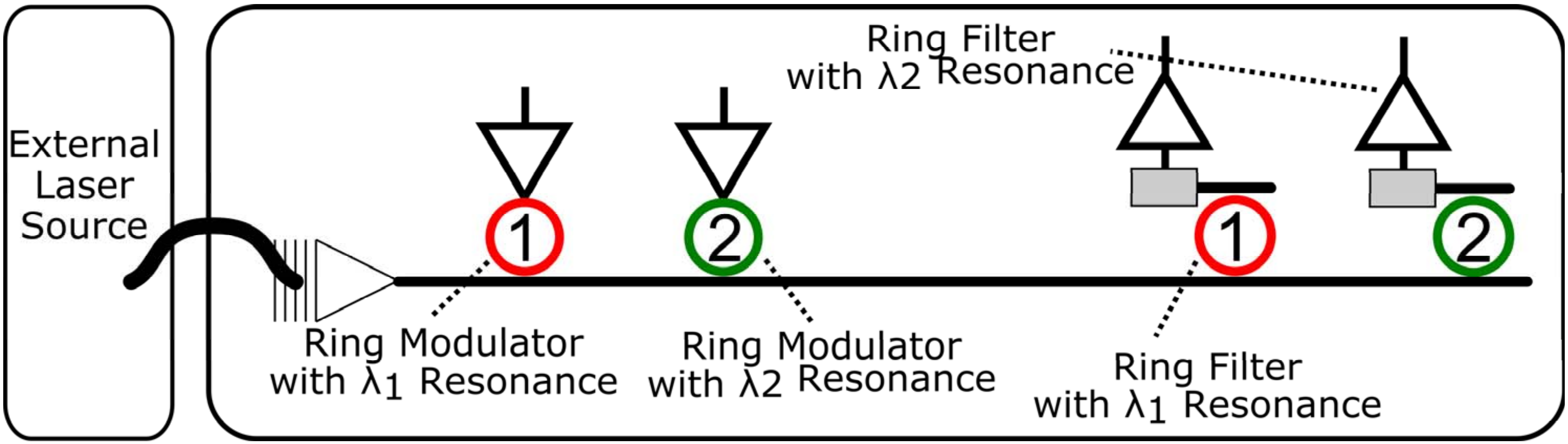
Filter drop loss = 1.5 dB

Silicon photonic link – WDM



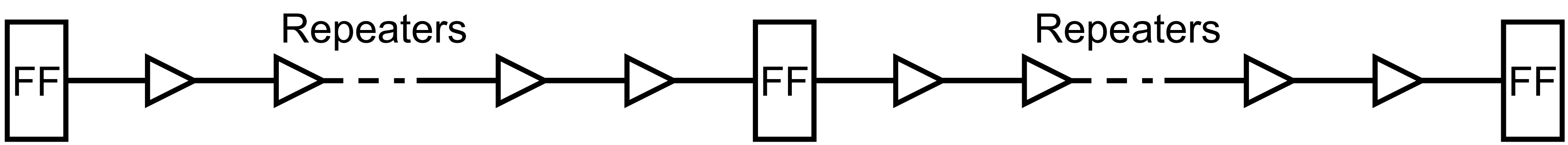
- Dense WDM (128 λ/wg, 10 Gbps/λ) improves bandwidth density

Silicon photonic link – Energy cost



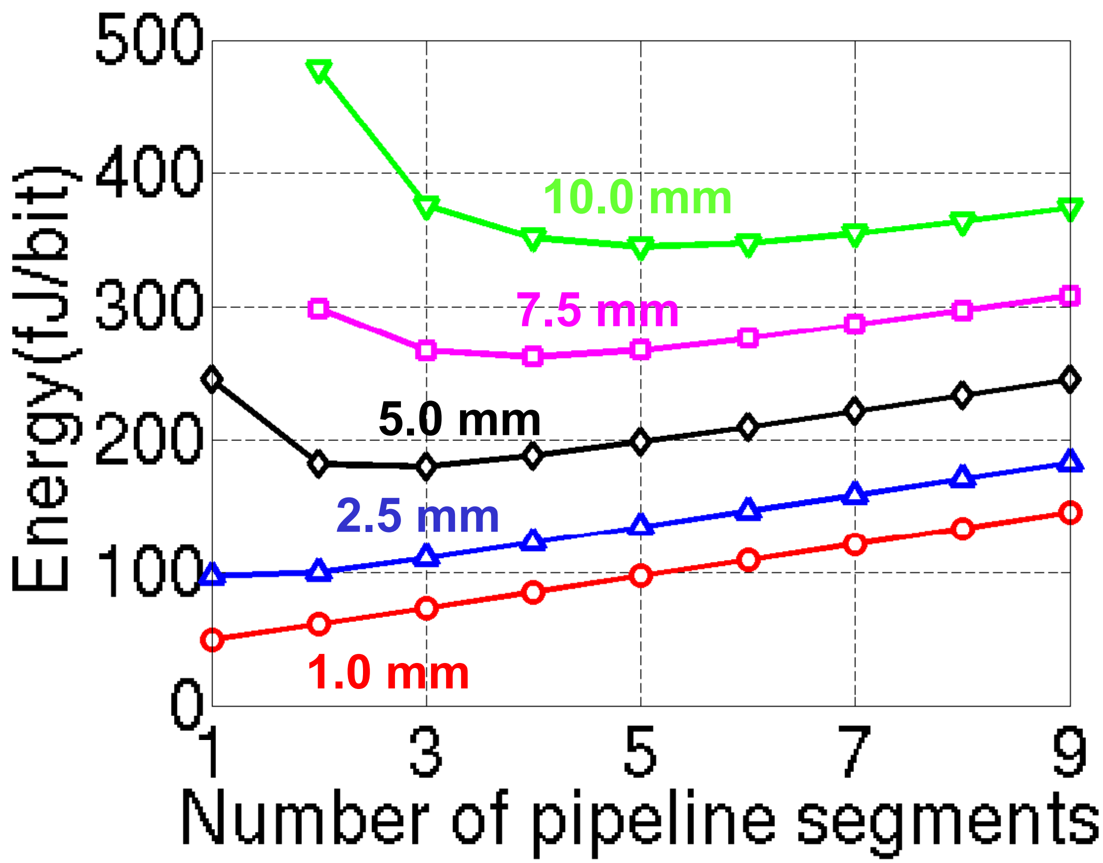
- E-O-E conversion cost – 50-150 fJ/bt (independent of length)
- Thermal tuning energy (increases with ring count)
- External laser power (dependent on losses in photonic devices)

Electrical technology

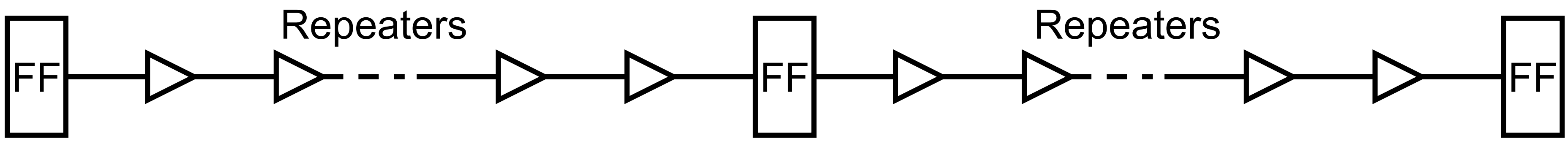


Repeater inserted pipelined wires

- Design constraints
  - 22 nm technology
  - 500 nm pitch
  - 5 GHz clock
- Design parameters
  - Wire width
  - Repeater size
  - Repeater spacing



Electrical technology



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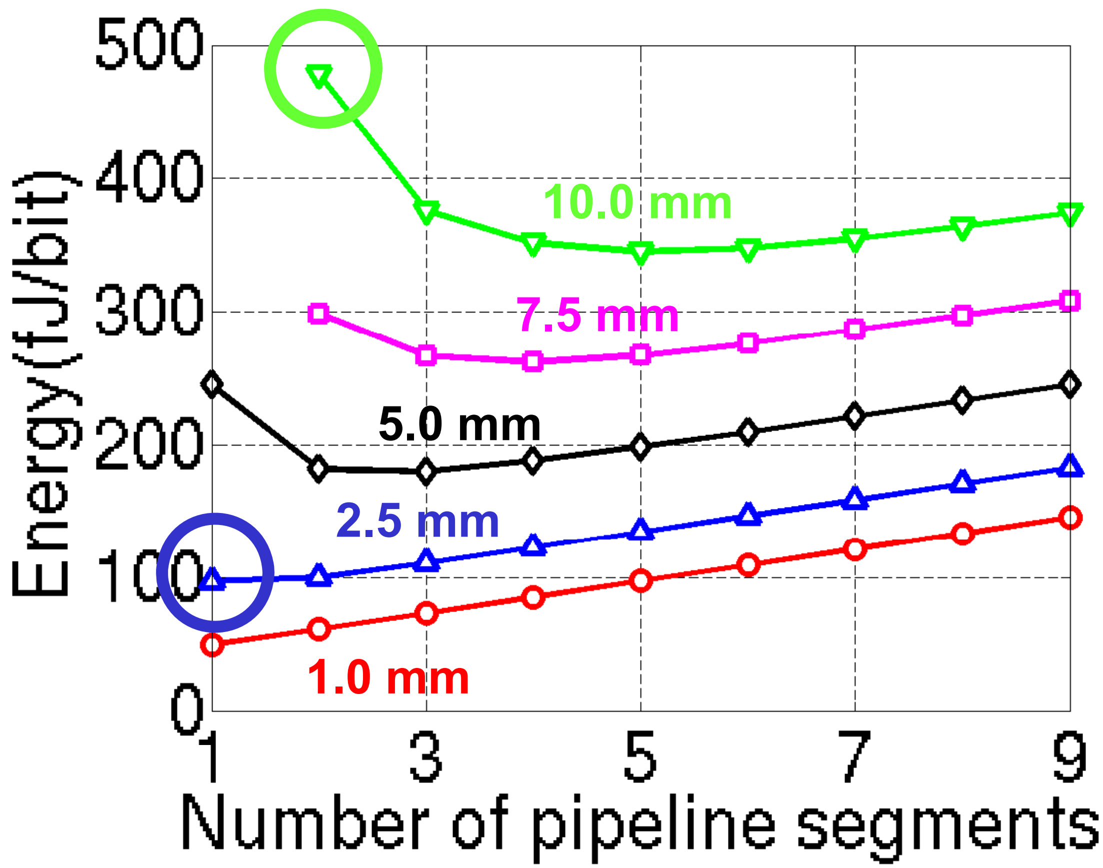
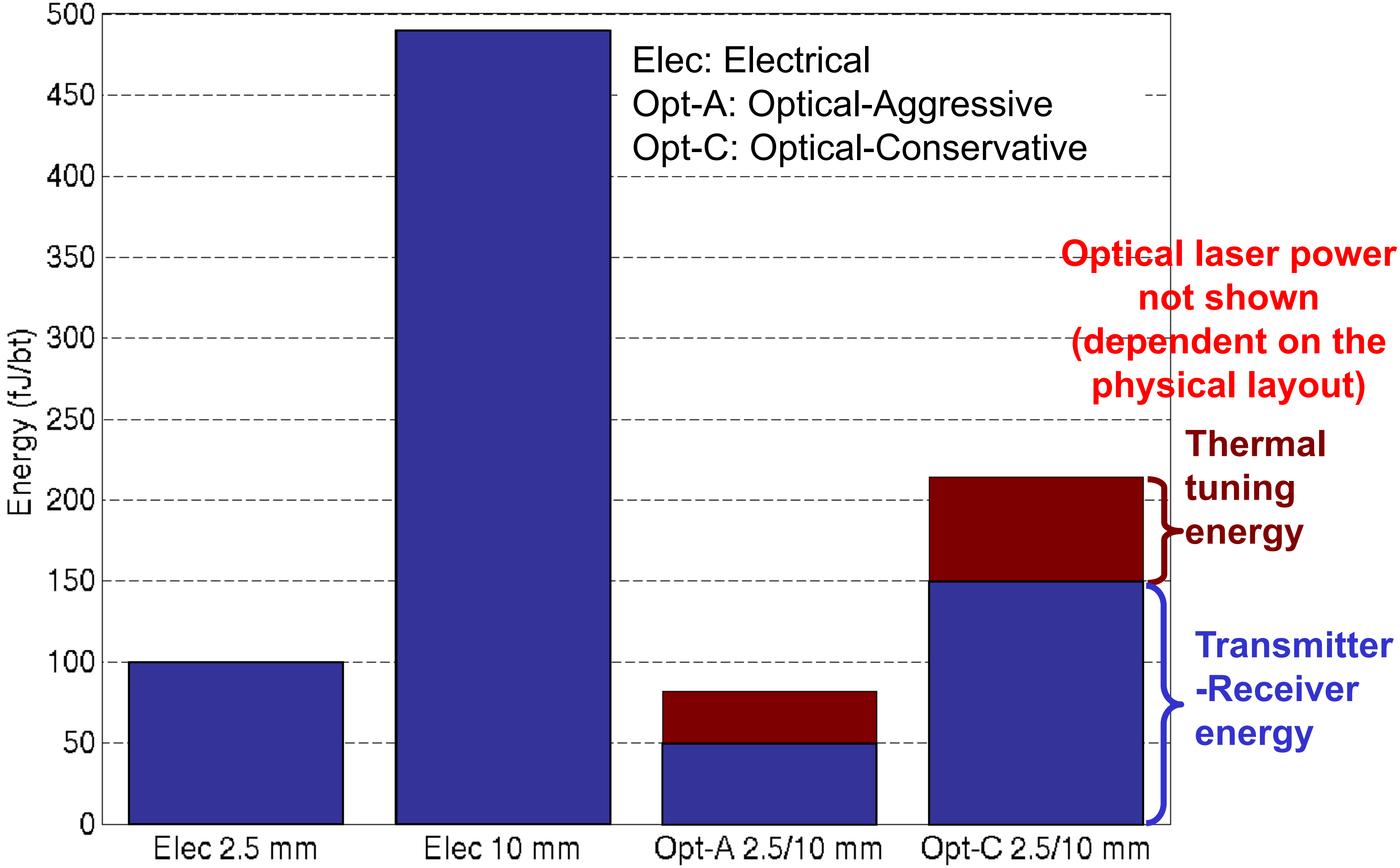
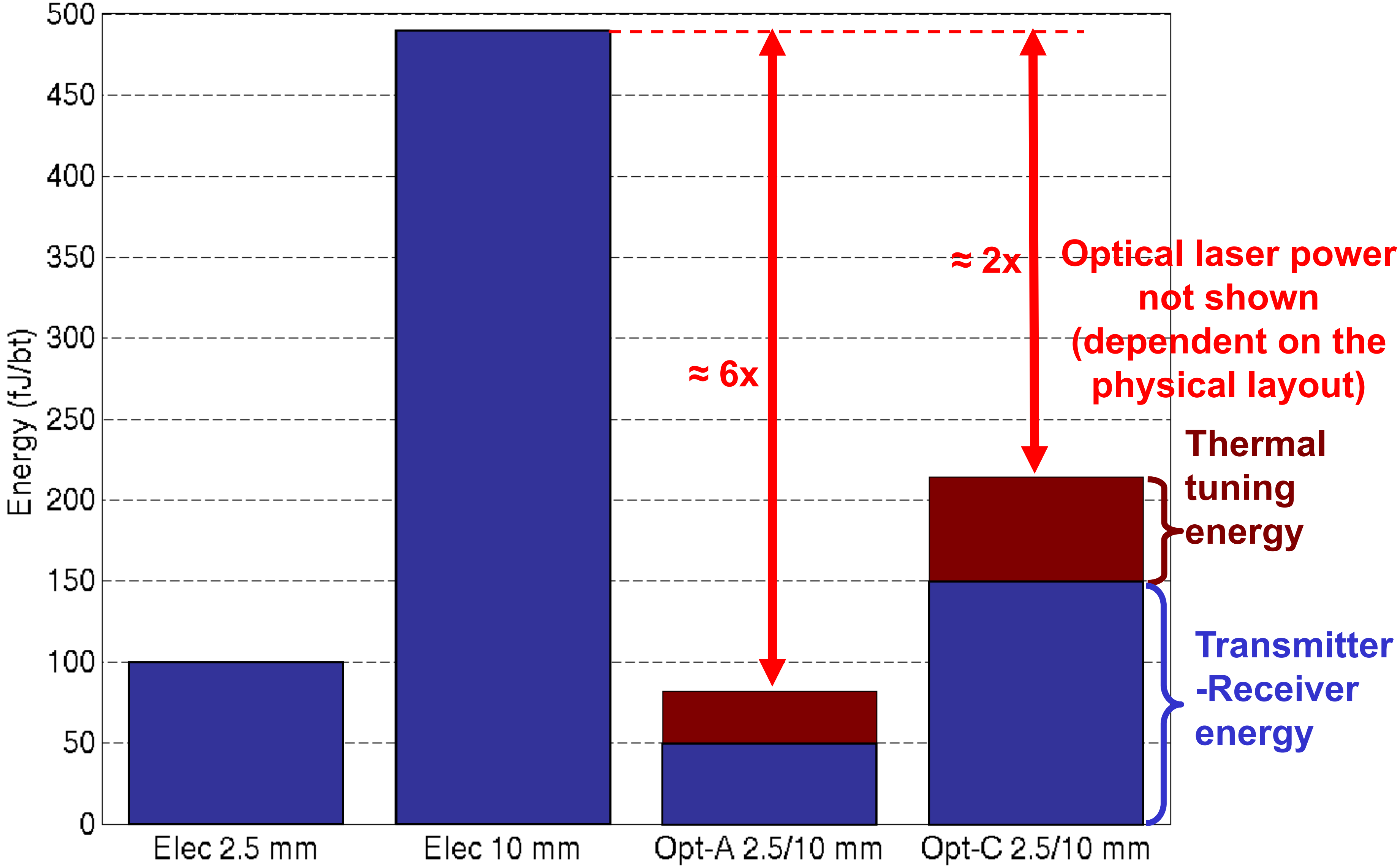


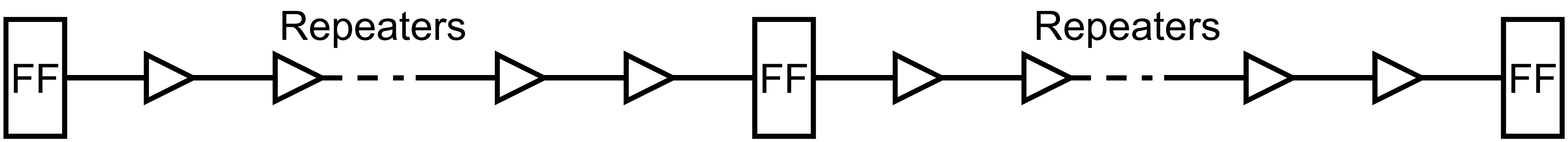
Electrical vs Optical links – Energy cost



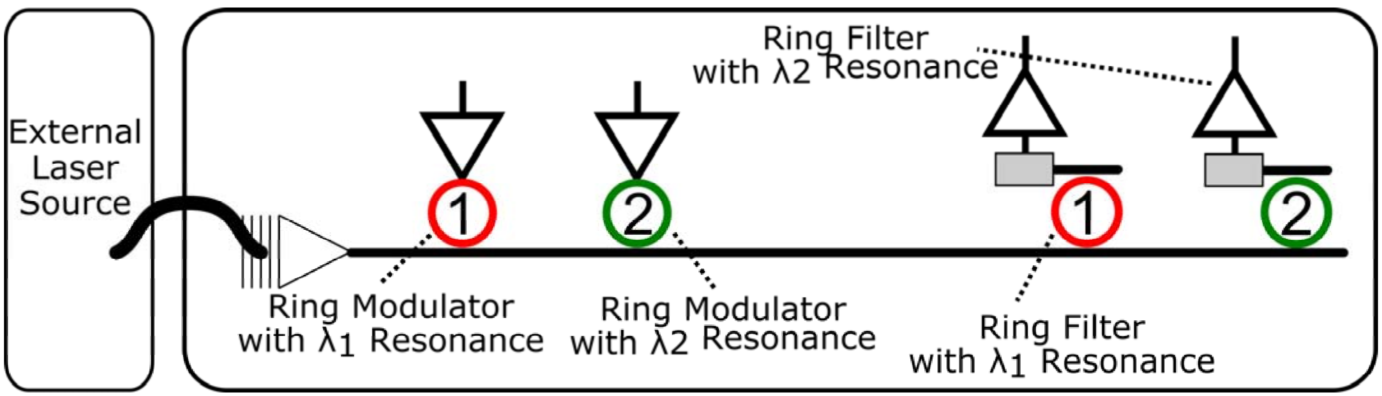
Electrical vs Optical links – Energy cost



Electrical vs Optical links – Bandwidth density



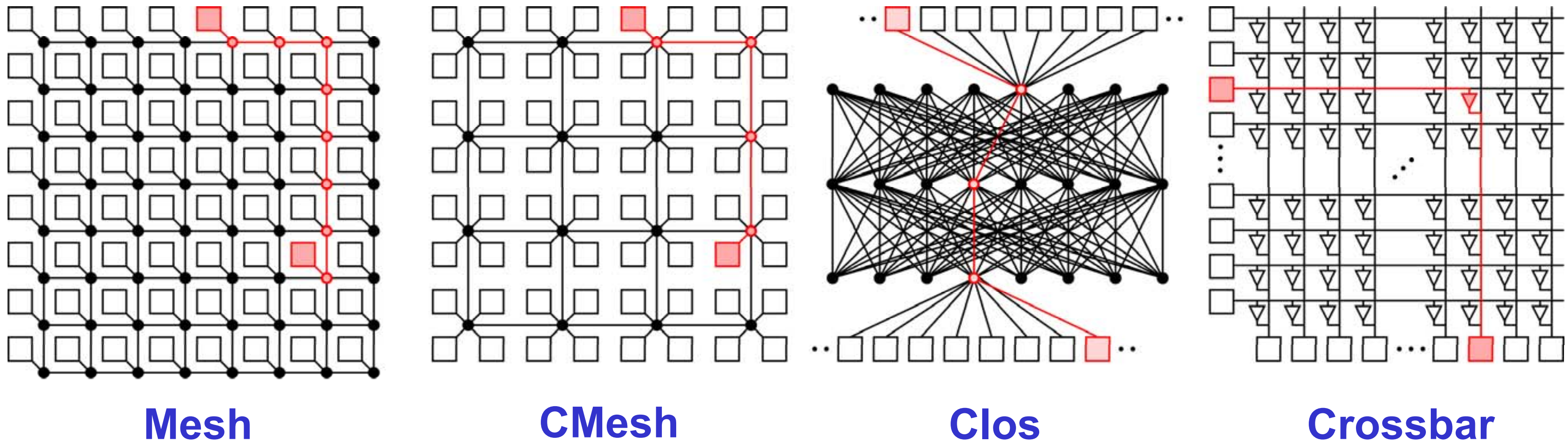
Repeater inserted pipelined wires – 10 Gbps/μ



Wavelength-division multiplexed photonic link – 320 Gbps/μ

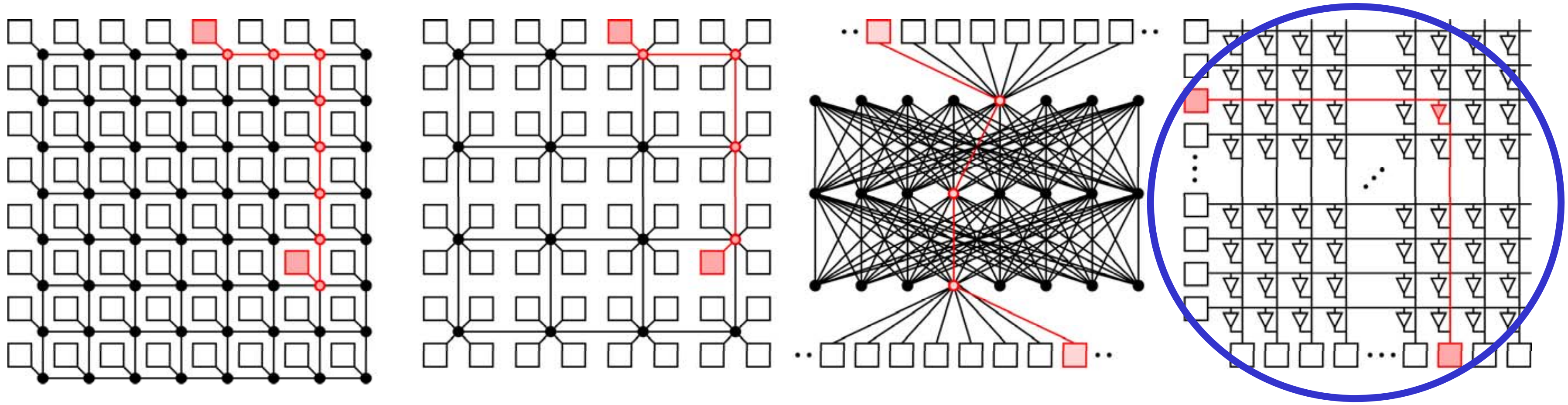
30x bandwidth density advantage using optical links

Outline



- Photonic interconnect technology
- Photonic networks
- Electrical vs Photonic networks

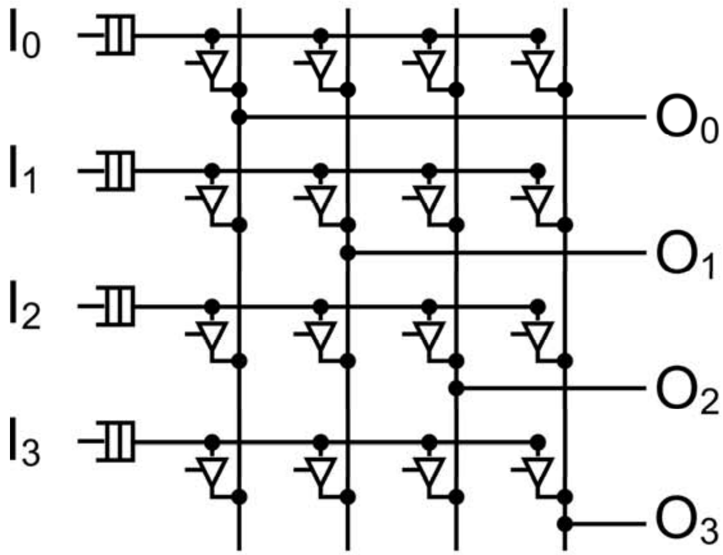
Outline



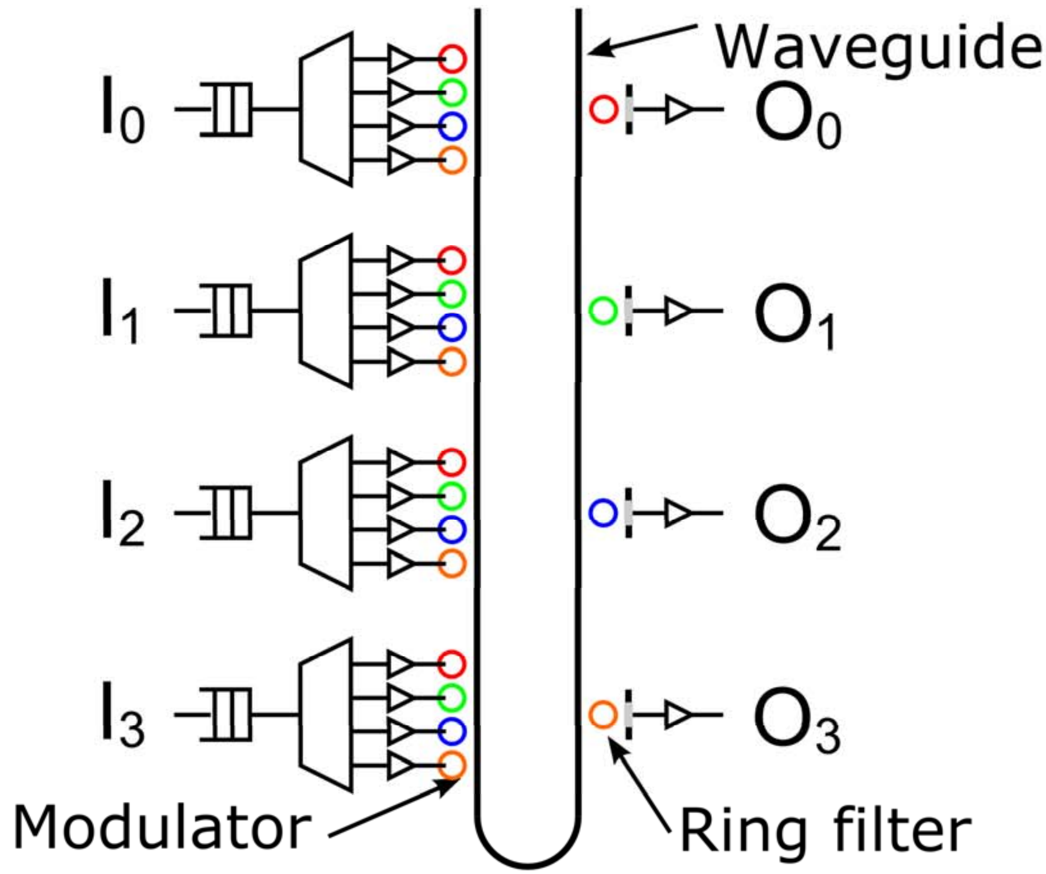
Mesh | CMesh | Clos | Crossbar

- Photonic interconnect technology
- Photonic networks
- Electrical vs Photonic networks

Distributed Multiplexer Crossbar

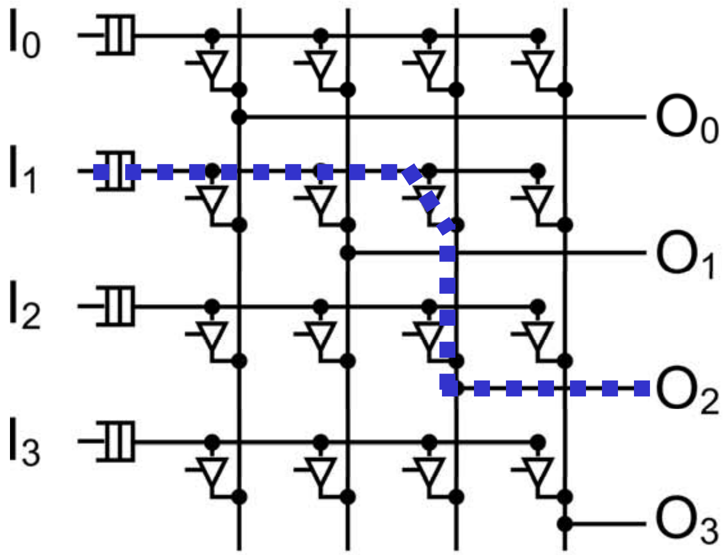


Electrical design

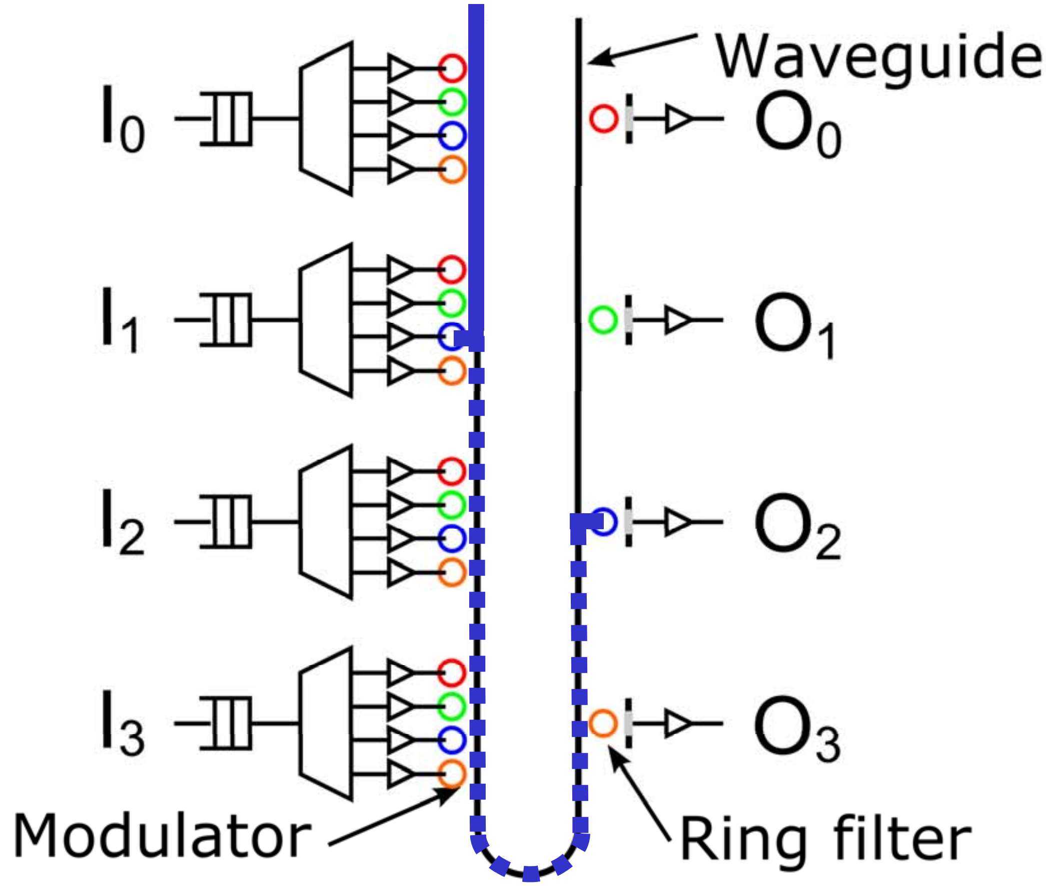


Photonic design

Distributed Multiplexer Crossbar

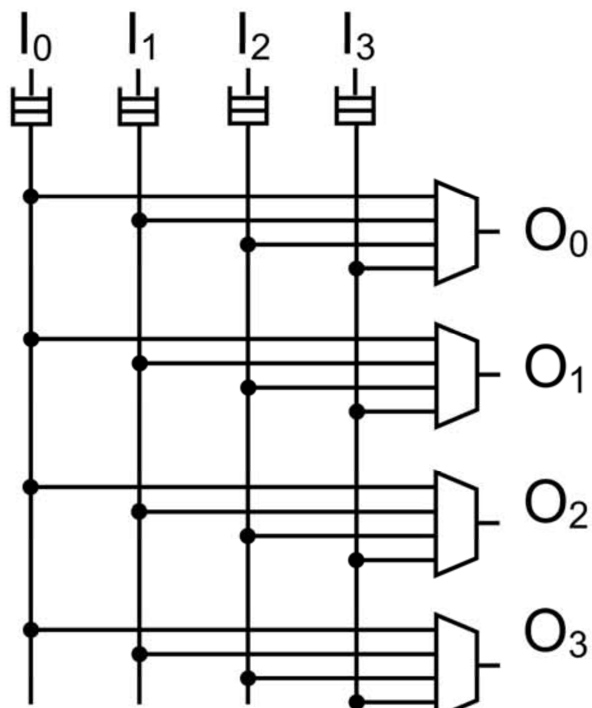


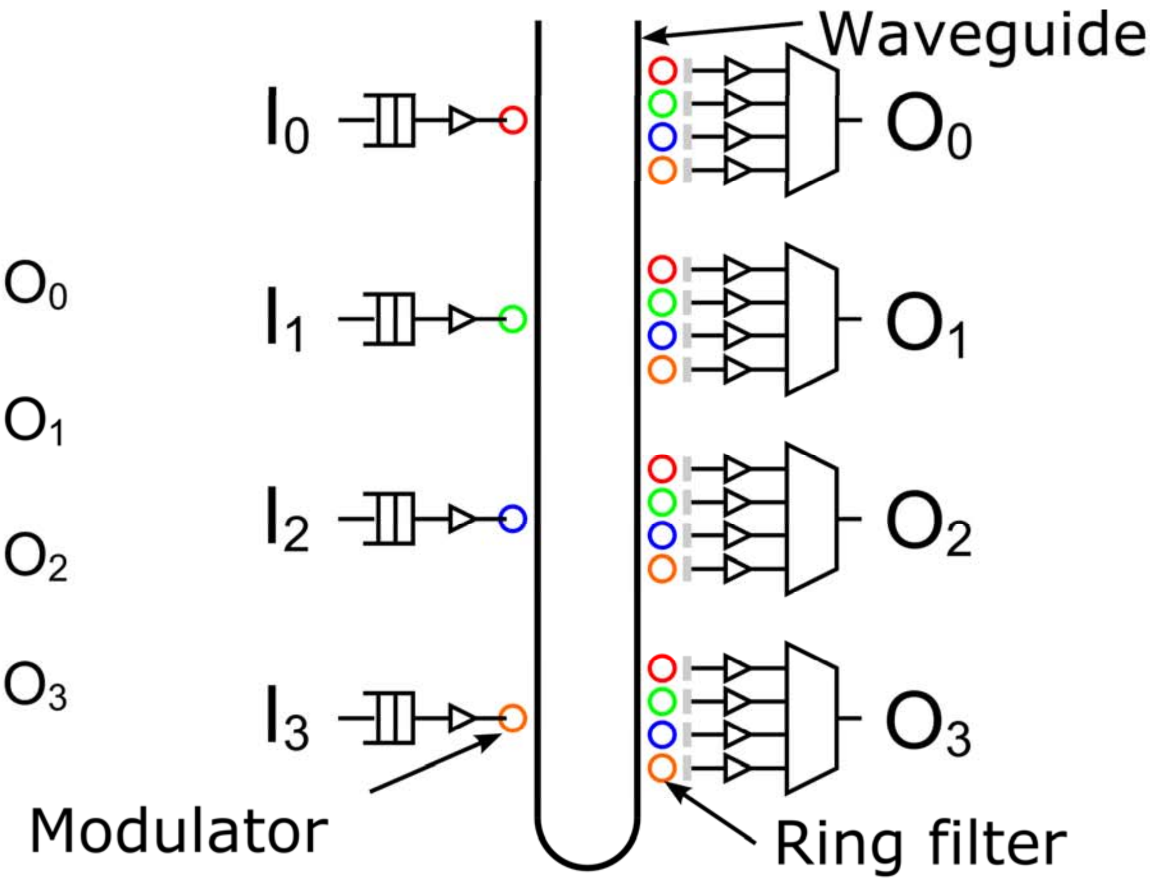
Electrical design



Photonic design

Centralized Multiplexer Crossbar

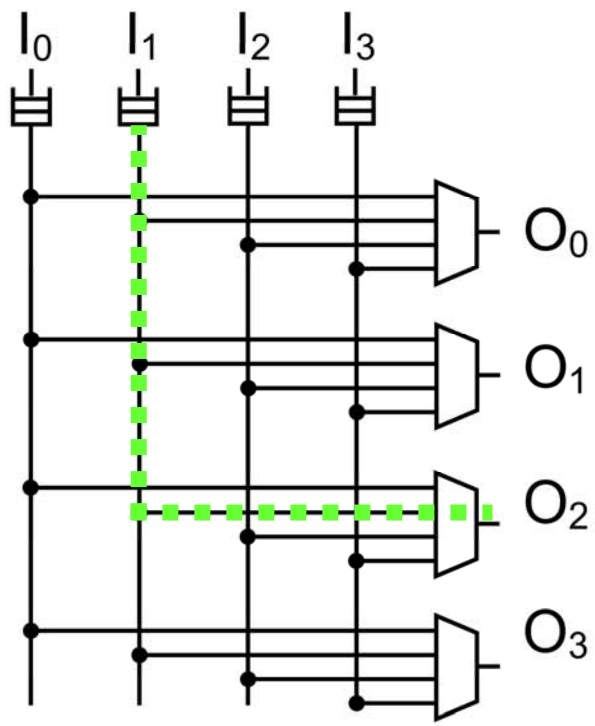


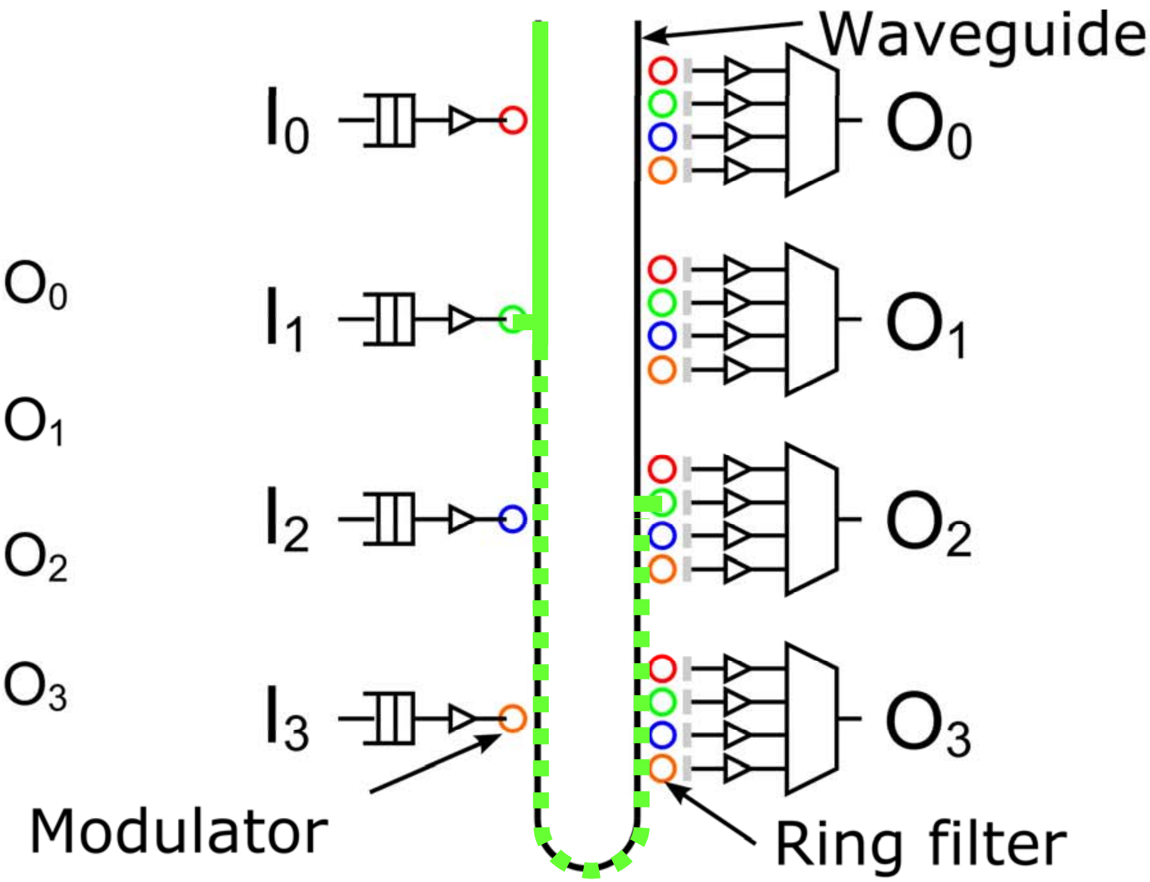


Electrical design

Photonic design

Centralized Multiplexer Crossbar

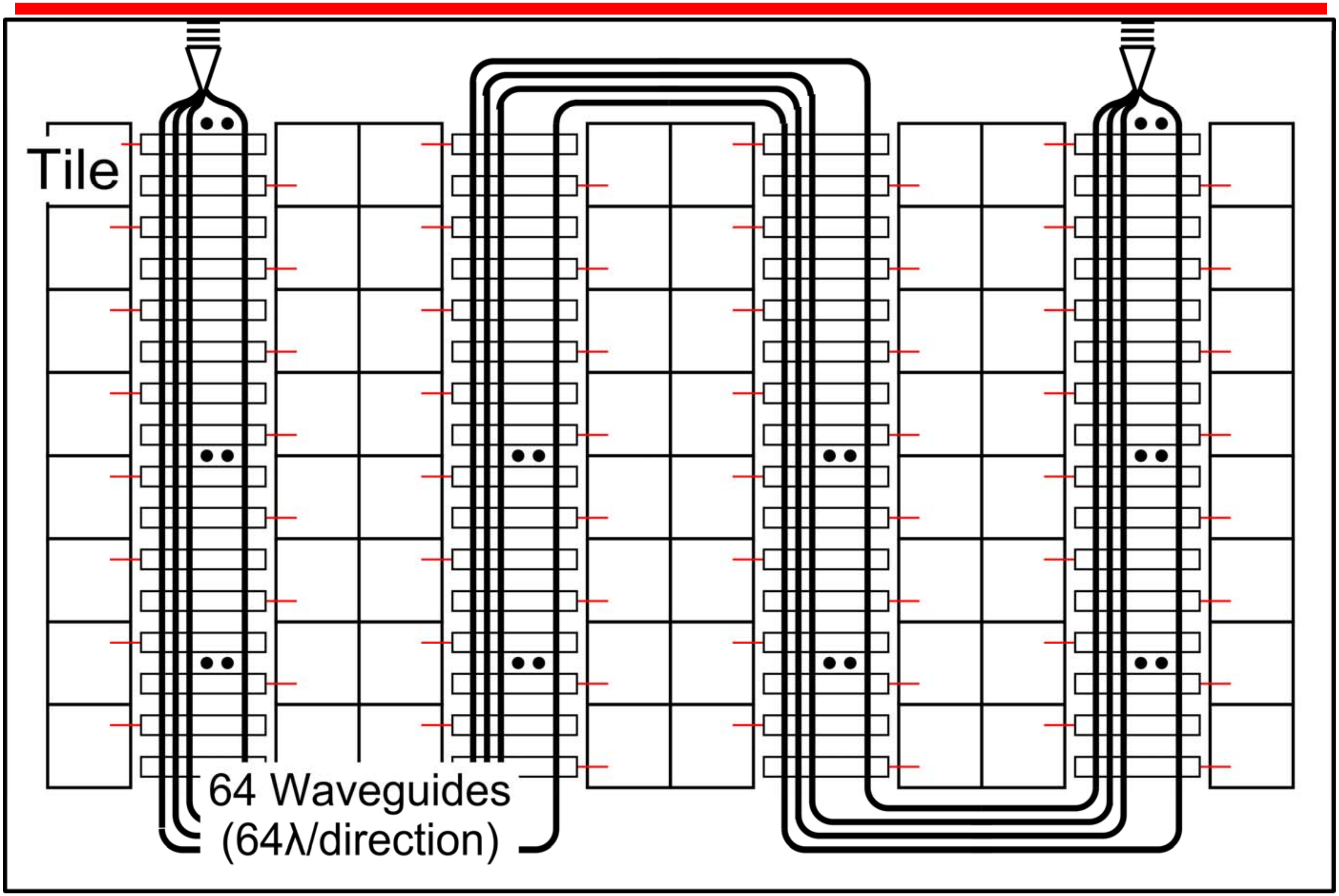




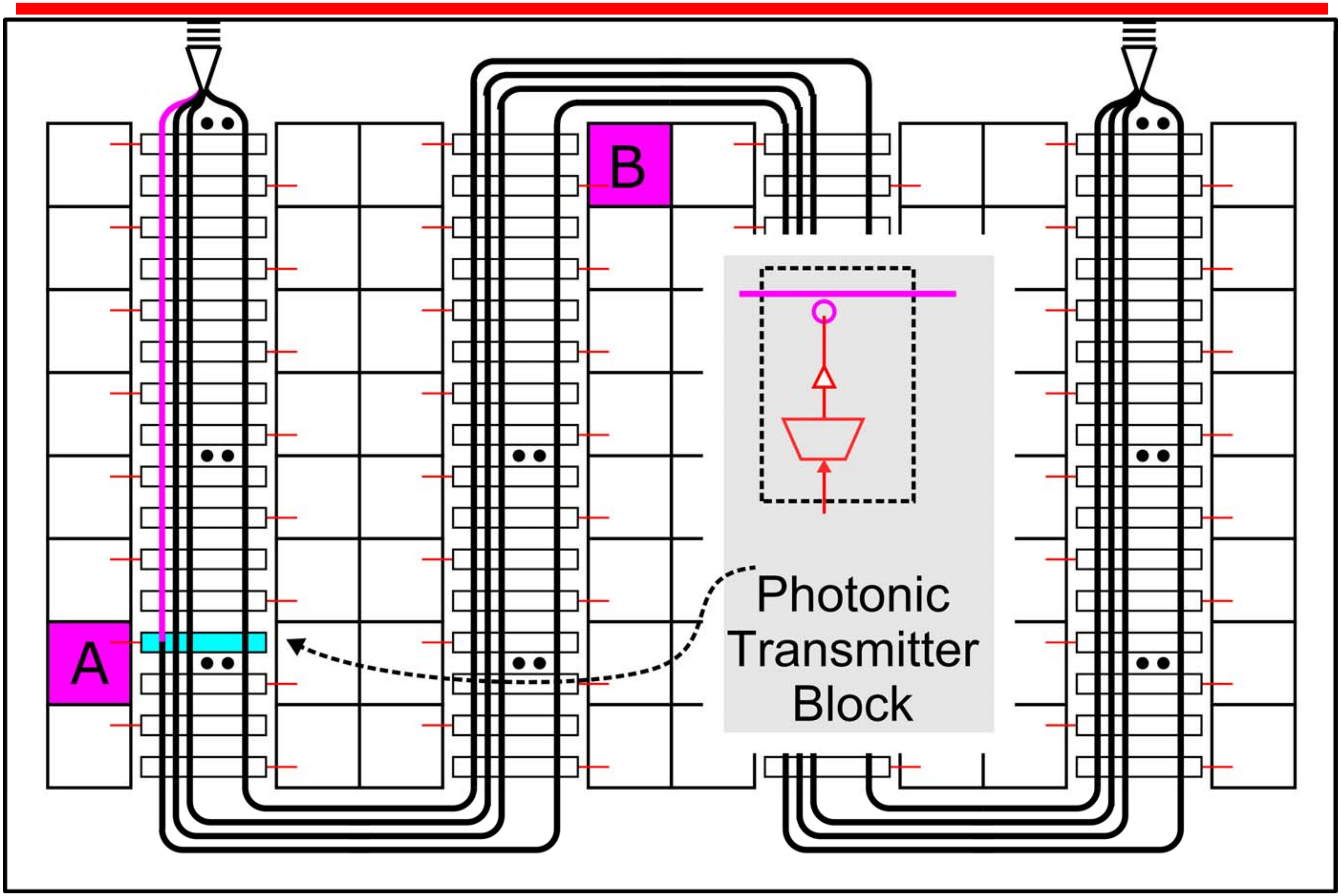
Electrical design

Photonic design

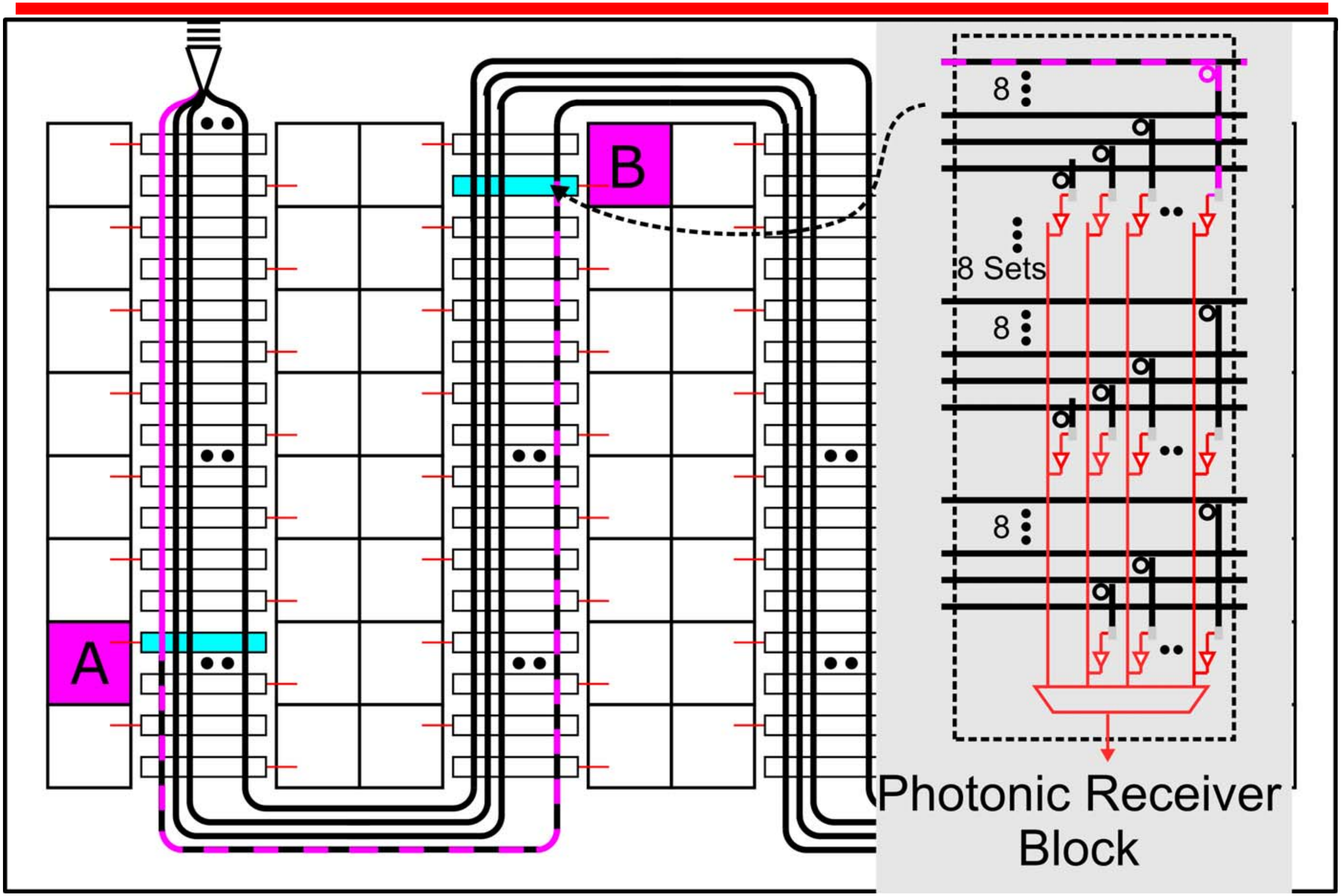
Photonic crossbar for a 64-tile system



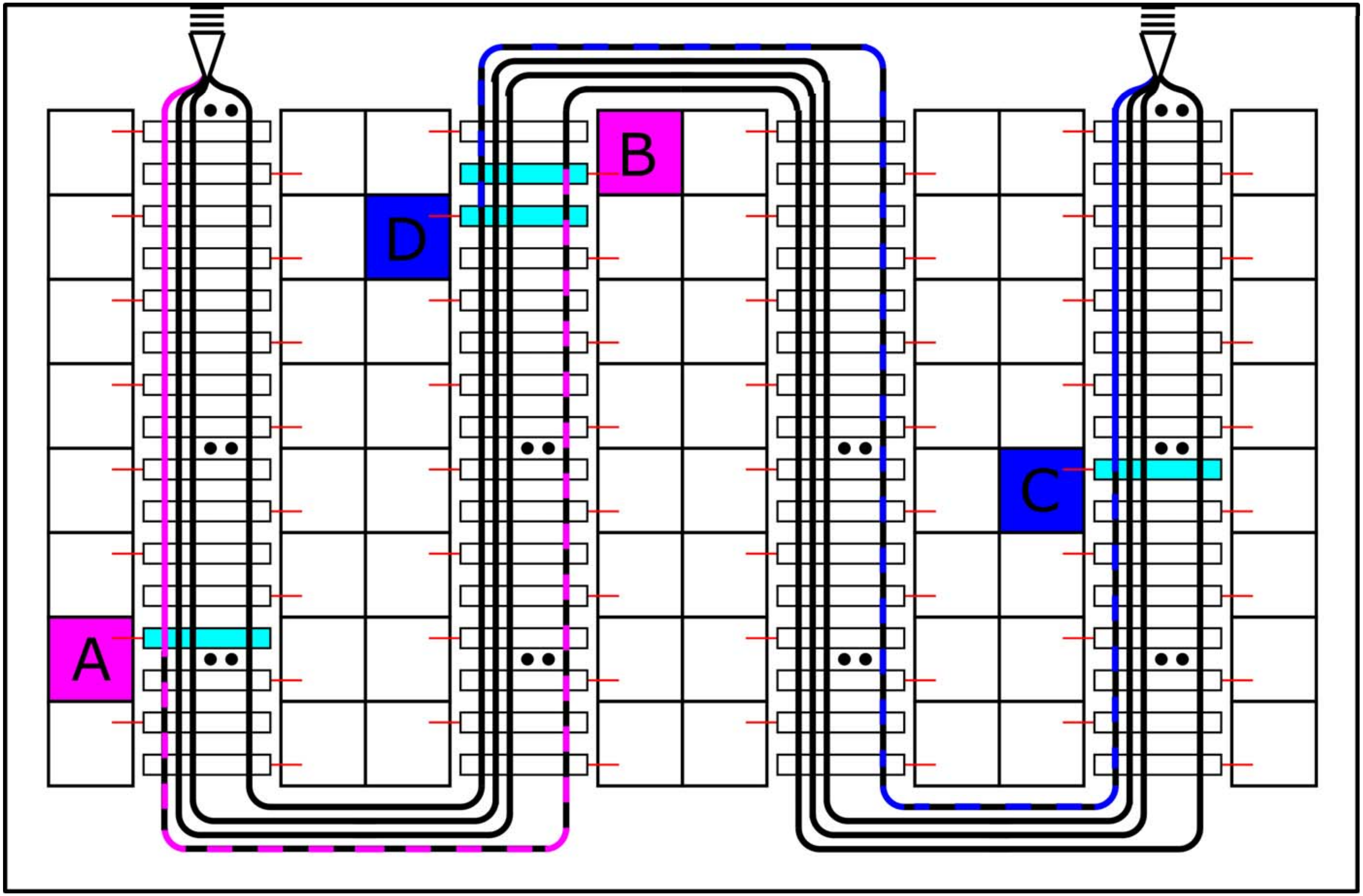
Photonic crossbar for a 64-tile system



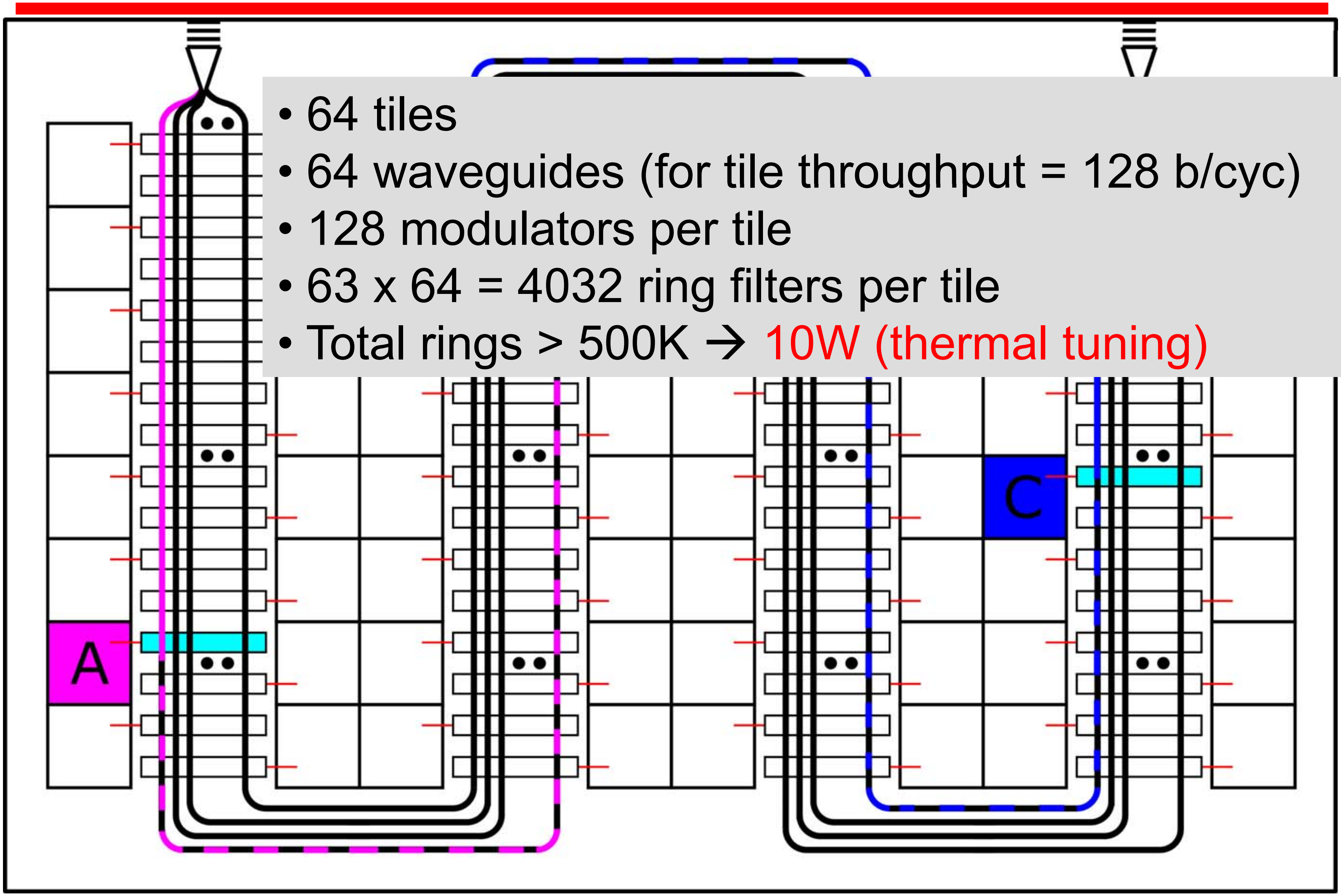
Photonic crossbar for a 64-tile system



Photonic crossbar for a 64-tile system

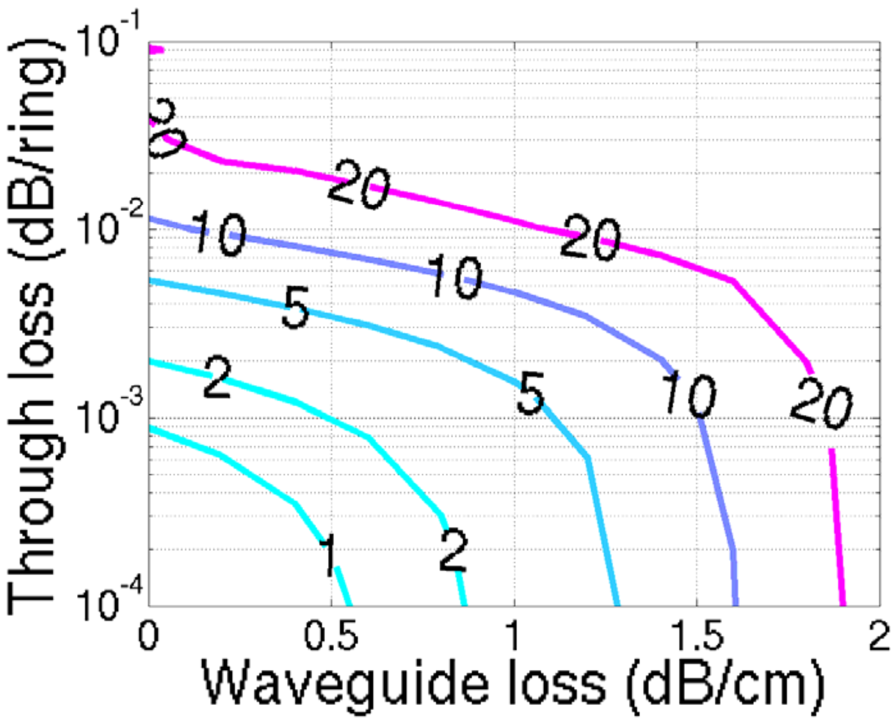


Photonic crossbar for a 64-tile system

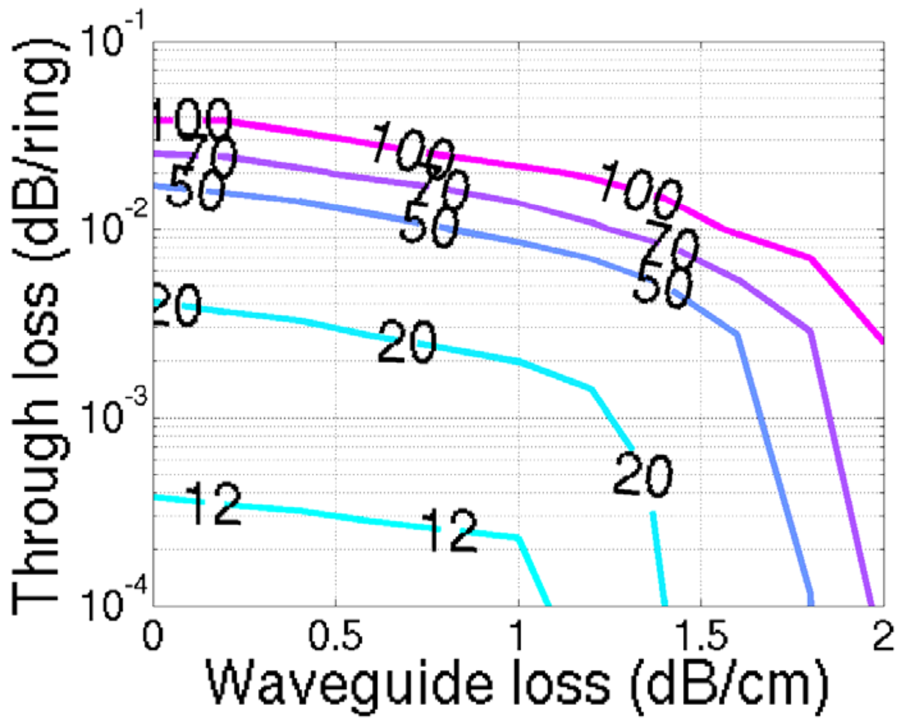


- 64 tiles
- 64 waveguides (for tile throughput = 128 b/cyc)
- 128 modulators per tile
- 63 x 64 = 4032 ring filters per tile
- Total rings > 500K → 10W (thermal tuning)

Photonic device requirements in a crossbar

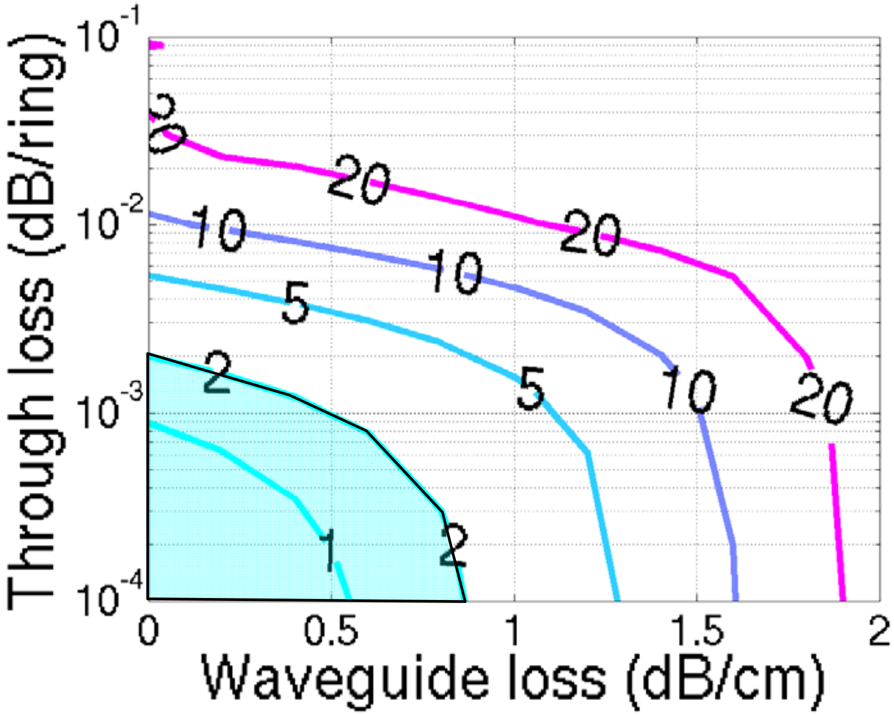


Optical laser power (W) contour



Percent area of photonic devices contour

Photonic device requirements in a crossbar



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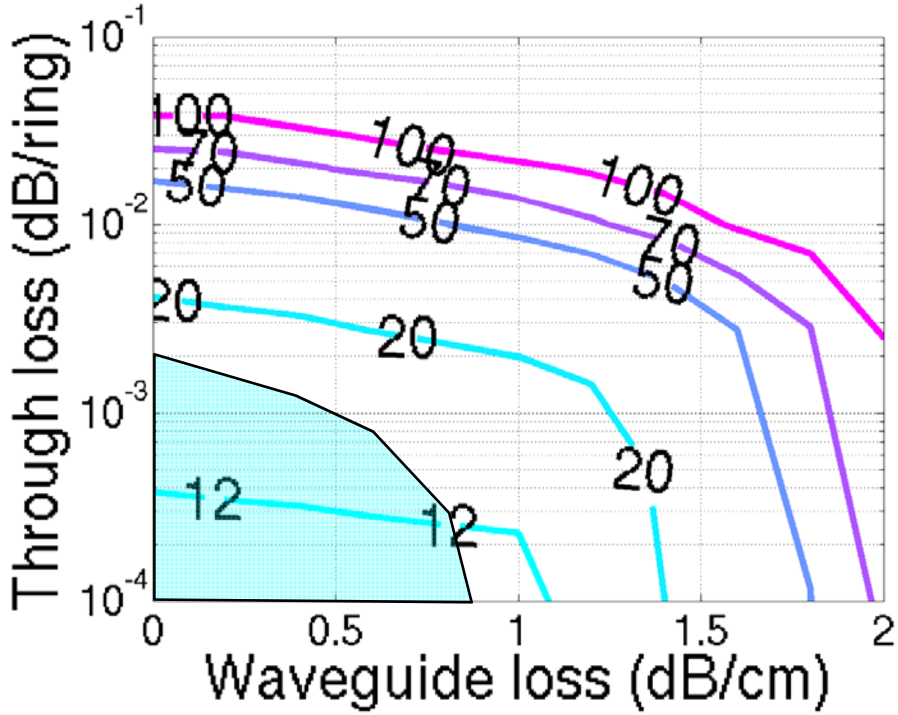
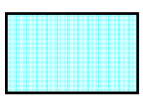
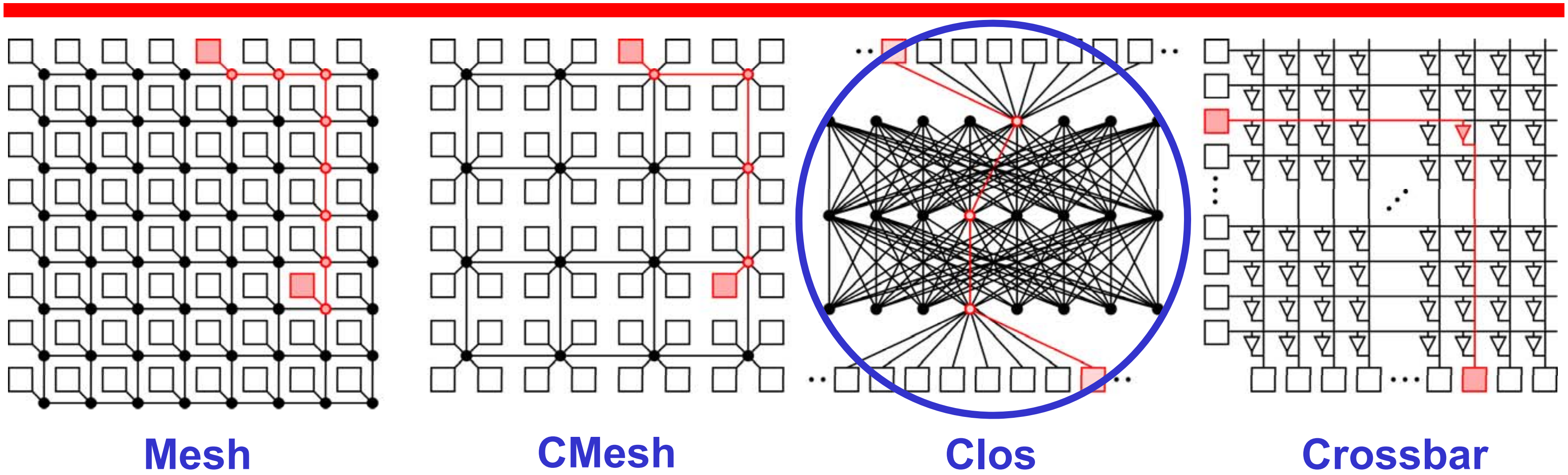


Percent area of photonic devices contour



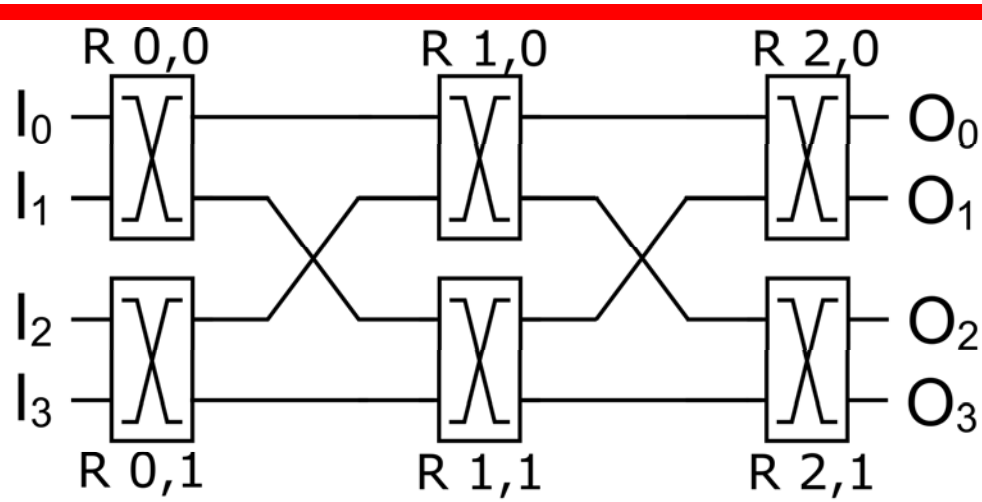
Waveguide loss and Through loss limits for 2 W optical laser power (30% laser efficiency) constraint

Outline

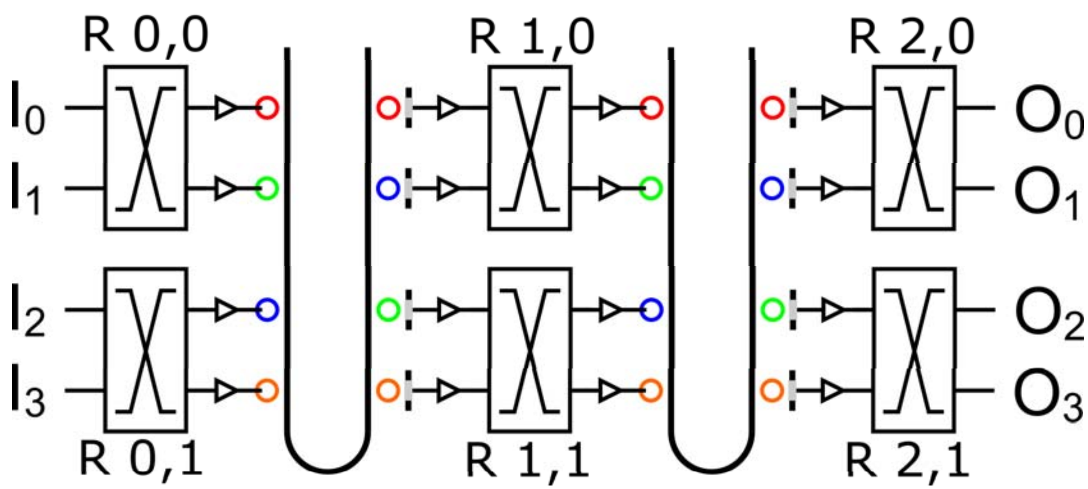


- Interconnect technologies
- Photonic networks
- Electrical vs Photonic networks

Clos network using point-to-point channels



Electrical design



Photonic design

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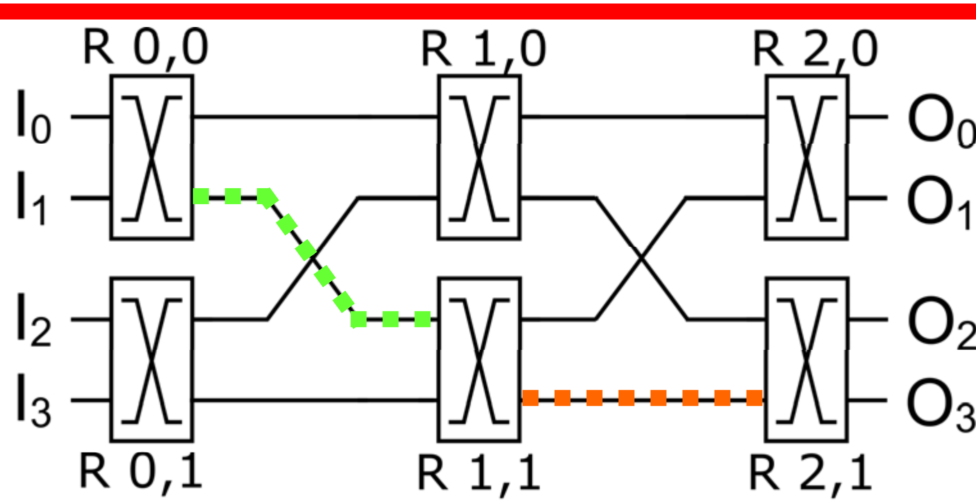
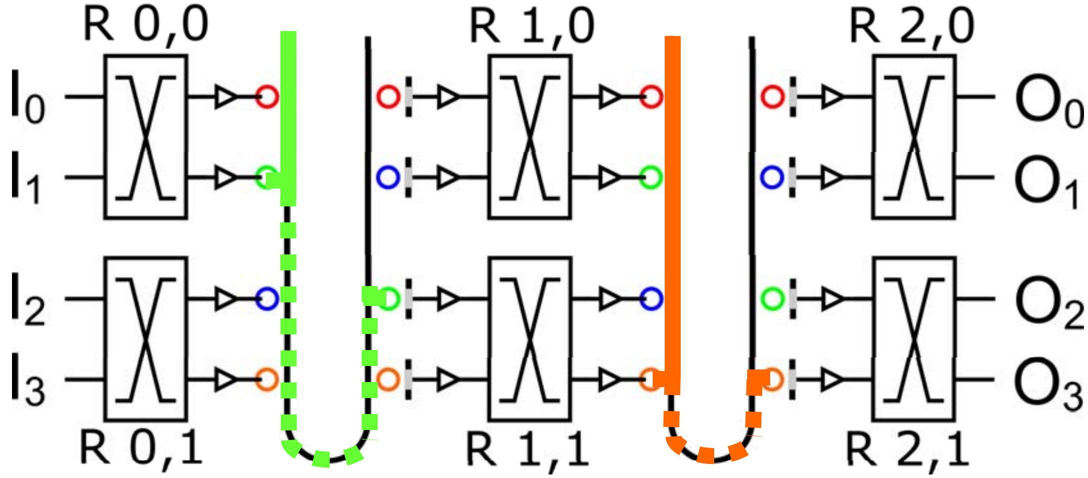
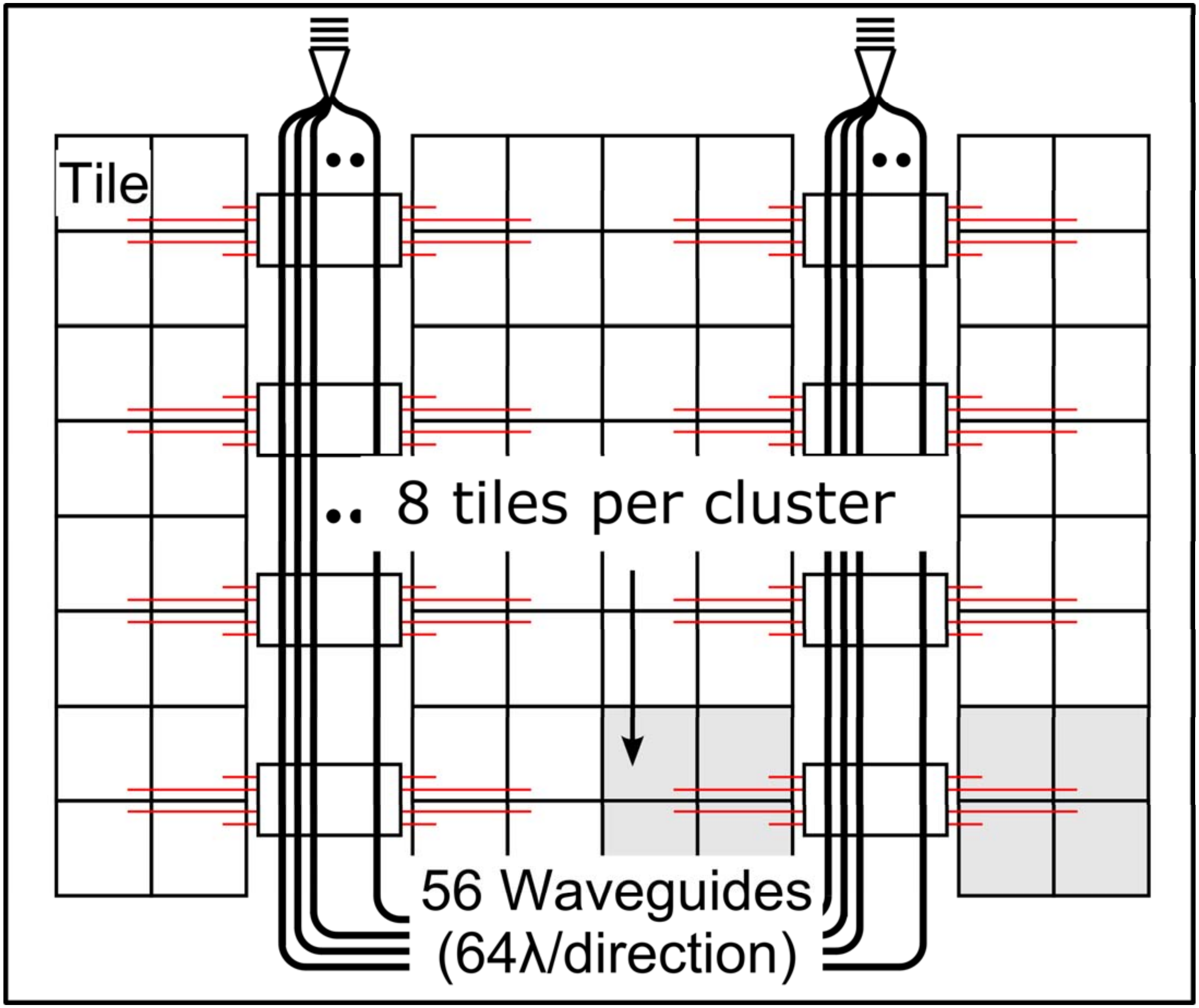


Electrical design



Photonic design

Photonic Clos for a 64-tile system



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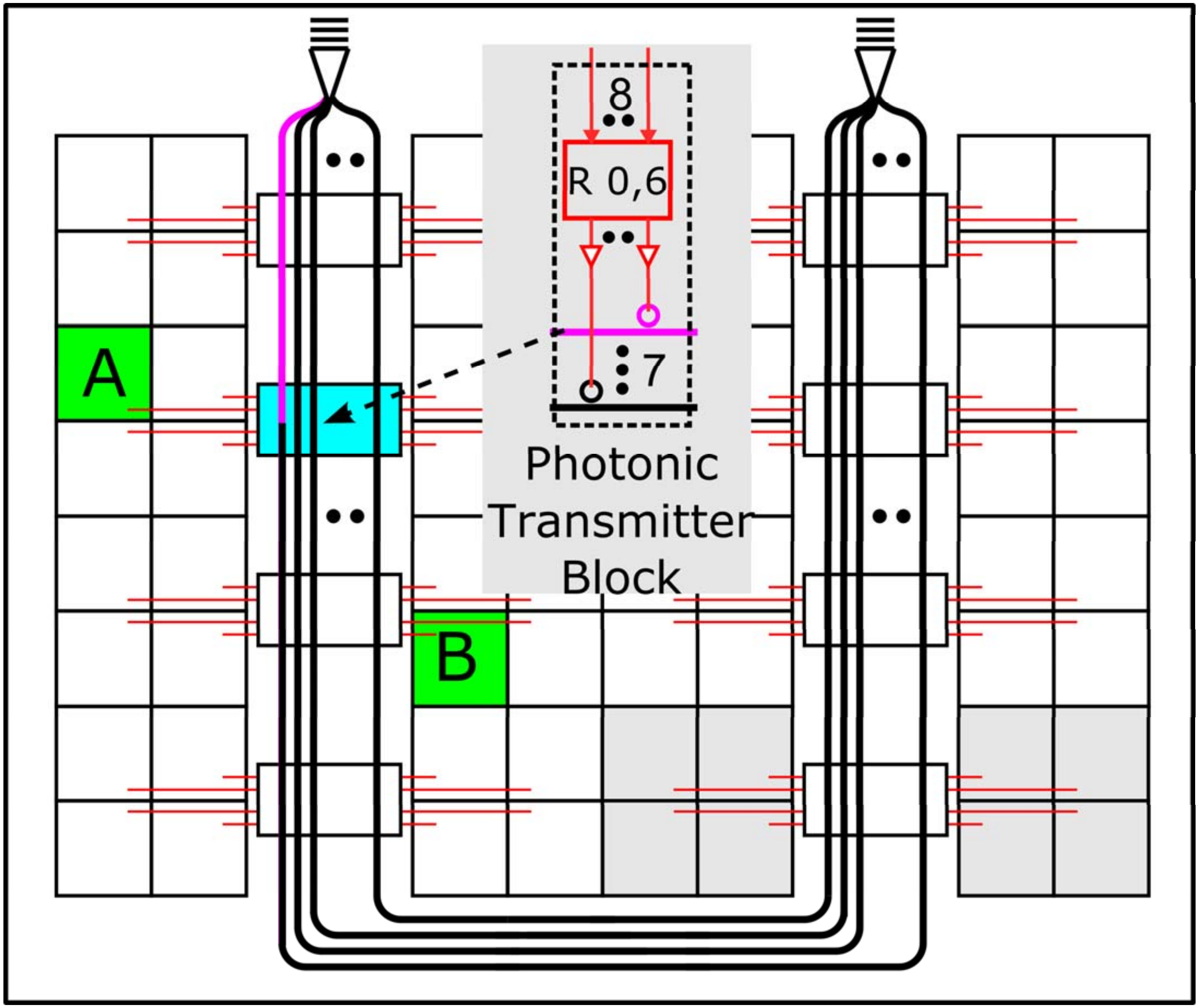

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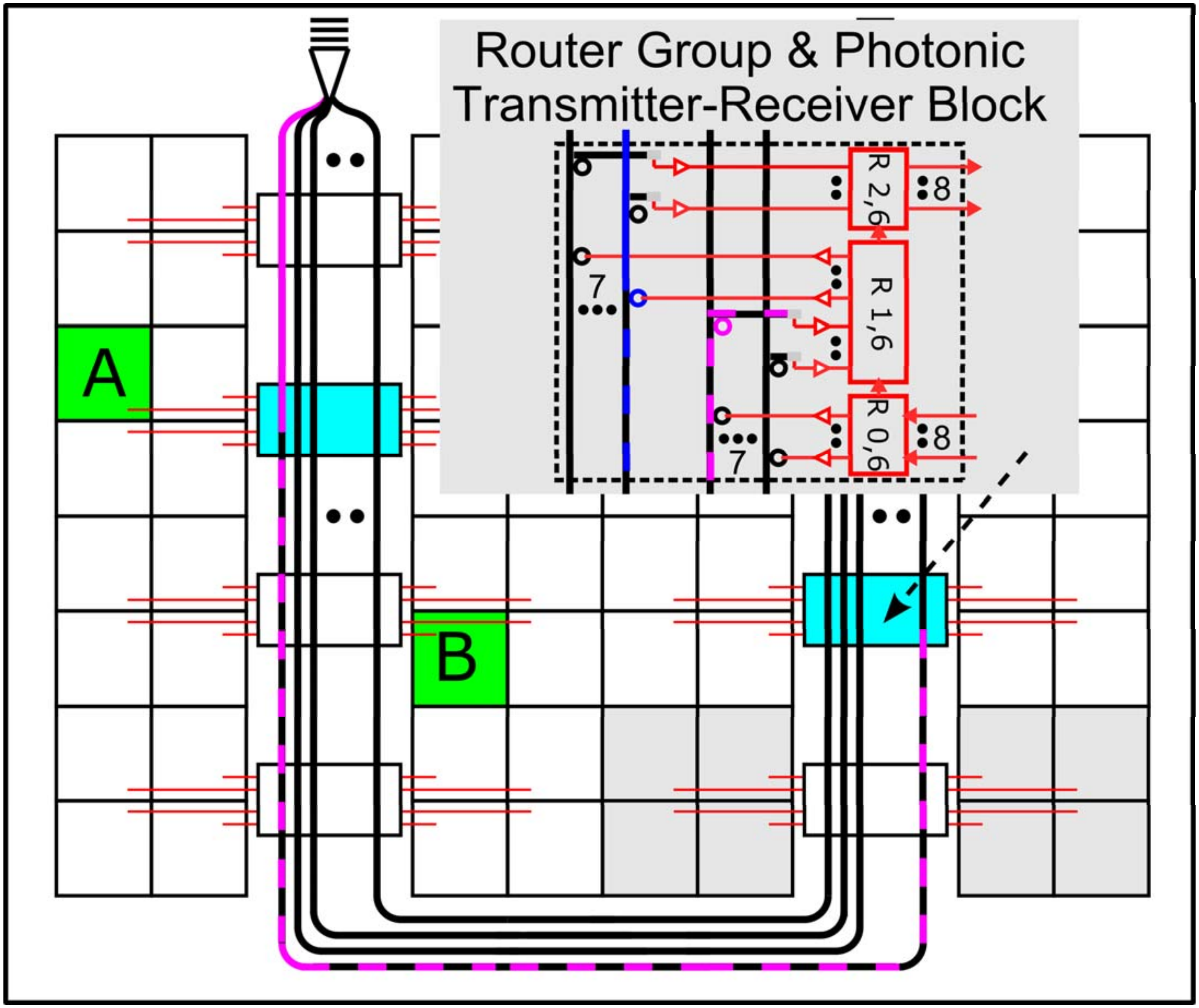

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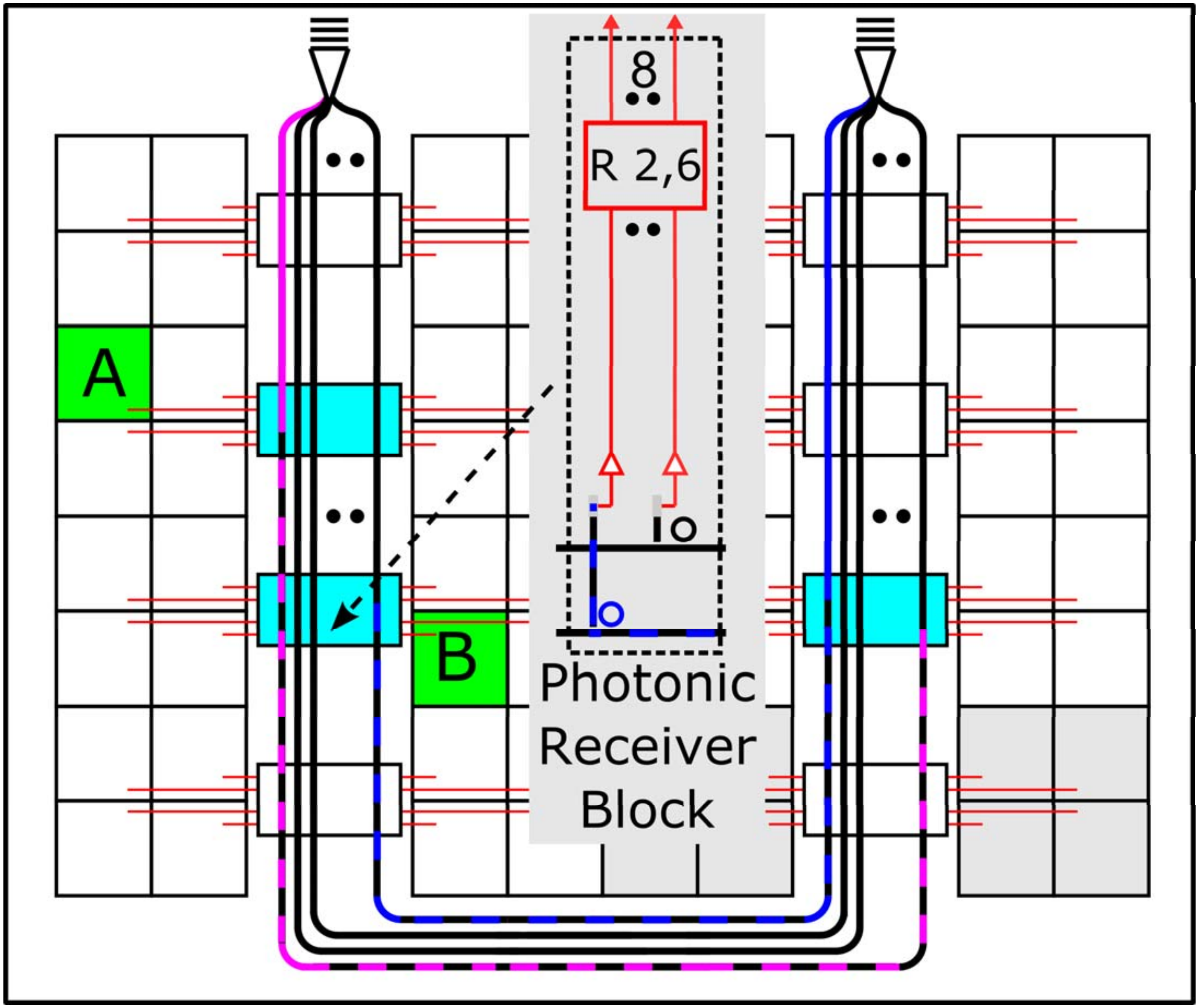

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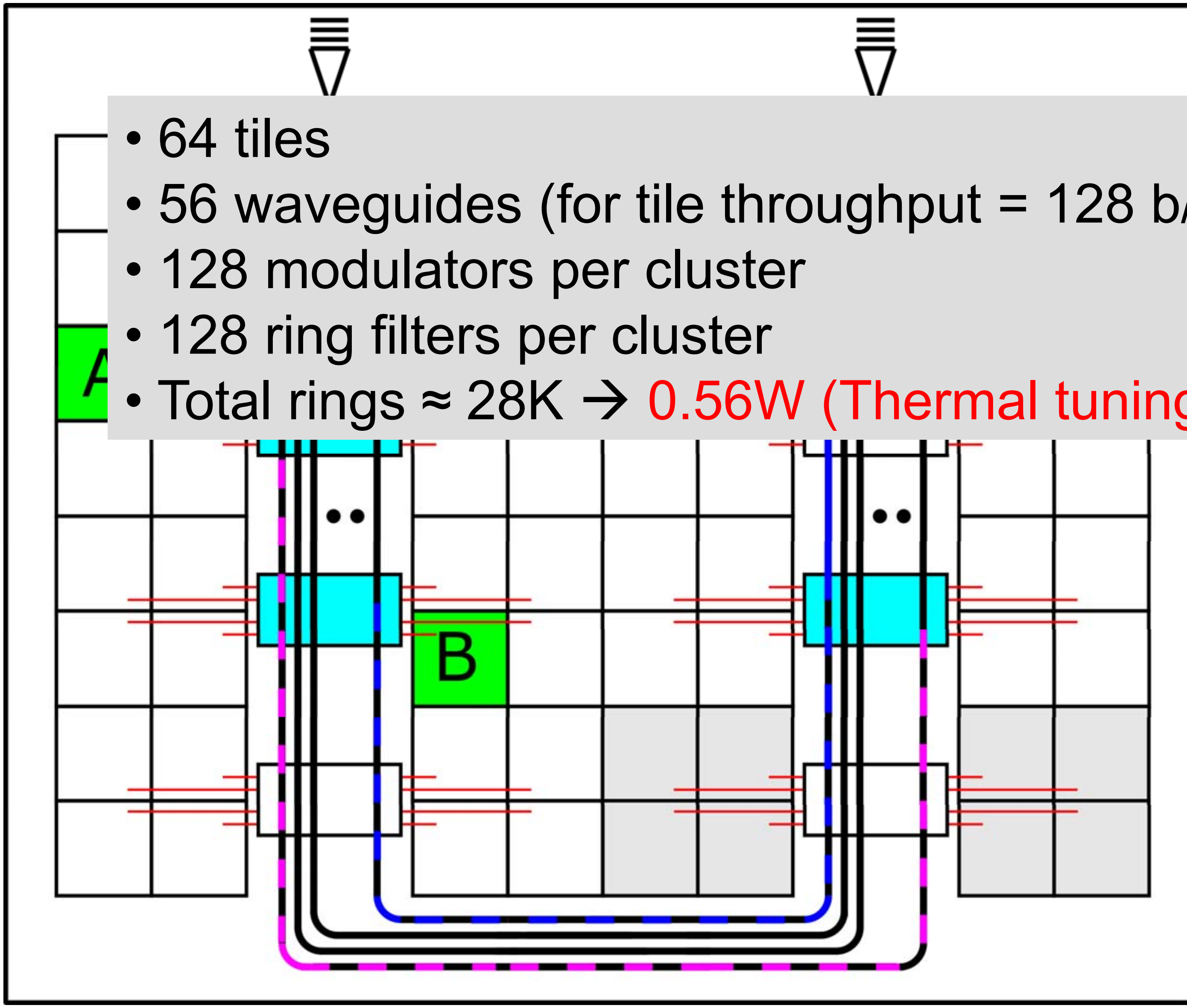
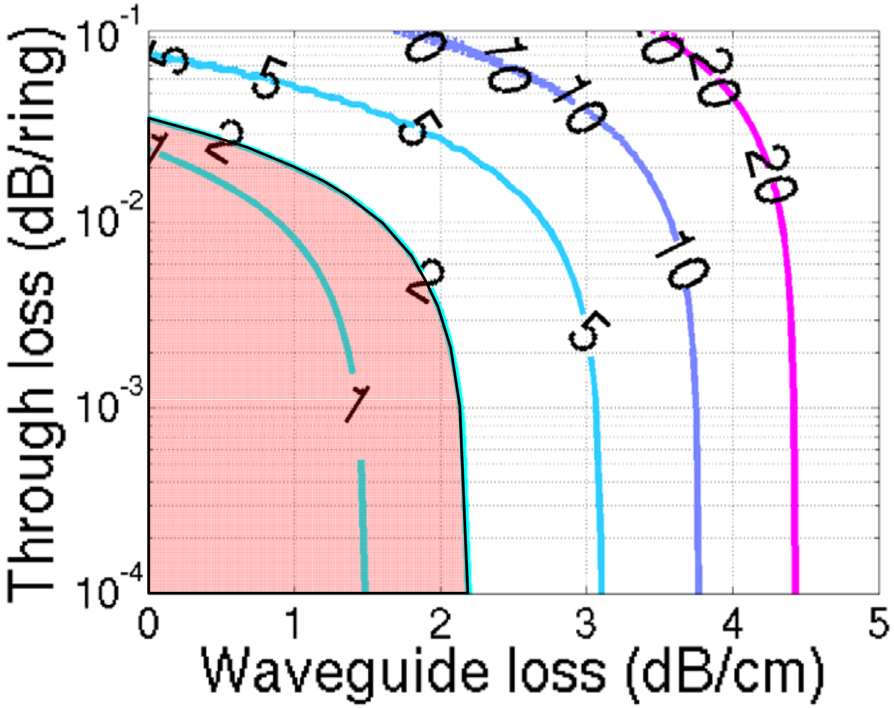
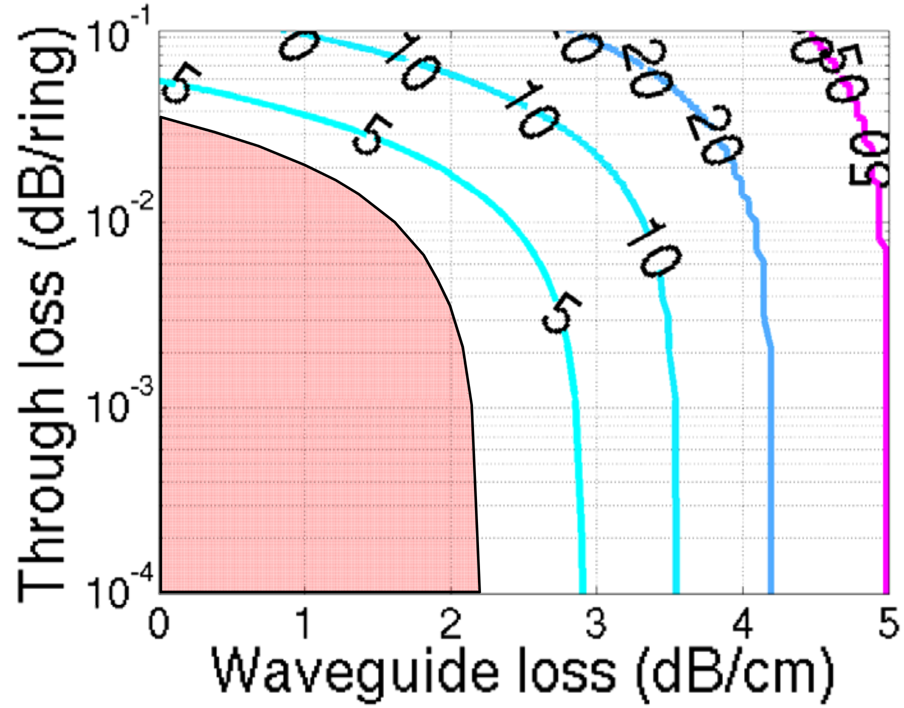


- 64 tiles
- 56 waveguides (for tile throughput = 128 b/cyc)
- 128 modulators per cluster
- 128 ring filters per cluster
- Total rings ≈ 28K → 0.56W (Thermal tuning)

Photonic device requirements in a Clos



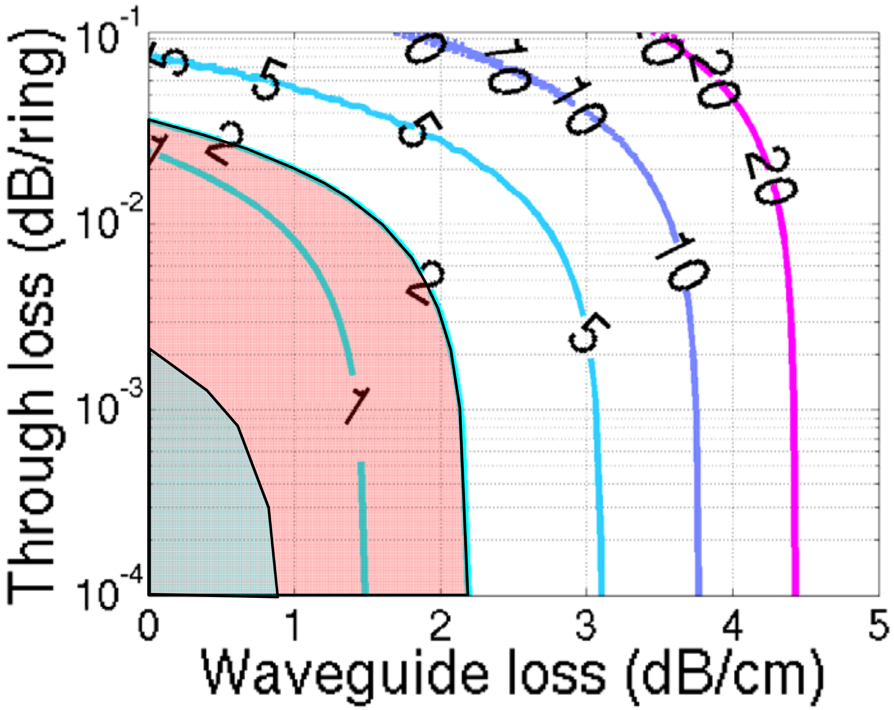
Optical laser power (W) contour



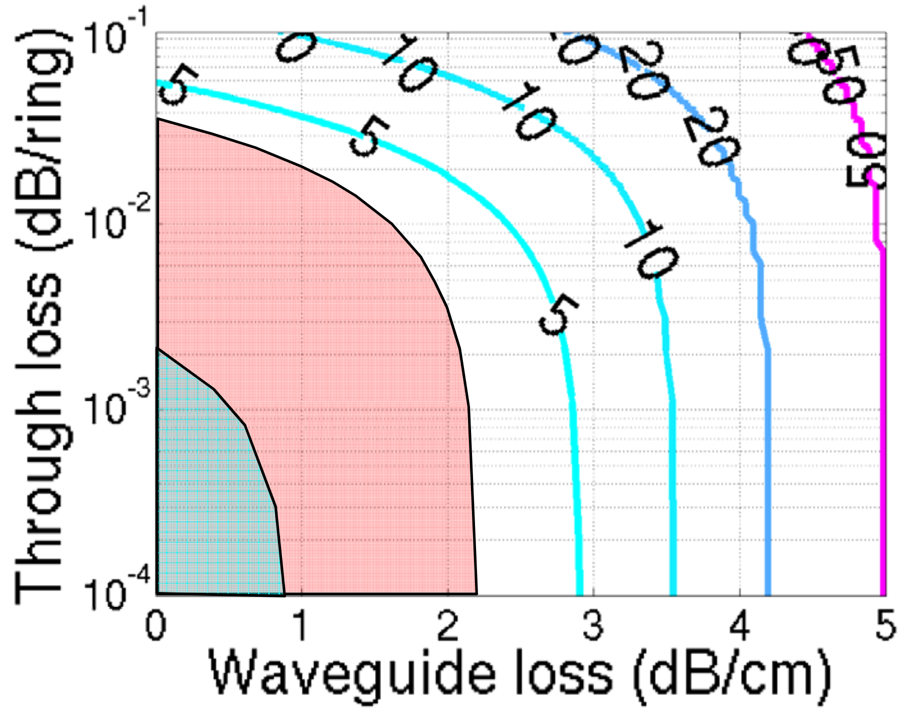
Percent area of photonic devices contour

Waveguide loss and Through loss limits for 2 W optical laser power (30% laser efficiency) constraint

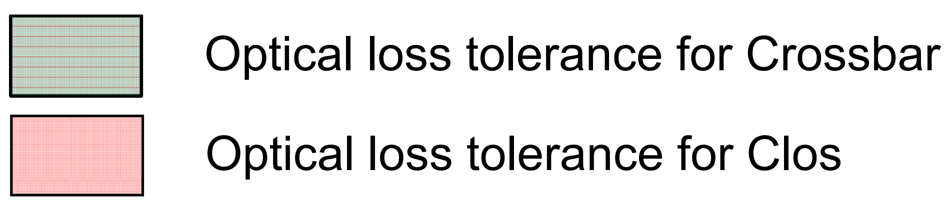
Photonic device requirements in a Clos



Optical laser power (W) contour

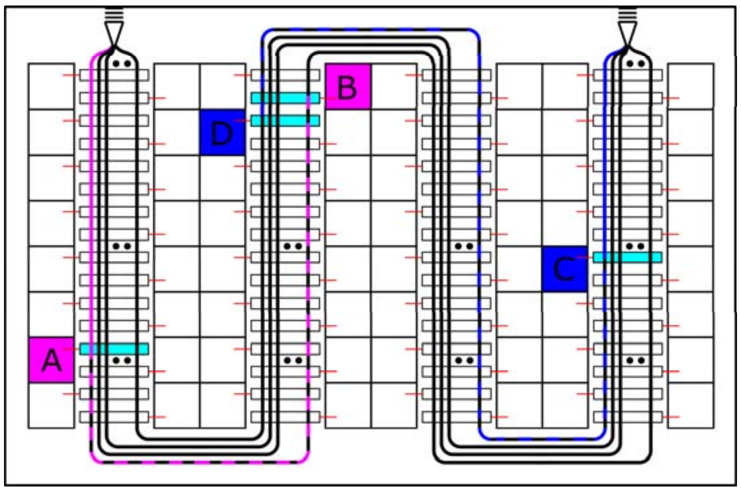


Percent area of photonic devices contour

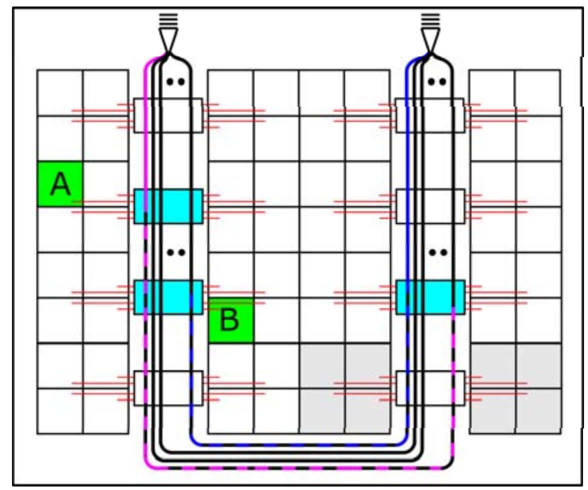


Photonic Crossbar vs Photonic Clos

Crossbar



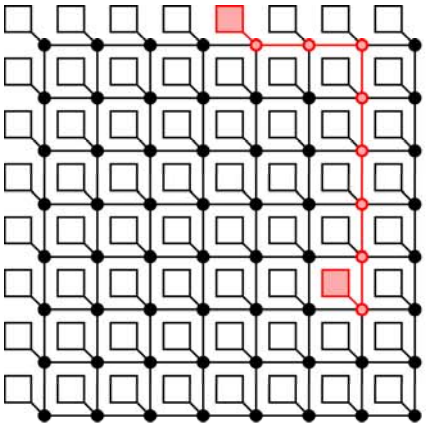
Clos



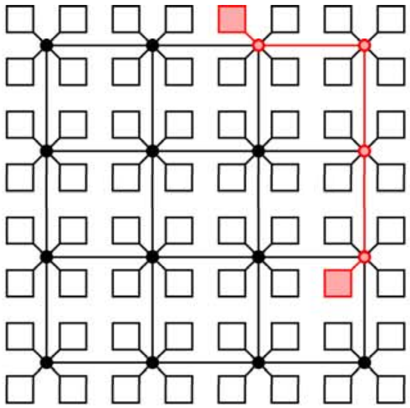
- 10 W power for thermal tuning circuits (1 μW/ring/K)
- For 2 W optical laser power
  - Waveguide loss < 1 dB/cm
  - Through loss < 0.002 dB/ring

- 0.56 W power for thermal tuning circuits (1 μW/ring/K)
- For 2 W optical laser power
  - Waveguide loss < 2dB/cm
  - Through loss < 0.05 dB/ring

Outline



Mesh



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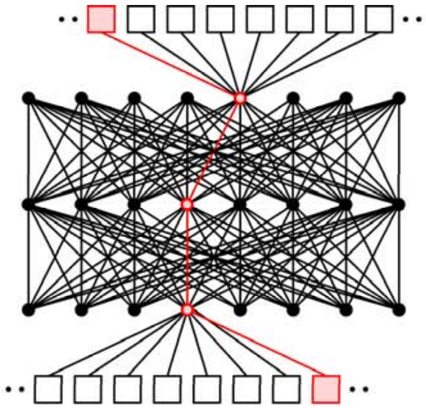
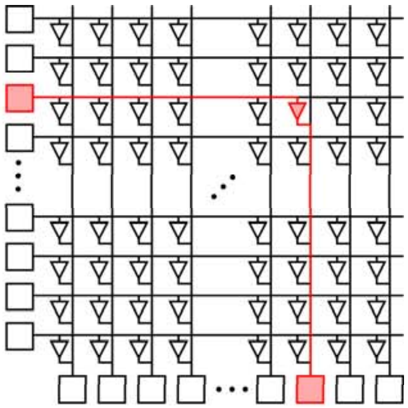


Clos

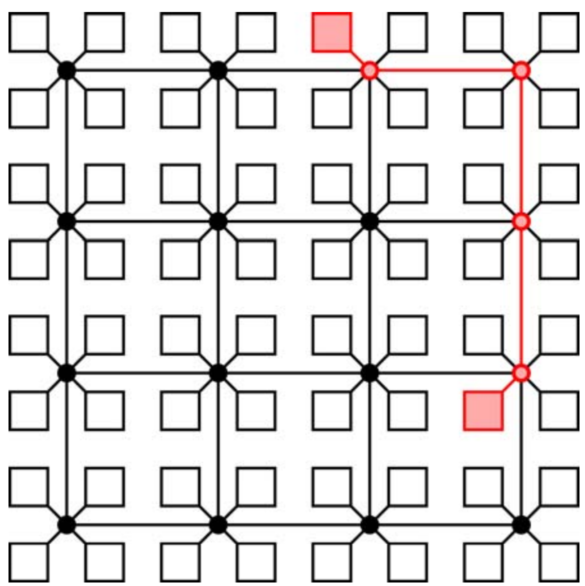


Crossbar

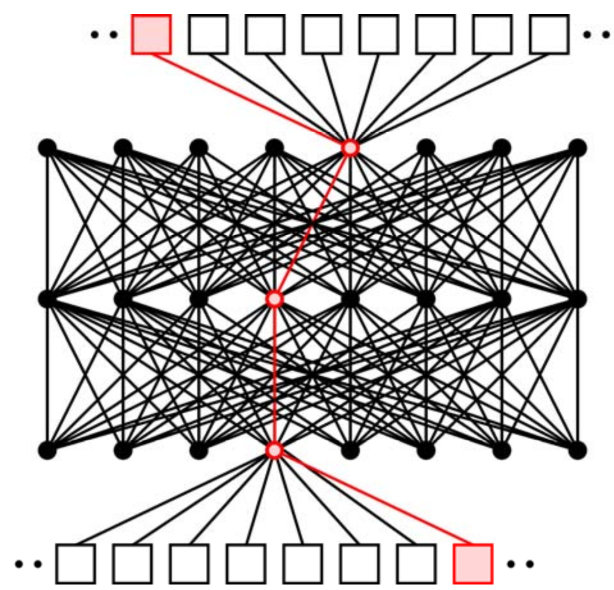
- Photonic interconnect technology
- Photonic networks
- Electrical vs Photonic networks

Simulation setup

- Cycle-accurate microarchitectural simulator
- Traffic patterns based on partition application model
  - Global traffic – UR, P2D, P8D
  - Local traffic – P8C
- 64-tile system, 512-bit messages
- Events captured during simulations to calculate power

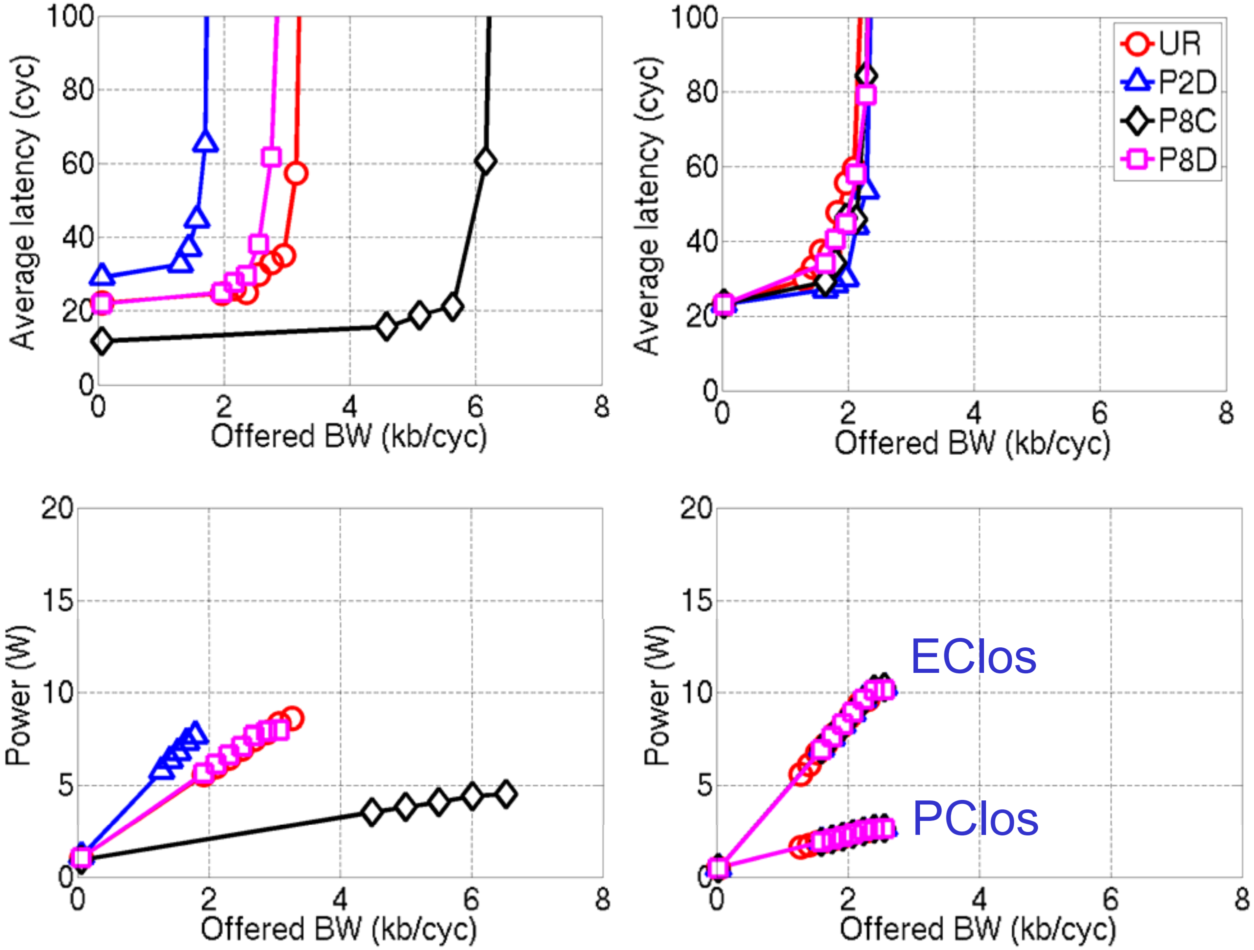


CMesh



Clos

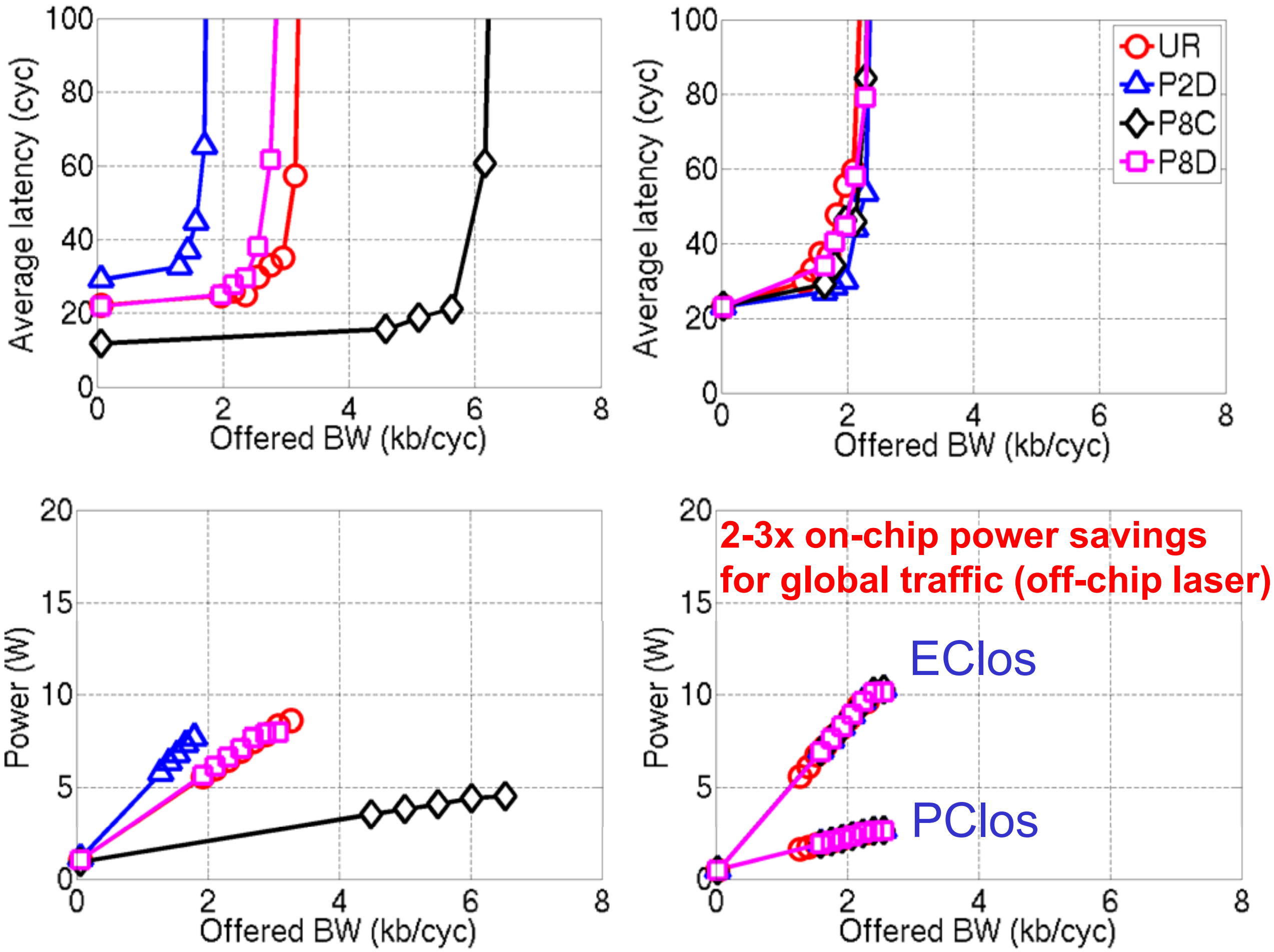
Power-Bandwidth tradeoff



CMeshX2
Channel width = 128b

Clos
Channel width = 64b

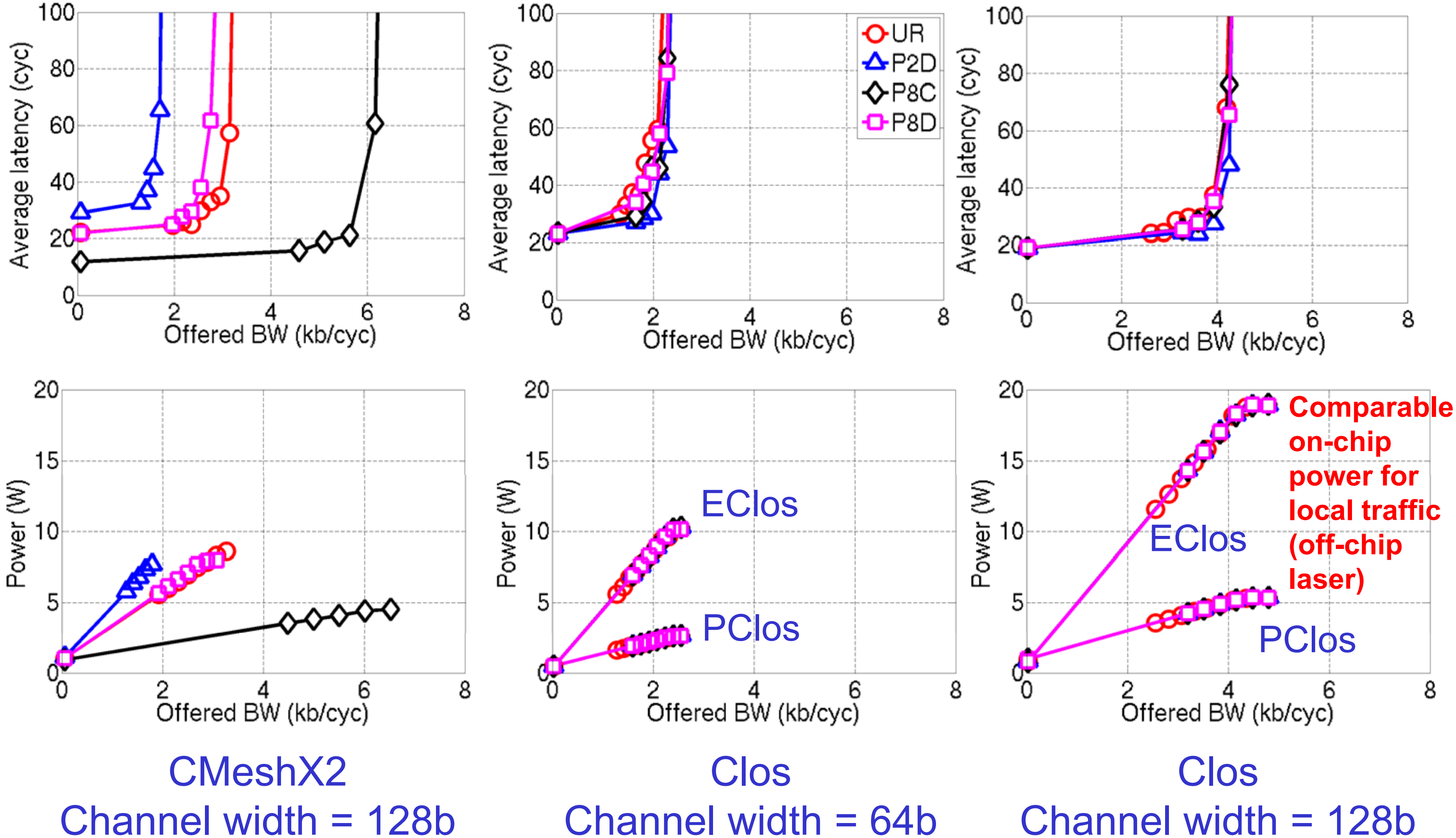
Power-Bandwidth tradeoff



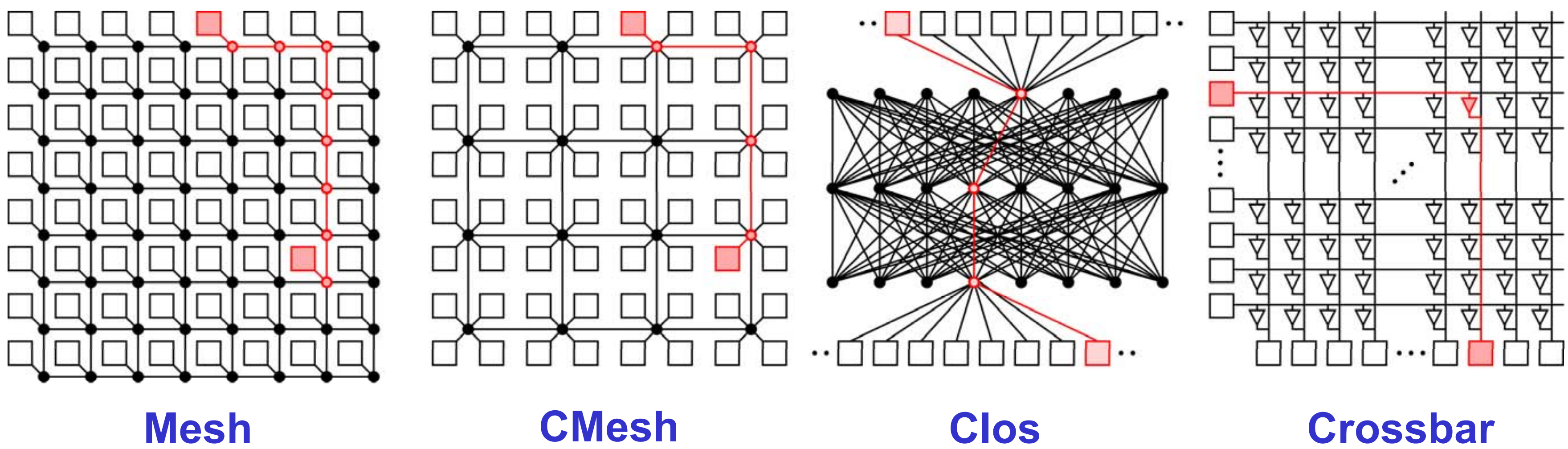
CMeshX2
Channel width = 128b

Clos
Channel width = 64b

Power-Bandwidth tradeoff



Conclusion



- Accurate baseline electrical design required
- Need to carefully account for the energy components in optical interconnects
  - E-O-E conversion, Thermal tuning power, Optical laser power
- Clos network provides comparable throughput at lower energy for global traffic patterns
- More work required on the photonic device design

Acknowledgement

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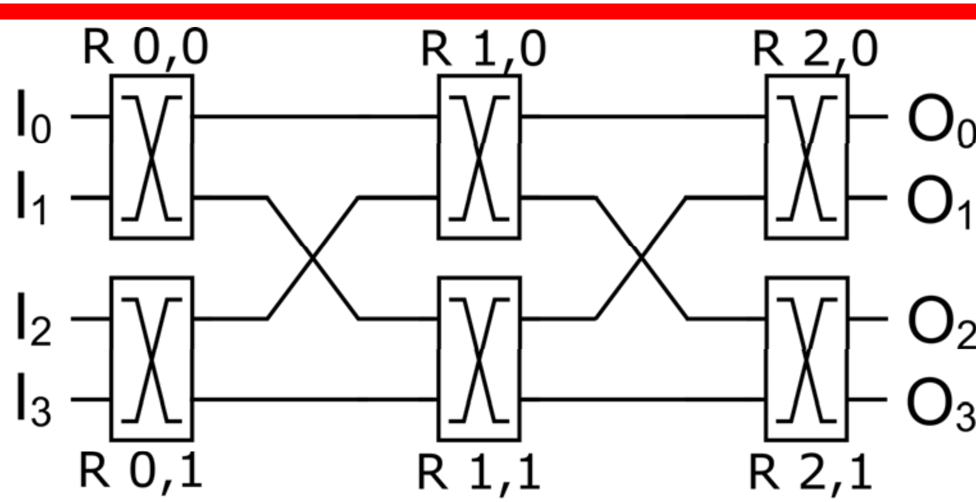
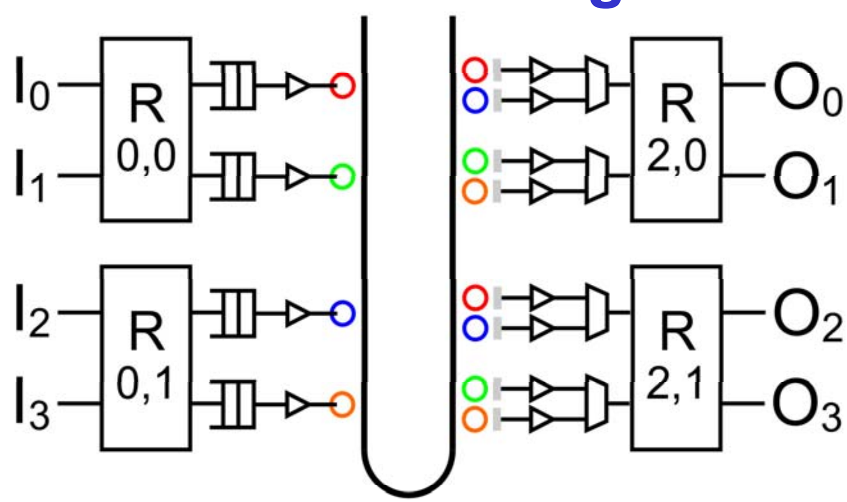
  - Franz Kärtner, Rajeev Ram, Judy Hoyt, Henry Smith
  - Jason Orcutt, Anatoly Khilo, Benjamin Moss, Charles Holzwarth, Jonathan Leu, Michael Georgas, Jie Sun, Miloš Popović, Hanqing Li
- Funding sources
  - DARPA
  - Intel Corp.

Backup

Clos network using intermediate crossbar

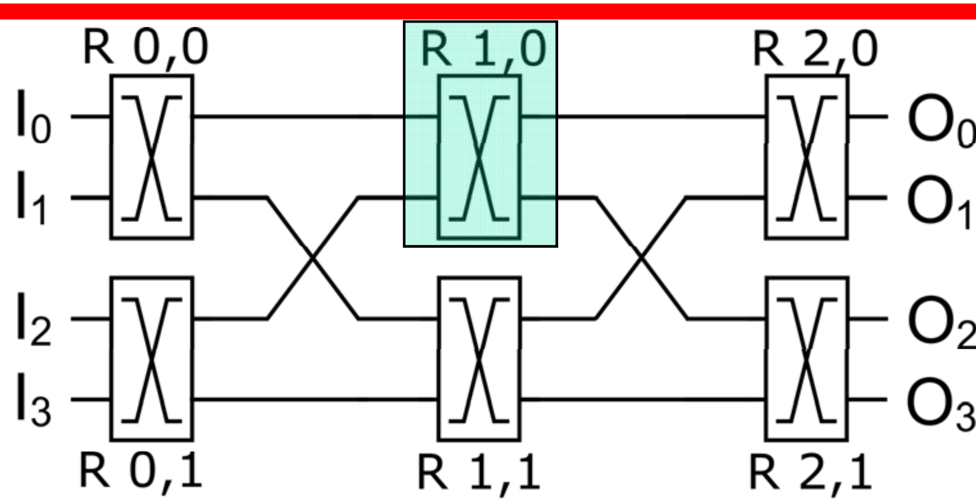


Electrical design

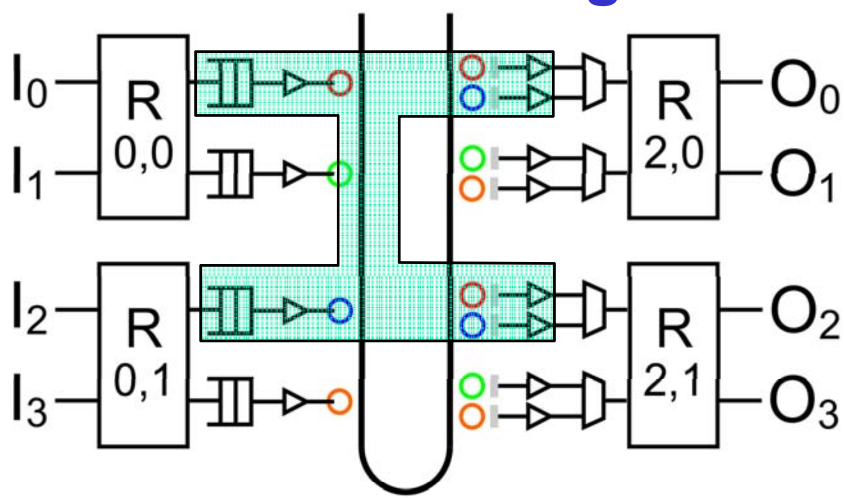


Photonic design

Clos network using intermediate crossbar

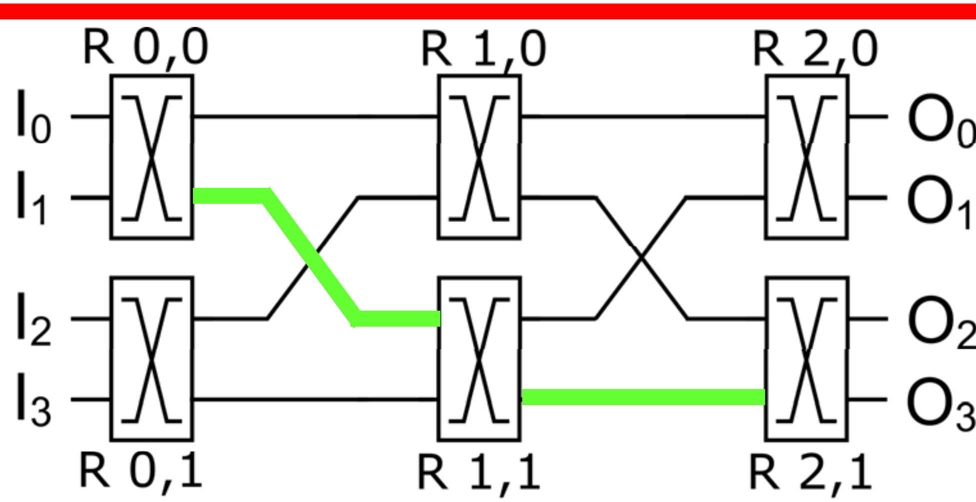


Electrical design

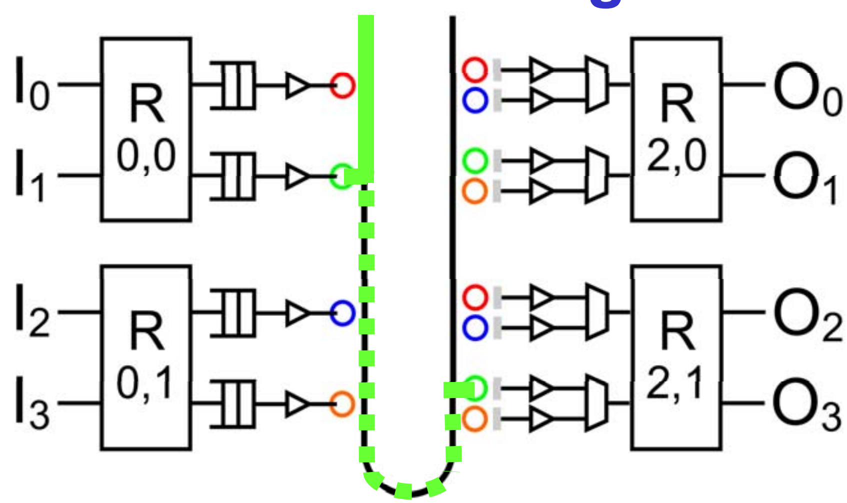


Photonic design

Clos network using intermediate crossbar



Electrical design



Photonic design