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Ultralow Power Silicon Microdisk Modulators and Switches

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Applied Photonic Microsystems

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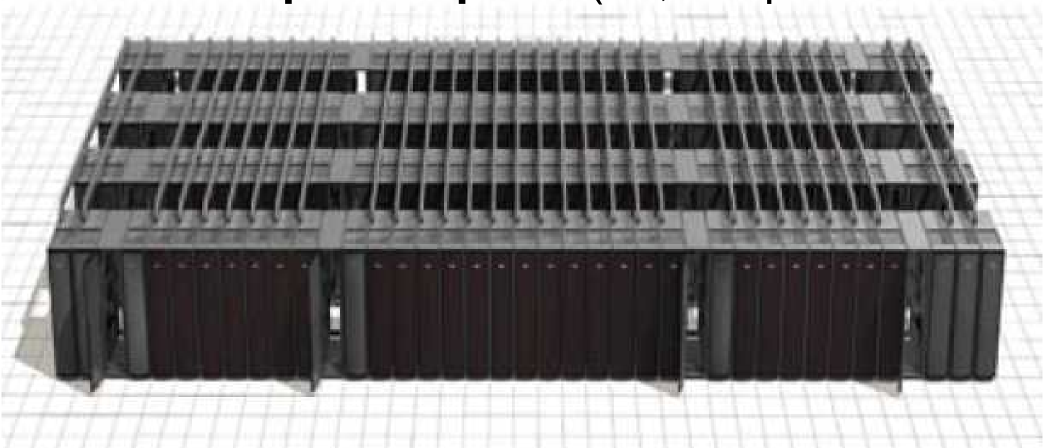
Motivation: Power / Bandwidth in Supercomputers

"Based on current trends, by 2011 data center energy consumption will nearly double again, requiring the equivalent of 25 power plants. The world's data centers, according to recent study from McKinsey & Company, could well surpass the airline industry as a greenhouse gas polluter by 2020."

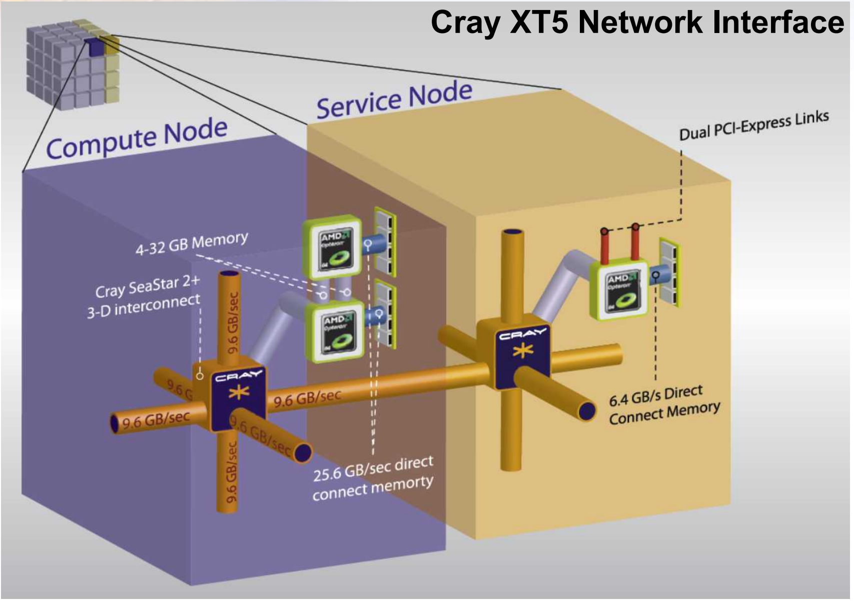
Quote from "Demand for Data Puts Engineers in Spotlight," New York Times, June 17, 2008

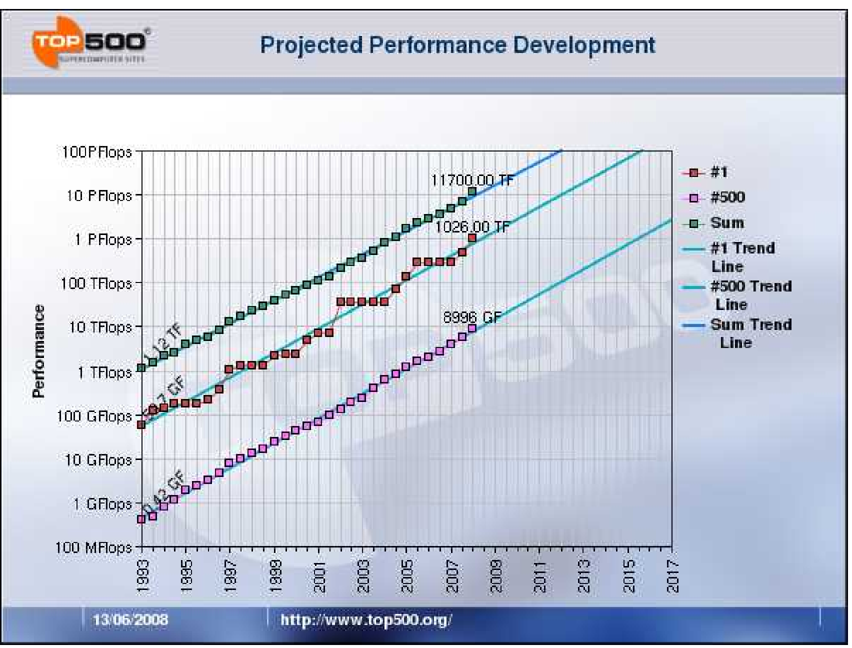
Sandia's Red Storm Supercomputer (26,569 processor cores, ~3.5MW power)



- **Question:** Now at 1PFLOPs, what does it take to get to 1-ExaFLOPs?
- **Power:** Hoover Dam provides ~1GW . . . what will future supercomputers need?
- **Bandwidth:** To scale real-world application performance, communications must scale with compute performance (i.e. bytes/FLOP ~ 1 Bidirectional)

Interconnect Requirements for Super-Computers





Today (2008)

- **BW/node:** 14×9.6GB/s → 1.08Tb/s/node
- **BW/core:** 1.08Tb/s (Red Storm, originally)
  - now BW/core is ~250Gb/s
- Top machines achieve ~1PFLOPs peak

Future (2018)

- By 2018 DOE expects to reach 1-ExaFLOPs
- ITRS projects we will reach 14nm node
- Cores/chip >100, conservatively
- 100cores/chip*1.08Tb/s/core = 108Tb/s/chip

Can the bandwidth requirements be achieved with electrical signaling at reasonable power levels?

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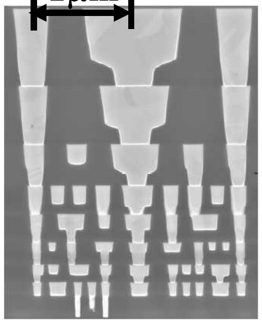
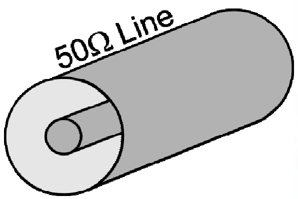
Can Electronics meet BW Requirements?



Intrachip Electrical: Charged Lines

- **Energy: $CV_0^2/4 \rightarrow$ ~0.5pJ/bit/cm (50W for 100Tb/s)**
- **Bandwidth:** Achieve **~1Gb/s/1μm** → 10Tb/s/cm/layer → **10 layers**
- **Conclusion:** On-chip electrical signaling is troublesome in 2020

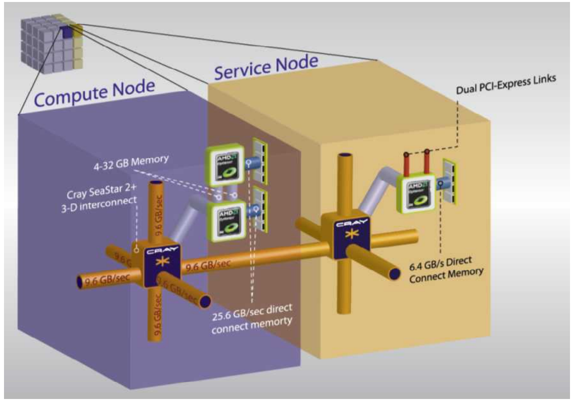


Interchip Electrical: Transmission Lines

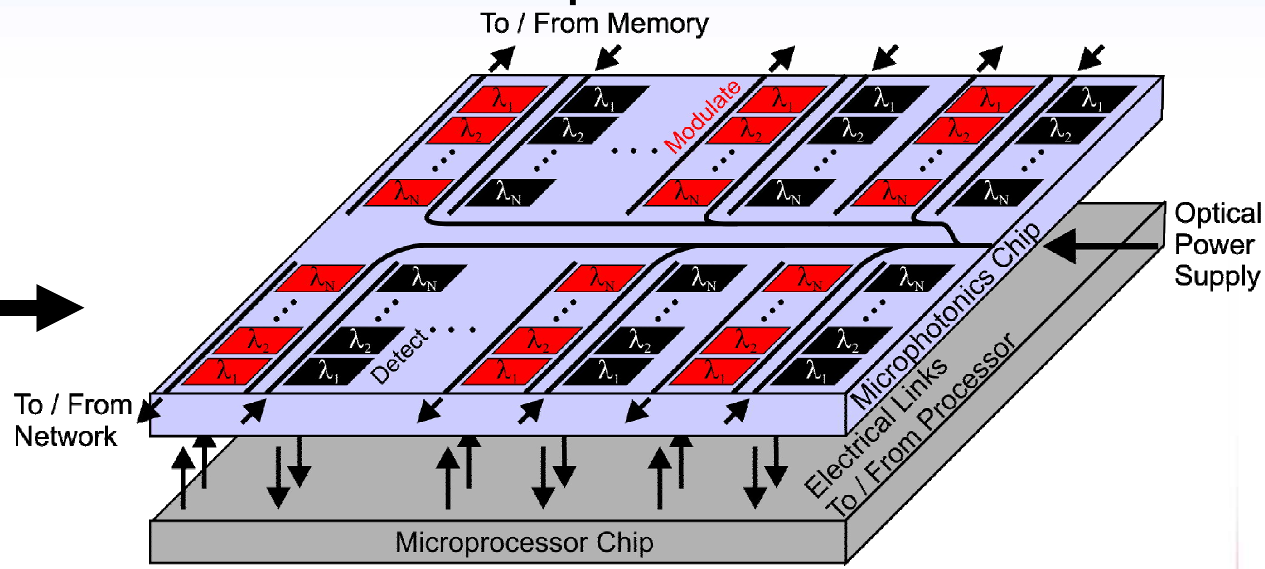
- **Energy: $\tau V_0^2/2Z_0 \rightarrow$ ~10pJ/bit** (50Ω line, 1ns pulse, 1-Volt signal)
  - Chip Comm. Power: 100Tb/s × 10pJ/bit → **1kW/chip**
  - System Comm. Power: 1-ExaFlOPs → **3.2GW Communications Power**
- **Bandwidth**
  - **Board: 10Gb/s/mm/layer** (**1000 layers → 100Tb/s**)
  - **Pins-to-board:** 10Gb/s → **10000 pins/chip → 100Tb/s**
  - **Inter-Rack:** 10000 wires/chip, 1000-chips/rack → **10M wires/rack**
- **Conclusion:** Logistically, off-chip electrical signaling becomes impossible, power consumption is out of control!!!

What about an Optical Network Interface?

Electrical Network Interface



Microphotonic Network Interface



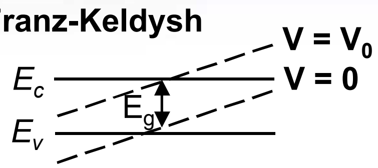
Optical Communications (Tightly Integrated with CMOS)

- **Energy = $h\nu V_0 C/(\eta q)$**
  - Receiver: <**1fJ/bit** required to flip a gate (Miller, 1989)
  - Modulator: Limited by capacitance (can get below **10fJ/bit**)
- **Bandwidth**
  - Optical bandwidth: >1-Tb/s (10Gb/s @100λ's), 50GHz spacings $\rightarrow$ **5THz (40nm)**
  - Bandwidth (on-chip): > 200Gb/s/μm $\rightarrow$ **1Tb/s on a 5um pitch**
  - Bandwidth (off-chip) > ~10Tb/s/mm (**10mm $\rightarrow$ 100Tb/s**)
  - Routing of data could be O-E-O or in the optical domain . . .

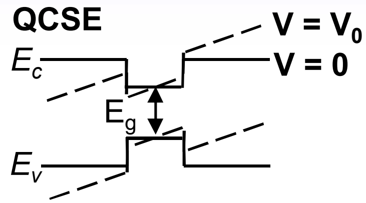
Possible Effects in Si/Ge Systems

Band-Edge Effects (Electro-Absorption $\Delta\alpha$)

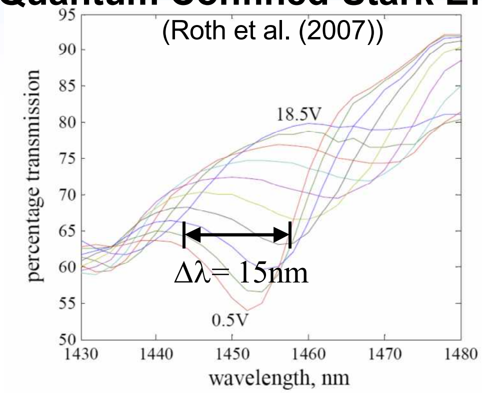
Franz-Keldysh



QCSE



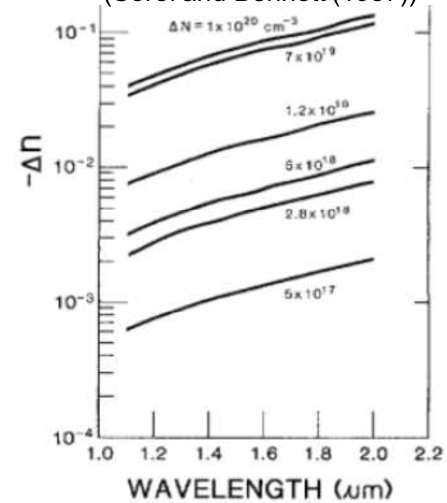
Quantum Confined Stark Effect



- Franz-Keldysh (Liu et al. *NP,* July 2008)
- Quantum Confined Stark (Roth et al. *OE,* April 2007)
- **Advantage:** Strong effect → small, low power devices (Liu claims 50fJ/bit)
- **Disadvantages:** → Limited Optical Bandwidth ($\Delta\lambda$ = 10nm-to-15nm) Limited Contrast ($\Delta\alpha/\alpha \sim 3$), Intricate Fabrication

Free-Carrier Effect

(Soref and Bennett (1987))



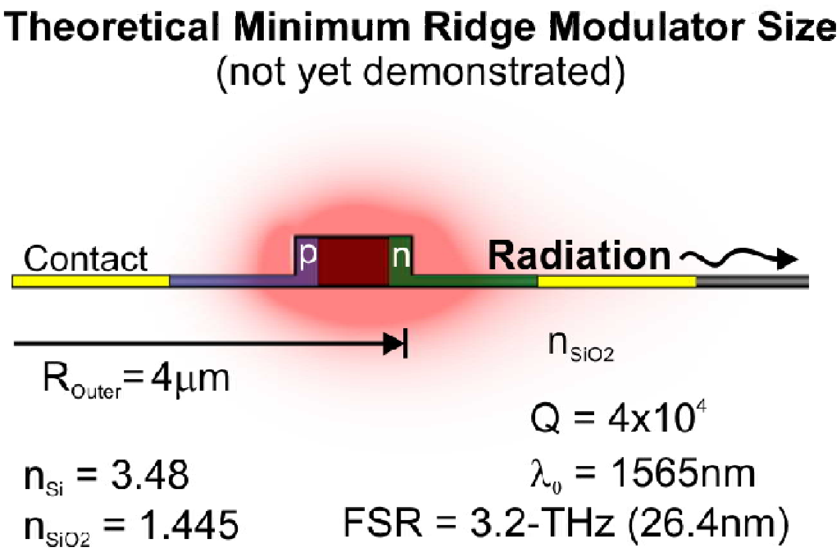
Free-Carrier Effect (Electro-Refraction Δn)

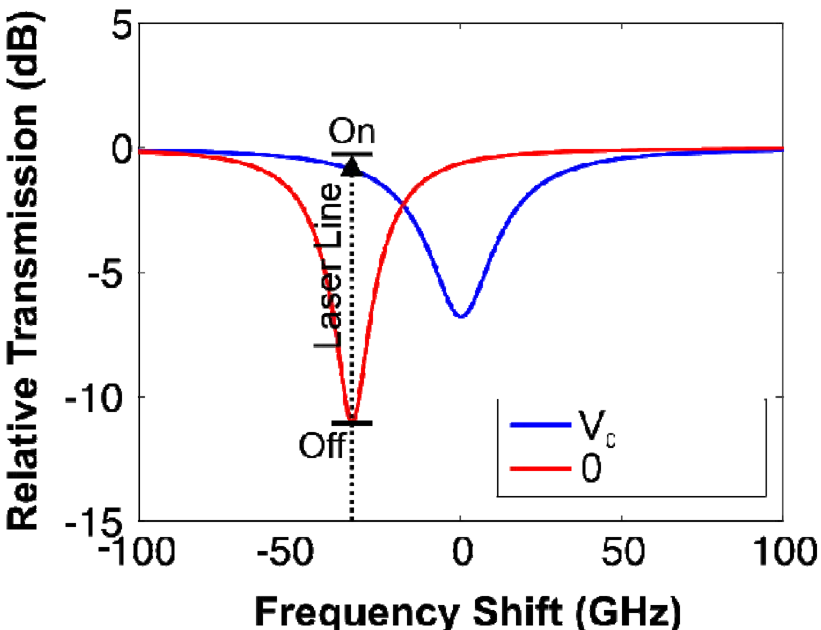
- **Advantages:** Broadband effect ($\Delta\lambda$ >> 100nm), easy CMOS implementation
- **Disadvantages:** Weaker effect → need resonance for low energy/bit, but already have thousands of resonators on-chip

Silicon Modulators

Prior Art

- ❑ Liu (R-biased MZ 2004), Green (F/R-biased MZ 2007), Xu (F-biased Ring, 2005), etc.
- ❑ Note: Forward biased structures all require pre-emphasis to reach 10Gb/s





Goals

- ❑ 10Gb/s operation
- ❑ Low Power
- ❑ Large optical bandwidth

Solutions

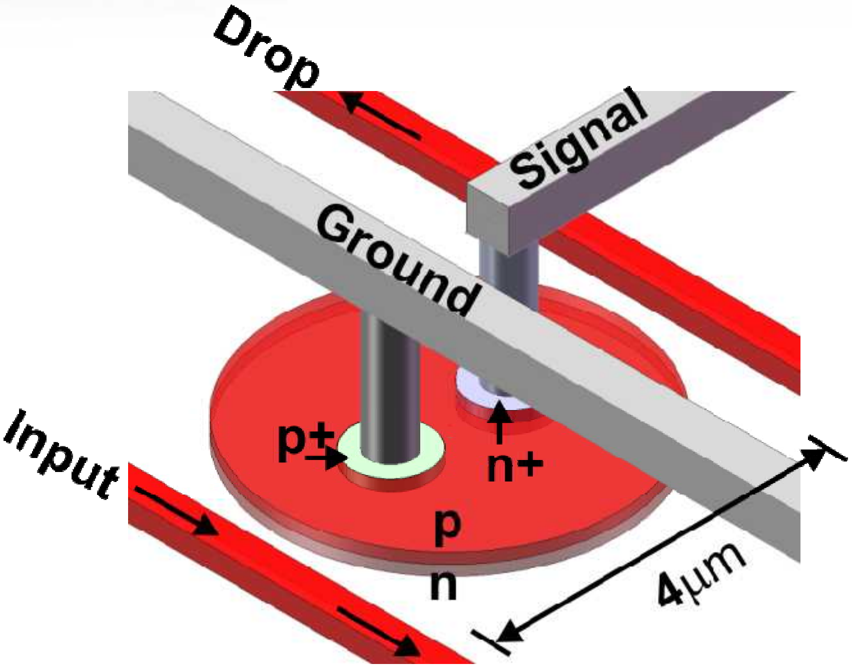
Reverse-Biased (no carrier lifetime issue)

Reverse-Biased, Large Overlap with Mode

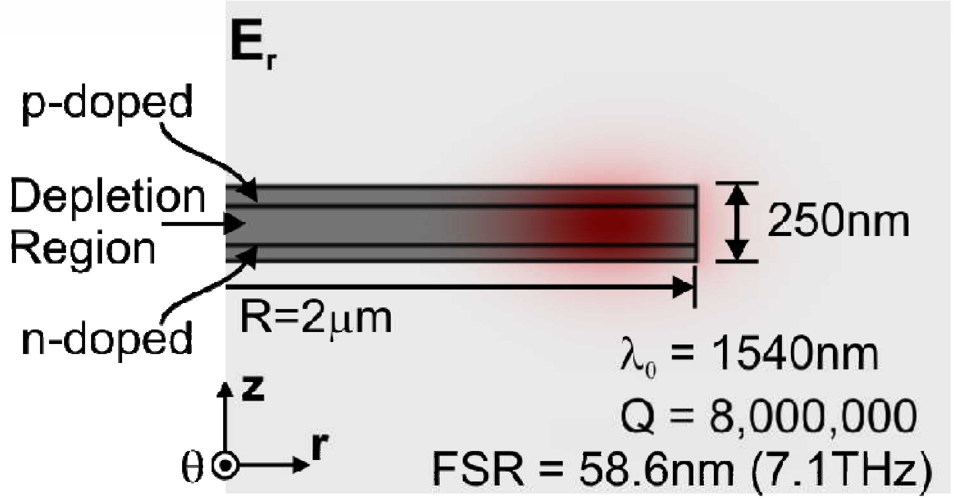
Small Disk/Ring (no ridge) for Large FSR

Microdisk Modulators: Design & Simulation

Vertical P-N Junction



TE$_{11}$ Cylindrical Mode



Advantages of a Vertical P-N Junction Modulator

- ❑ Vertical P-N junction enables tighter confinement and greater modal overlap with depletion region
- ❑ Devices as small as R = 1.5μm are possible
- ❑ Huge Free-Spectral-Range (> 9 THz possible w/ R=1.5μm)
- ❑ Smaller devices, no pre-emphasis → faster / lower power

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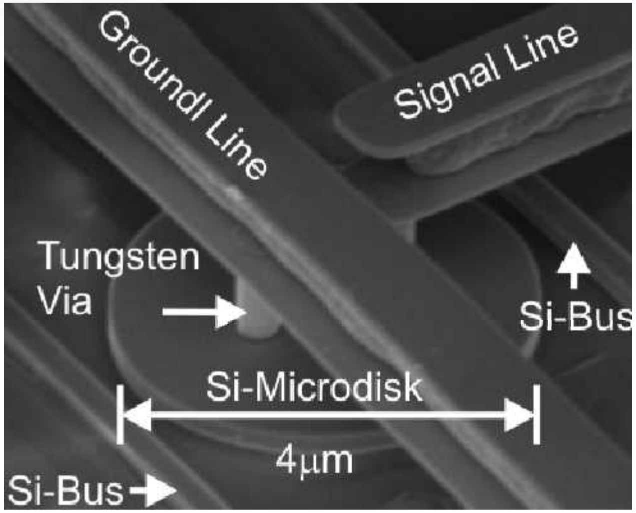
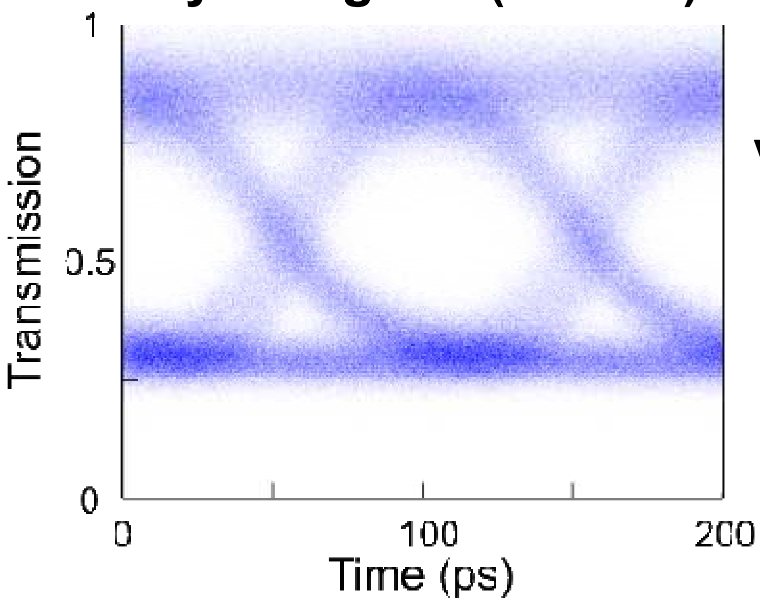
Microdisks Modulator Demonstration

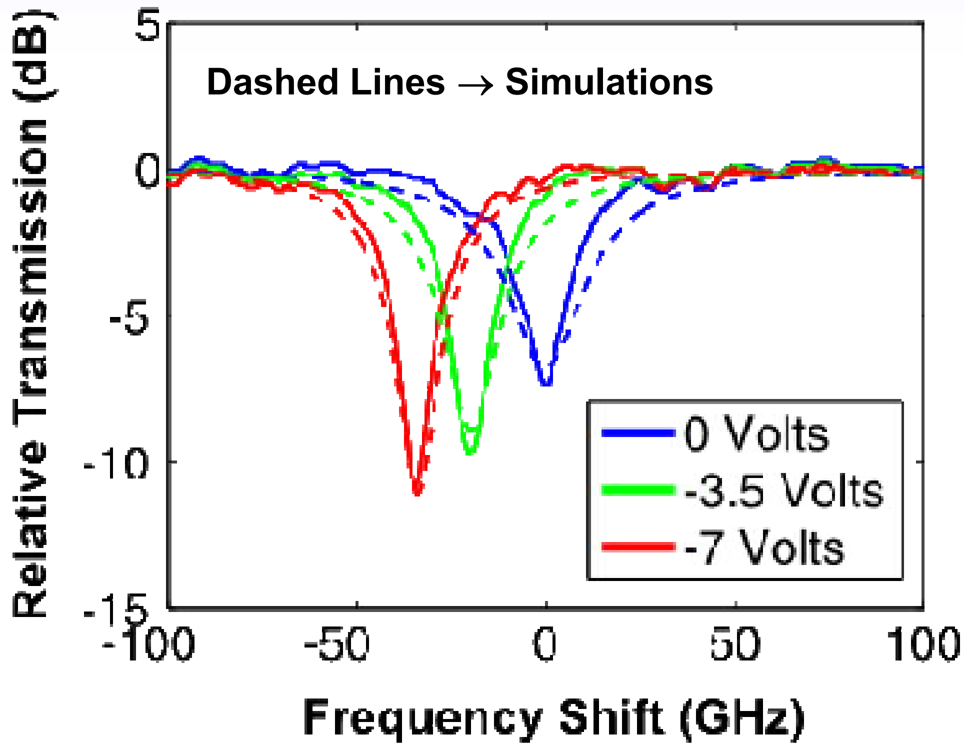
SEM of the Microdisk



Eye Diagram (10Gb/s)



Frequency Shift vs. Reverse Bias



Vertical Junction Reverse-Biased Results

- ❑ 35-GHz freq. shift demo'ed, >70-GHz possible
- ❑ Achieved a BER<10^{-12} at 10Gb/s
- ❑ First resonant modulator with CMOS compatible drive (1.8V incident, ~3.5V due to reflection)

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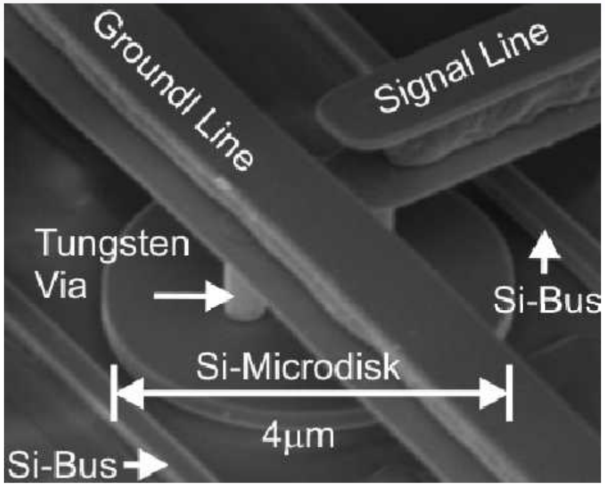
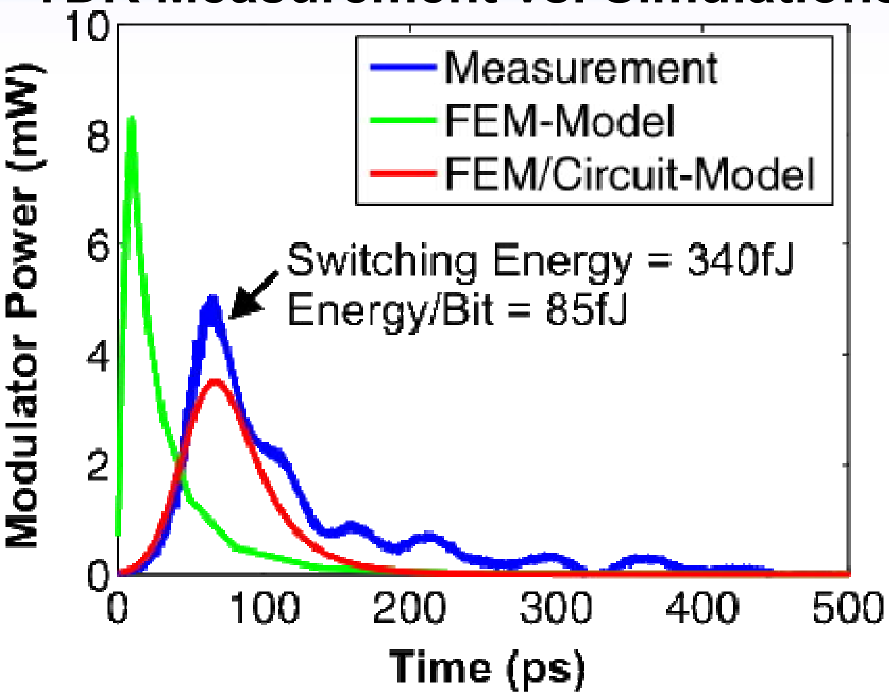
Power Efficiency Measurement (energy/bit)

SEM of the Microdisk



TDR Measurement vs. Simulations



Time Domain Reflectometry Measurement Results (@3.5V)

- Reverse-biased approach dissipates essentially no static power
- Switching Energy = 340fJ
- PRBS Energy/Bit = Switching Energy/4 = 85fJ **(100X less than electrical)**
- New designs indicate ~10fJ/bit is possible

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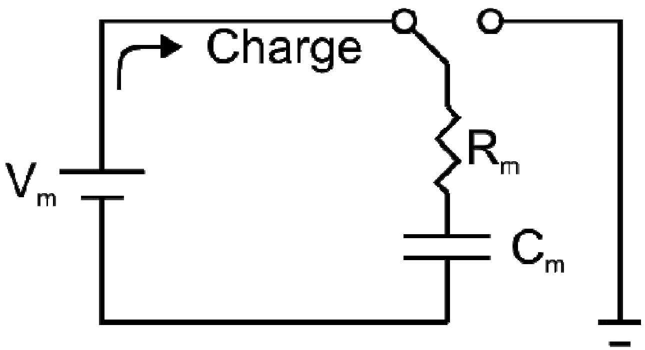
Energy/Bit in a Capacitive Modulator

Definition: $Energy/Bit = \frac{1}{BR \cdot T}\int_0^T P(t)dt, \quad where\ BR = Bit\ Rate$

Energy

Total Bits

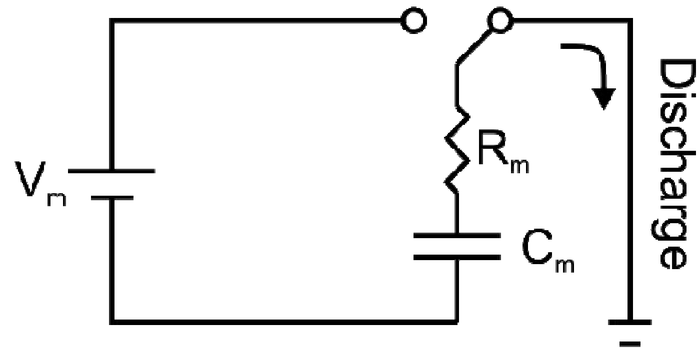
0-to-1 Transition



CV^2 Energy Supplied

($CV^2/2$ Dissipated, $CV^2/2$ Stored)

1-to-0 Transition



0 Energy Supplied

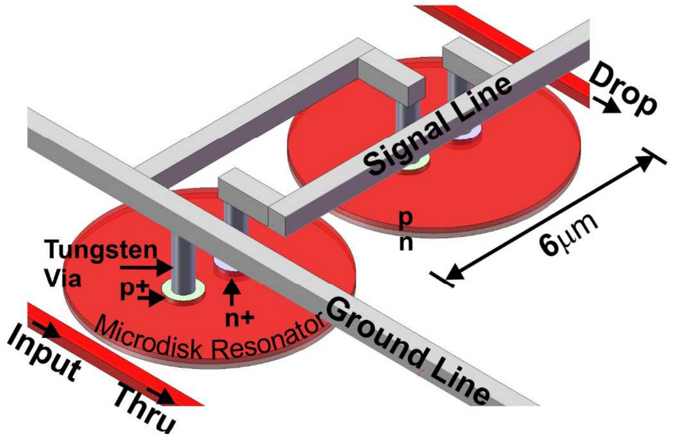
($CV^2/2$ Dissipated)

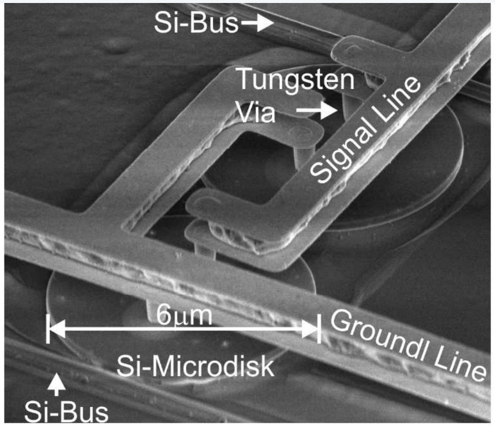
- **Switching Energy:** $E_s = CV^2$ *($CV^2/2$ dissipated, $CV^2/2$ stored)*
- **Clocking Energy/"Bit":** $CV^2/2$ *(because 0-1-0-1-0-1, etc.)*
- **E(energy/bit|0)** = P(0-1|0-state)*$energy_{diss}$(0-1)+P(0-0|0-state)*$energy_{diss}$(0-0)
  = 0.5*$CV^2/2$+0.5*0 = $CV^2/4$
- **E(energy/bit|1)** = P(1-0|1-state)*$energy_{diss}$(1-0)+P(1-1|1-state)*$energy_{diss}$(1-1)
  = 0.5*$CV^2/2$+0.5*0 = $CV^2/4$
- **PRBS E(energy/bit)** = P(0)*E(energy/bit|0)+P(1)*E(energy/bit|1) = $CV^2/4$
- *So, Liu et al., you may have a 25fJ/bit modulator*

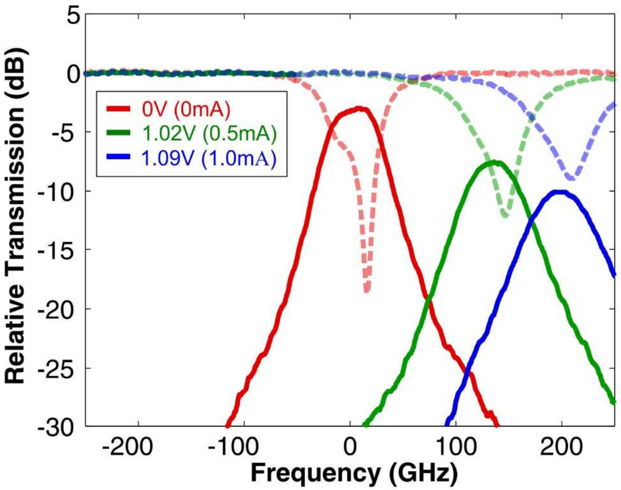
Reconfigurable Networks: Bandpass Switch

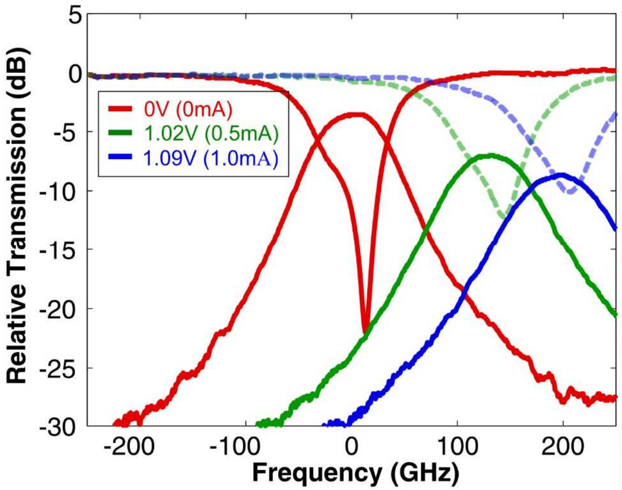
Demonstration

- ❑ 1st demonstration of high-speed, electrically active, silicon bandpass switches
- ❑ Completely shift resonator bandpass out of the channel









Benefits

- ❑ Potential for ultralow power switching in the optical domain (to avoid OEO conversions)

M. R. Watts et al., OFC Postdeadline Presentation (Feb. 2008)
Note: Optically Active Switch Based on Q-Switching by Y. Vlasov et al., Nature Photonics (Mar. 2008)

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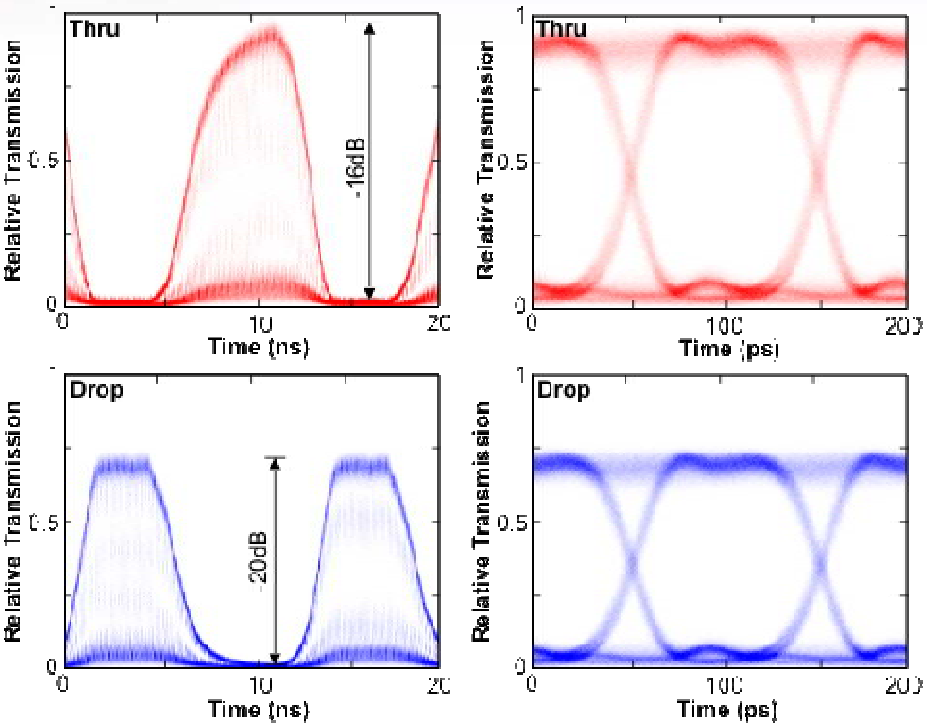
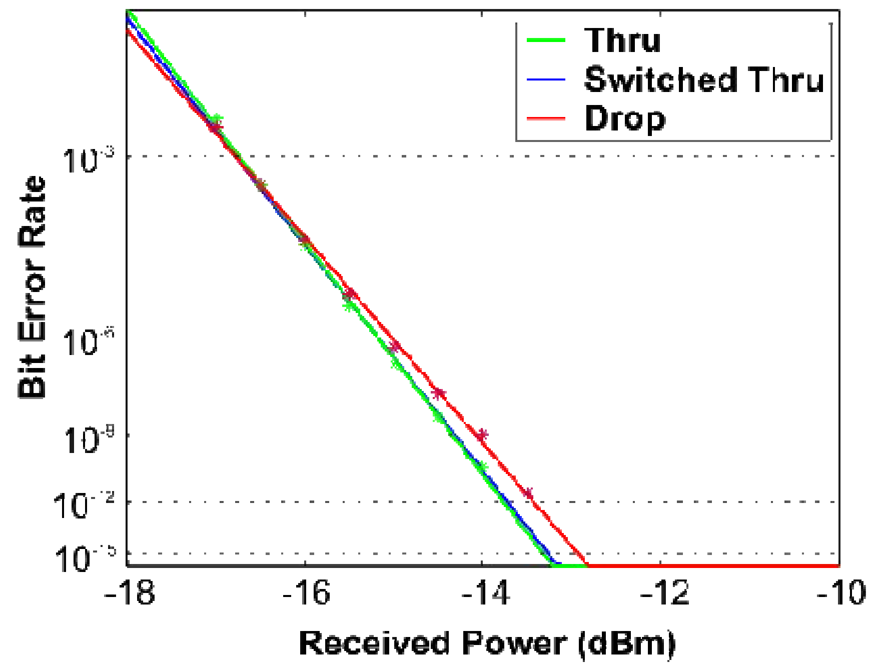
Data Routing with Bandpass Switch





Switch Results

- ❑ Data switched error-free (BER<10^{-12}) with little power with ~2ns rise time
- ❑ Power penalty measured to be <0.4dB in Drop Port and <0.1dB in Thru Port
- ❑ Driven with ~0.6V (~1V due to reflection), so CMOS compatible

Quick Review

Modulators

- Demonstrated, smallest, highest speed, lowest energy/bit (100X less energy/bit than electrical), and lowest voltage resonant silicon modulators

Bandpass Switches

- First, high-speed silicon bandpass switches
- Requires ~1V to shift bandpass by ~200GHz

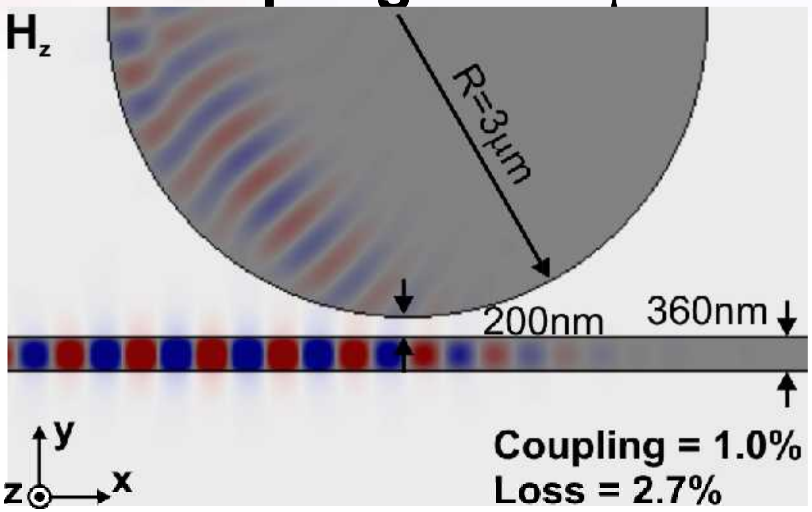
Optical-Electrical-Optical or Optical Domain Routing?

- Both approaches are possible. Modulators and bandpass switches form the beginnings of a suite of available networking components

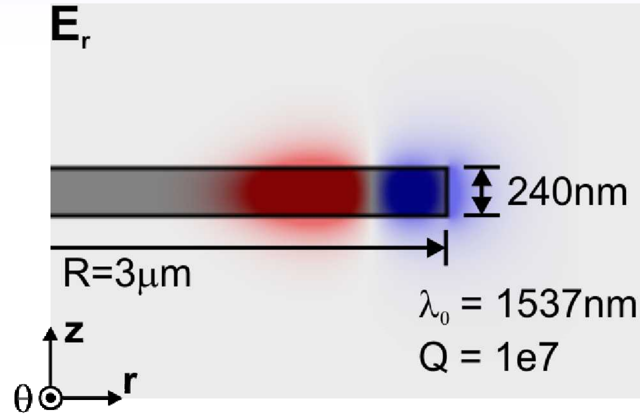
Still, there are some problems with microdisks . . .

Problem 1: Coupling Losses

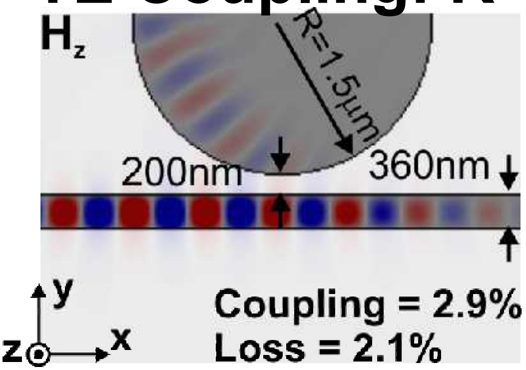
TE Coupling: R = 3μm



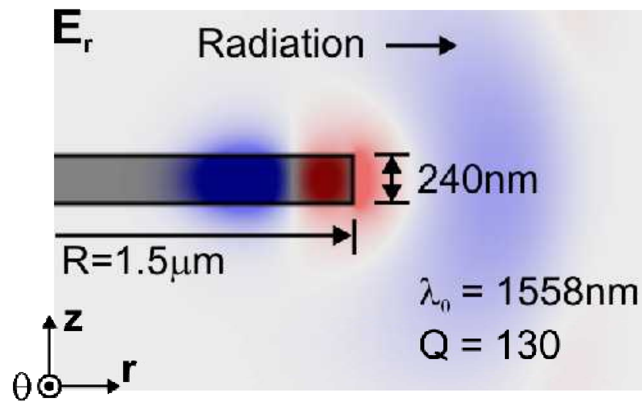
TE_{21} Mode: R = 3μm



TE Coupling: R = 1.5μm



TE_{21} Mode: R = 1.5μm



Important Considerations

- ❑ Smaller disk ⇒ Lower coupling loss? Why?
- ❑ Secondary mode can be cut-off, but requires very small disks

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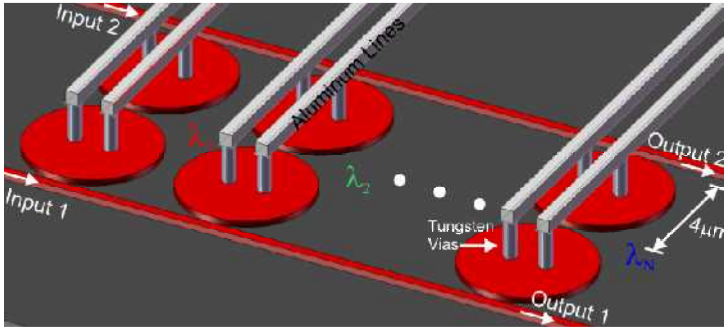
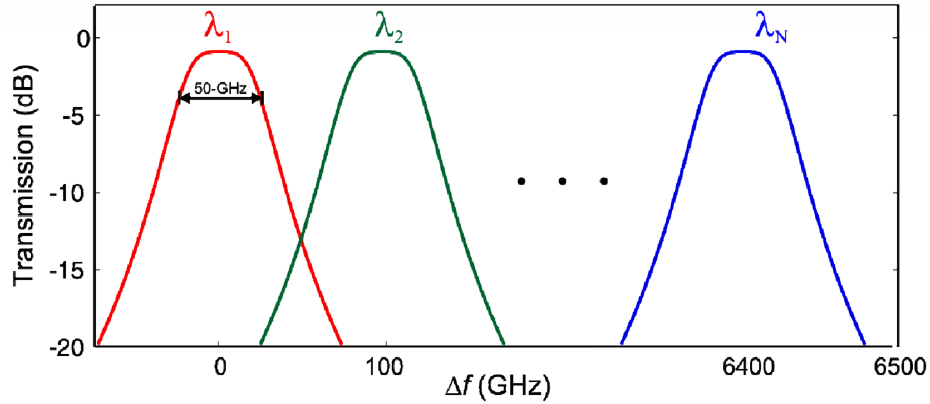
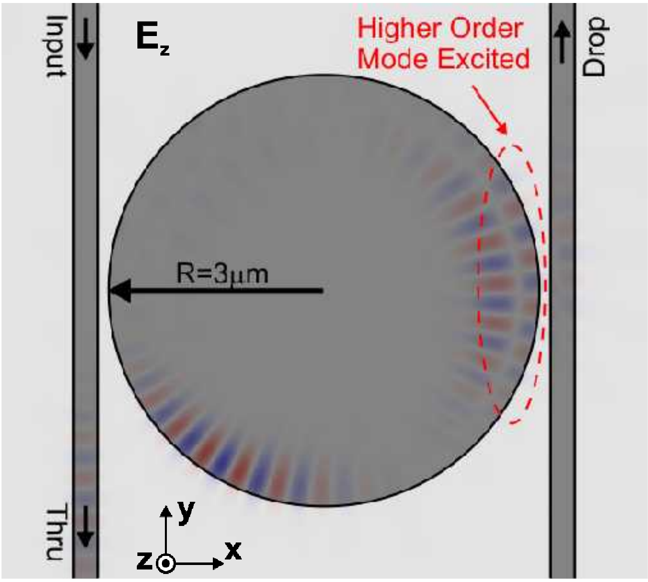
Problem 2: Limited Free-Spectral Range

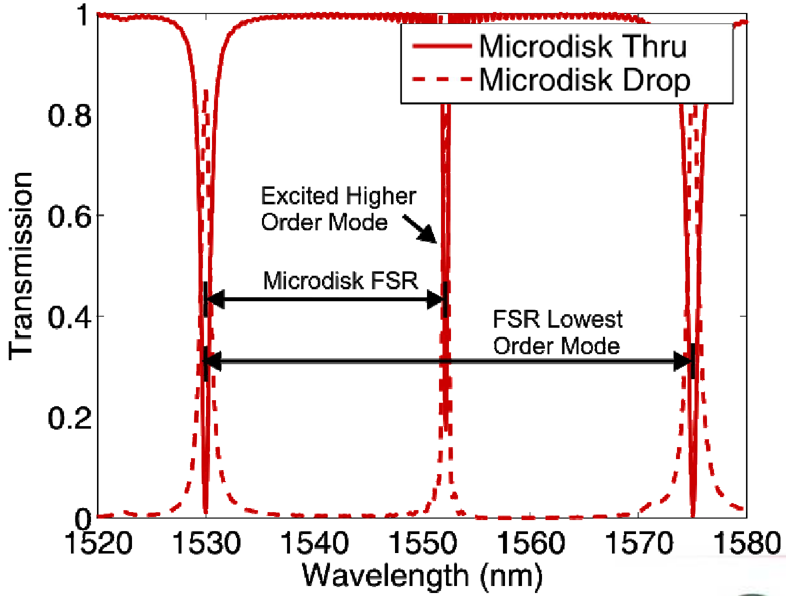
Goal: Large channel count, large bandwidth → Large FSR





Problem: Microdisks propagate multiple spatial modes, corrupting FSR





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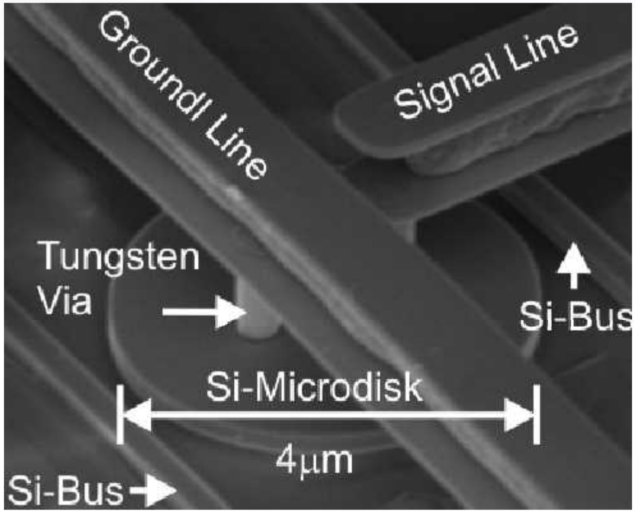
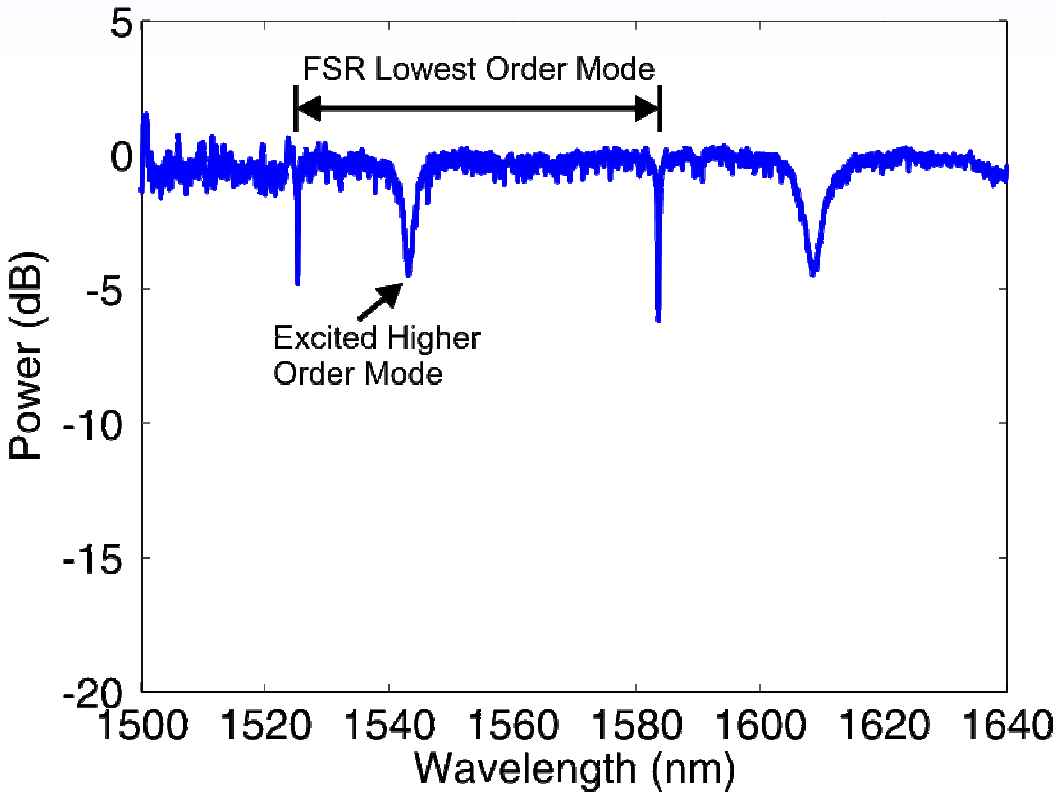
Experimentally Observed Microdisk FSR

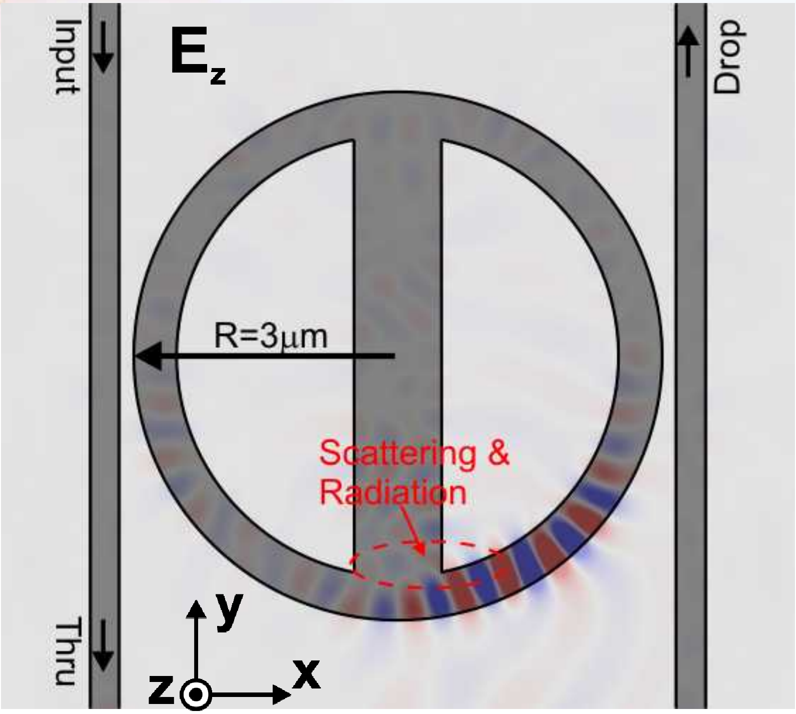


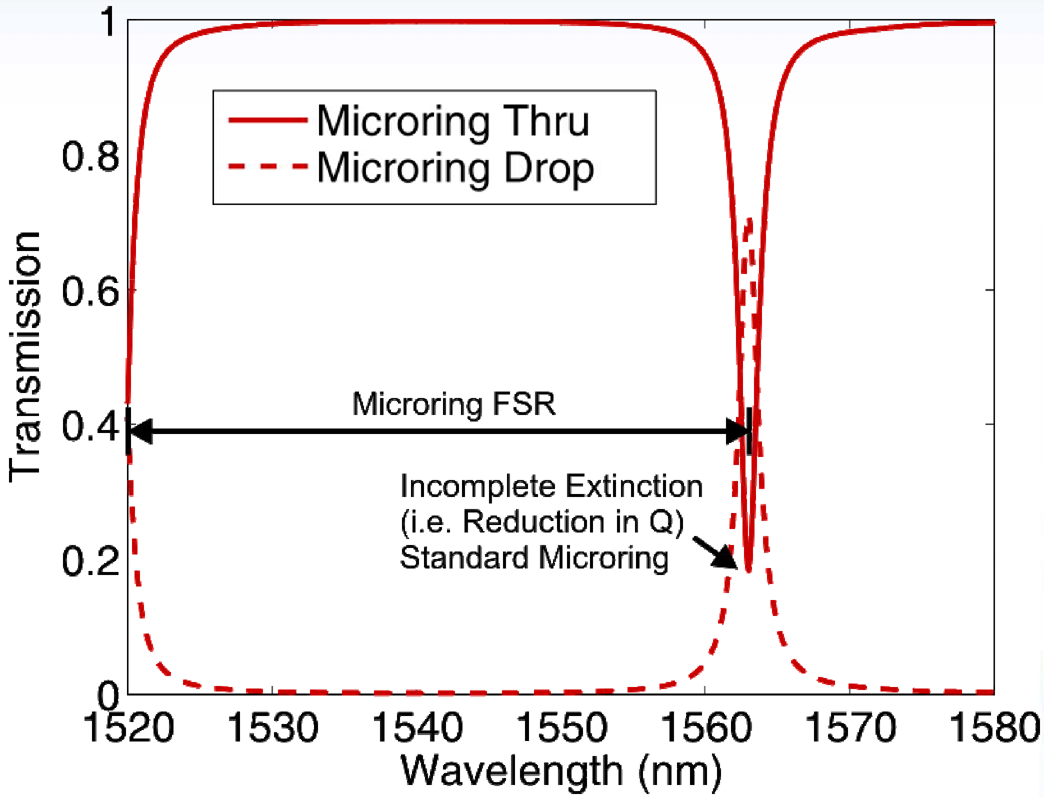


Results

- ❑ As expected, microdisk propagates higher order modes corrupting FSR and limiting the available line bandwidth
- ❑ Can be fixed with a microring, but how do you make electrical contact?

What about Directly Contacting a Microring?





Results

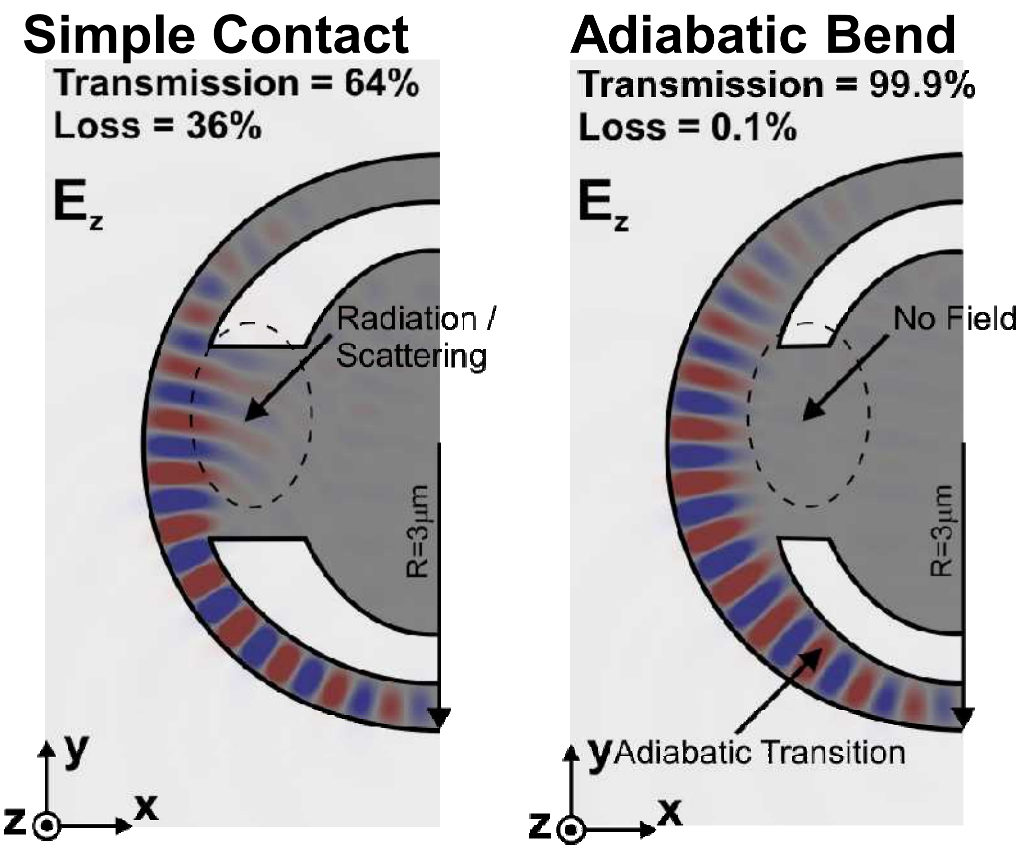
- ❑ Microrings enable a recovery of the full Free Spectral Range
- ❑ However, the contact leads to scattering and a reduction in Q
- ❑ Can we modify the ring geometry to enable contact without loss?

An Adiabatic Bend: Contact without Radiation

Principle: Slow perturbations ($\Delta\beta/\kappa$ >>1) do not result in coupled power

$$P(L) \propto \left|\frac{\kappa}{\Delta\beta}\right|^2 \left[1 - \cos(\Delta\beta L)\right]$$

Thought: So, what if we introduce an adiabatic taper into a bend?



Results

- ❑ Adiabatic bend reduces losses from 36% to 0.1%
- ❑ Surprising how rapidly "adiabatic" transition is made (enabled by large difference in propagation rates between modes)

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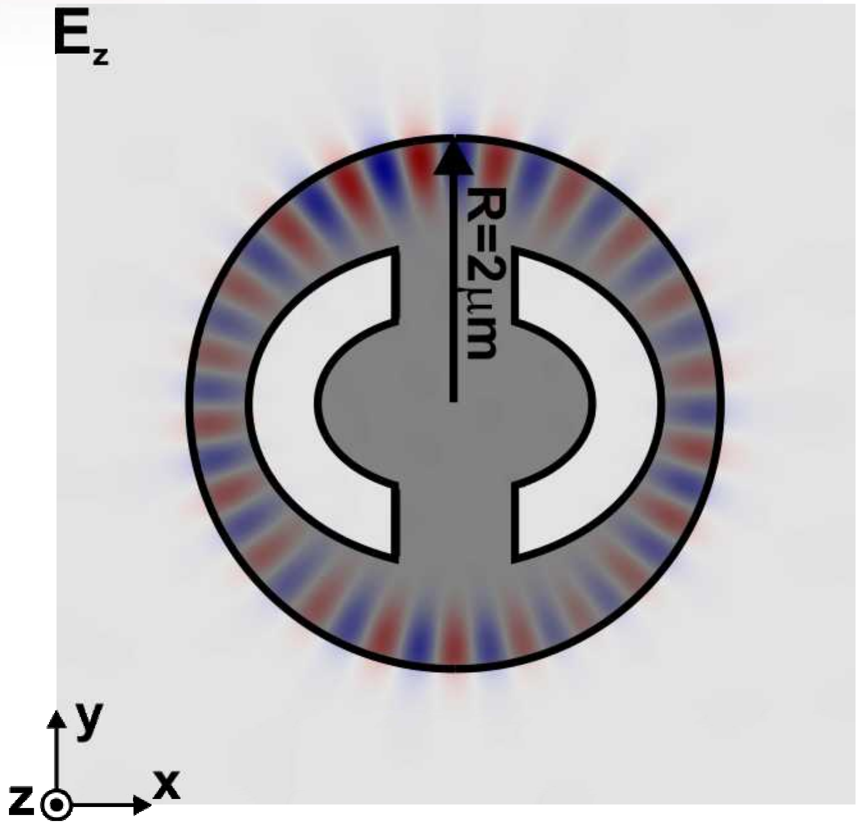
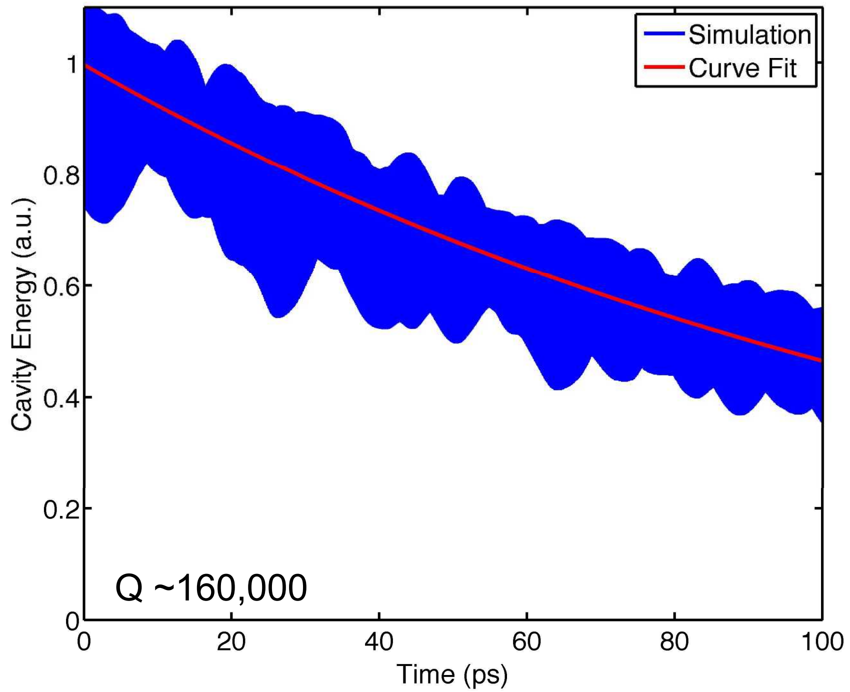
Adiabatic Microring-Resonator Q

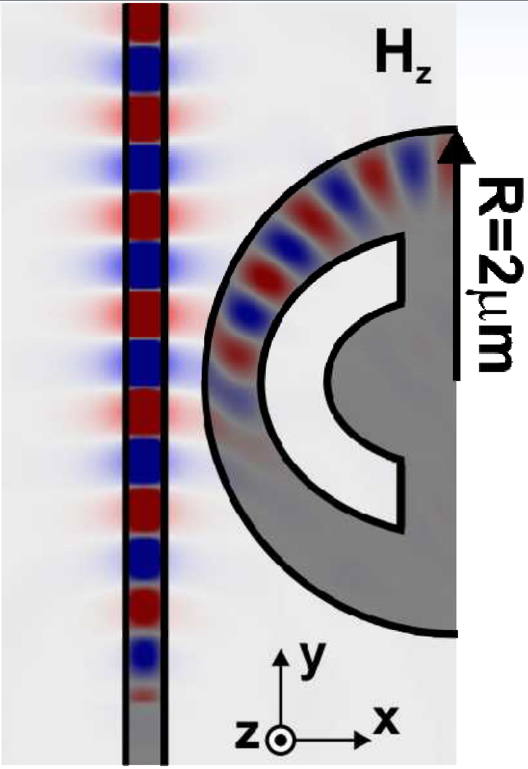




Results

- Internal Q's exceeding 10^5 are possible in small adiabatic microrings
- Q's exceeding 10^6 are likely by iterating on designs

Coupling Losses: Essentially Eliminated



Coupling = 1.5%
Loss = 0.16%

Approach / Results

- ❑ Higher order modes are eliminated in coupling region → lossless coupling
- ❑ Narrower bus than ring waveguide used to mode-match / suppress coupling to lossy supermodes with the structure*,**

*M. R. Watts, PhD MIT Thesis (2005)

M.A. Popović et al., Opt. Lett., **31, pp. 2571-2573 (2006)

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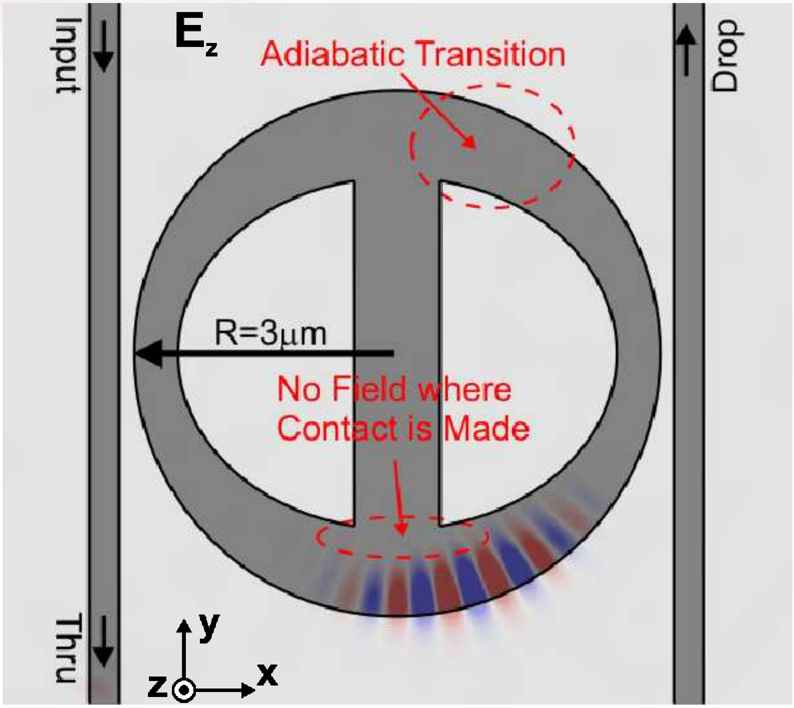
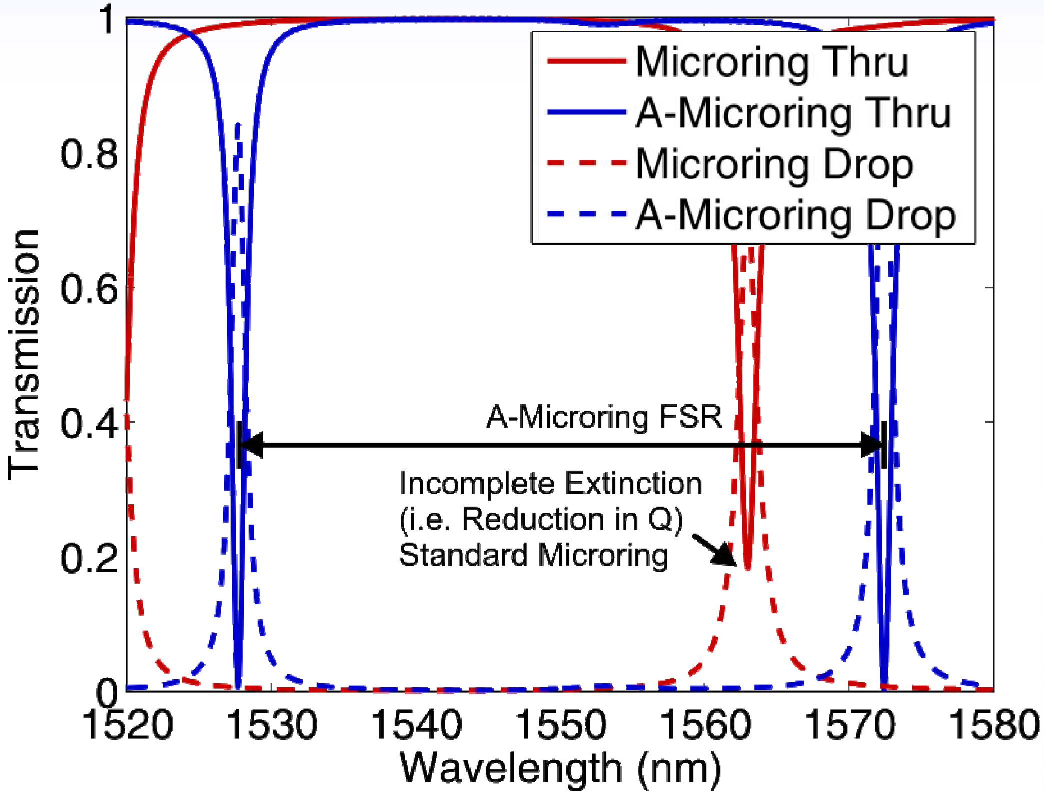
Free Spectral Range: Fully Recovered

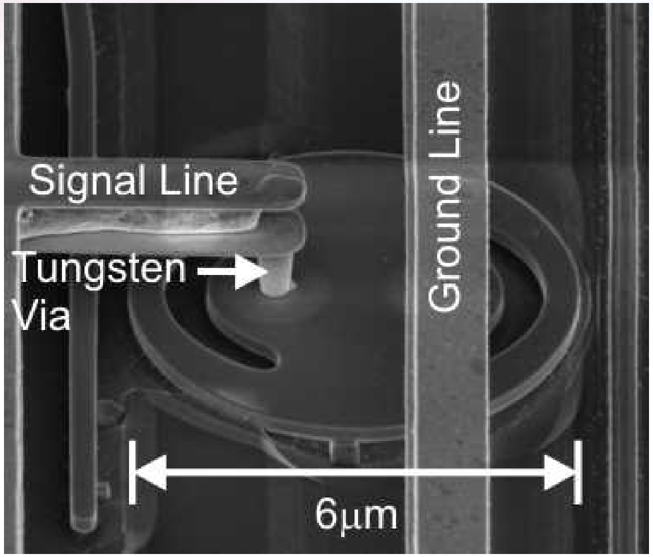


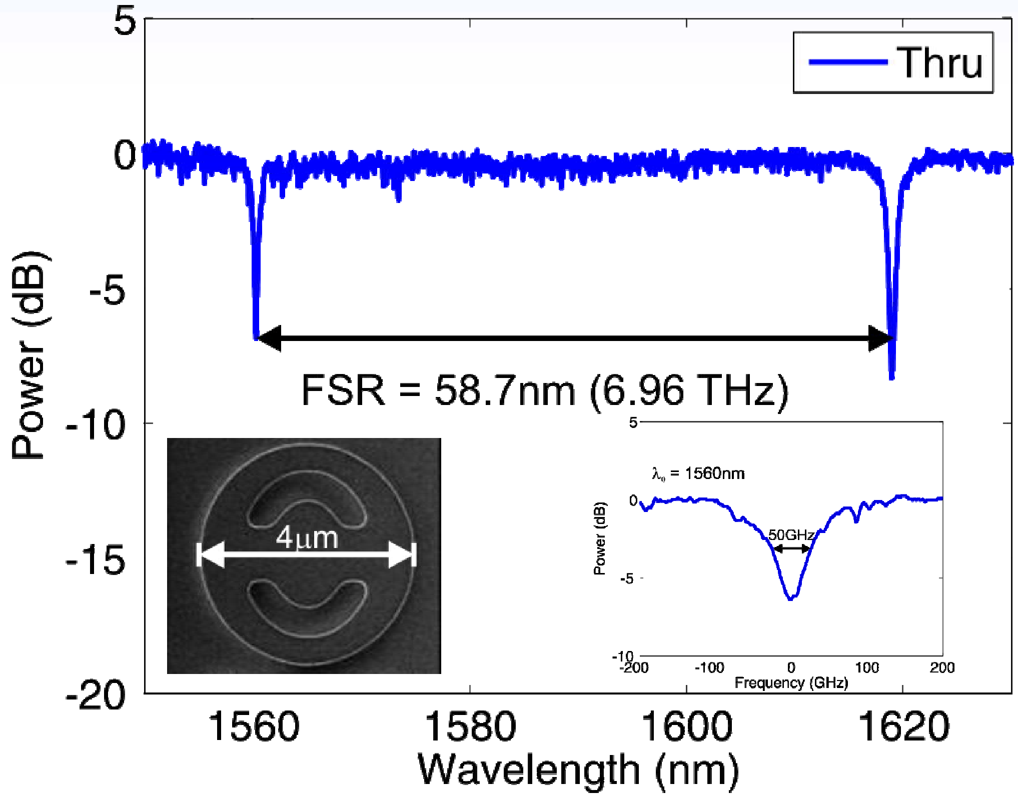


Results

- ❑ Adiabatic microrings enable a recovery of the full Free Spectral Range without inducing scattering and loss

Adiabatic Microring: Experimental Results





Results

- ❑ Uncorrupted 6.96THz Free-Spectral-Range
- ❑ Eliminated higher order modes without significant loss (Q_{ext}~4000)
- ❑ Slight reduction in Q due to fabrication bias (i.e. loss of ~100nm)
- ❑ Electrically active, 4μm rings currently have insufficient Q, 6μm rings have high-Q, testing now . . .

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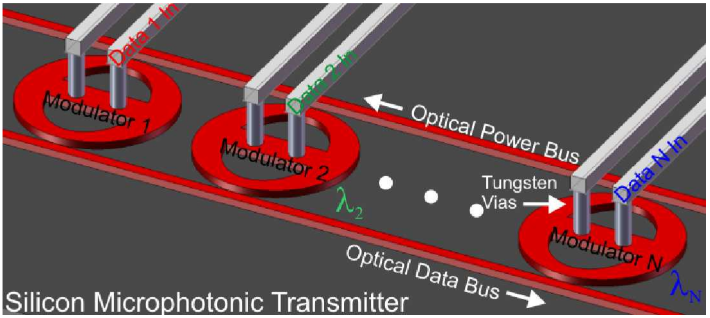
Summary and Future Outlook

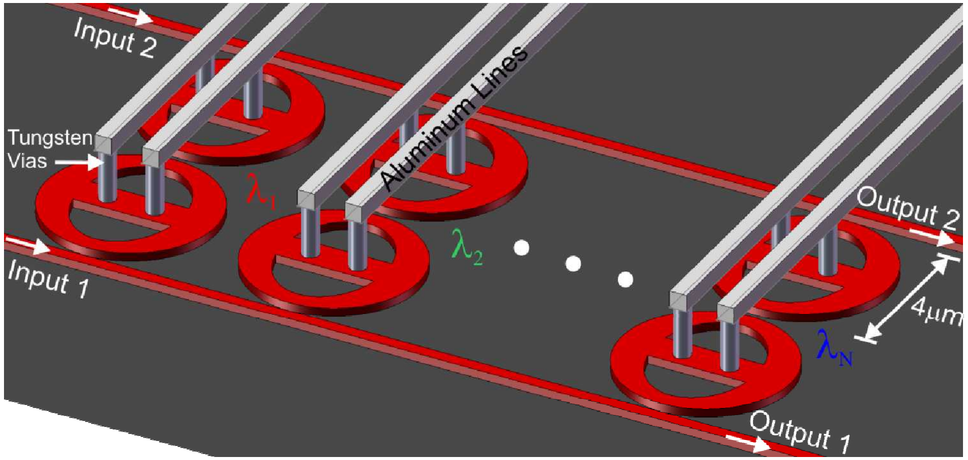
Modulators

- ❑ Demonstrated error-free, 10Gb/s NRZ data transmission (no pre-emphasis)
- ❑ Communications efficiency of 85fJ/bit **(100X less than electrical interchip)**
- ❑ Path to ~10fJ/bit with <2.5V drive is highly probable . . . **enabling 1-Tb/s @10mW**

1×N Silicon Modulators



1×N Bandpass Switches



Bandpass Switches

- ❑ First demonstrated electrically active high-speed (~2ns) silicon bandpass switch
- ❑ Can be driven with ~1V drive
- ❑ Did not require any post-fabrication trimming

Challenges Ahead

- ❑ Temperature control, fabrication tolerances, dense integration

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