Low Power Silicon Microphotonic Communications for Embedded Systems

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High Performance Embedded Computing (HPEC) Workshop

MIT Lincoln Labs

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Sandia National Labs, Albuquerque NM

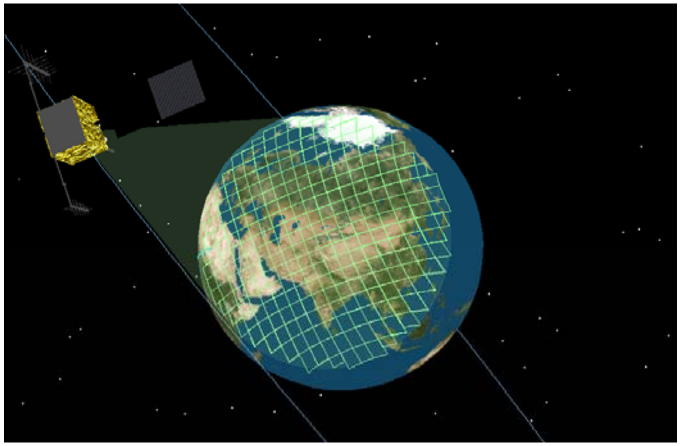
Applied Photonic Microsystems

Motivation: Sandia FPA Development

"See everything, everywhere, always, and do it fast"

Develop new focal plane array (FPA) architectures and key enabling technologies in preparation for the future production of advanced very large, high pixel count, very high sample rate FPAs for full earth persistent monitoring, fast event detection and national security missions.

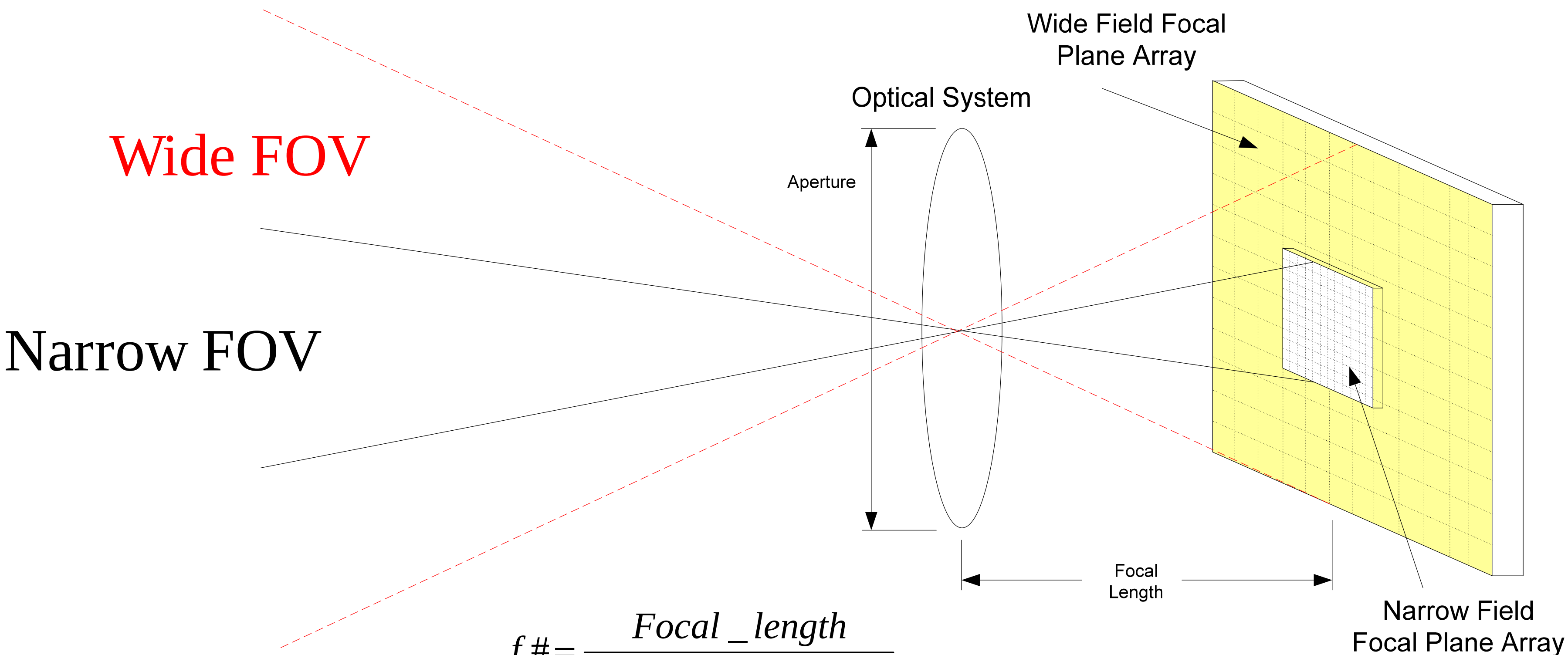
Emphasis on preserving transient information of interest while suppressing an enormous volume of background data



Sandia's remote sensing systems are <u>not</u> used for imaging, but rather for transient signal detection, recording, and processing

Why are Large FPAs Important

$$fpa\_size \approx Aperture\_diameter * f\#*FOV(rad)$$



$$f\# = \frac{Focal\_length}{Aperture\_diameter}$$

Wide Field of View ➔ Large Focal Plane Array
High Resolution ➔ High Pixel Density

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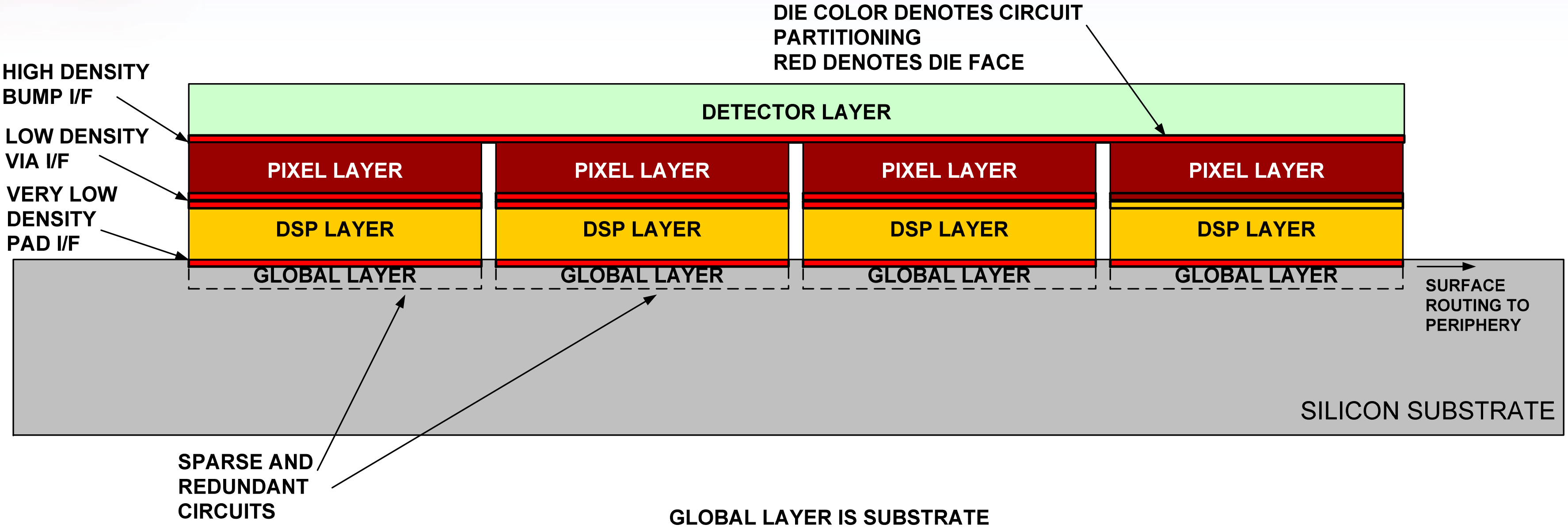
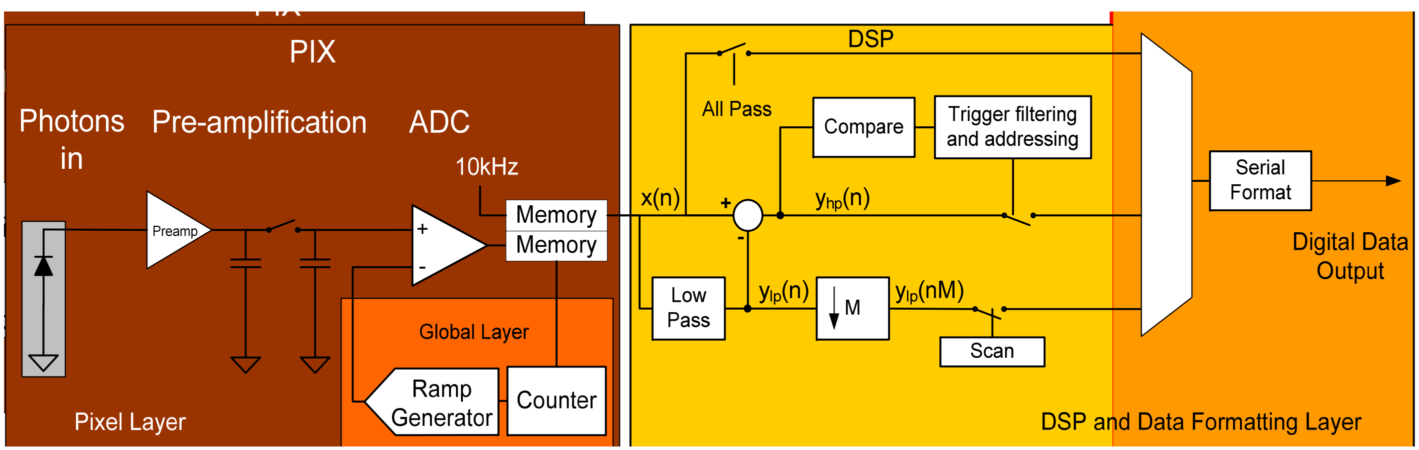
Large Arrays Through 3D Stacking



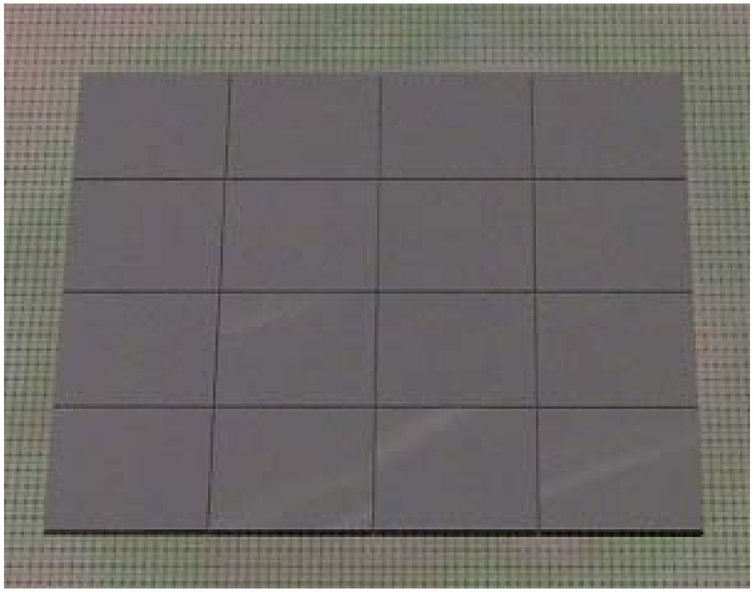
GLOBAL LAYER IS SUBSTRATE

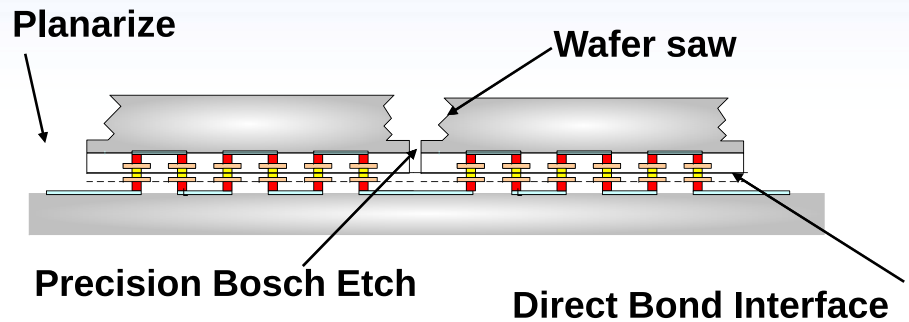


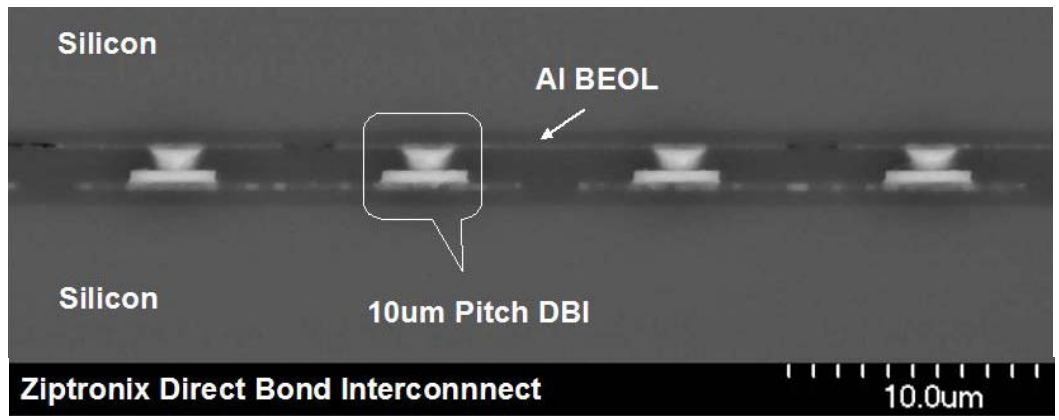
Signal Processing Utilized to Decimate the Data

The Tiling Process

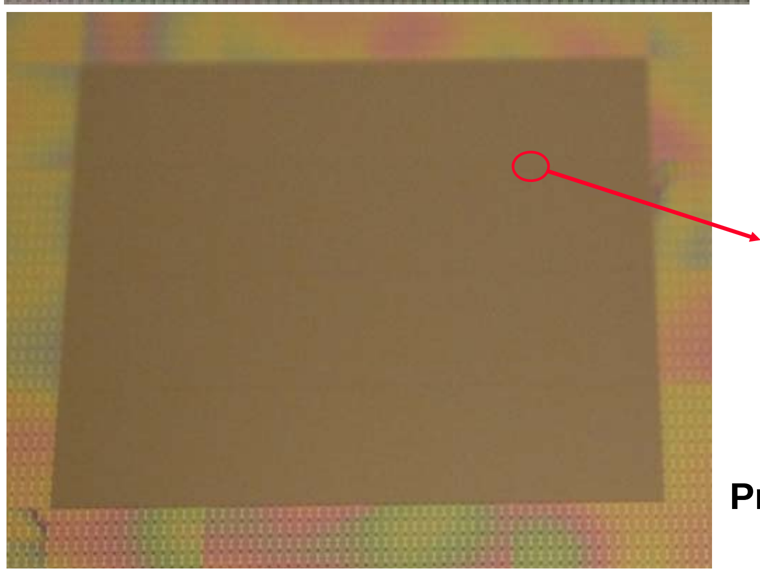
Tiled Assembly before Planarization
Large Wafer Saw Gaps are visible

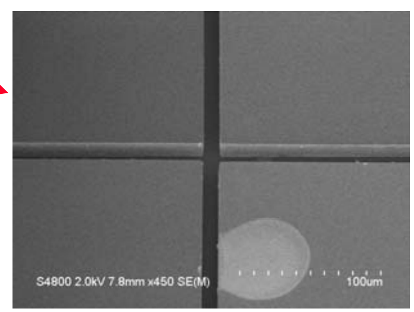






Oxide-Oxide Bonds Form Interface



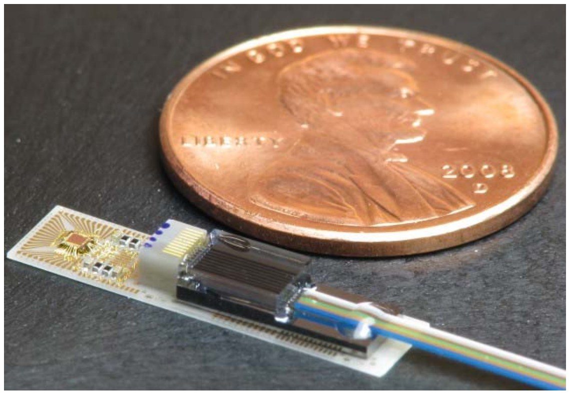


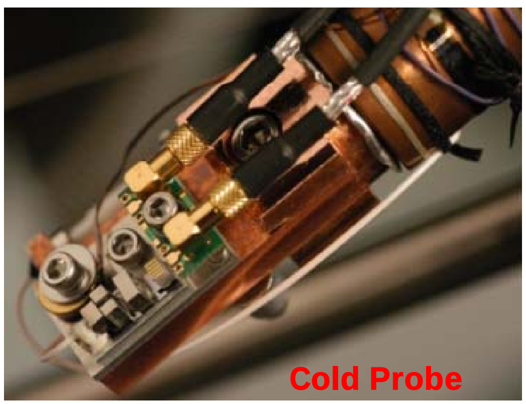
Precision Bosch Etch Tiles
10um +/2um gaps

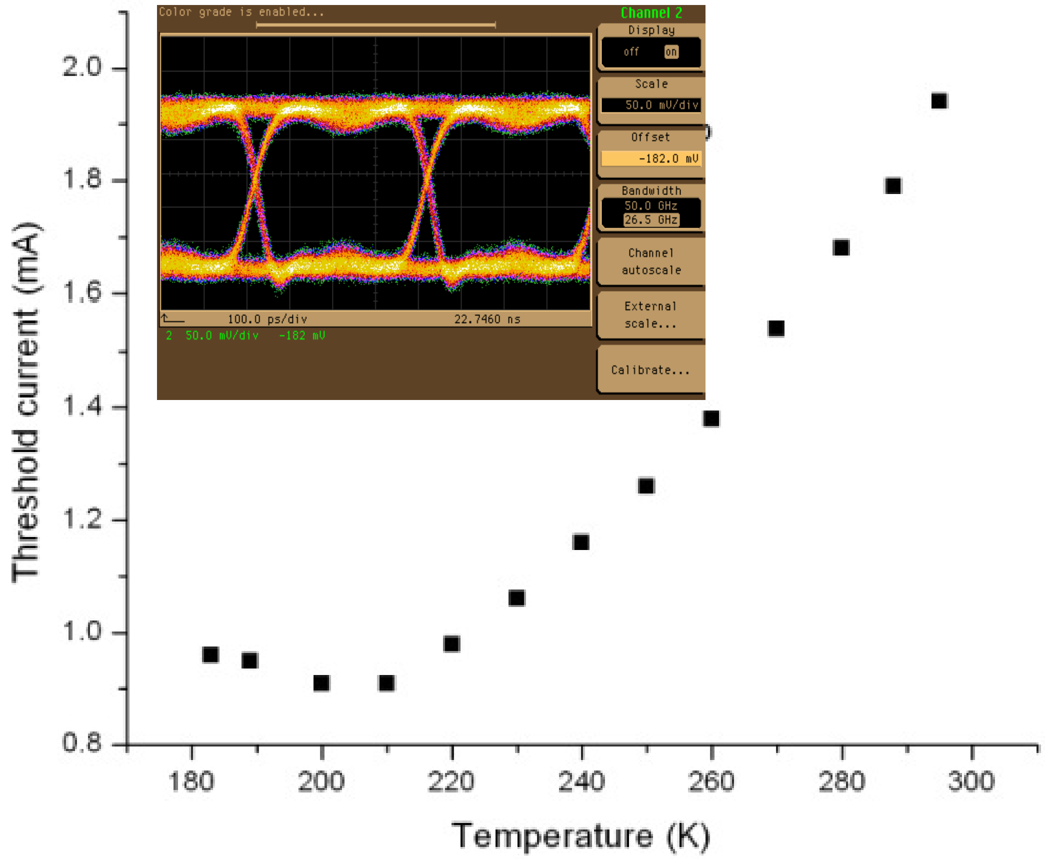
Off-Chip Optical Communications

Optical Communications (D. Serkland, G. Keeler et al., Sandia)

- ❑ VCSEL-Based Communications Optimized to Operate at 200K







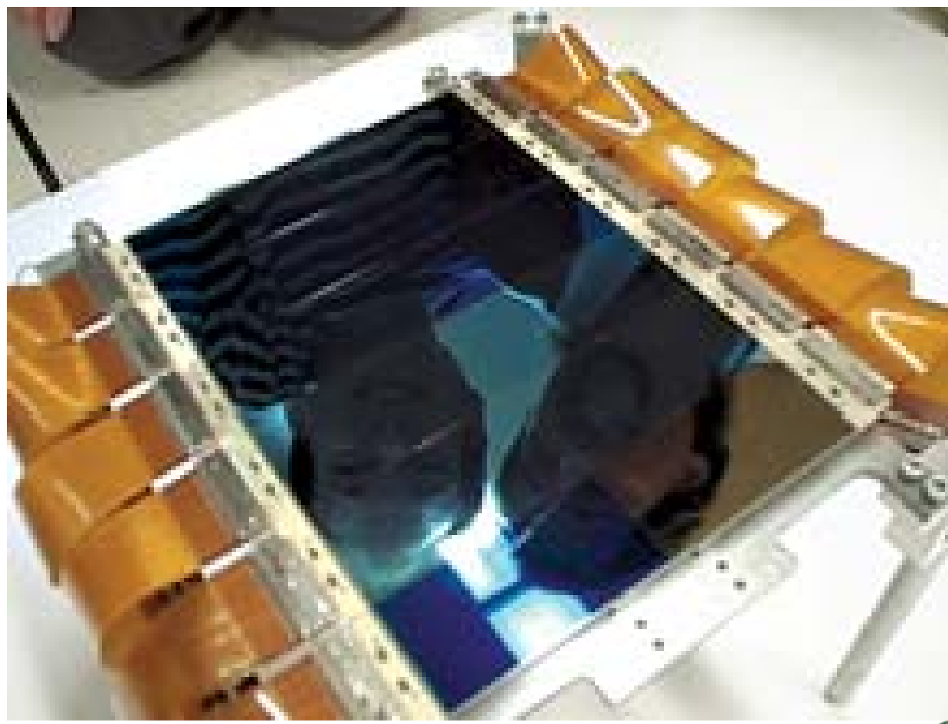
- ❑ Mux/Driver function demonstrated at 4.5mW/channel at 3Gb/s, considerably lower than commercial results
(Note: Result does not include clock recovery)

Large, High-Speed Imaging Arrays?

Sandia's systems do not image, but rather look for transient signal detection so much of the data can be reduced, solution is managable

Imagers: Large, High-Speed Imaging Arrays (Ex. from MIT Lincoln Labs)

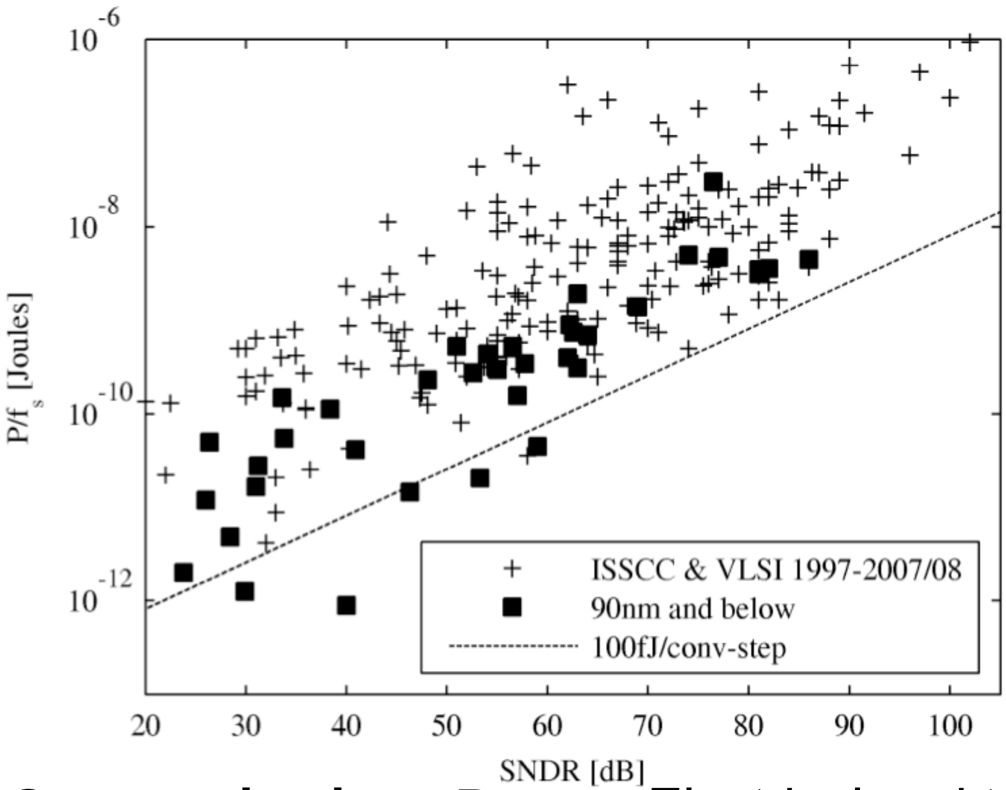
- ❑ **Canada-France-Hawaii-Telescope:** 100M Pixels
- ❑ **High Speed Camera:** 2MFrames/sec, 16k Pixels



Limits to Large, High-Speed Imagers

Assume: 100MPixel@100kFrames/sec @10-bits ➔ 100Tb/s

Analog-to-Digital Converter Power: 100fJ/bit, trending down (10W@100Tb/s)



B. Murmann, "A/D Converter Trends: Power Dissipation, Scaling and Digitally Assisted Architectures"

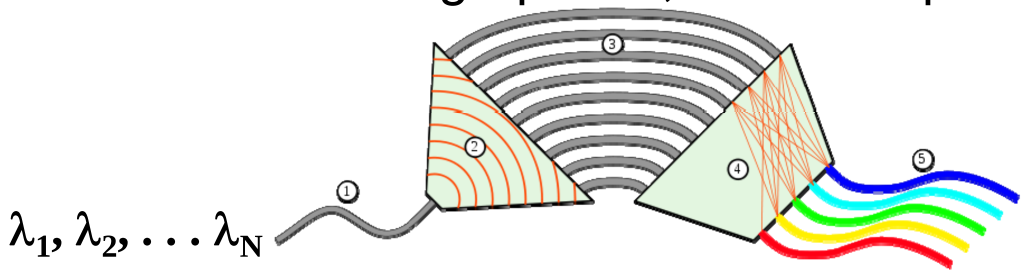
Communications Power: Electrical and traditional optical communications consume ~30-to-40pJ/bit. At 100Tb/s ➔ 3-to-4kW of power

Communications Bandwidth: At 10Gb/s/line ➔ 10,000 lines

Consider weight, thermal conductance, EMI, etc.

Silicon Photonics

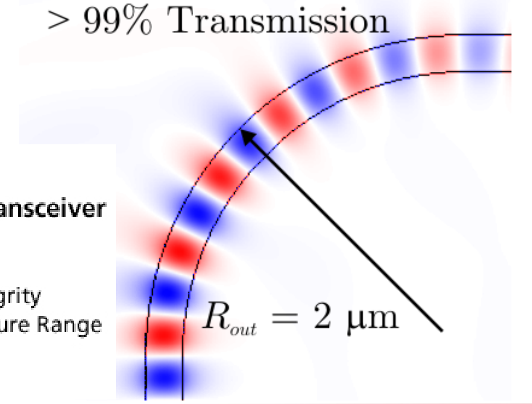
Telecom Networks: Achieve terabit/s data-rates down a single fiber, but are constructed of high-power, macroscopic components . . .

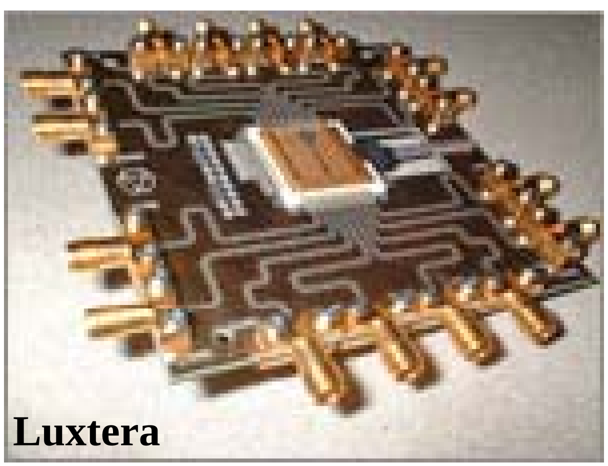


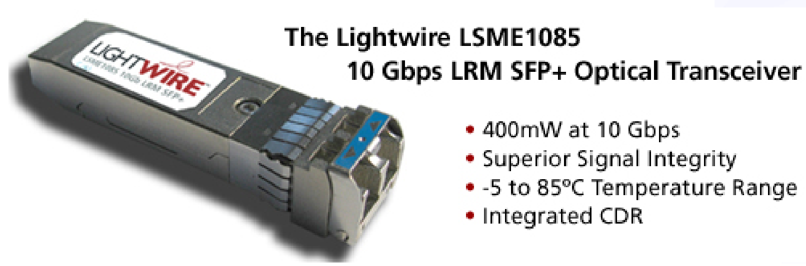
Silicon Enables High Index Contrast (Metallic-like) → Tight Confinement

- ❑ Sharp, Low-Loss Bends → Large Free-Spectral-Range (Tb/s/fiber)
- ❑ Dense Integration (shrinking PLCs by a factor of 1-Million)
- ❑ Ultra-compact resonators → low power consumption
- ❑ Photonics can be directly, or nearly directly with CMOS

$n_{core} = 3.48$ (Si)
$n_{clad} = 1.445$ (SiO2)
$> 99\%$ Transmission







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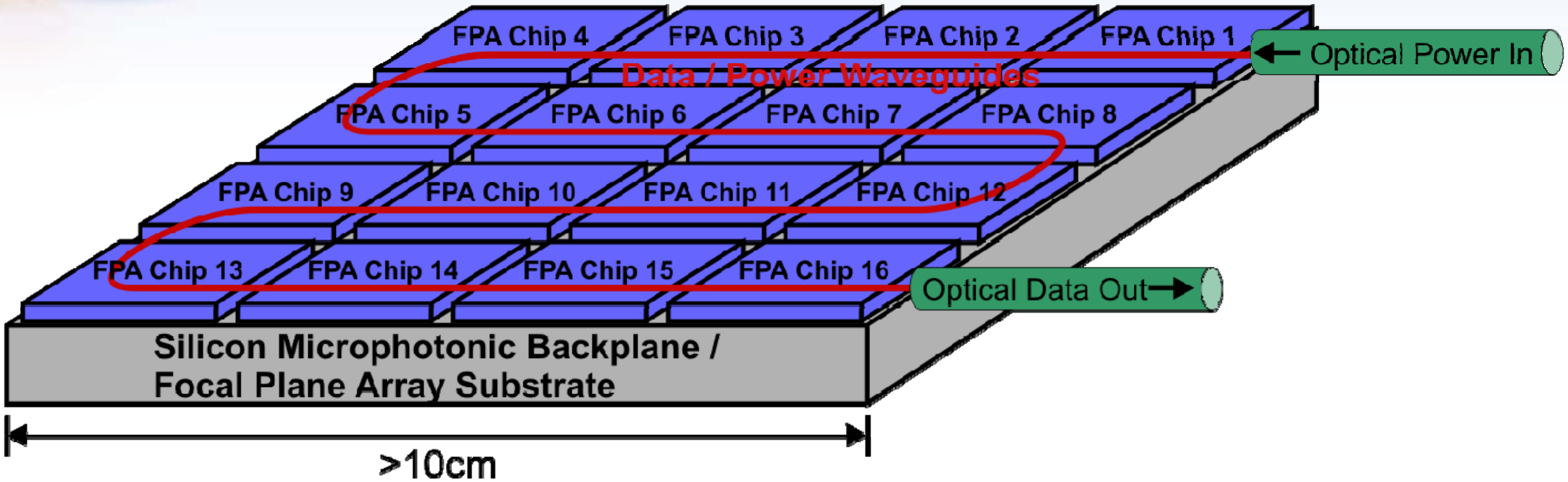
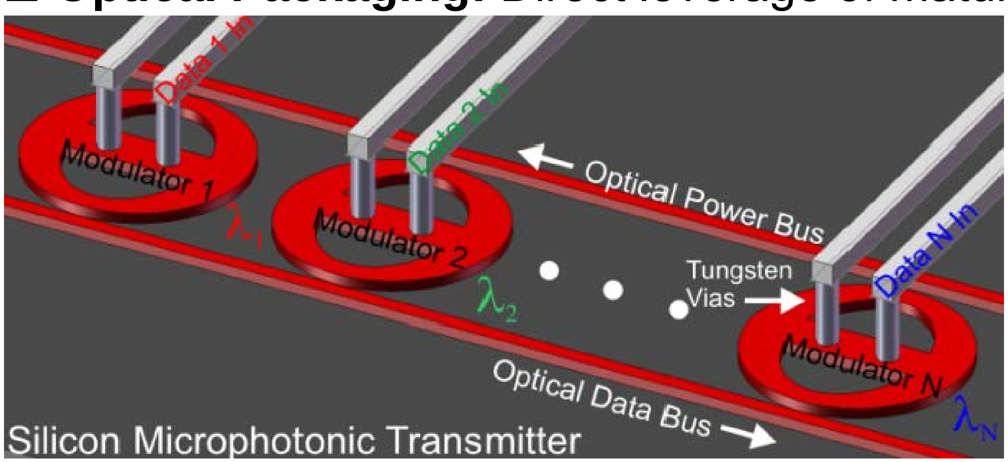
Consider: Silicon Optical Backplane

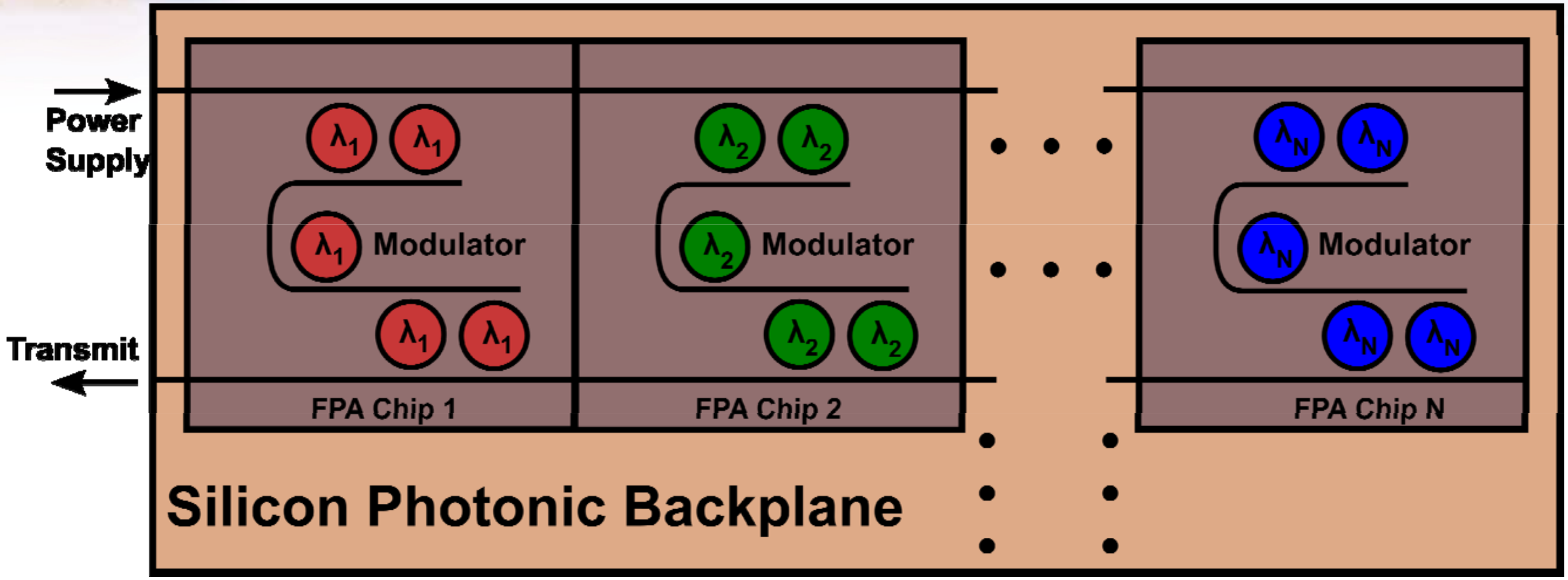


Solution: A Silicon Microphotonic Backplane

- ❑ **Communications Power:** 100-Tb/s @1pJ/bit (100W)
- ❑ **Bandwidth Density:** 1 WDM silica fiber carries as much info. as 100 metal lines
- ❑ **Electromagnetic Interference:** Eliminated, direct connections from optics to CMOS
- ❑ **Optical Packaging:** Direct leverage of mature and scalable electronic packaging



Silicon Photonic Backplane: In Detail



Components

- ❑ Wavelength Division Multiplexing (WDM) / Filtering
- ❑ Low Power Modulators
- ❑ Fabrication / Temperature Invariant Performance
- ❑ Low-Loss Waveguides
- ❑ Low Power Detectors (for receive-side)
- ❑ For Space Applications, Radiation Hard CMOS

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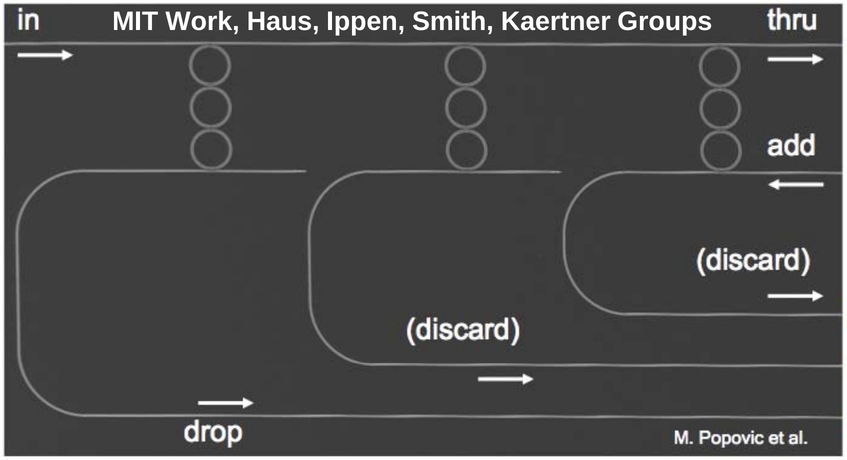
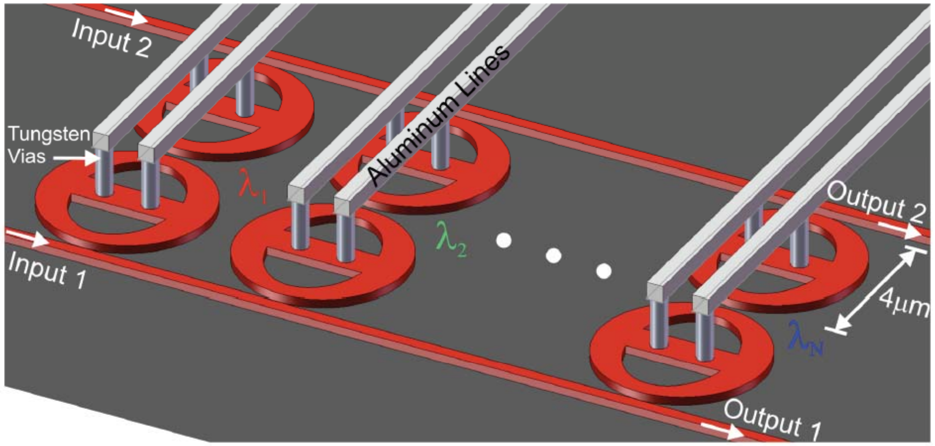
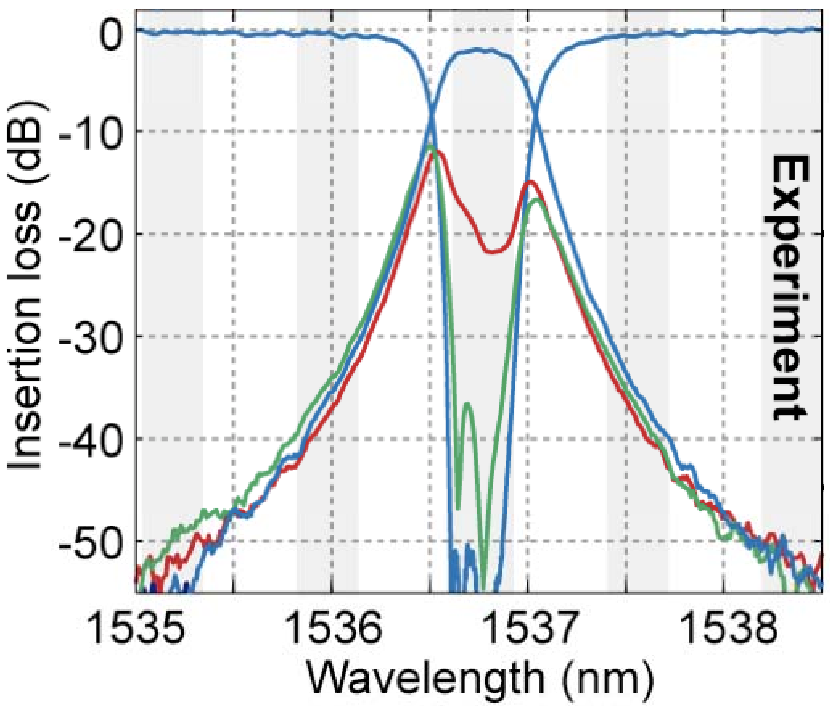
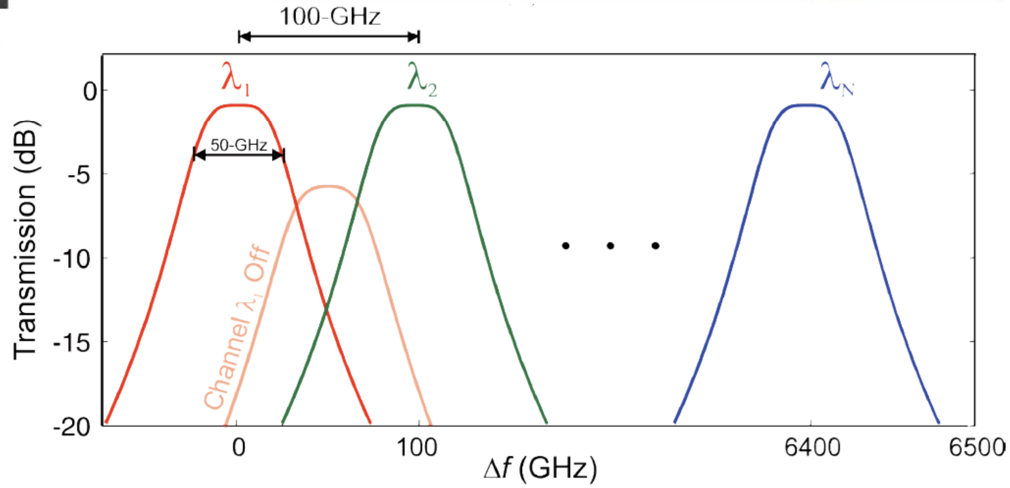
WDM Filtering: High-Order Microrings

High Order Microring Filters in Si/SiN

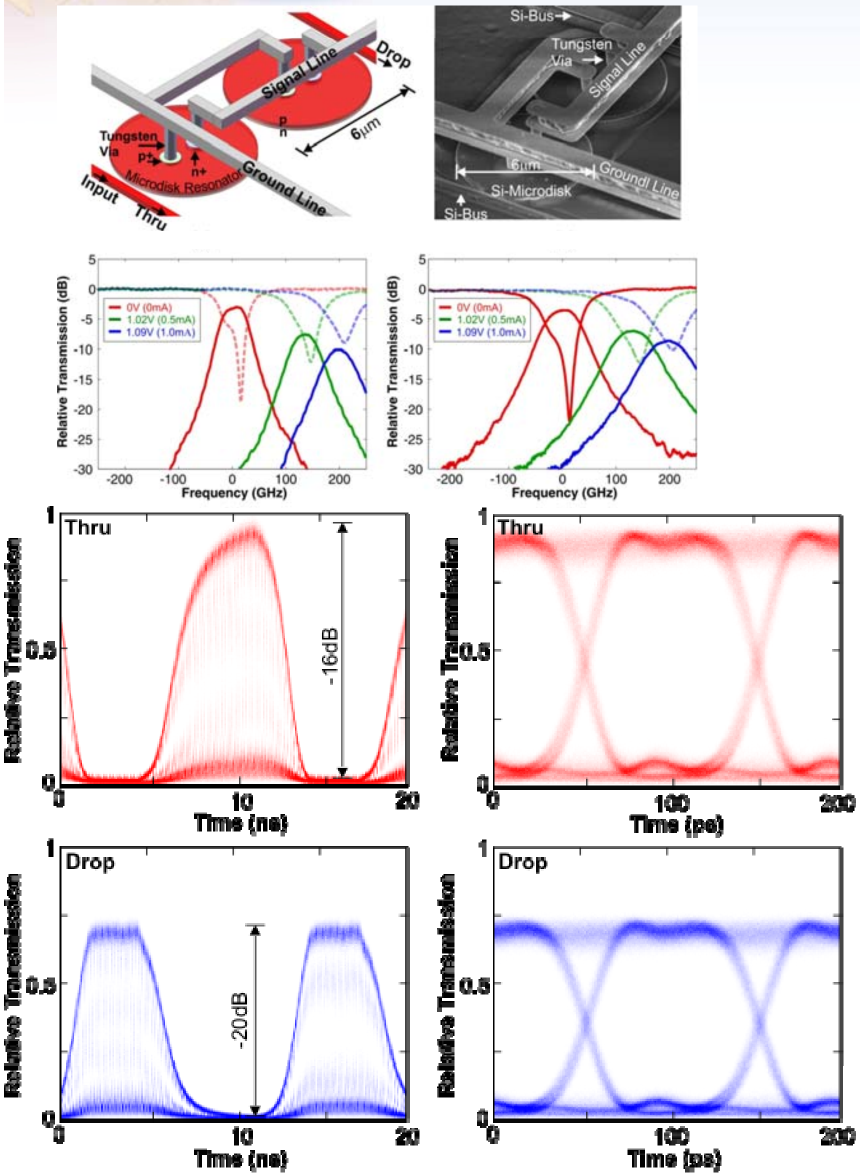






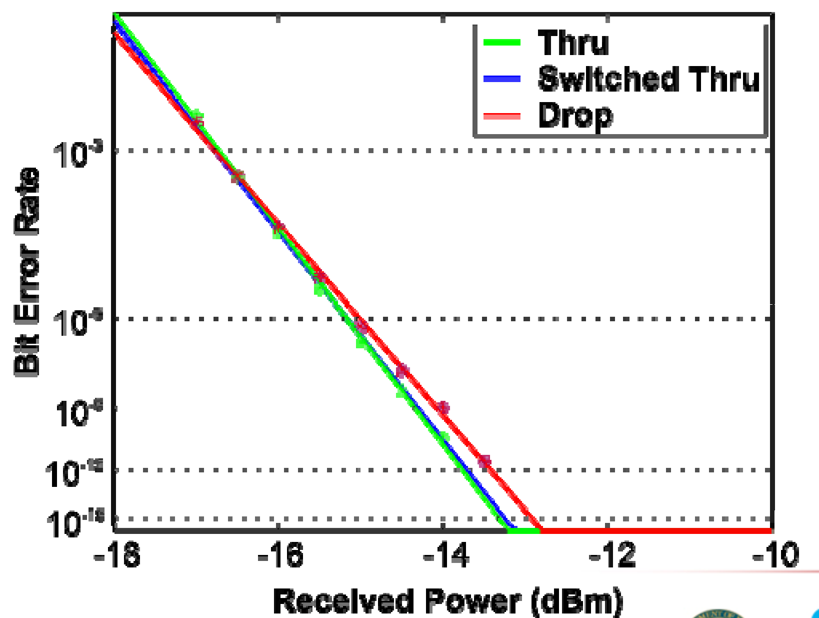


WDM Filtering: High-Speed WDM Switch



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



M. R. Watts et al., OFC Postdeadline Presentation (Feb. 2008)

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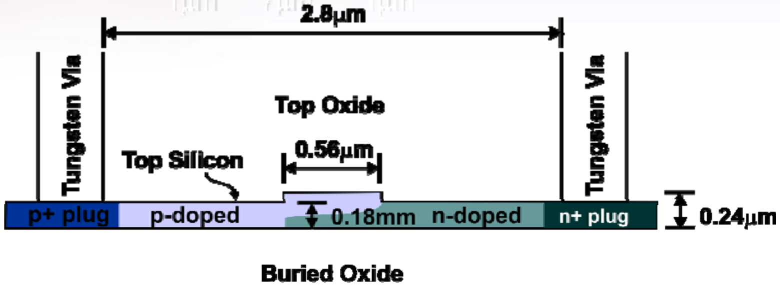
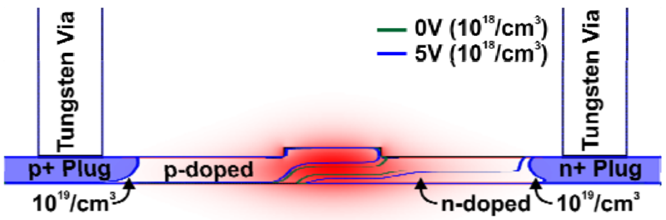
Modulators: Silicon Mach-Zehnder

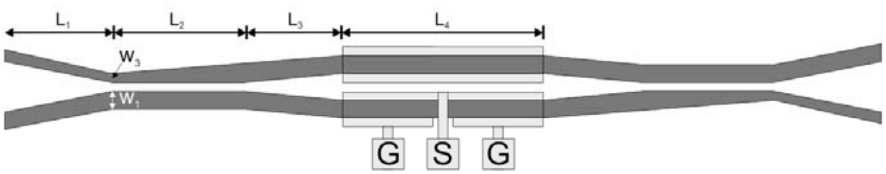


(a)

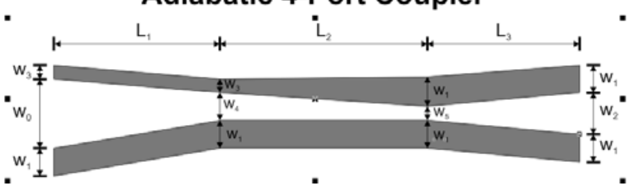


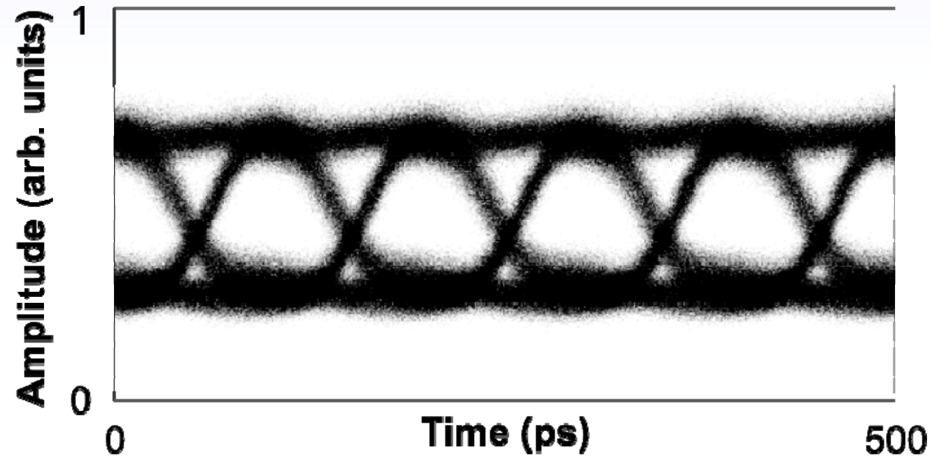
(b)

Mach-Zehnder with Complimentary Outputs

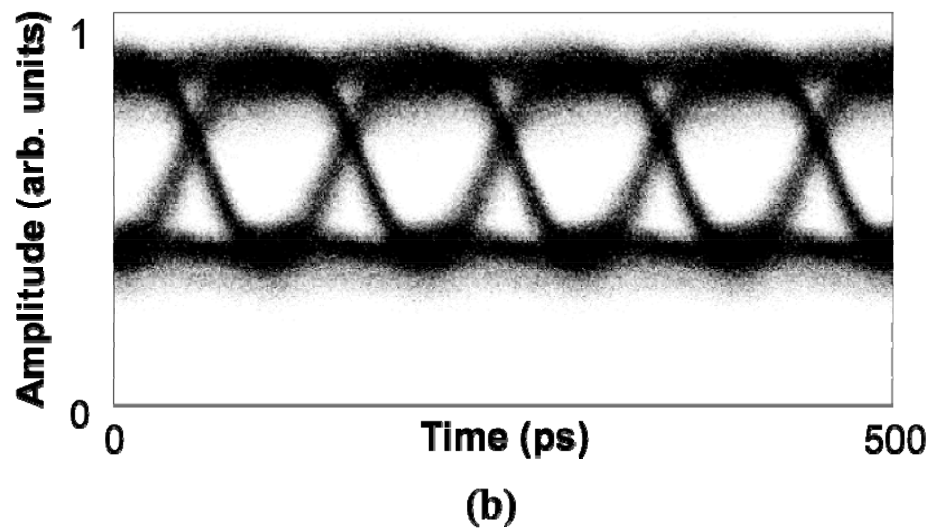


Adiabatic 4-Port Coupler





(a)

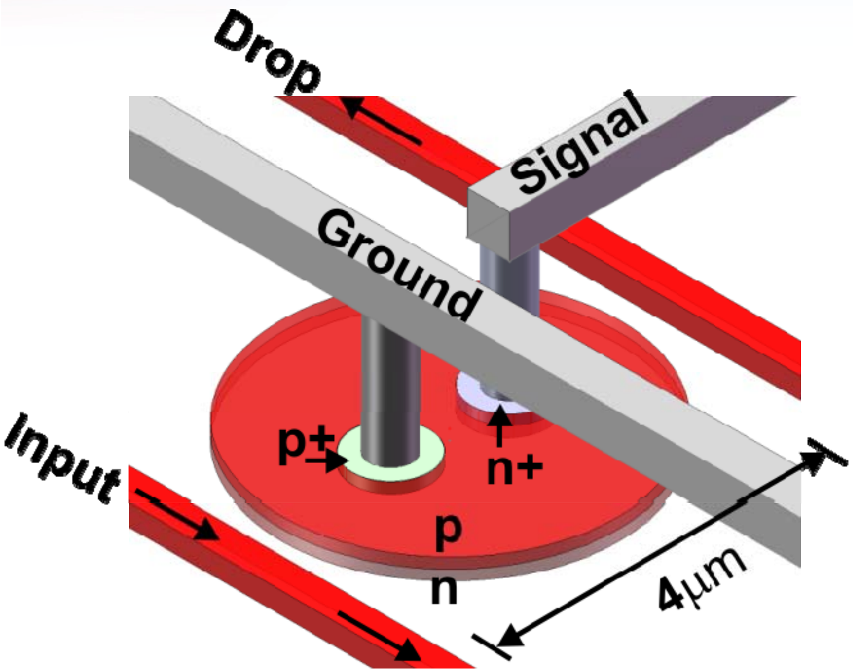


(b)

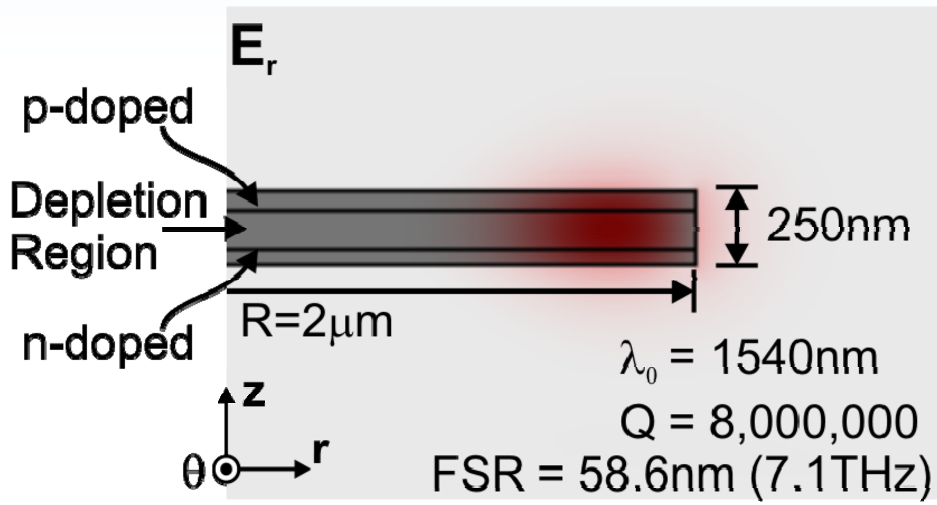
Works well, but consumes ~10pJ/bit

Modulators: Resonant Microdisks

Vertical P-N Junction



TE_{11} Cylindrical Mode

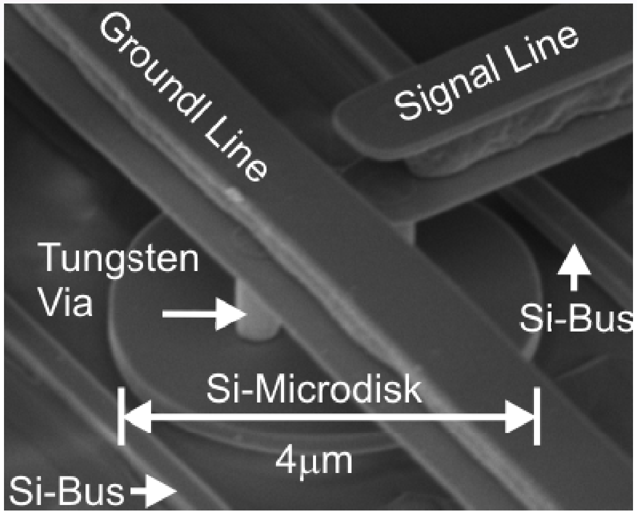


Vertical P-N Junction Resonant Modulator

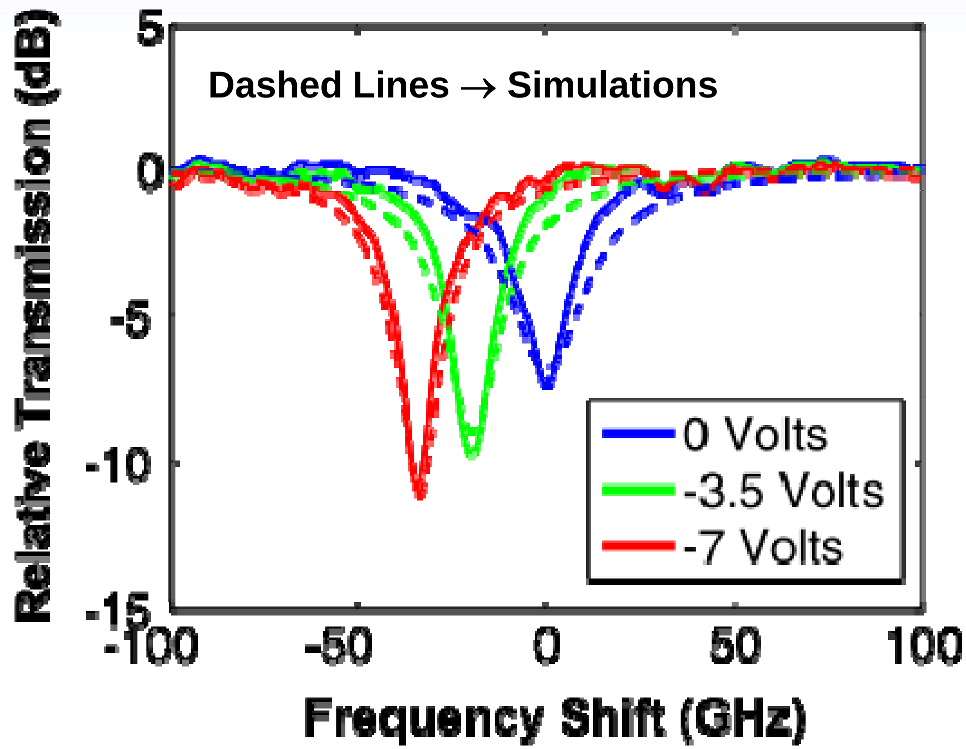
- ❑ Resonant modulator multiplies up the small silicon free-carrier effect
- ❑ Power consumption is simply $f \times CV^2/4$, and the capacitance is small
- ❑ Small devices, no pre-emphasis → fast / low power

Modulators: Microdisk Demonstration

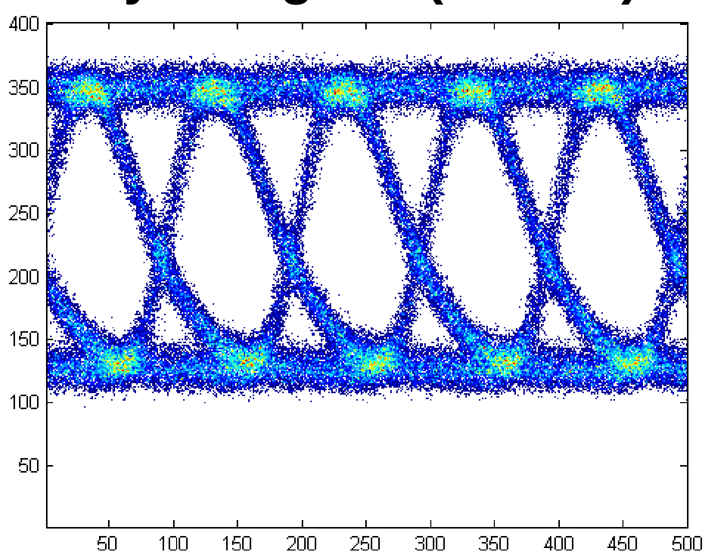
SEM of the Microdisk



Frequency Shift vs. Reverse Bias



Eye Diagram (10Gb/s)



Vertical Junction Reverse-Biased Results

- ❑ 35-GHz freq. shift demo'ed, >70-GHz possible
- ❑ Achieved a BER<10^{-13} at 10Gb/s
- ❑ CMOS compatible drive (3.3V)
- ❑ No pre-emphasis or equalization
- ❑ Measured energy/bit 85fJ

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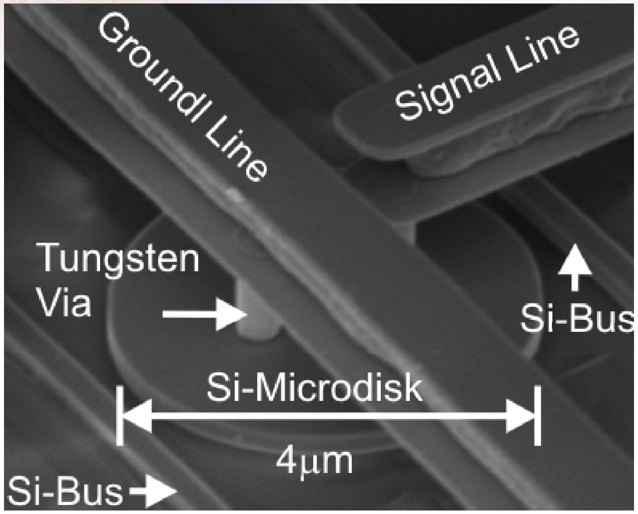
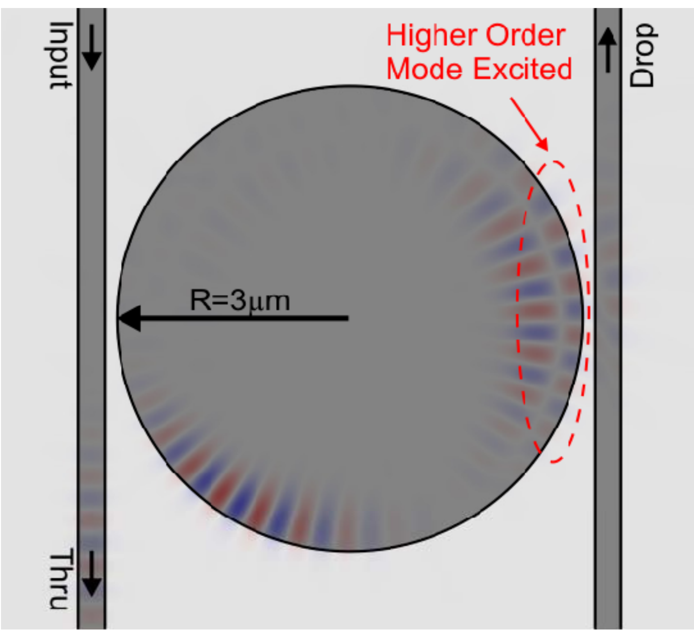
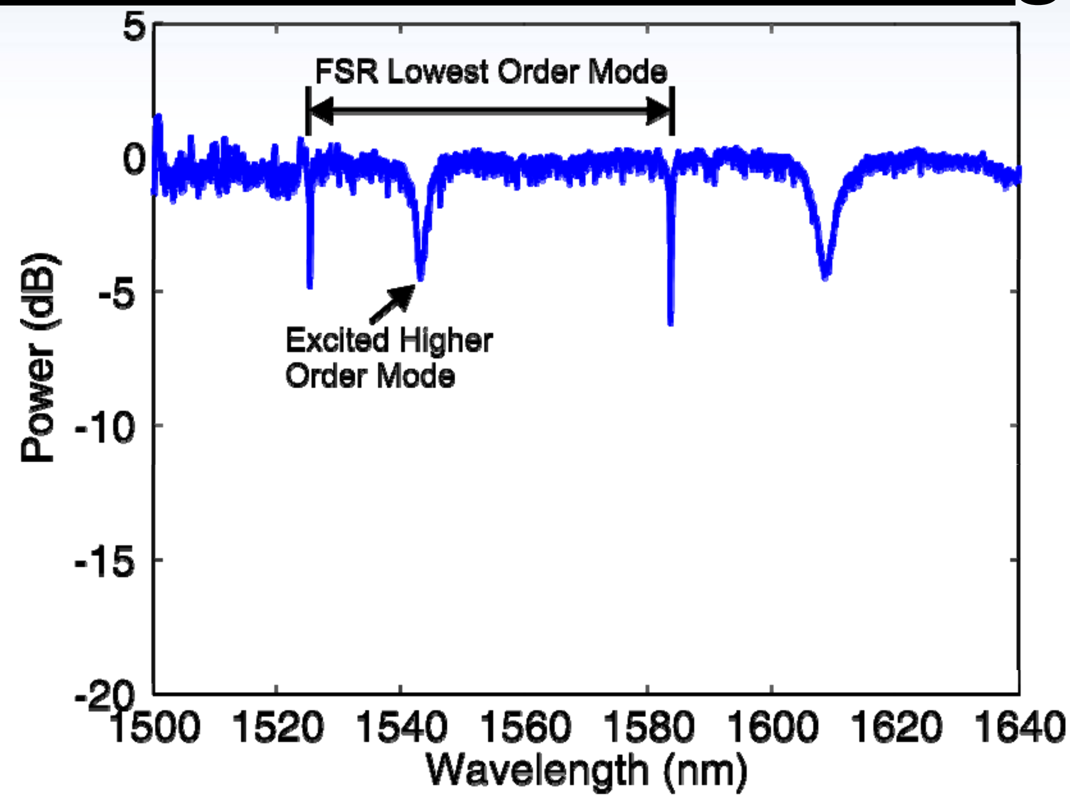
Challenge: Limited Free-Spectral Range







- ❑ Microdisks propagate higher order modes corrupting FSR and limiting the available line bandwidth.
- ❑ Can be fixed with a microring, but . . .

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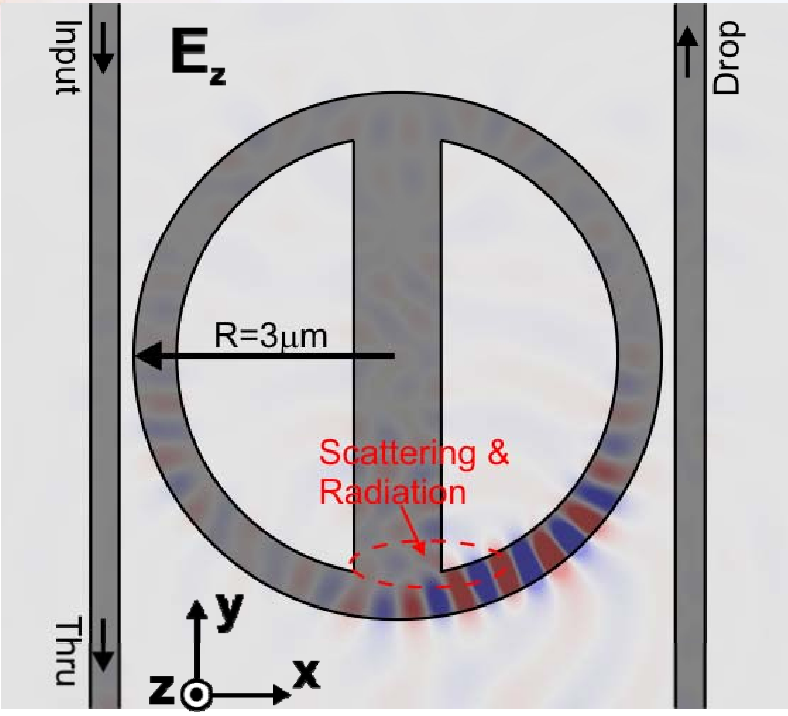
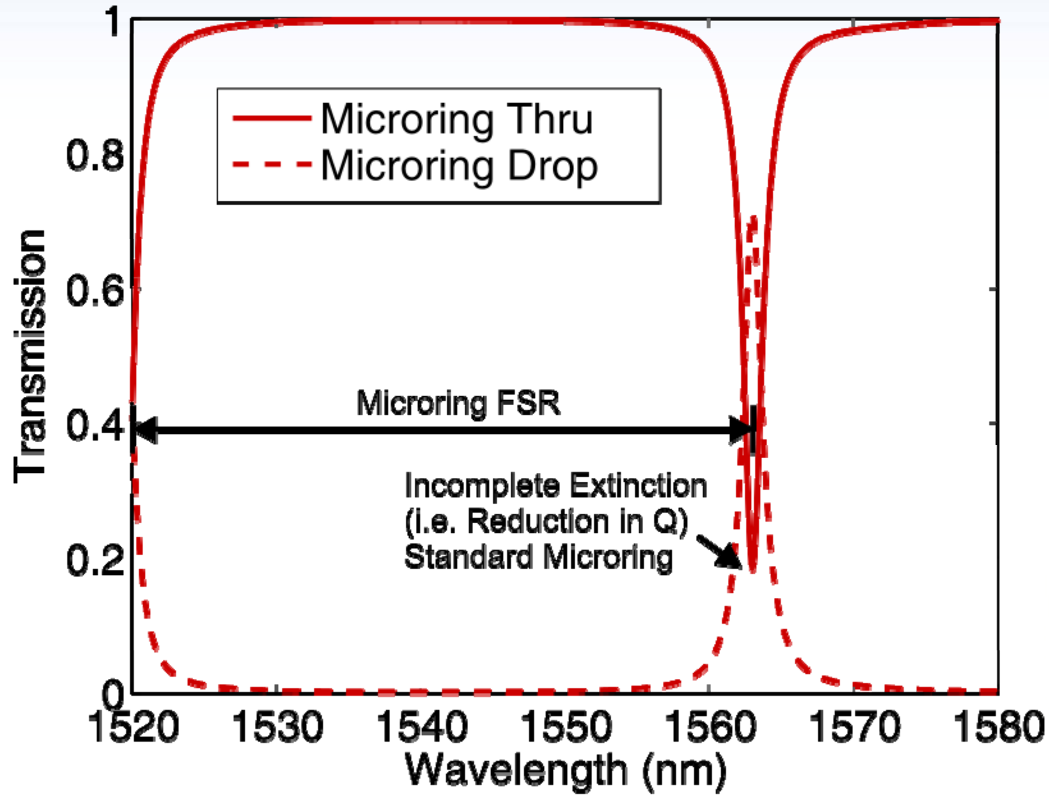
Directly Contact a Microring?

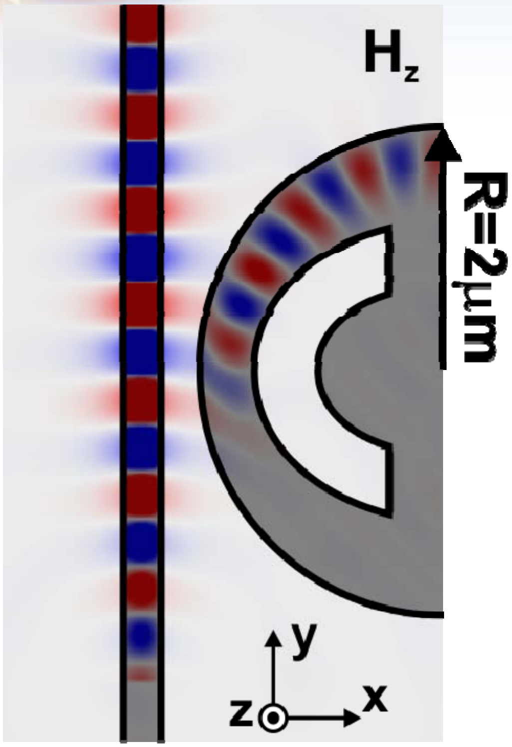




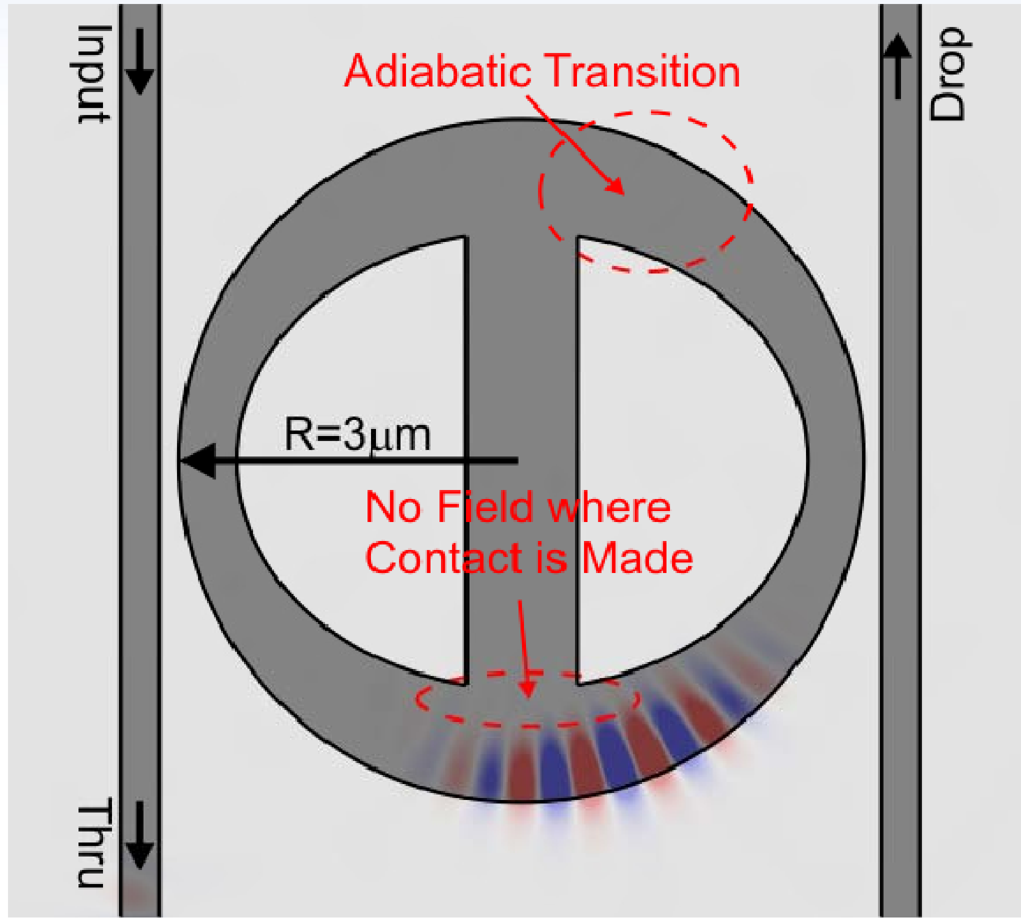
Results

- ❑ 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?

Adiabatic Resonant Microrings (ARMs)



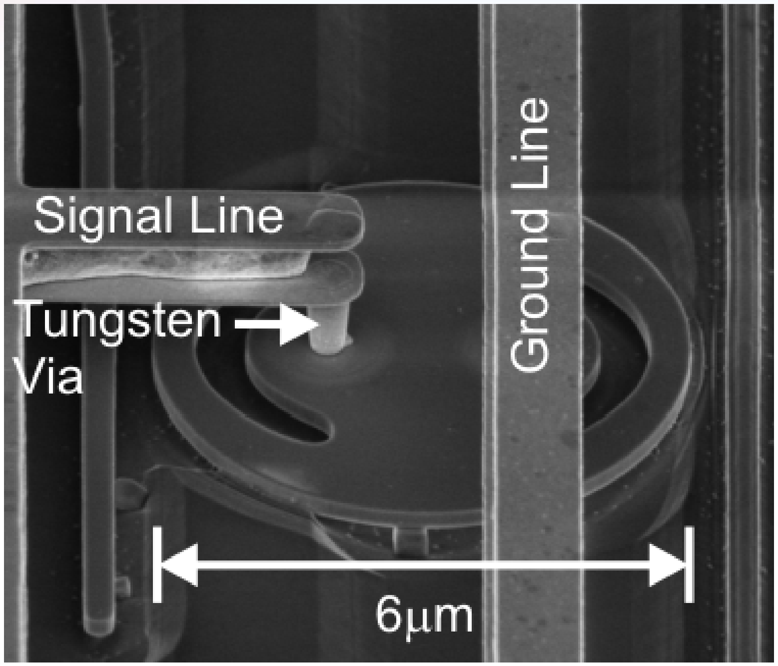
Coupling = 1.5%
Loss = 0.16%

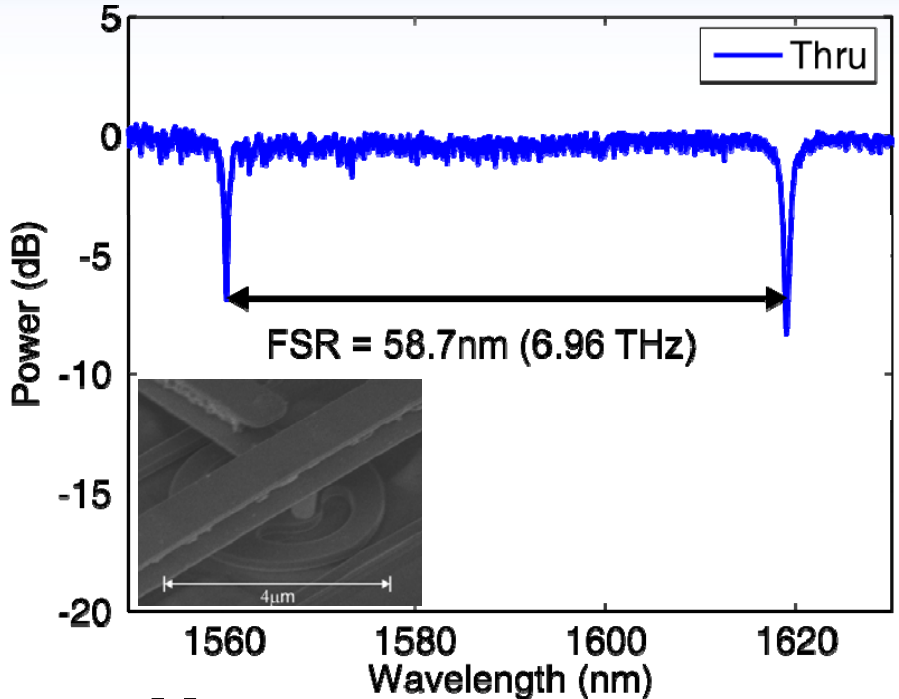


Approach / Results

- ❑ Adiabatic Resonant Microrings (ARMs) enable contact without radiation
- ❑ Essentially, a cross between a ring and a disk
- ❑ Recovers the full Free-Spectral-Range (FSR)

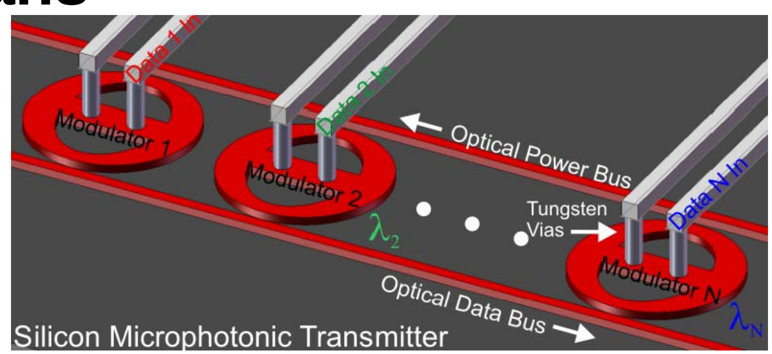
A Large Free-Spectral-Range (FSR)





7-Terhertz Free-Spectral-Range Means

- ❑ 70 WDM Channels at a 100-GHz spacing
- ❑ 140 WDM Channels at a 50-GHz spacing
- ❑ At 10Gb/s this corresponds to 700Gb/s and 1.4Tb/s data rates/fiber



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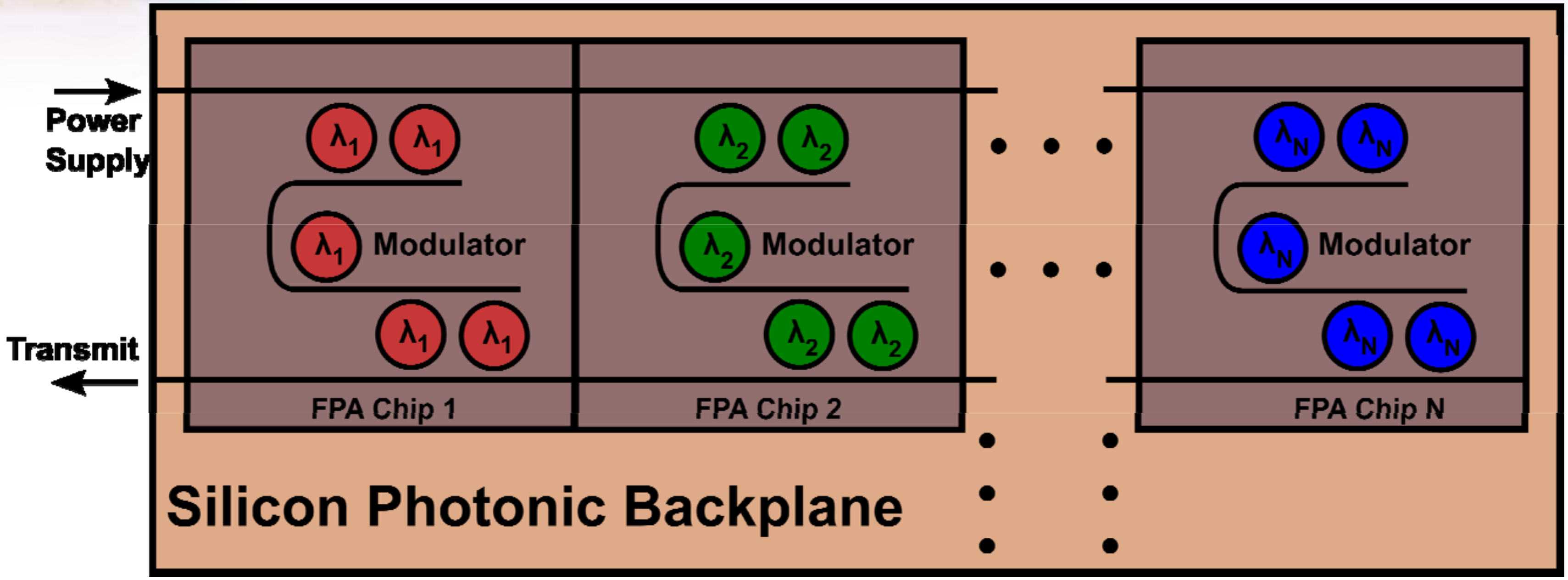
Silicon Photonic Backplane: In Detail



Components

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- ❑ Low Power Modulators
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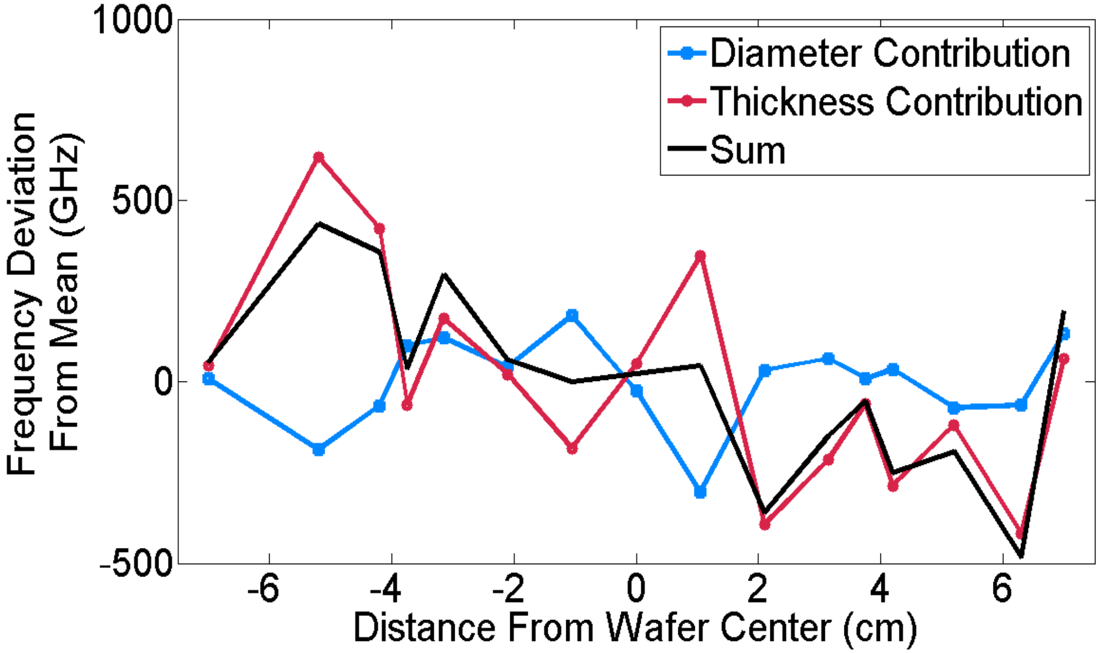
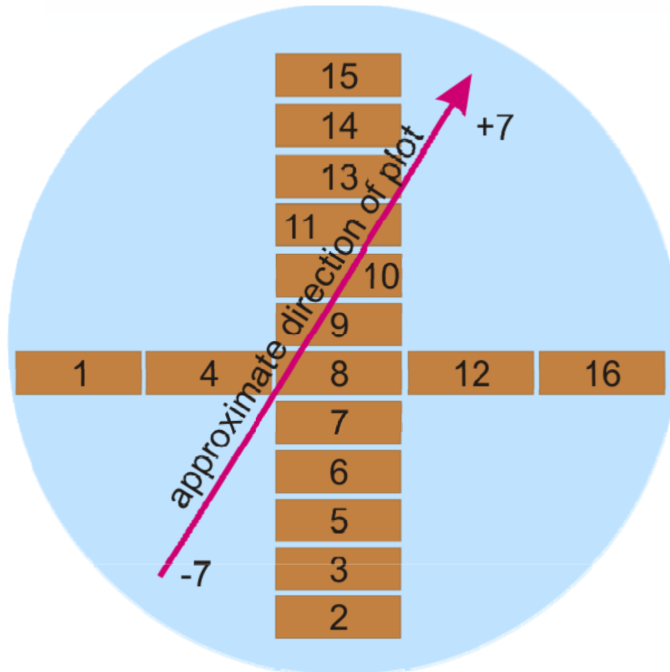
- ❑ For Space Applications, Radiation Hard CMOS

Resonant Frequency Variations

Measured Resonant Frequencies



Wafer Map Measured Devices



Components

- ❑ Total variations on the order of ~1THz
- ❑ Variations can be reduced to ~100GHz with tighter tolerances on layer thickness, but probably not less . . .

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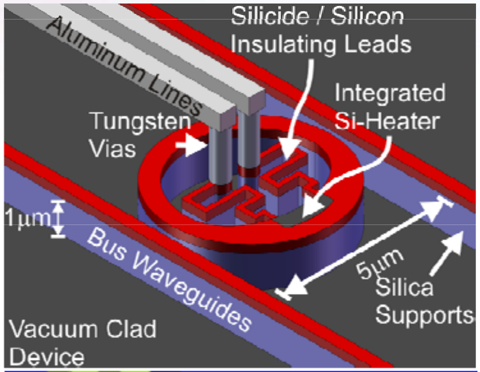
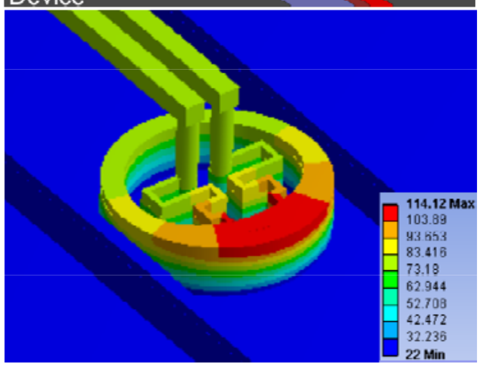
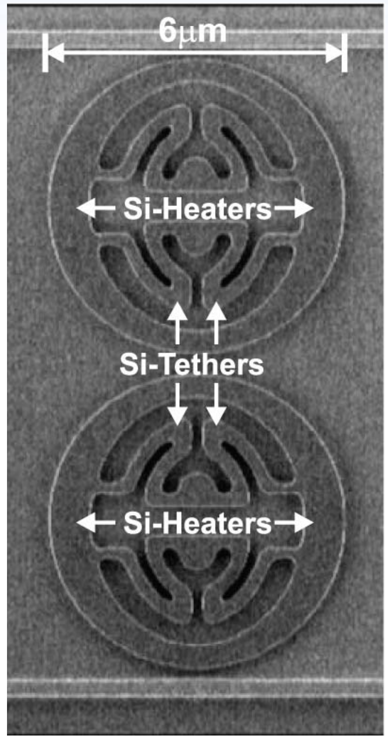
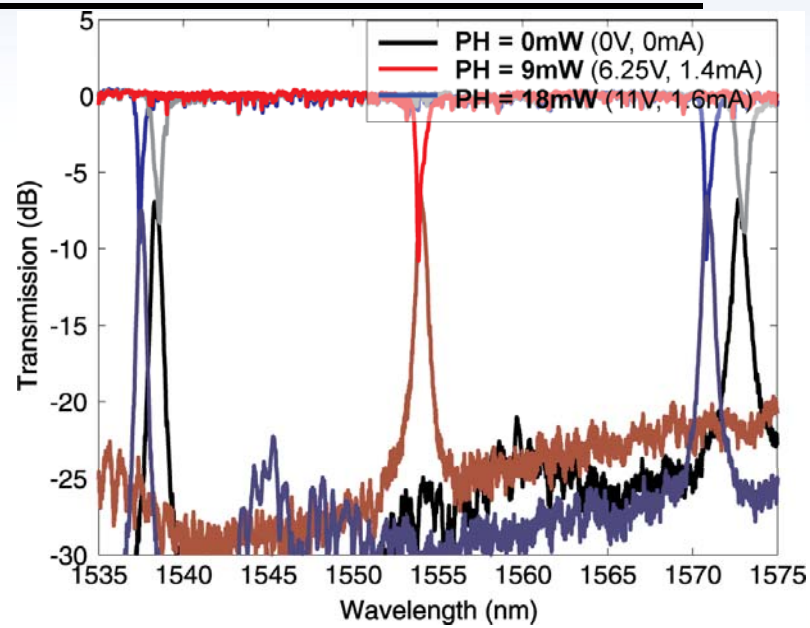
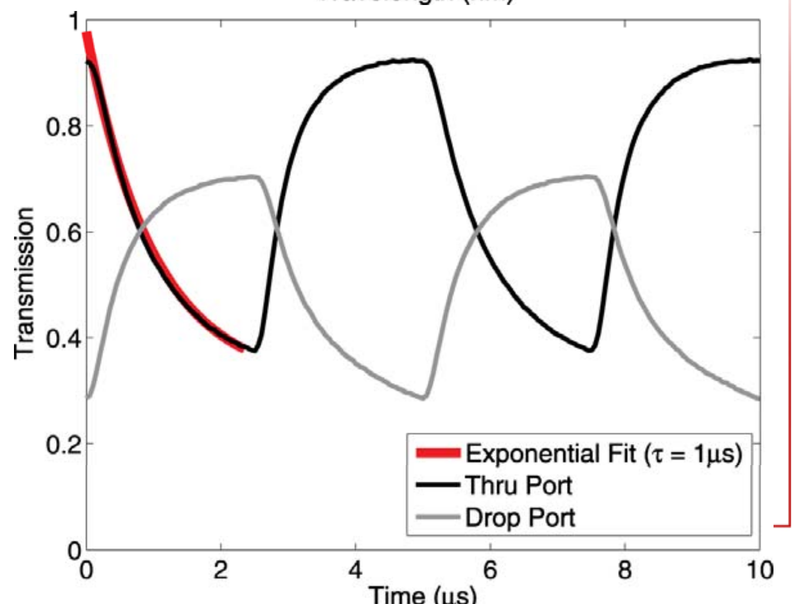
Ultralow Power Thermal Control







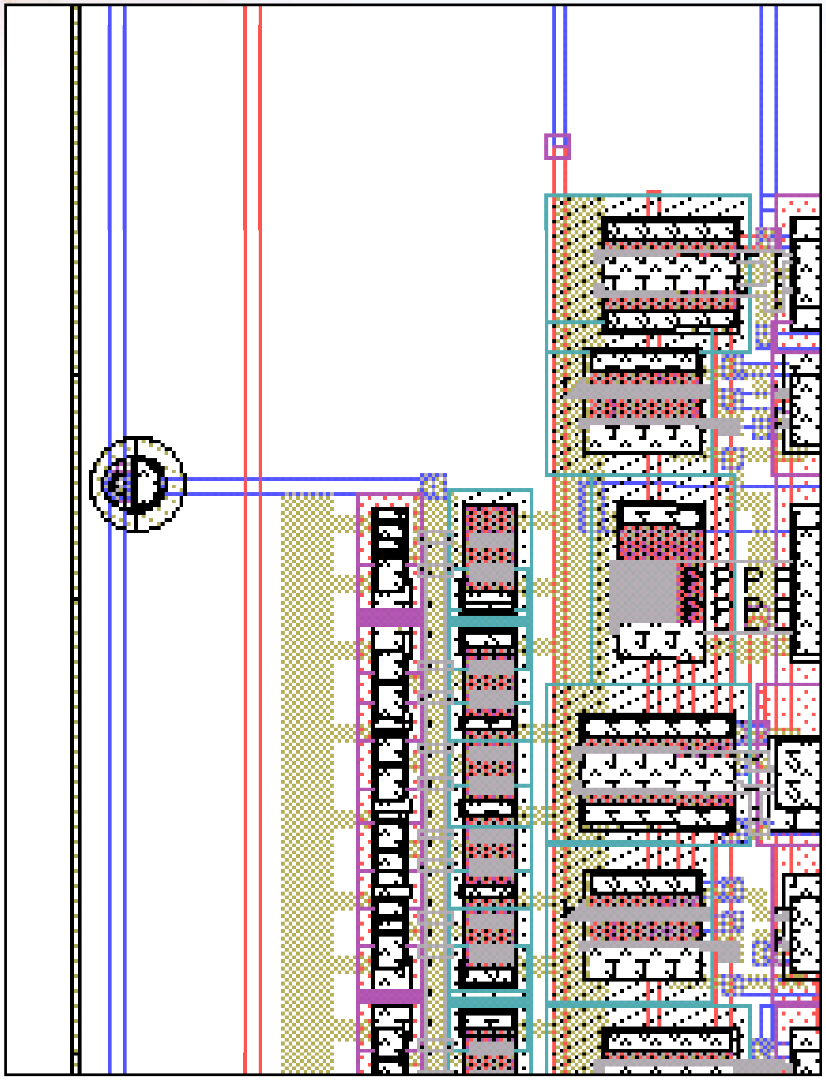


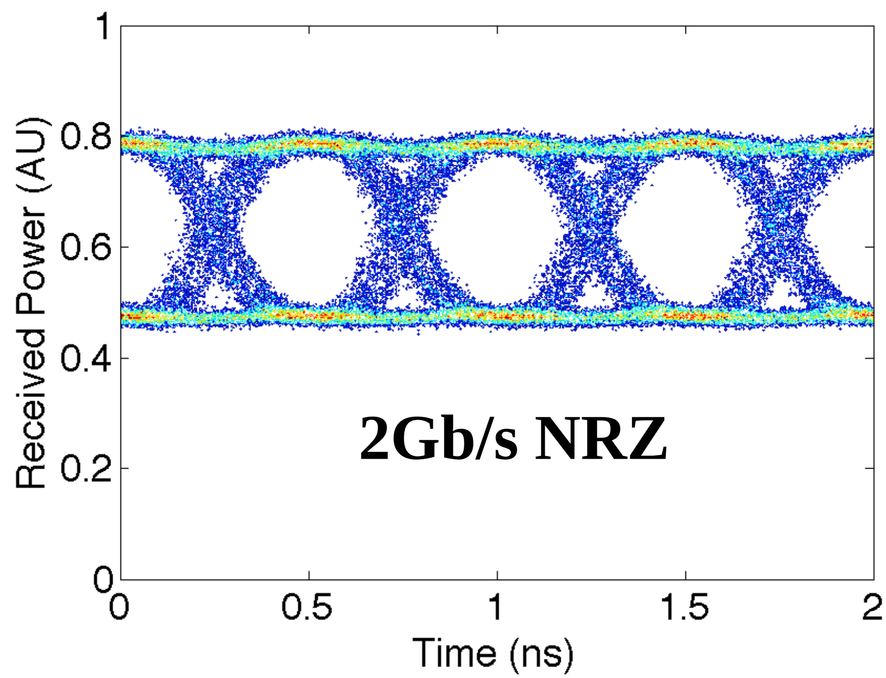


- 1st C-Band thermally tuned microring
- Lowest-power thermal tuning (4.4µW/GHz)
- 50µW/°C, a 20°C range at 200fJ/bit (@10Gb/s)
- If 5 rings are used in the network, then 1pJ/bit, but expect to be able to reduce power by 5X
- Record, 1µs thermal time constant

Laboratories

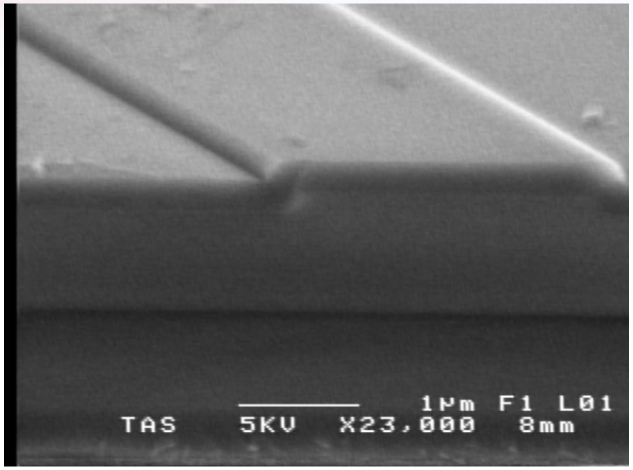
CMOS: Electronic-Photonic Integration



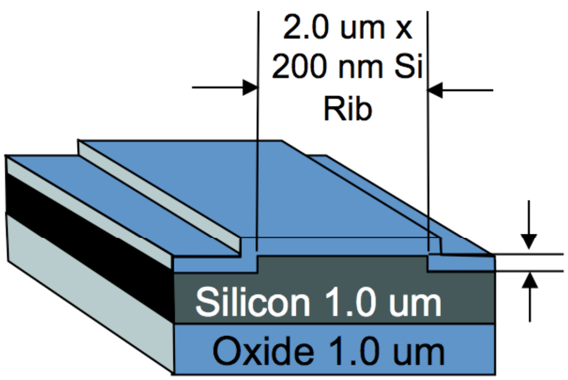


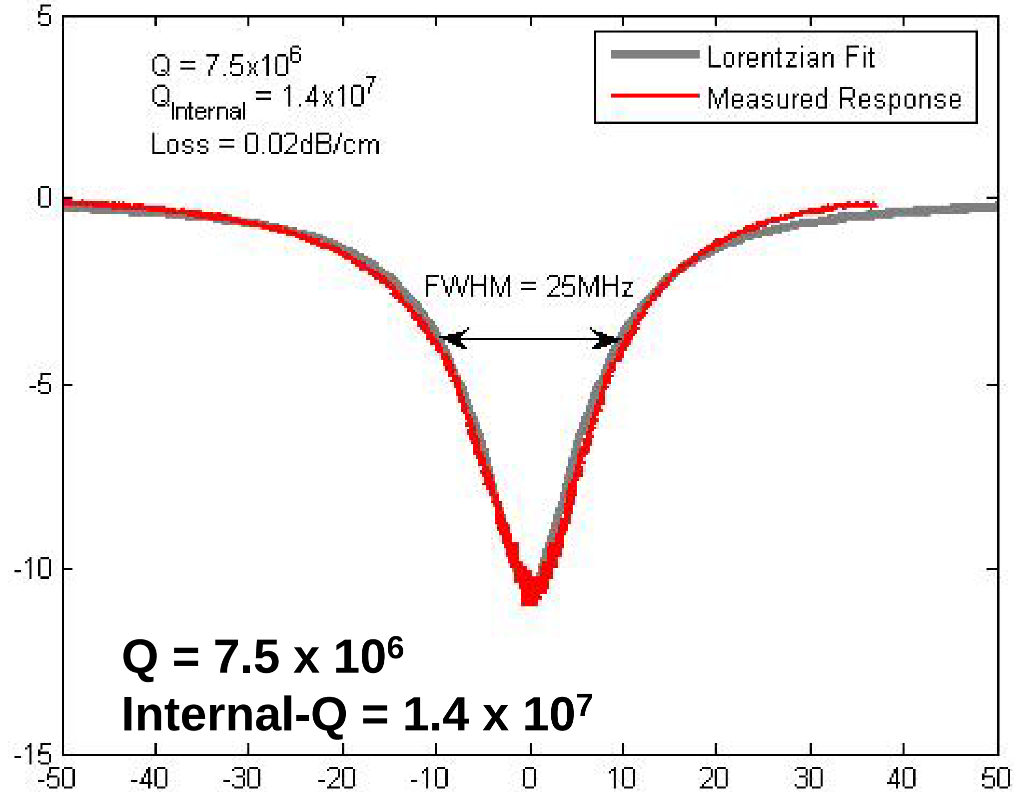
- Direct integration of Sandia CMOS and silicon photonics, potential space-qual.
- Data rate (2Gb/s) limited only by CMOS
- Enables ultralow power, highly scalable, silicon photonic platform

Low Loss: Silicon Ridge Waveguides



Reflowed Photo Resist with Oxidation of SOI Rib Waveguide



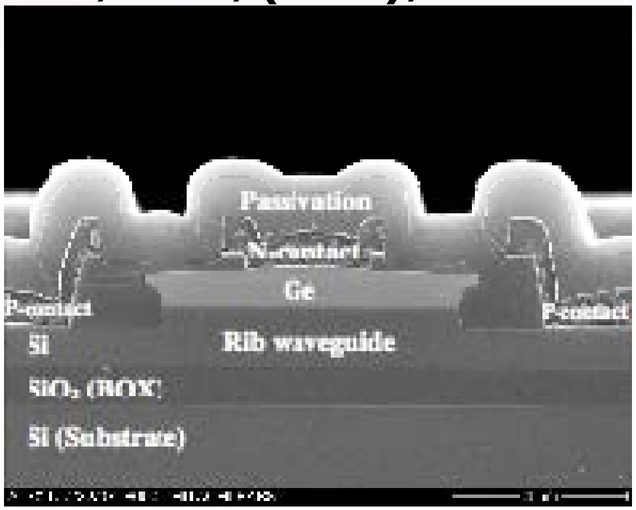


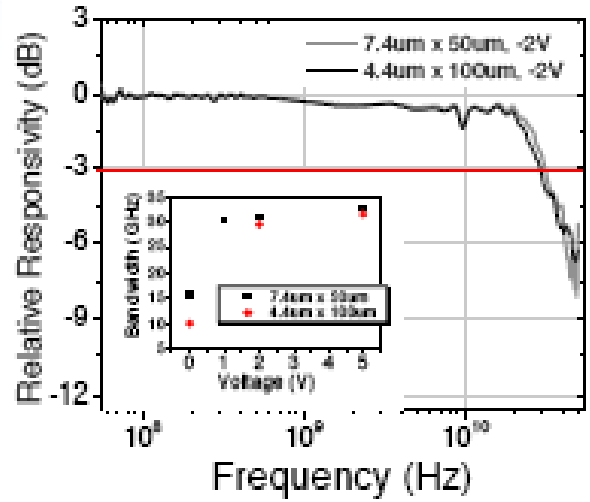
Q = 7.5 x 10^6^
Internal-Q = 1.4 x 10^7^

Impact: Potential for cross-wafer communication (50cm → 1dB loss)

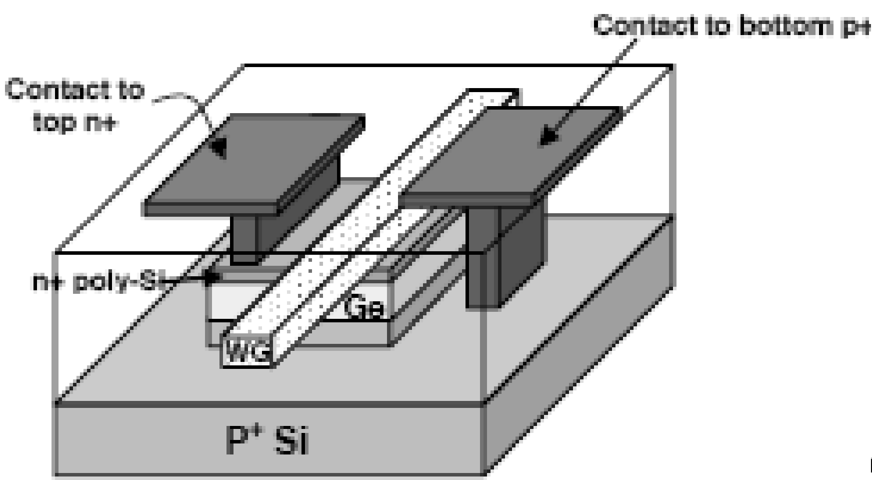
Germanium Detectors

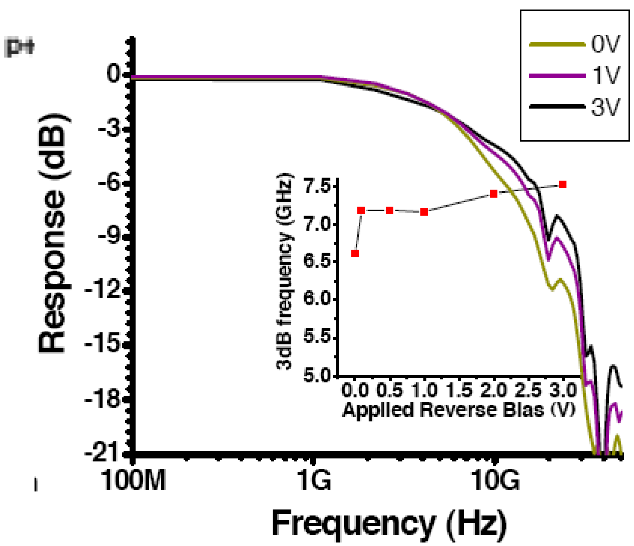
Yin, et al, (Intel), 31 GHz Germanium on Silicon Detector





Ahn, et al, (MIT), >7GHz Germanium on Silicon Detector





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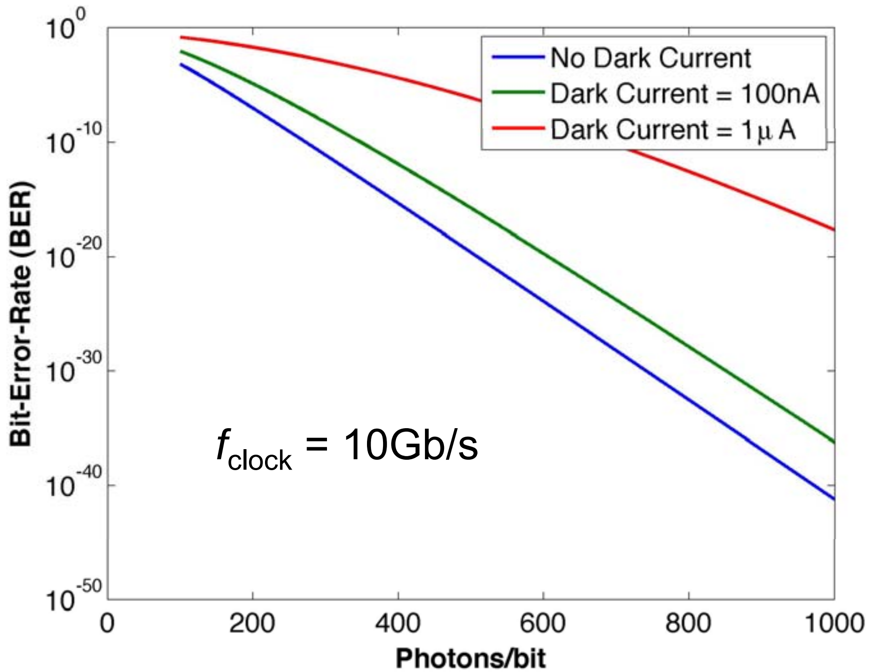
Optical Communications Power

Bit-Error Rate (Fundamental)



Results Based Shot, Johnson, and Dark Current Noise

- ❑ Require Dark Current < 100nA
- ❑ 1000 Photons/Bit is sufficient
- ❑ Only 0.15µW/Gb/s

Receiver Performance (Tech)

- ❑ P-I-N Sensitivity ~ -20dBm
- ❑ APDs ~ -27dBm

	Source Power Budget
Electrical Power	**2mW**
Optical Power	**-10dBm (5% efficient)**
Comm. Efficiency	**200fJ/bit (0.2mW/Gb/s)**
Fiber-to-Chip Losses	-3dB (1dB/connection)
Filter Drop Losses	-3dB (1dB/Drop)
Filter Thru Losses	-4dB (0.1dB/Thru)
Modulator Losses	-4dB (3dB Mod./1dB Loss)
Power at Receiver	**-24dBm**

- ❑ Add source, heat, mod., det. ~ 0.5pJ/bit
- ❑ SERDES, Clock recovery, etc. ~0.5pJ/bit
- ❑ Total ~1pJ/bit or 1mW/Gb/s

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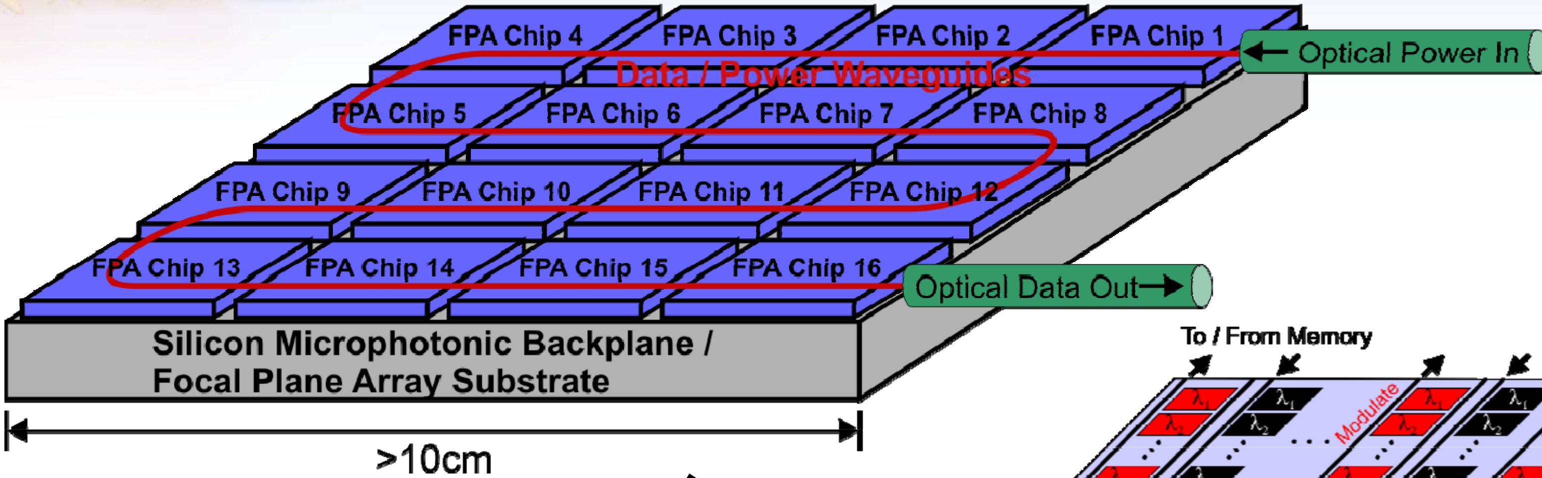
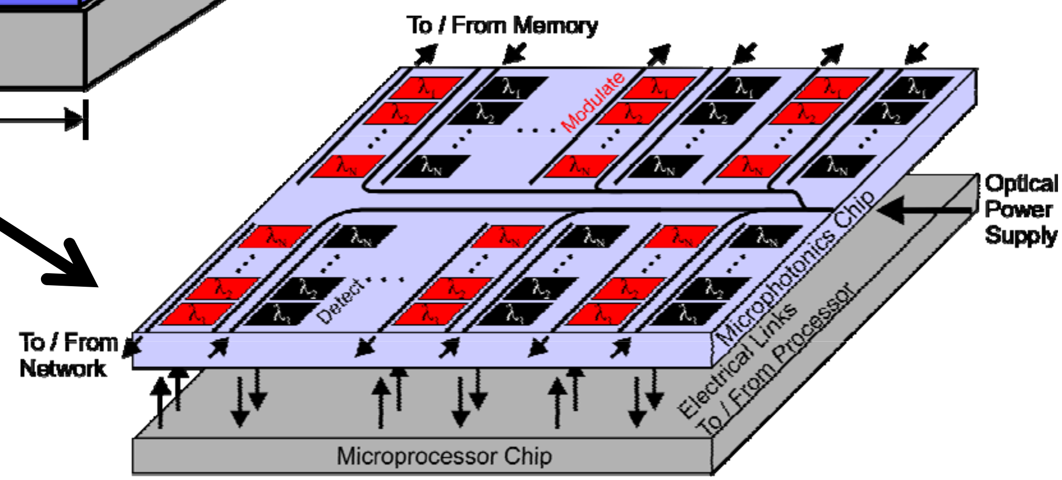
Summary



Connect to Microprocessor



- ❑ **Components Exist:** Filters, Modulators, Detectors, Thermal, etc..
- ❑ **Power:** Expect to get below 1pJ/bit, including electronics, or about 30X
- ❑ **Bandwidth**: 100X increase in BW density, 100, 10Gb/s channels
- ❑ **Example:** 100Tb/s @1pJ/bit ➔ 100W, require 100-fibers
- ❑ **Side Benefits:** Reduced thermal conductance, EMI, packaging . . .
- ❑ **Challenges:** ROICs, SERDES, clock recovery, etc . . .

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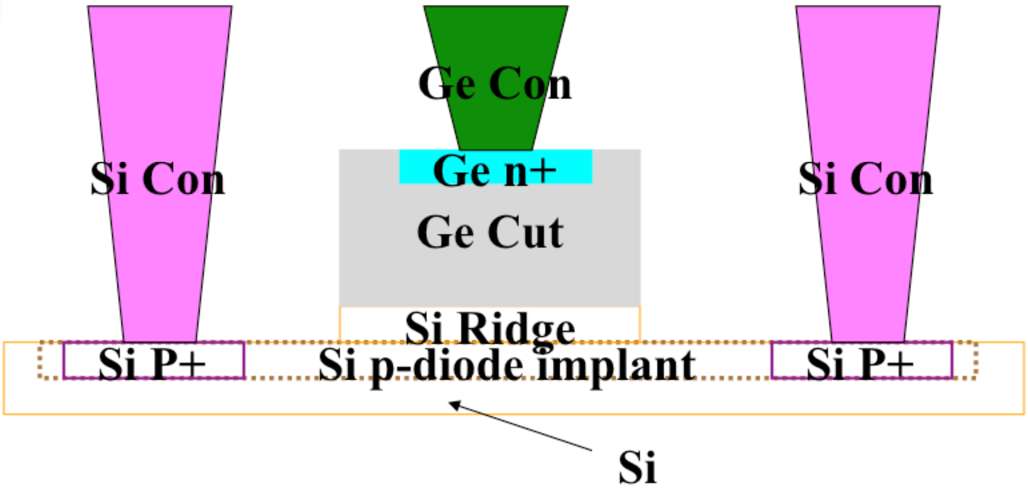
Acknowledgements

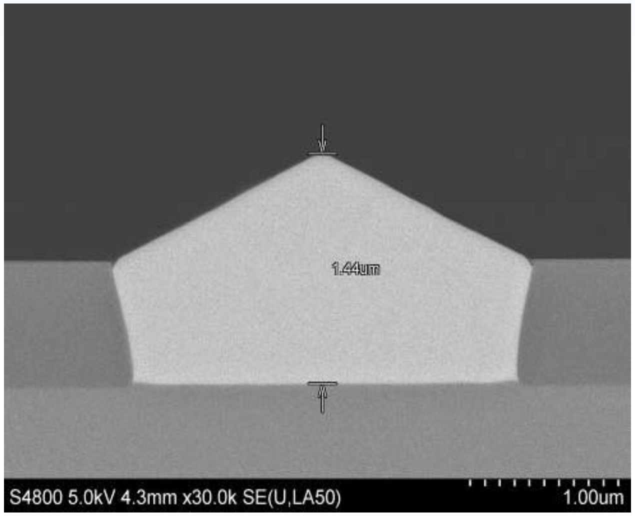
FDTD Code: Christina Manolatou

Cylindrical Modesolver: Milos Popovic

Funding: Sandia LDRD and DARPA MTO (M. Haney and J. Shah)

Detectors: Germanium on Silicon

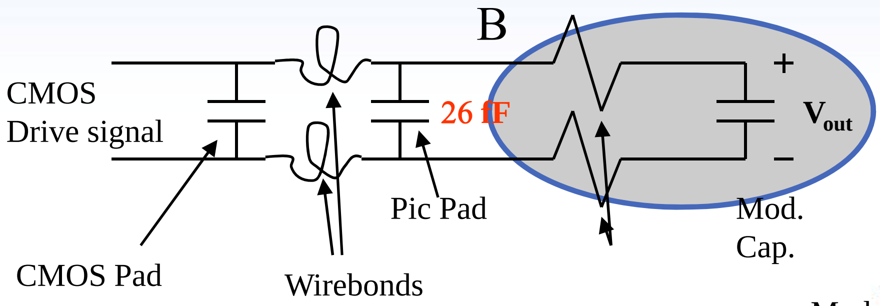


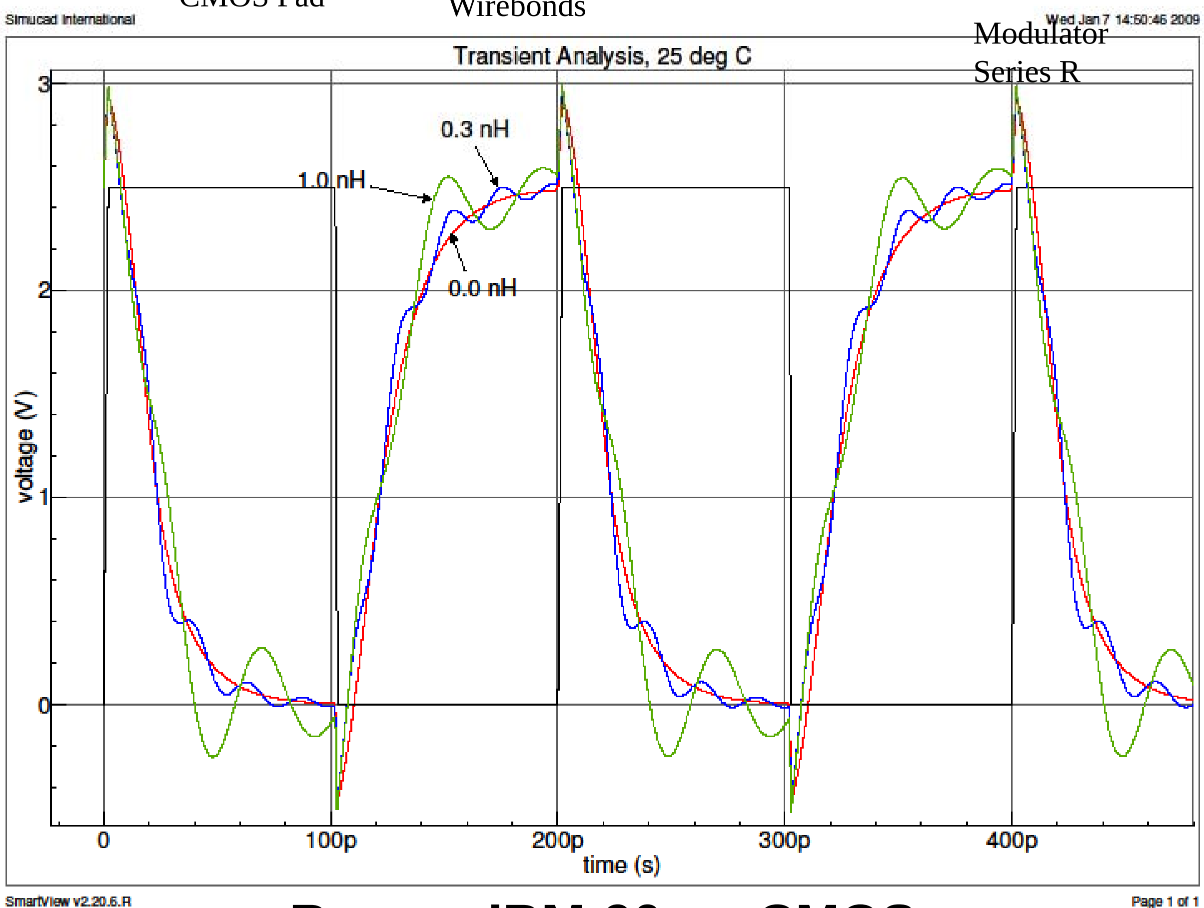


Germanium can be grown epitaxially on silicon with excellent results

- Low dark currents (<1nA @1V)
- High bandwidths (>30GHz reported)
- Fabricated in production epitaxial tools
- Many groups including, Intel, BAE, MIT, Cornell, Luxtera, etc. have demonstrated impressive results with Ge-on-Si detectors

CMOS: Microdisk Modulator Driver





Run on IBM-90nm CMOS