Emerging Optical I/O Solutions for Data centers, Quantum Computing, and HEP Detector Read-out

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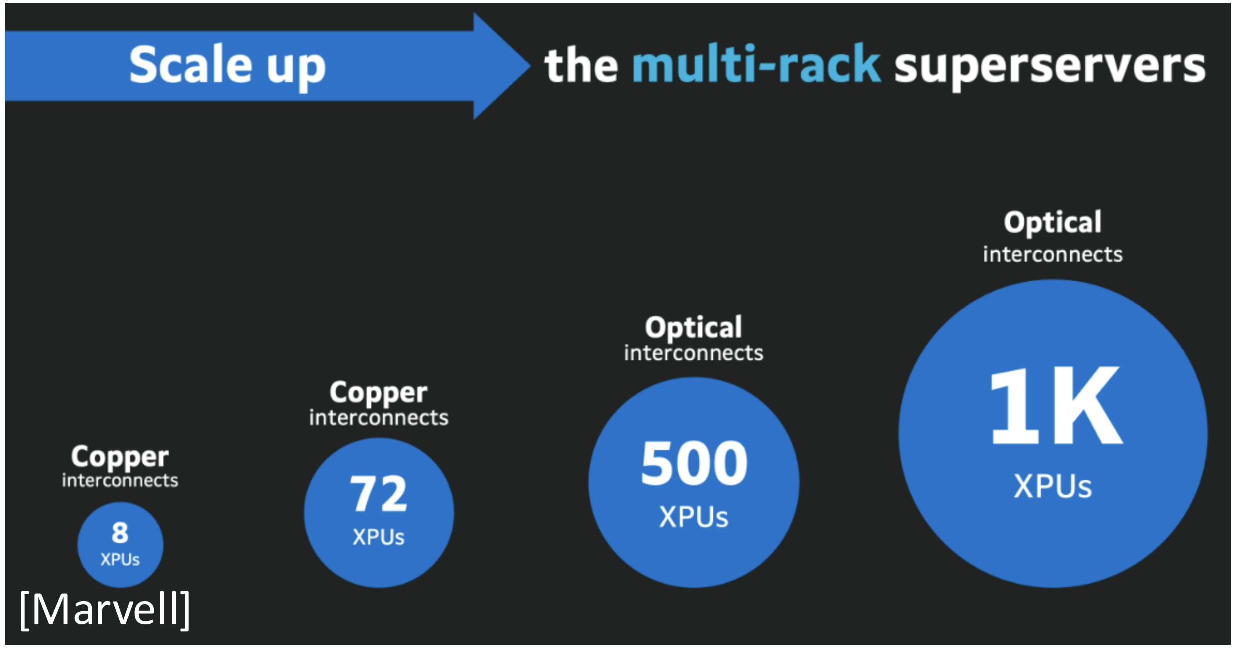
Optical I/O bottleneck to scale AI Data Centers

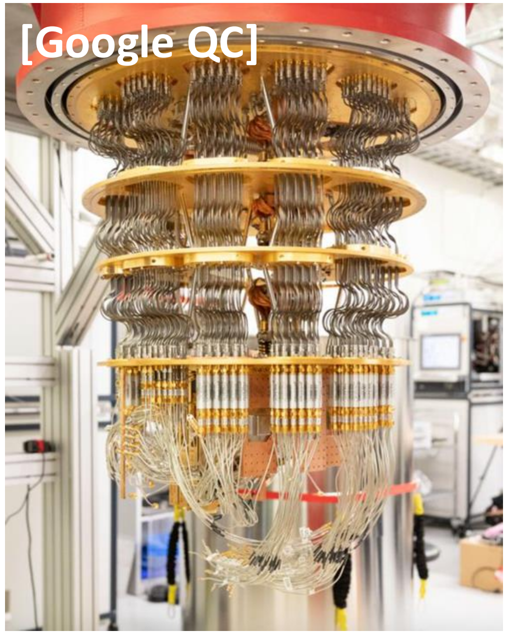
- Compute unit is now a +10 kGPU Cluster (mainly for training now)
- Scale up & Scale out for AI scaling!
- Copper interconnects are reaching their limits …
  - Limited reach
  - Limited bandwidth
- **Optical interconnects are seeing surging market and bandwidth demands!**



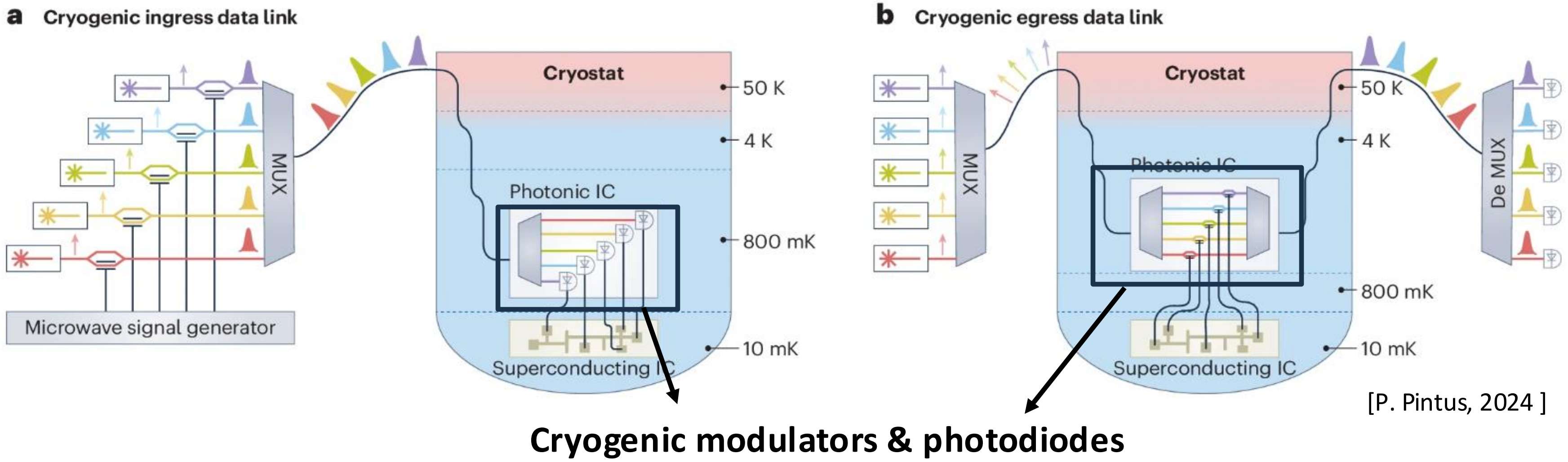
[Marvell]

[xAI]

Interconnects for Quantum Computing



Cryogenic Optical Data Link



Any physical realization of quantum computers benefits from optical fiber I/O:

- Reduced heat load and thermal noise (glass vs. copper!)
- Both for digital I/O as well as RF-photonics (e.g., superconducting qubit control)
- This is becoming more crucial once we pass +1k qubit systems

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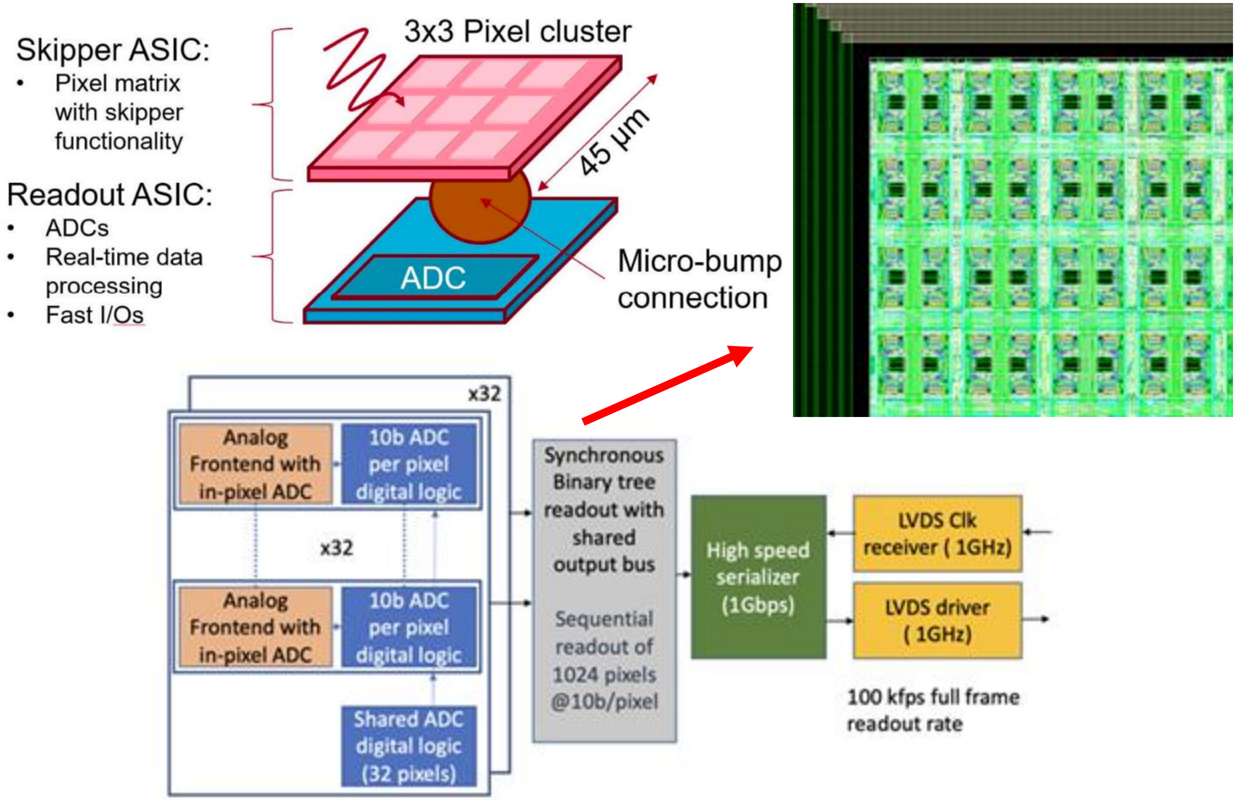
Data Aggregation for HEP

- Modern scientific detectors produce Tb/s of data per second (large pixel arrays & detection rates)
- Located in challenging environments (rad-hard, cryogenic)
- Far (+km-range) from the data processing unit
- Constraints: Power, Area/Formfactor, Temperature, …

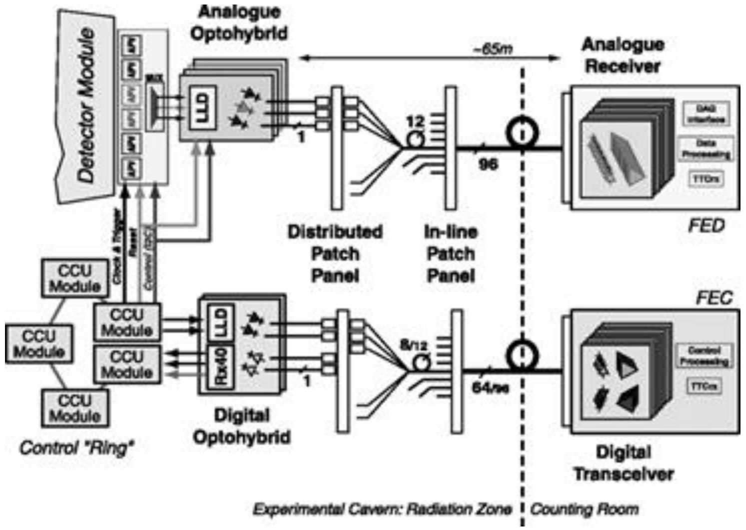


Skipper CCD-in-CMOS [FermiLab]

10bit x 100 kHz x 1 MPix = 1 Tbps!

Optical Fiber Links for HEP

- Optical links are state of the art for internet backbone and data centers
- Loss < 0.5 dB/km for a wide spectrum
- Robustness to EM interference & crosstalk
- Decouples thermal noise
- 100 ~ 1,000x lower heat load
  - Important for mK ~ 4 K cryogenics (esp. for quantum applications)
- Wavelength Division Multiplexing (WDM) to reduce number of fibers



CMS Detector Readout Architecture

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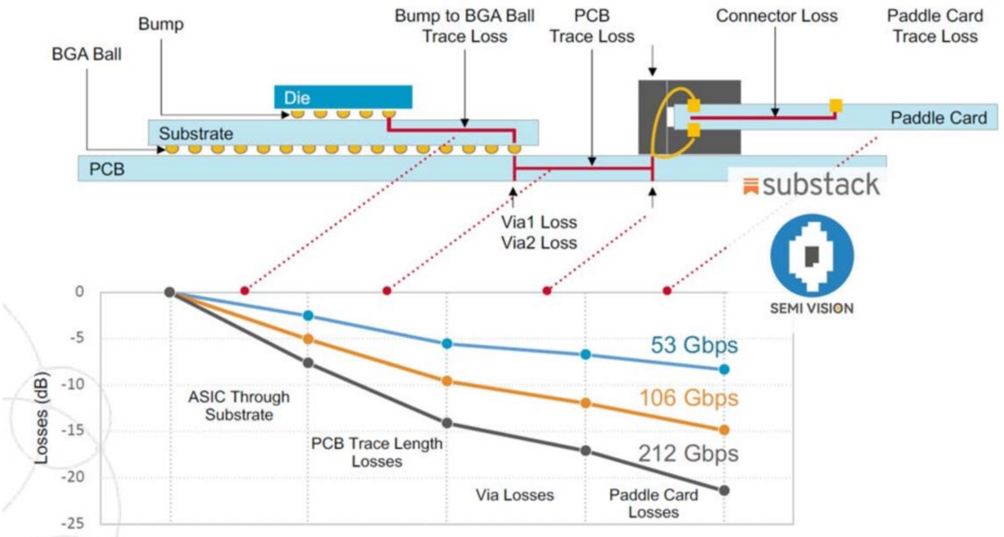
Commercial Optical Transceivers

[Cisco 100G QSFP Modules]

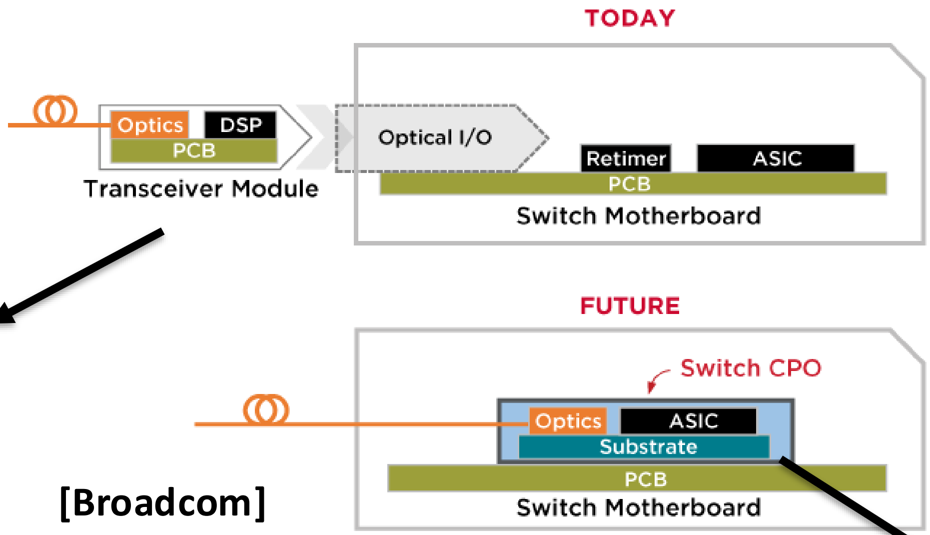
- Pluggable active optical cables (AOC)
  - Energy Efficiency: ~20-30pJ/b
  - Edge Bandwidth Density: 10-100Gb/s/mm
  - Electrical path signal loss at high frequency



- Not optimized for cryogenic nor rad-hard applications
- Co-packaging with "Pixel/Detector" might be challenging – Large Formfactor

Need for Co-packaged Optics (CPO)

[Broadcom]



[Broadcom]

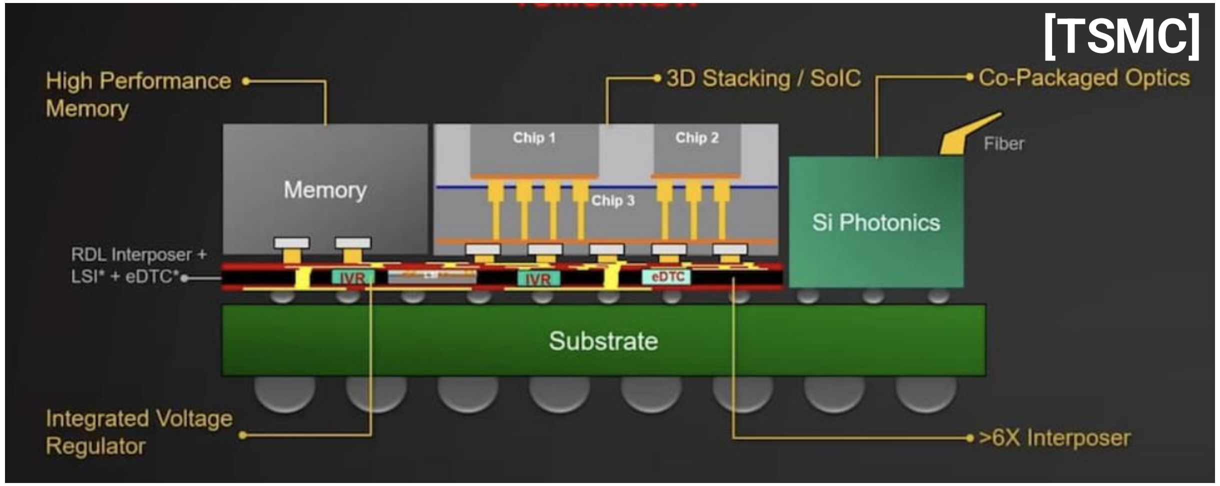
[Nvidia SW w CPO]

Goal for Co-Packaged DWDM

	IPoser	PCB	CPO	Cable	AOC	
Power	10^{-13}	$5x10^{-12}$	10^{-12}	$5x10^{-12}$	10^{-11}	J/b
Cost	10^{-15}	10^{-13}	10^{-10}	10^{-10}	10^{-9}	$-s/b
Density	10^{13}	$5x10^{11}$	$2x10^{12}$	$5x10^{10}$	10^{11}	b/s-mm
Reach	.005	0.5	100	5	100	m

Lower power than cable with comparable cost
Density higher than PCB
Reach comparable to AOC

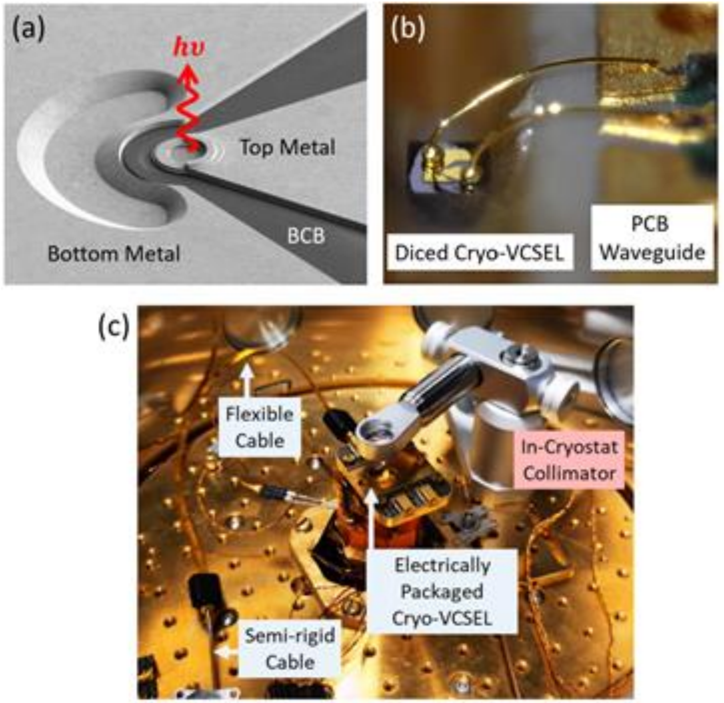
[Dally OFC 2022]



[TSMC]

State-of-the-art Optical Transmitters

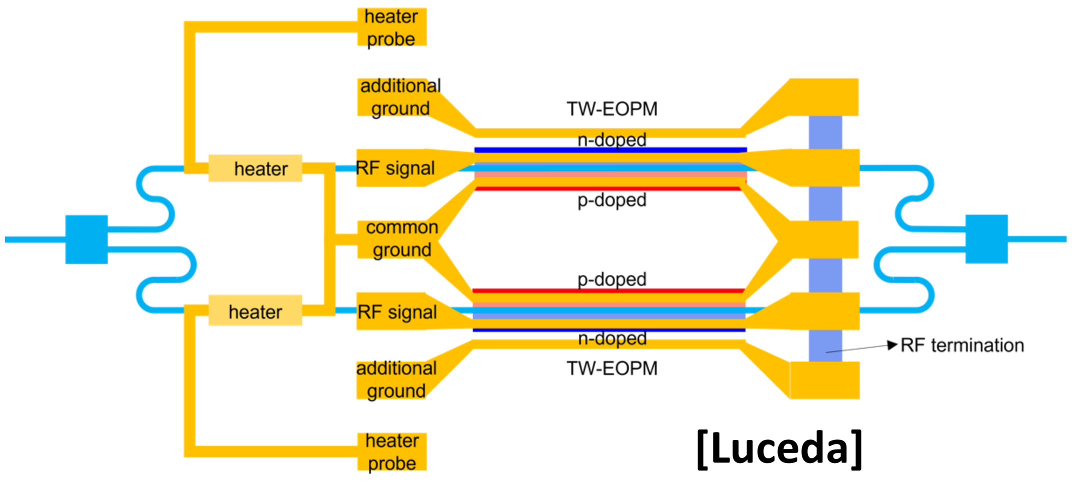
- Modulation:
  - Intensity modulation + direct detection (IM-DD)
  - Coherent links
- Directly Modulated Laser vs. Externally Modulated Laser
  - VCSEL-based links
  - Modulator based links (with an external laser):
    - **Micro-ring modulator (MRM)**
    - Mach-Zehnder Modulator (MZM)

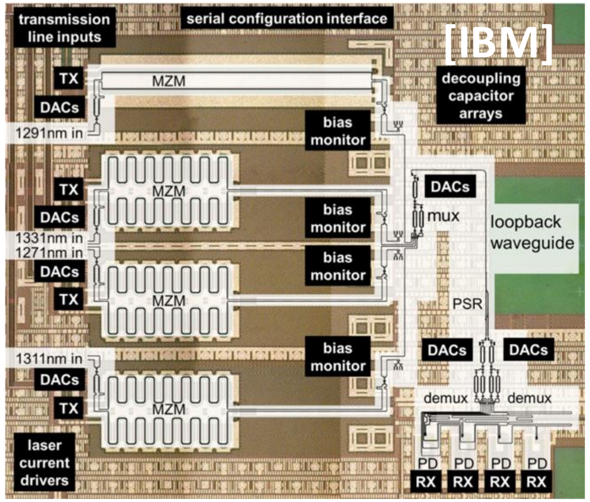


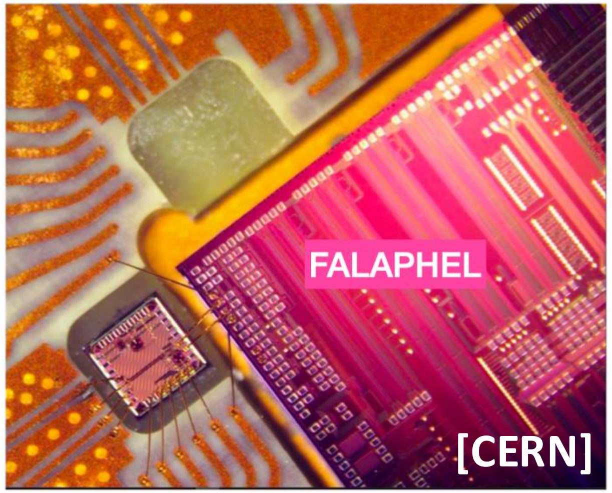
4K VCSEL (~5pJ/b @ 20Gb/s)

[Feng Group, UIUC 2022]

State-of-the-art Optical Transmitters

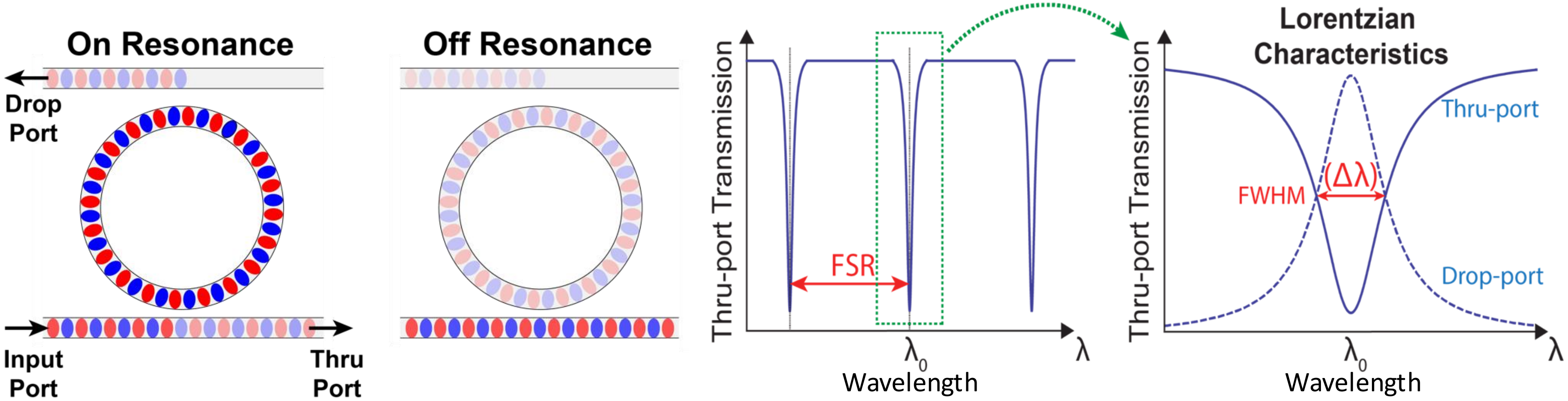




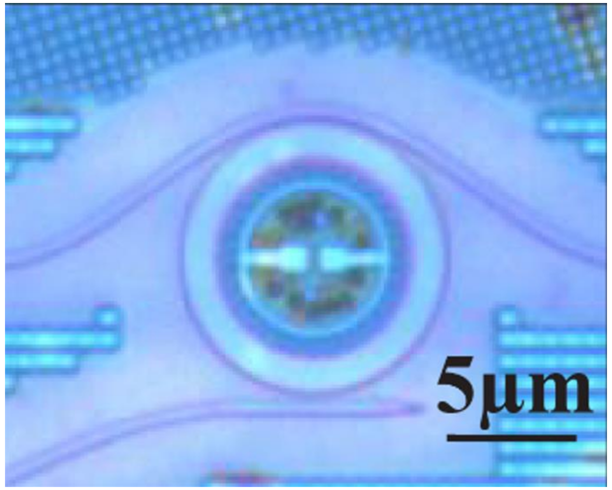


- MZM devices have …
  - Large footprints (mm-scale long) -> pF capacitive load!
  - Poor energy efficiency (5-10pJ/b)
- ***Silicon Photonics***: Silicon based devices using CMOS foundries (GF, AMF, AIM, …)

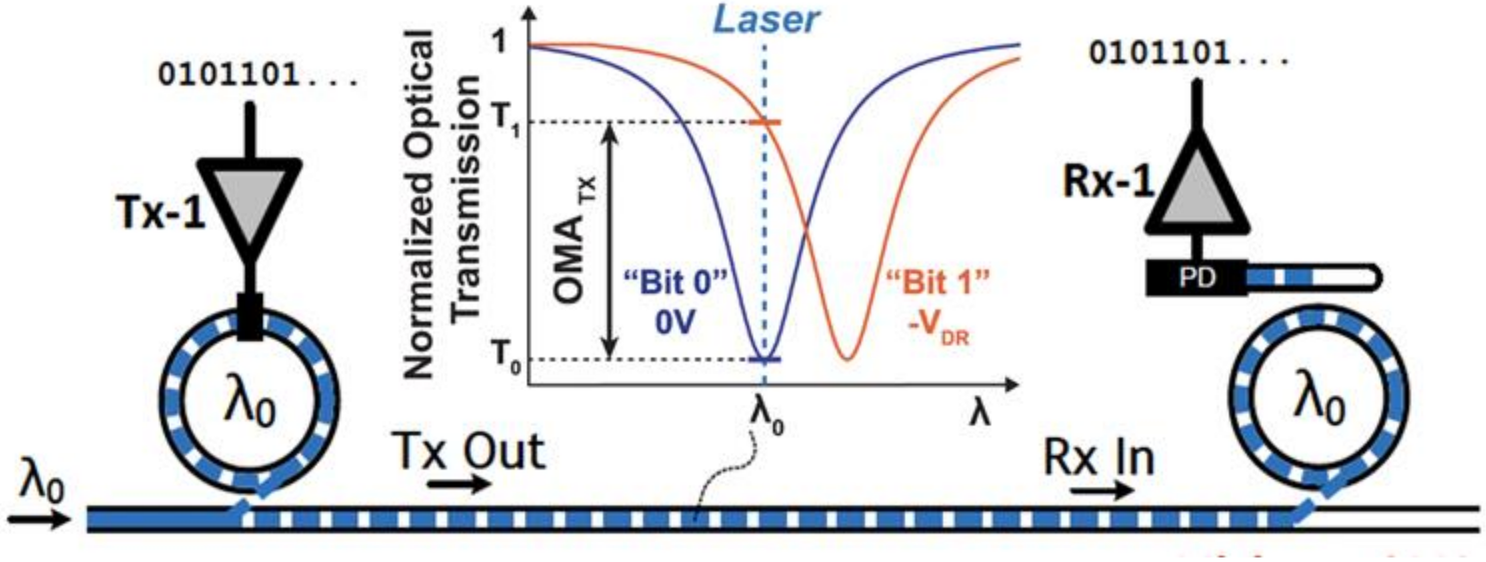
Micro-Ring Modulators (MRMs)

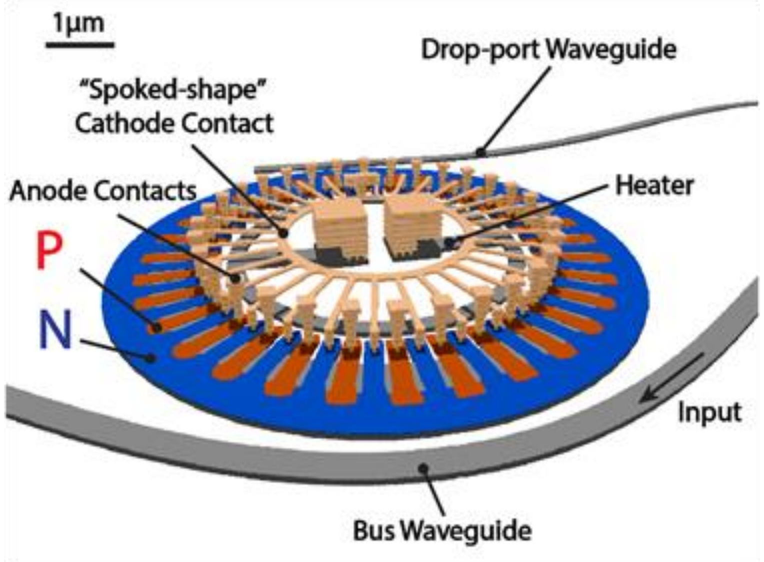


- Resonance wavelength: $\lambda_0 = n_{eff} L/m$, m = 1,2,3,...
  - Q-factor: $Q = \lambda_0 / \Delta\lambda$
- Compact device (radius of 5µm)
  - Energy & area efficient modulator/filter
- Supporting wavelength division multiplexing (WDM)



Micro-Ring Modulators (MRMs)





Modulation Scheme:

1. Deplete/Inject carriers using PN junctions
2. Δfree carriers -> Δindex of refraction [Carrier-Plasma Effect] -> Resonance shift
3. On-Off Keying (OOK) modulation (***OMA**: Optical Modulation Amplitude)

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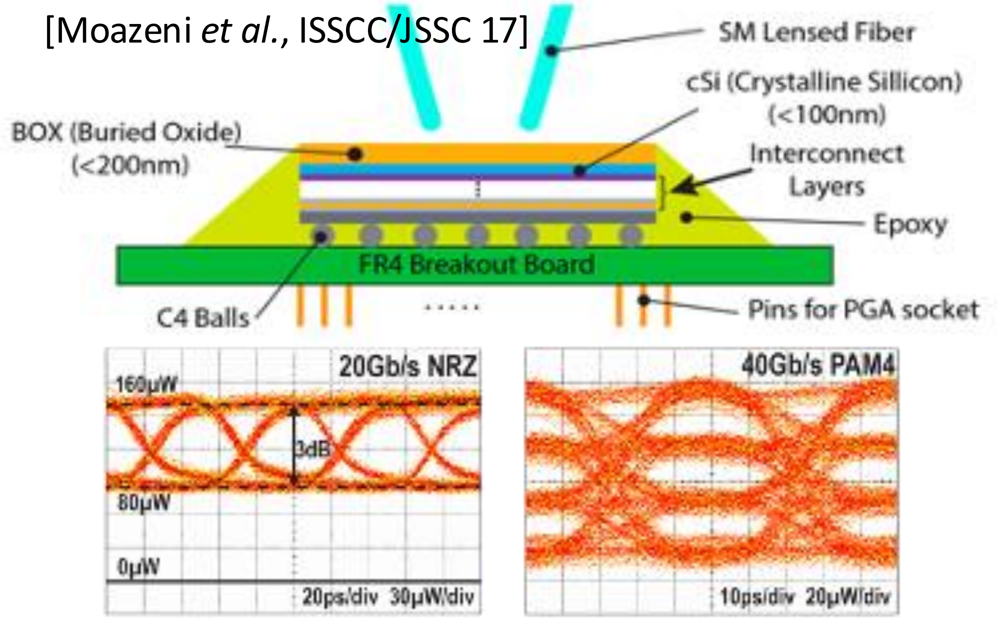
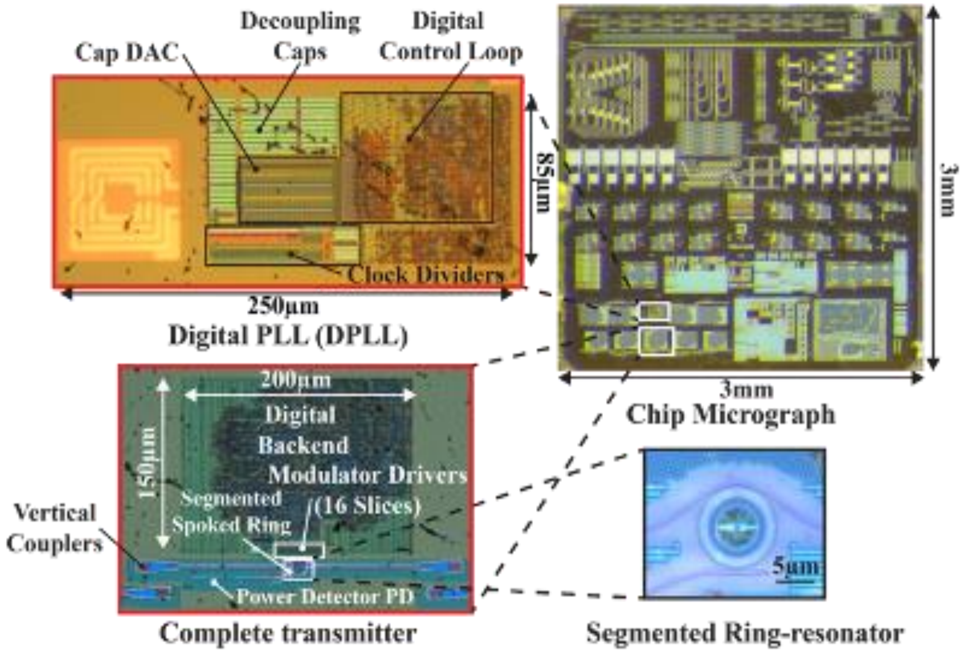
MRM in Advanced Silicon Photonics

[Moazeni *et al.*, ISSCC/JSSC 17]





GF 45nm SOI

- Low-power (Sub-pJ/b) & high bandwidth (+50GHz) optical I/O
- MRMs used in R&D and research mainly -> 2025 in Nvidia CPO Switch
- Available in most of major silicon photonics processes such as GlobalFoundries, AMF, and recently in TSMC.

Rad-hard & Cryogenic Photonics

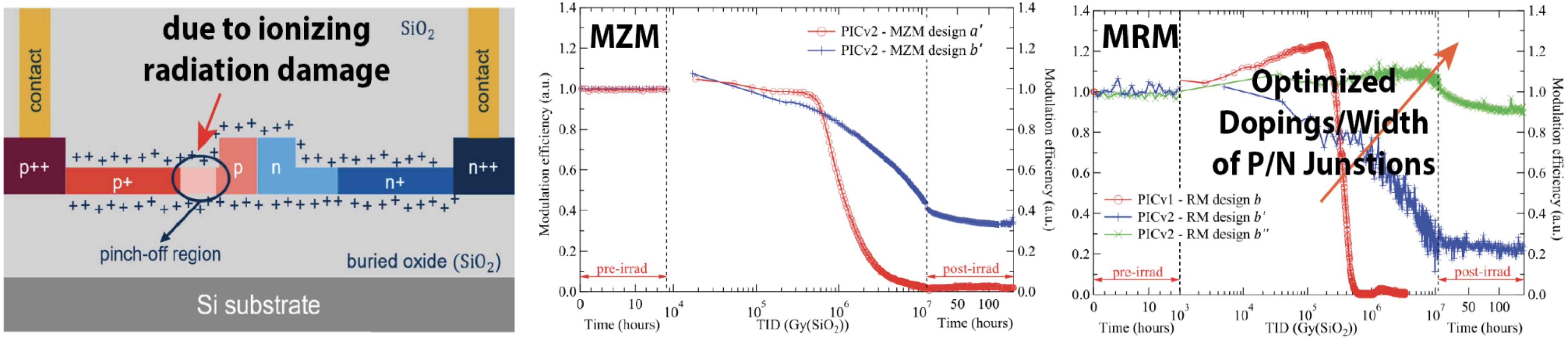


Figure 7 Impacts of ionization radiations on MRM/MZM photonic modulators and how device design optimization can help (c) in green a highly doped device is [CERN Study]

- **MRMs are more robust to radiation/temperature effects compared with MZMs (mainly due to smaller footprint)**
- **Low-thickness slab sections of PN junctions will have reduced resistance …**
  (1) Due to career freeze-out in cryogenic temperatures
  (2) Due to TID effects under radiation

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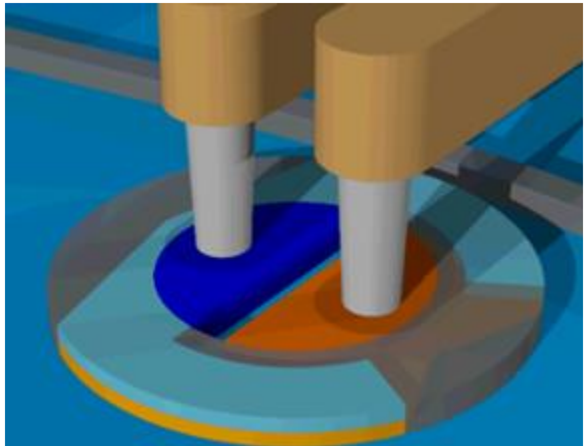
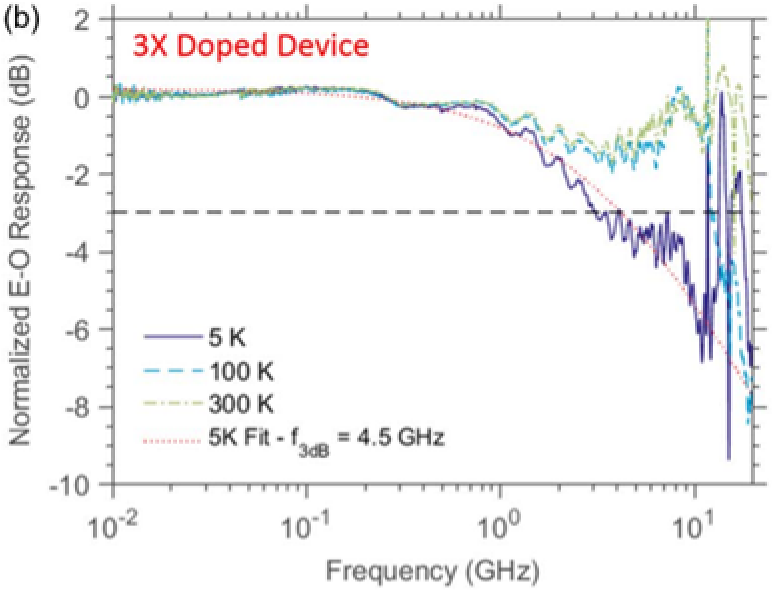
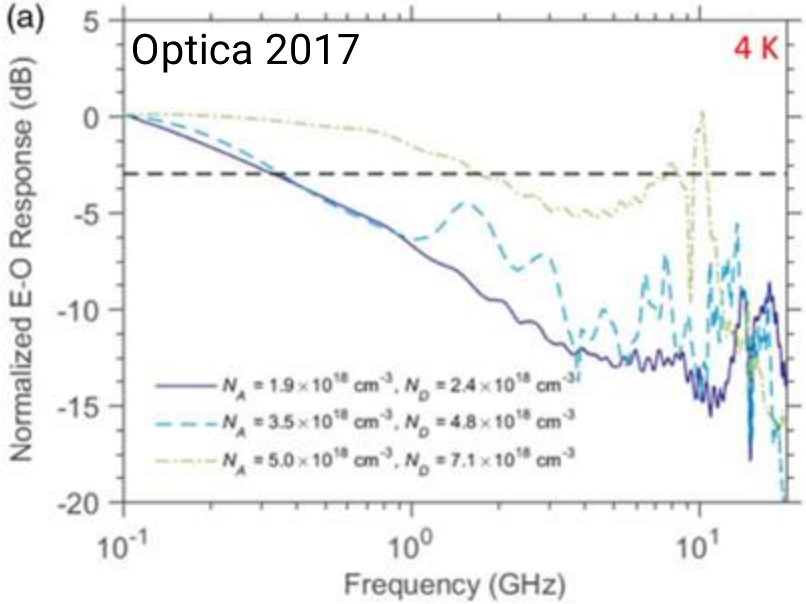
Challenge 1: Limited Bandwidth of Cryo MRMs



[M. Gehl, Optica 4, 374-382 (2017)]





- Electro-optical (EO) BW depends on: (1) RC time-constant of PN junctions, (2) Optical FWHM
- MRM's EO BW reduces at 4K due to carrier freeze-out! (under-radiation this is due to "pinch-off" effect)

Need to optimize doping and reduce junction resistances

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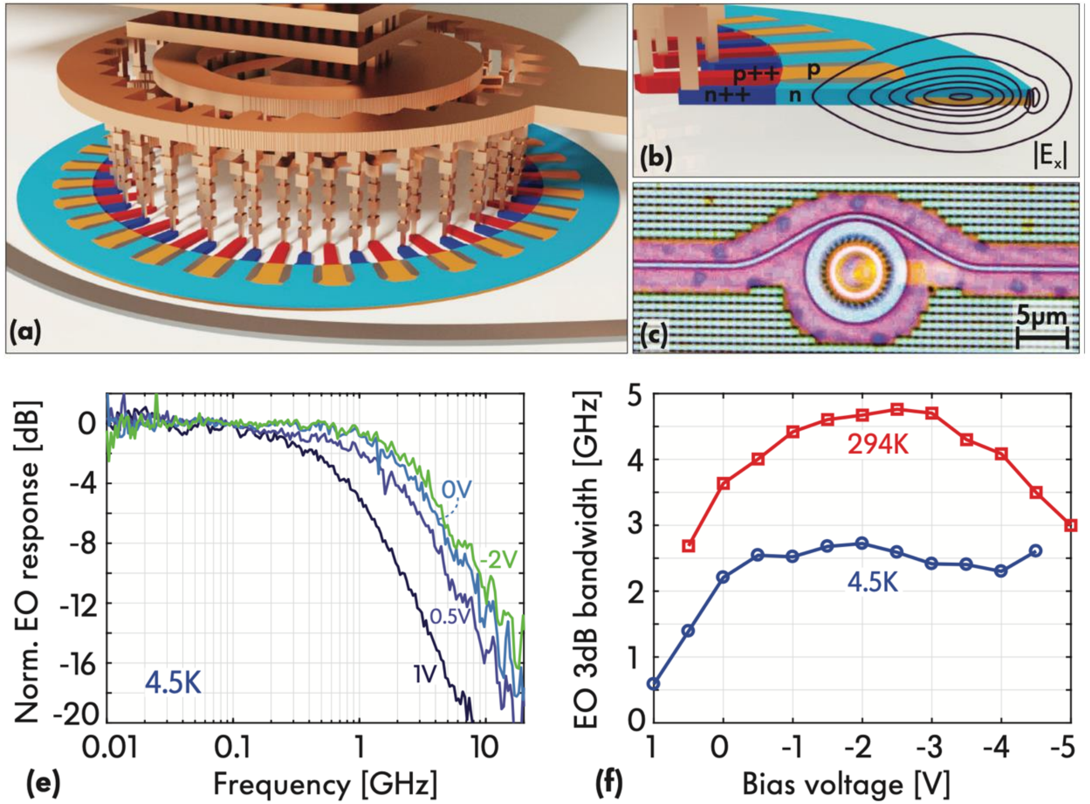
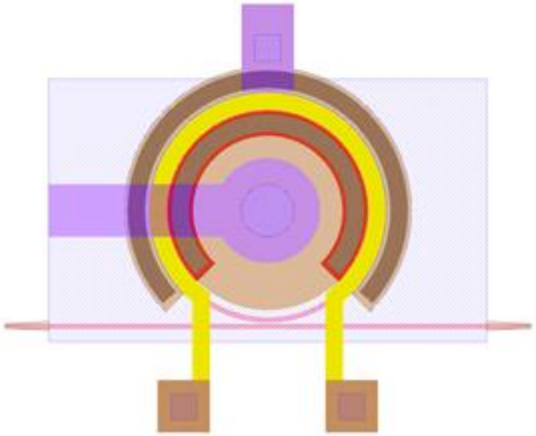
Challenge 1: Limited Bandwidth of Cryo MRMs

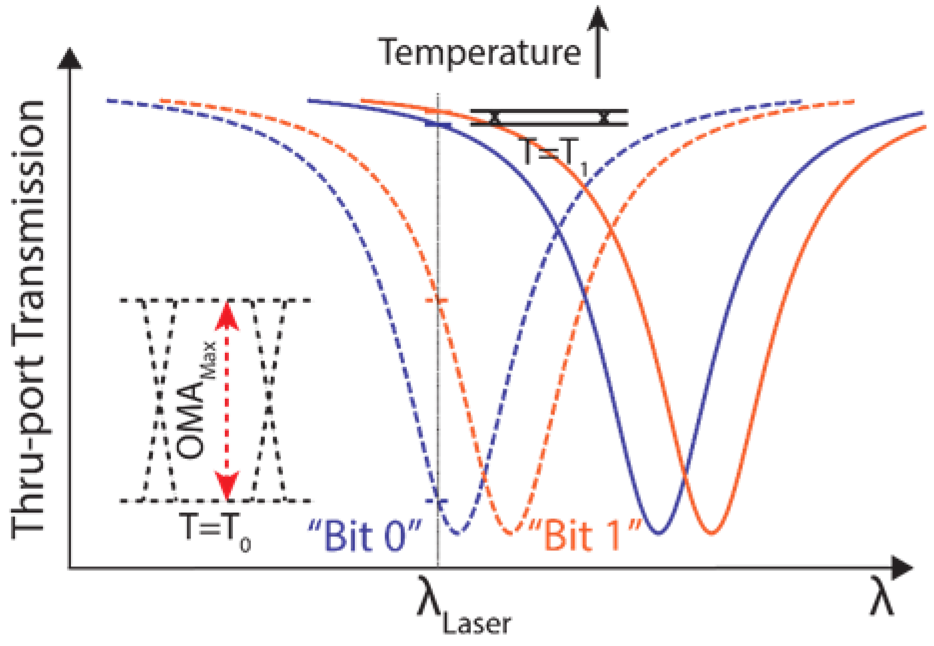


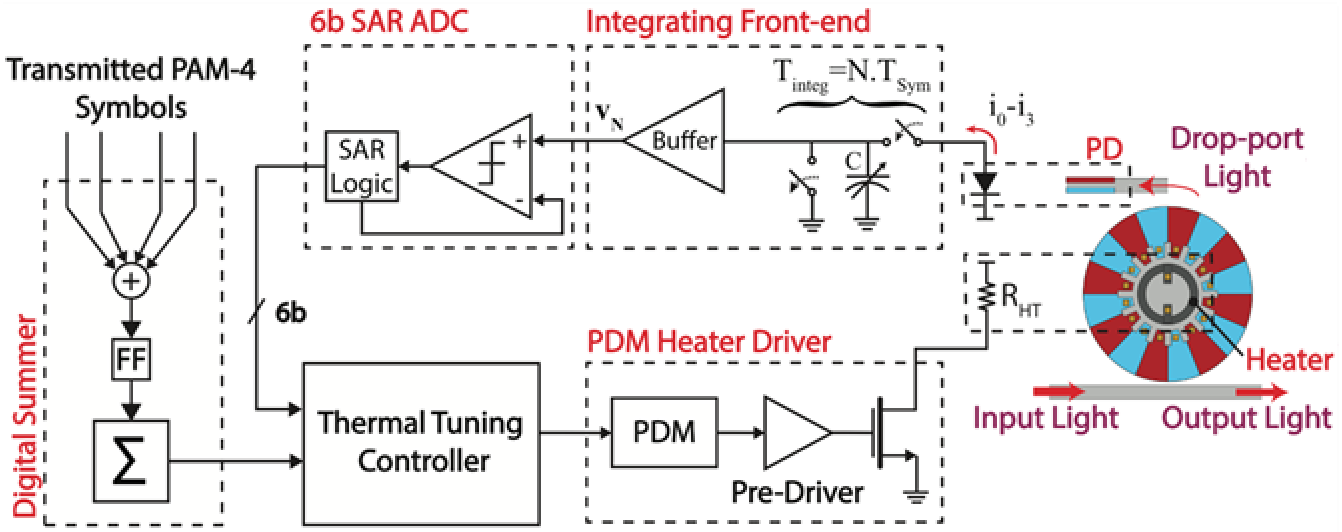
[Hayk Gevorgyan, et al., OFC 2021]

- Lateral junctions with lower PN junction lengths
- Design the MRM with moderate doping (instead of lower doping)



Challenge 2: Tuning Cryogenic MRMs





[Moazeni *et al.*, ISSCC/JSSC 17]

- Resonance wavelength and laser has to be precisely aligned
  - Due to process variation & temperature fluctuations
  - Closed-loop thermal tuning has been demonstrated for this issue at room temperature

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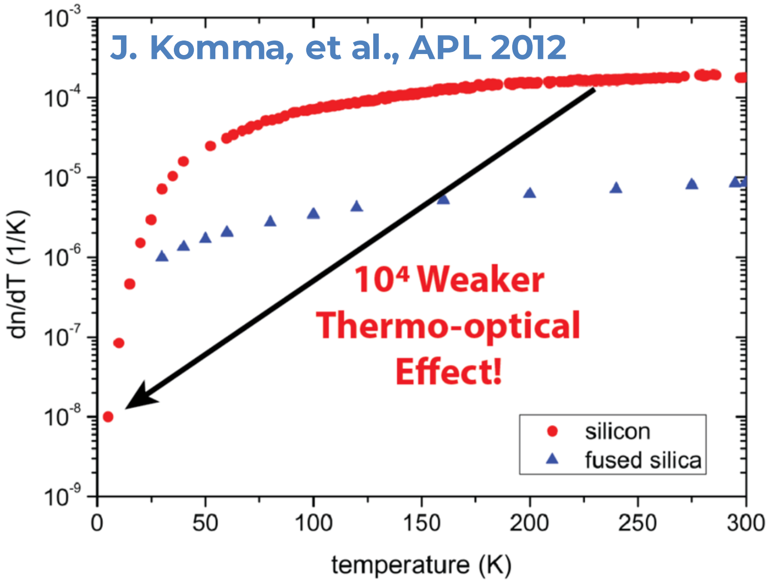
Challenge 2: Tuning Cryogenic MRMs

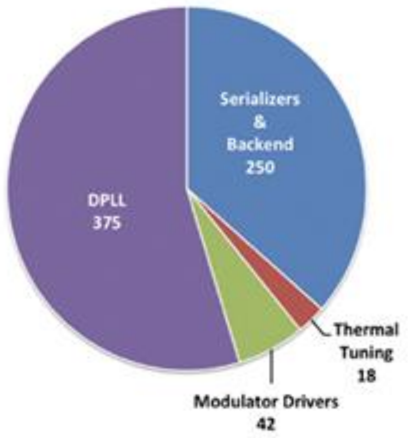


Tuning	Method	Device Footprint	Tuning Speed	Tuning Range	Operation Voltage	Power Efficiency
	Magneto-optic effect	Small	Moderate	Moderate	-	Low
	InAlGaAs QW-on-Si, QCSE	Moderate	Moderate	Moderate	Low	High
	MEMS / optomechanical effects	Small	Low	Large	Large	Low
	Phase Change Materials (PCM)	Small	Low	Large	Large	High (Non-volatile)

- Thermo-optical effect are extremely weak at 4K! (less challenging for 70K)
- Alternative are not energy-efficient, can require large voltages, and are not compact!
- Using tunable lasers is not a practical and scalable solution!
- We propose to use Phase change materials (PCM) for non-volatile tuning … (we get back to this soon …)

Challenge 3: Electronic/photonic Co-design

40Gb/s PAM-4 Tx (0.5pJ/b)
[Moazeni *et al.*, ISSCC17]



[P. Chang, JLT 2023]

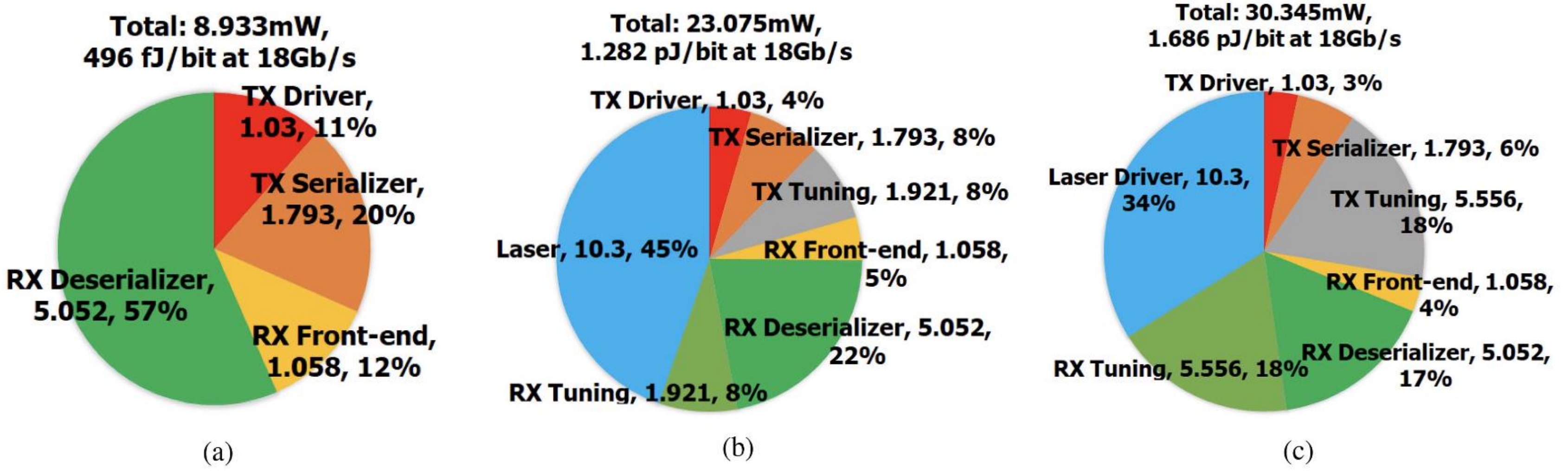
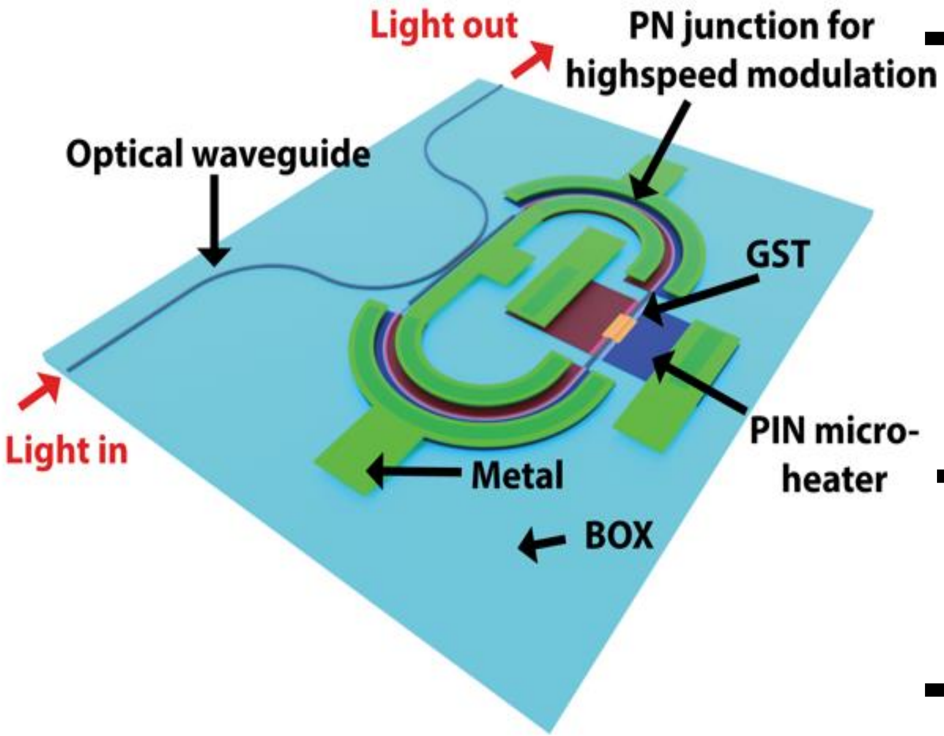


Fig. 13. (a) Power consumption breakdown of individual channel/wavelength optical transceiver at 18 Gb/s. (b) Link power efficiency at 18 Gb/s based on link budget analysis of Table I with passively cooled laser and wavelength shuffling tuning scheme of [17], and (c) based on tuning of 3σ wavelength variation.

- Sub-pJ/b energy-efficiency requires ultra-low power CMOS design (co-designed with photonics), and resonance thermal tuning mechanism
- Co-design Examples: using optical DAC rather than electrical, trades on MRM Q-factor and OMA, etc.

Non-volatile Tunable Cryogenic MRMs



Highspeed modulation with carrier plasma-dispersion effect

=> With optimized doping & device design

Non-volatile resonance tuning using PCM

=> zero energy for tuning!

Commercial foundry compatible

=> Post-processed PCM for now!

Adya, Uthkarsh, Rui Chen, I-Tung Chen, Sanskriti Joshi, Arka Majumdar, Mo Li and Sajjad Moazeni. "Non-volatile Tuning of Cryogenic Optical Resonators." (2024).

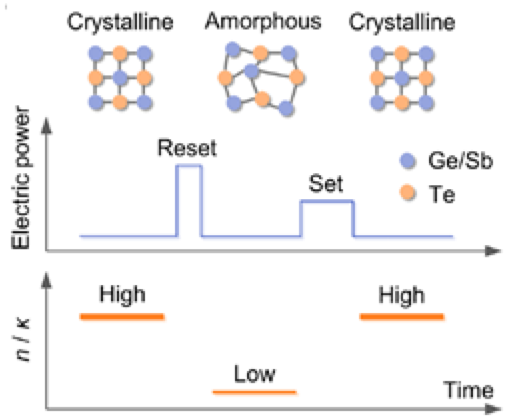
Phase Change Material (PCM)

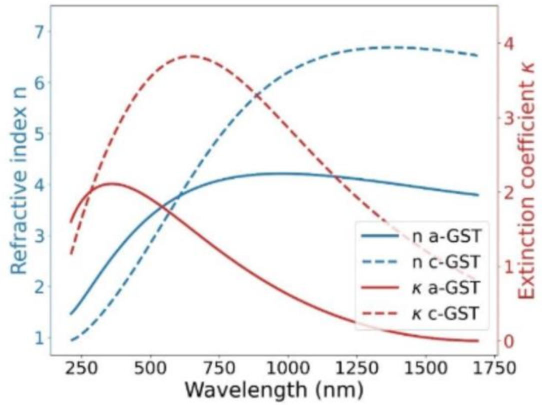
Properties of interest in PCM

- Phase transition (Crystalline -> Amorphous)
- Reversibility (Amorphous -> Crystalline)
- Non-volatile phase transition
- **Drastic change in optical properties on phase transition**
- **Switching mechanisms: Electrical or Optical**

Examples: **GST**, GeTe, SbS, SbSe etc

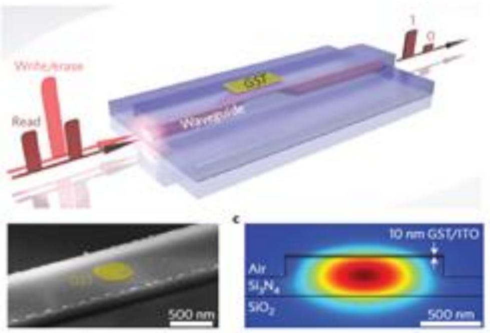
Suitable for photonic applications as they provide a non-volatile EO-reconfigurability



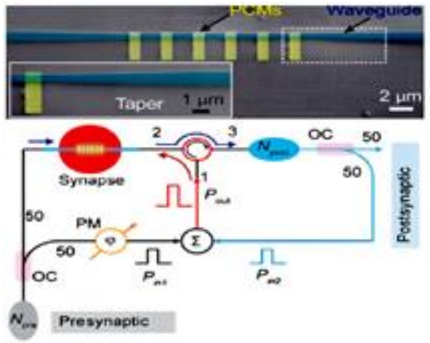


Optical Properties of GST [J. Zheng 2020] [R. Chen 2020]

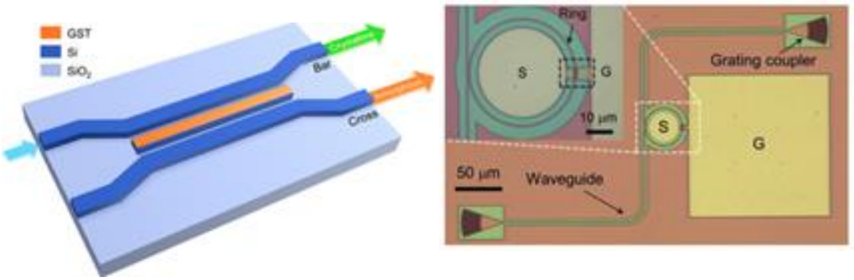
Applications majorly include programmable units that require infrequent switching →



Photonic memory
[C. Rios, 2015]



Neuromorphic computing
[C. Rios, 2017]



Optical programmable units
[P. Xu, 2019] , [Zheng, 2020]

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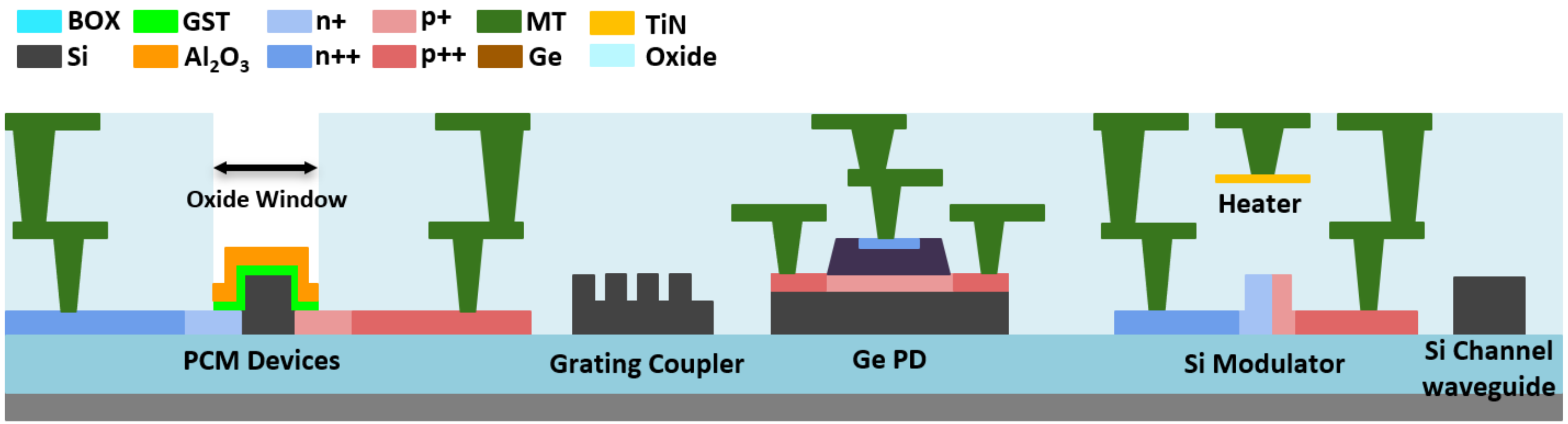
Integrating PCM in Commercial SiPh process

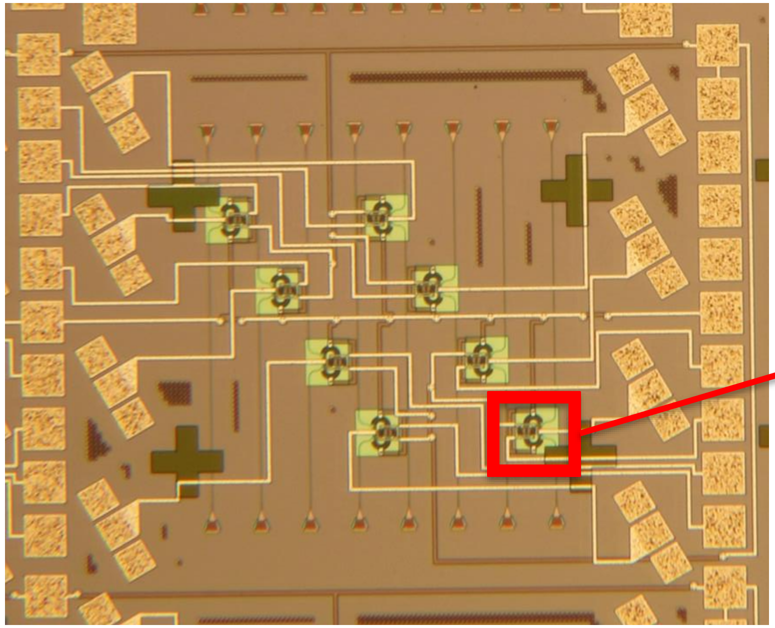
Cross-Section of commercial silicon photonics platform with PCM-based devices:

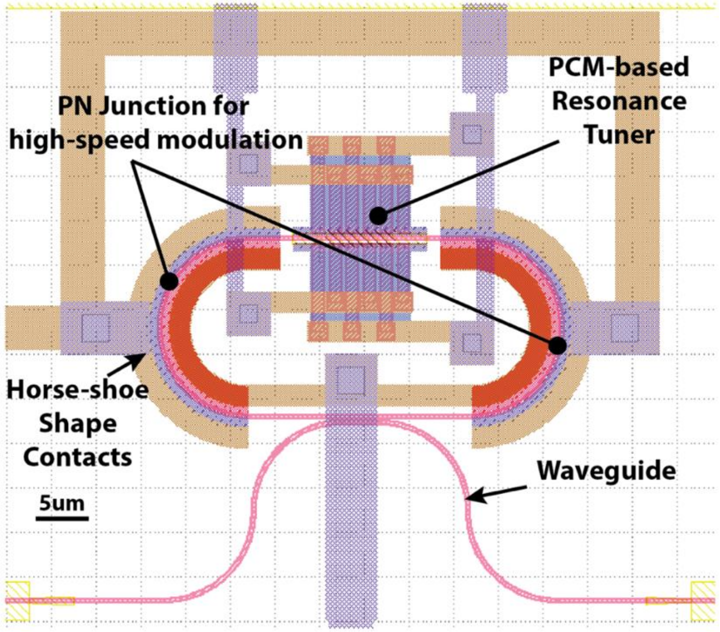


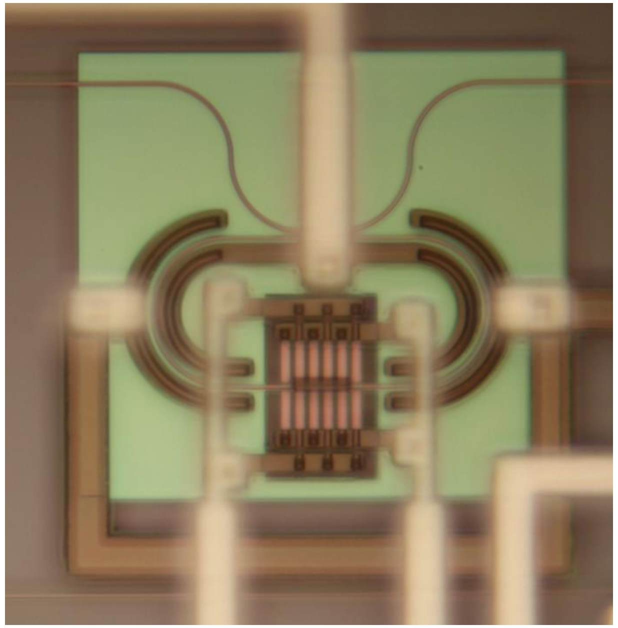
[U Adya, Optics Express2024]

- Our devices were fabricated in the AMF silicon photonics process, followed by a zero-change monolithic integration of PCM
- Postprocessing was performed on a die level using a few fabrication steps and coarse resolution photolithography

MRM with Integrated PCM







Adya, Uthkarsh, et al "Non-volatile Tuning of Cryogenic Optical Resonators." (2024).

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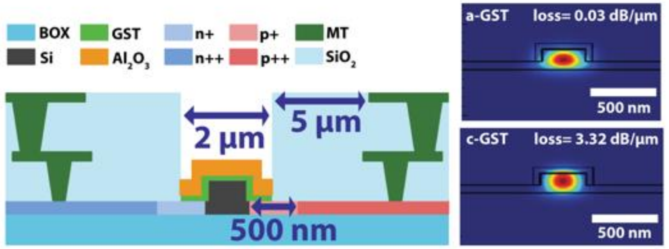
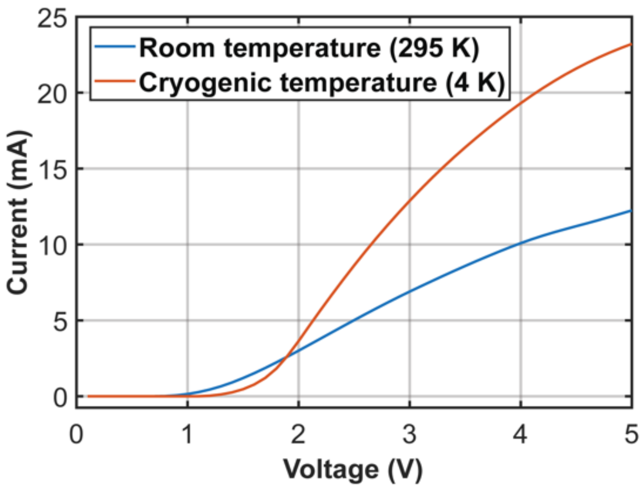
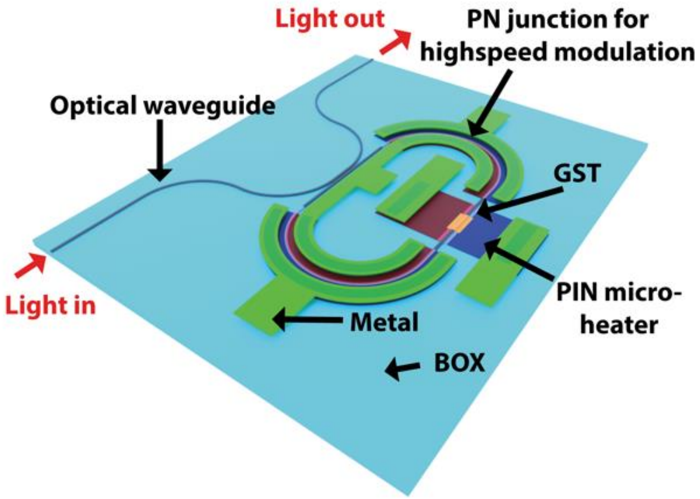
PCM-integrated Cryogenic MRM

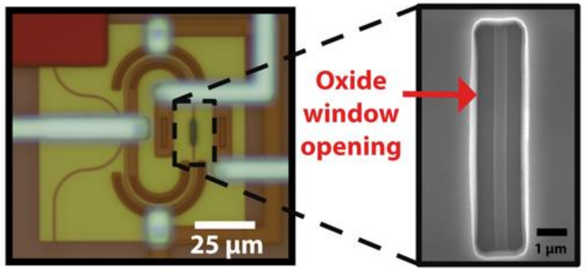
PIN heater for cross-section





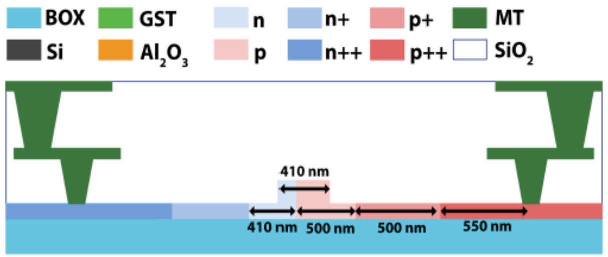
IV characteristics of PIN heater

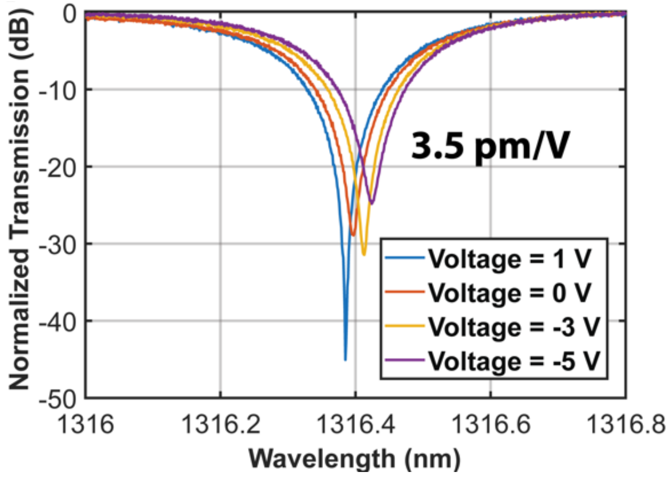




Microscope image of PCM-integrated MRM

PN junction cross-section





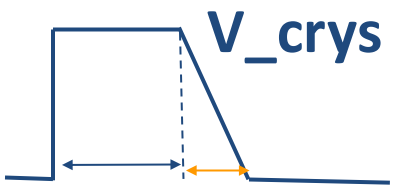
Resonance shift for DC bias voltages at 4 K

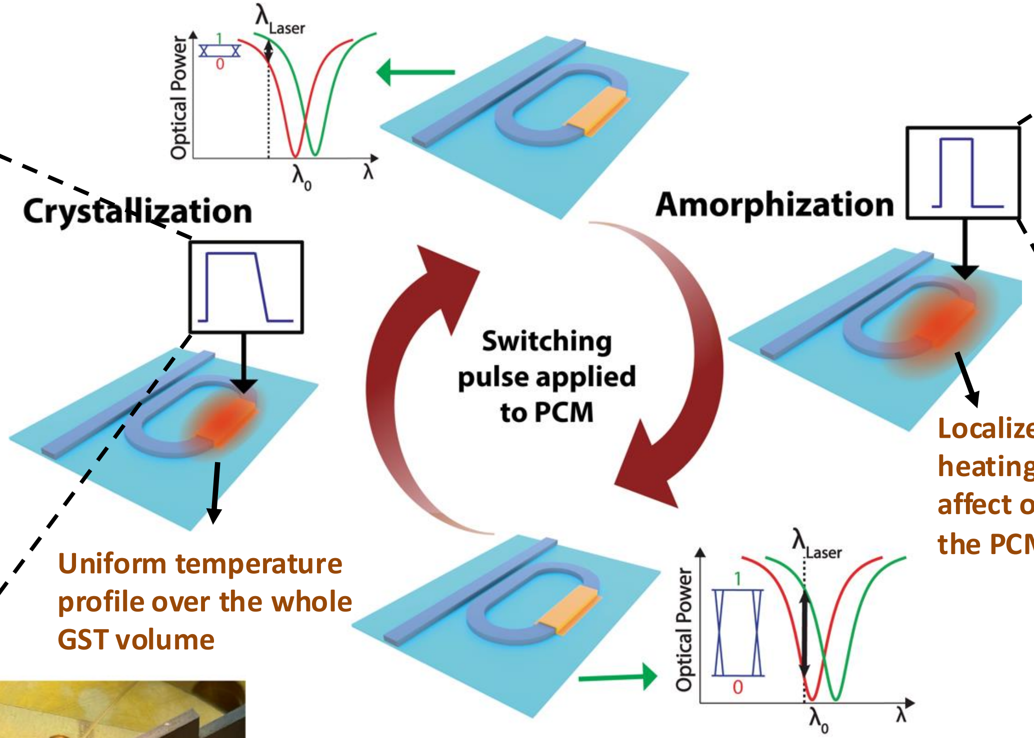
Adya, Uthkarsh, et al "Non-volatile Tuning of Cryogenic Optical Resonators." (2024).

PCM-based Tuning of Cryogenic MRM

Amorphous-> Crystalline

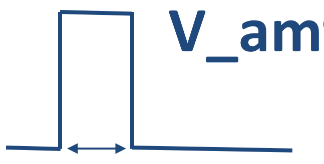
- Long pulse & Slow cooling
- 423 K < T < 923 K (GST)

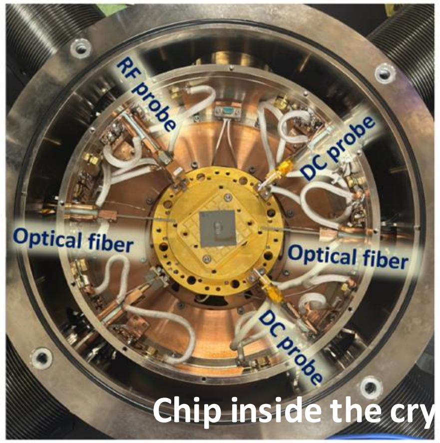


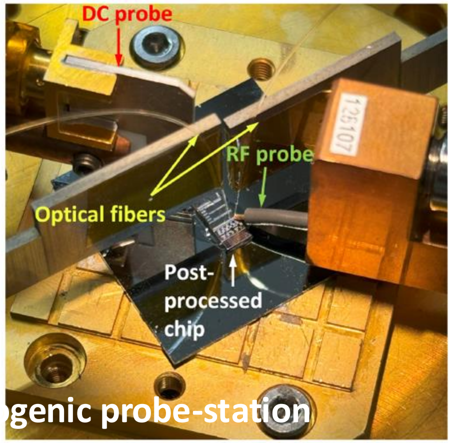


Crystalline-> Amorphous

- Short pulse & Fast cooling
- T > 923 K (GST)







Chip inside the cryogenic probe-station

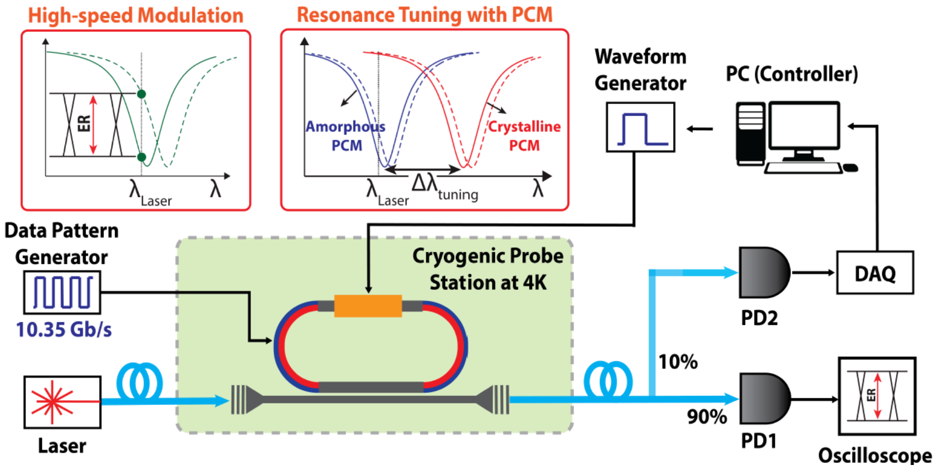
Properties in PCM that make it ideal for cryogenic tuning

- **Reconfigurability [Multilevel switching]**
- **Non-volatile [Zero-Static Power dissipation]**
- **Infrequent switching [Cryogenic environment]**
- **Small footprint**
- **Commercial foundry compatible**

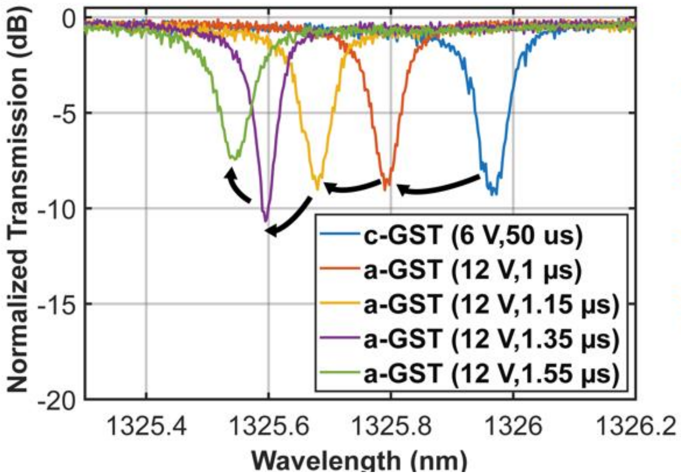
Adya, Uthkarsh, et al "Non-volatile Tuning of Cryogenic Optical Resonators." (2024).

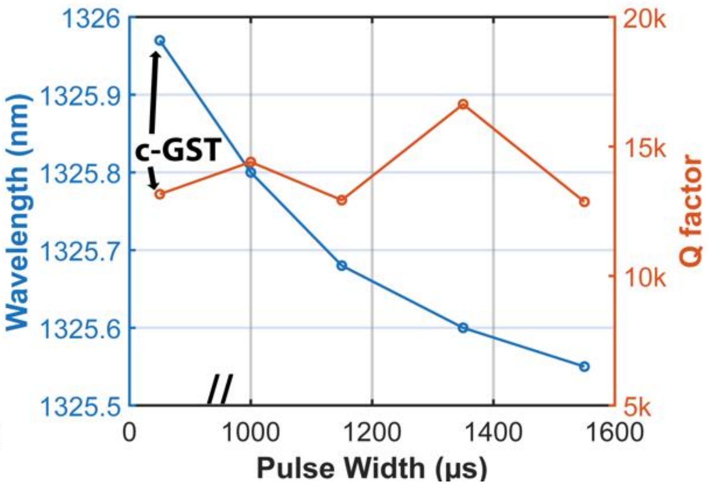
Resonance Tuning of the Cryogenic MRM

Adya, Uthkarsh, et al "Non-volatile Tuning of Cryogenic Optical Resonators." (2024).



Test setup to characterize resonance tuning and high-speed modulation in cryogenic MRM

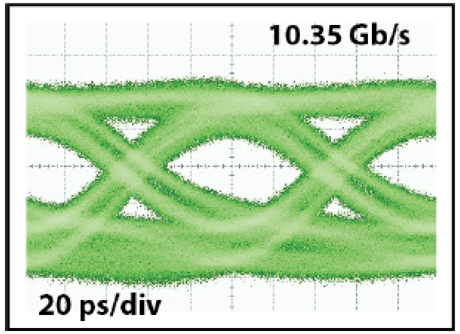




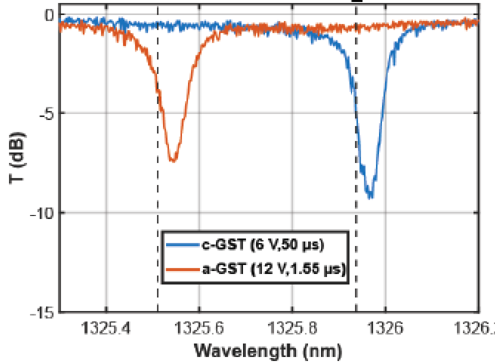
Multilevel switching of PCM at 4K

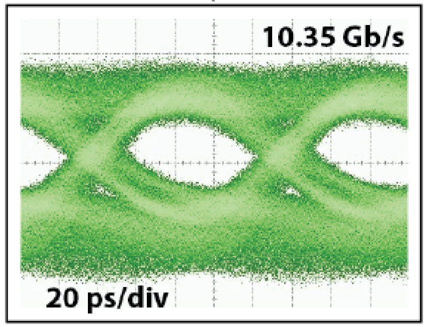
Optical Modulation with Amorphous GST State

Optical Modulation with Crystalline GST State



OMA = 0.36 and IL = 2.73 dB





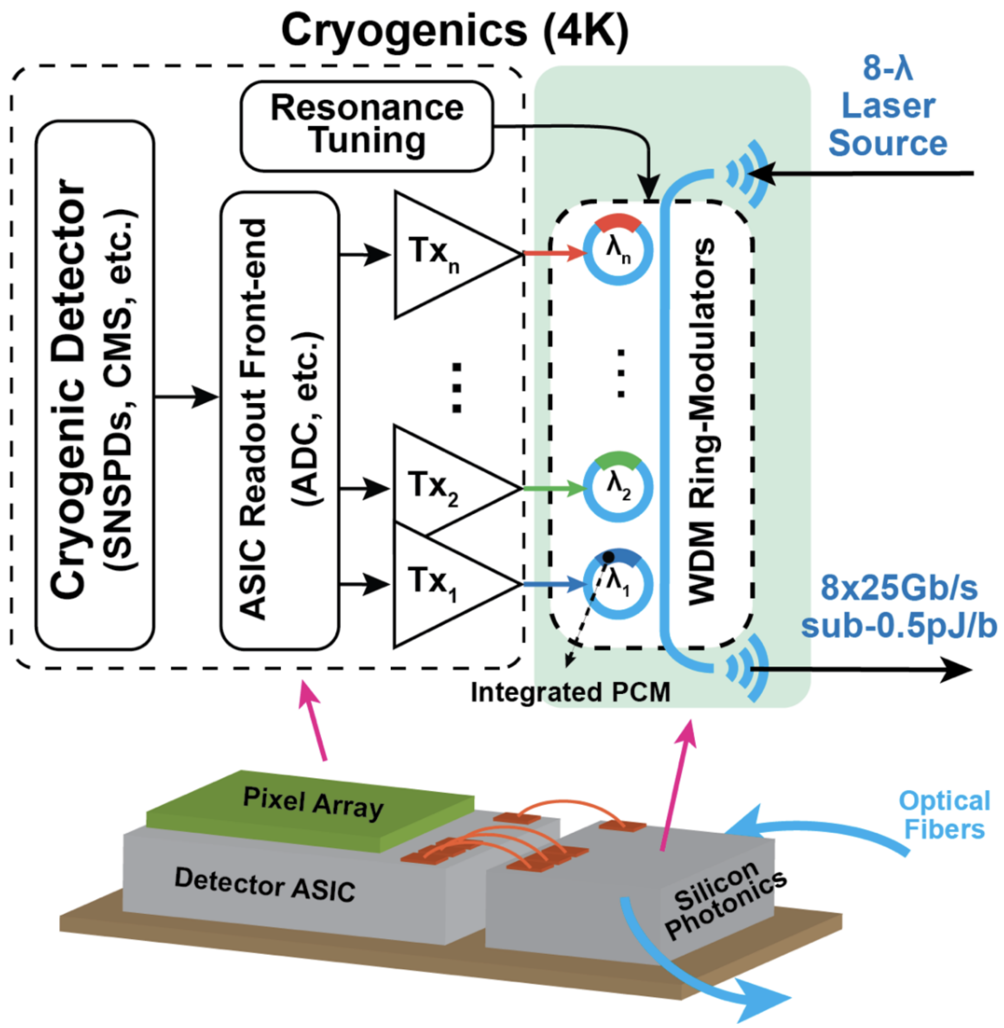
OMA = 0.29 and IL = 3 dB

Sub-100fJ/b Driver Energy

MRM Integration for HEP with FermiLab

- Silicon photonics integration with CMOS (Monolithic, 3D, wire-bond)
- Integration with the detector chip
- Fiber/Optical packaging

- Target specs for initial demo:
  - 4 Kelvin Operation
  - Wavelength-Division Multiplexing (target 4 wavelengths)
  - +100 Gb/s per fiber
  - < 1pJ/b @25Gb/s per wavelength



Conclusion

- Ultra-low power MRM-based silicon photonic links is the most suitable communication link for HEP & Quantum applications
  - High data-rate, km-range reach, and path for co-packaging with detectors

- Several challenges need to be addressed for cryogenic/rad-hard operations & co-packaging with detectors/ASIC:
  - MRM's tuning & limited EO bandwidth
  - Integration with CMOS and Detector
  - Optical packaging

- We have demonstrated first-ever non-volatile tuning at 4K using PCM & foundry silicon photonics with +10Gb/s MRM transmitters

Acknowledgment

- We would like to thank Fermi Lab, and Department of Energy (DOE) for their support.