Ring Resonator Transmitter and Prospects in Cryogenic Application

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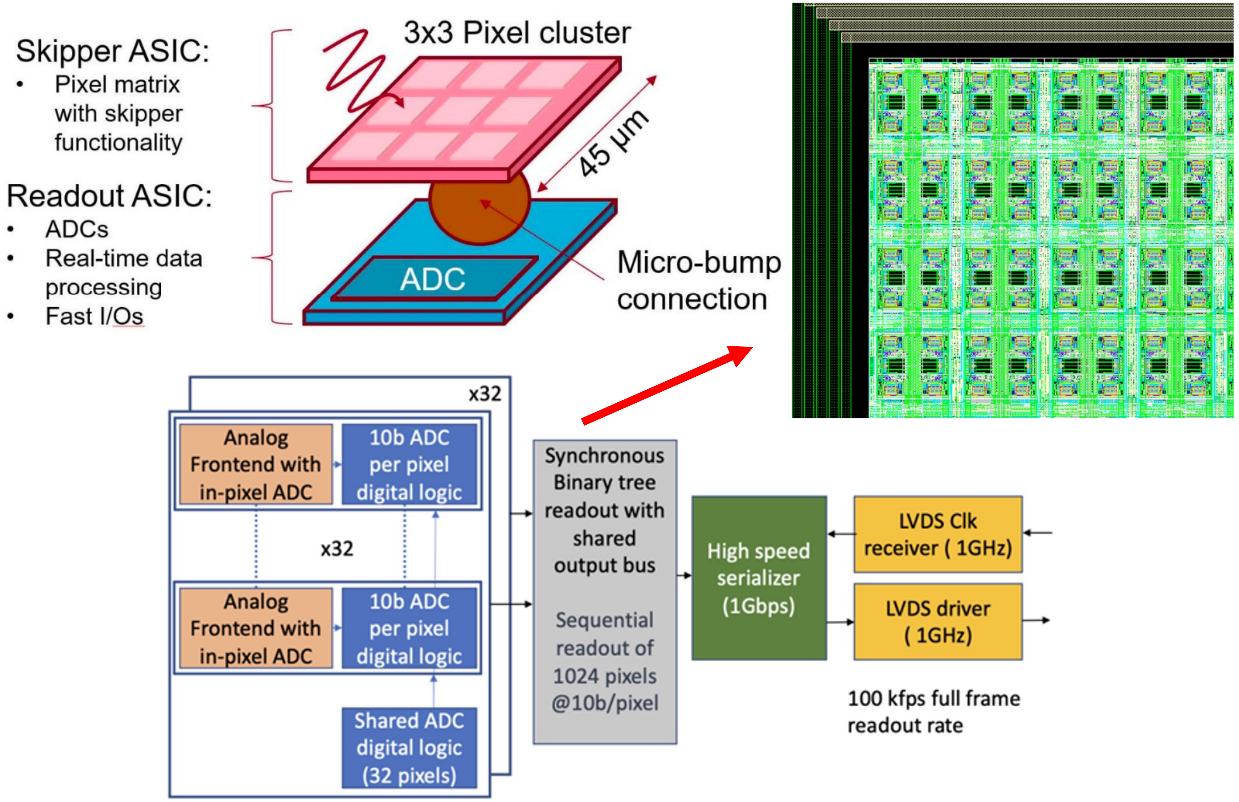
Data Aggregation for HEP/Quantum

- Modern scientific detectors produce Tbs 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, …

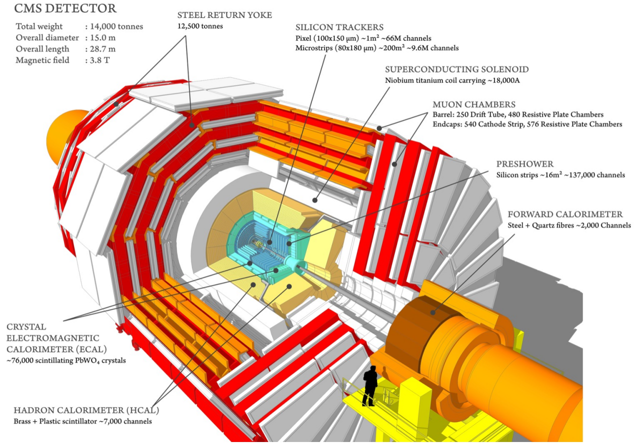


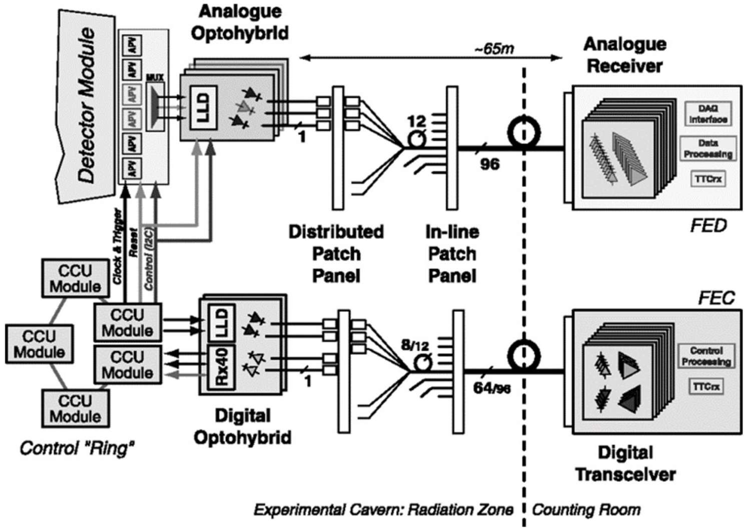
Skipper CCD-in-CMOS [FermiLab]

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

Optical Fiber Links

- 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



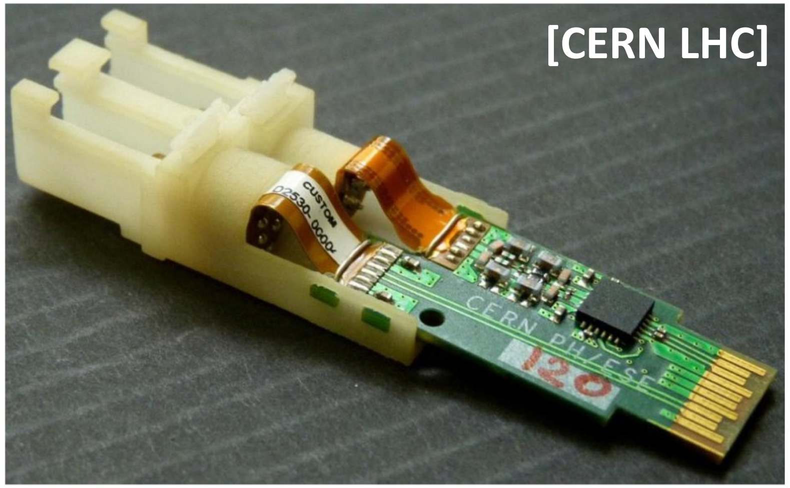


CMS Detector Readout Architecture

Commercial Optical Transceivers

- Pluggable active optical cables (AOC)
  - Energy Efficiency: ~10-30pJ/b
  - Edge Bandwidth Density: 10-100Gb/s/mm
- Not optimized for cryogenic nor rad-hard applications
- Have been verified/used in CERN for LHC systems (4.5Gb/s links)

[Cisco 100G QSFP Modules]

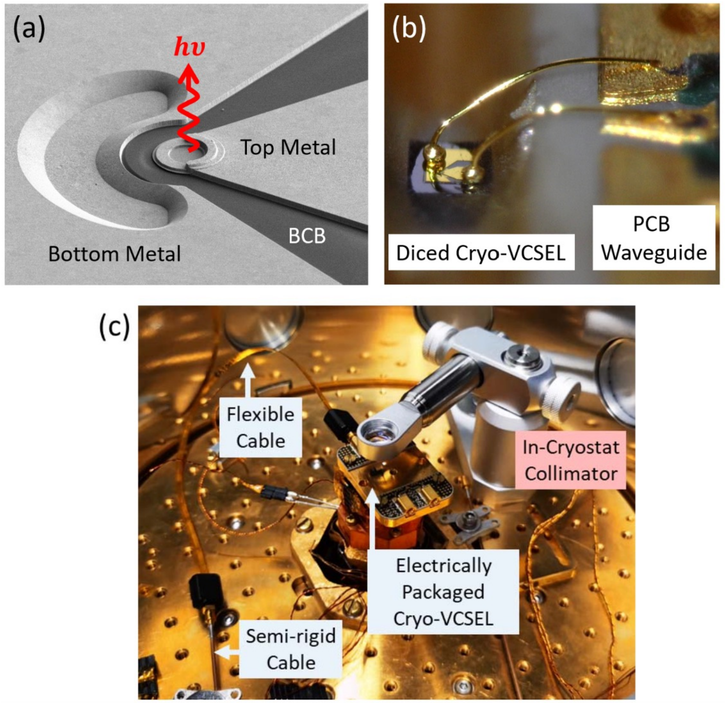


[CERN LHC]

State-of-the-art Optical Transmitters

- Modulation:
  - Intensity modulation + direct detection
  - Coherent links

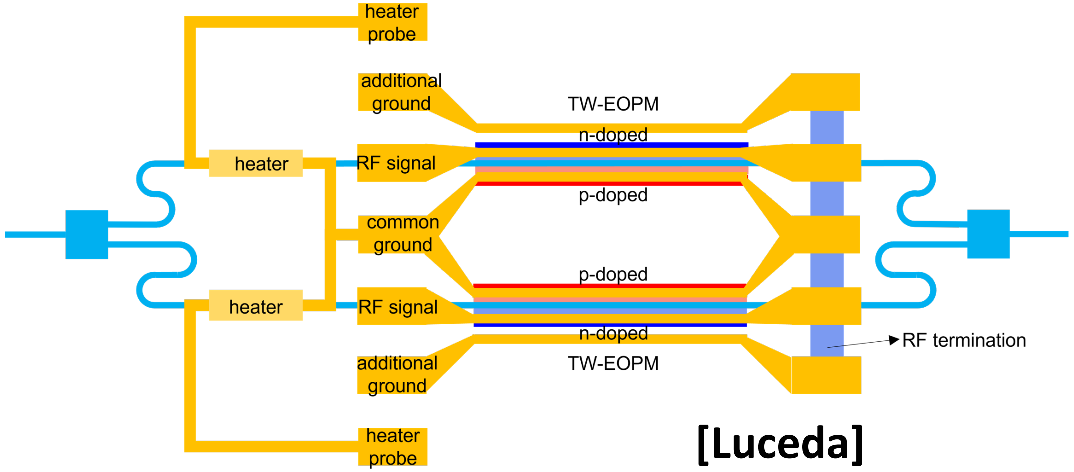
- Directly Modulated Laser vs. Externally Modulated Laser
  - VCSEL-based links
  - Modulator based links (with an external laser):
    - Micro-ring modulator (MRM)
    - Mach-Zehnder Modulator (MZM)

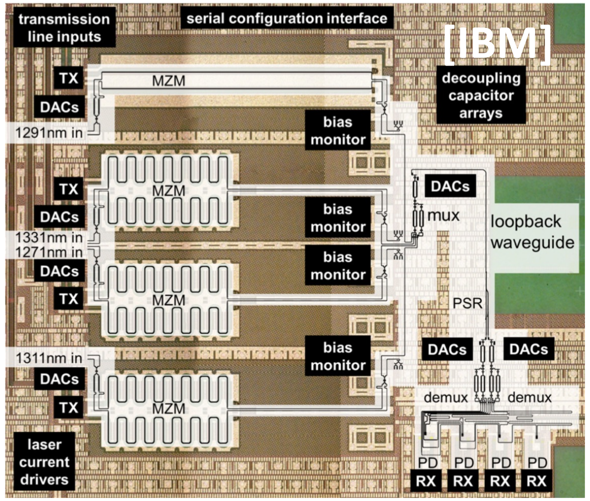


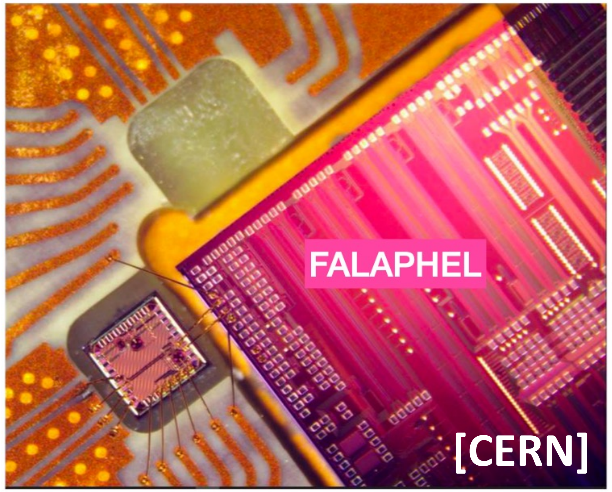
4K VCSEL (~5pJ/b @ 20Gb/s)

Feng Group, UIUC 2022

State-of-the-art Optical Transmitters

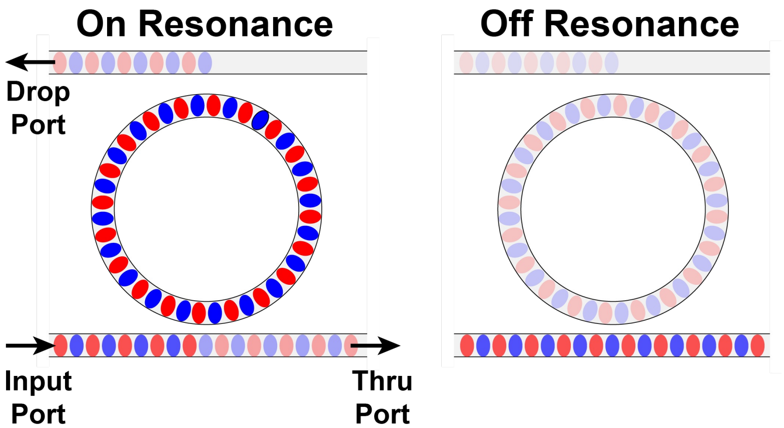


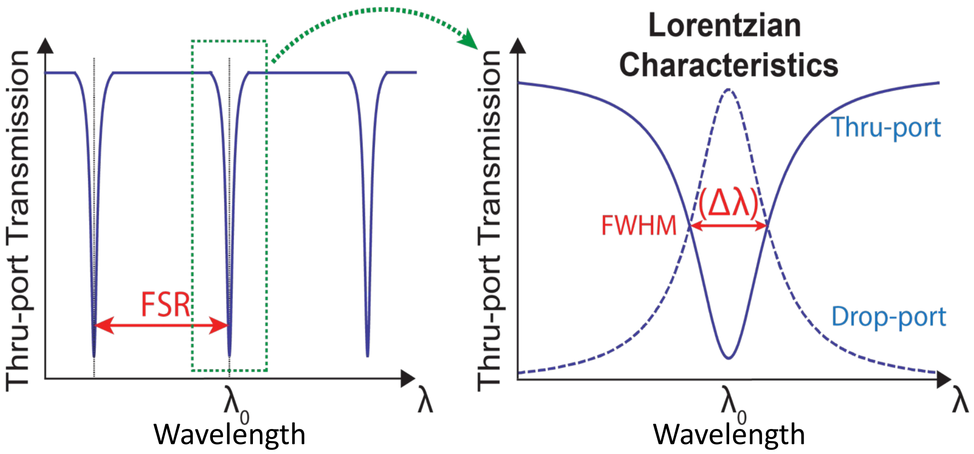




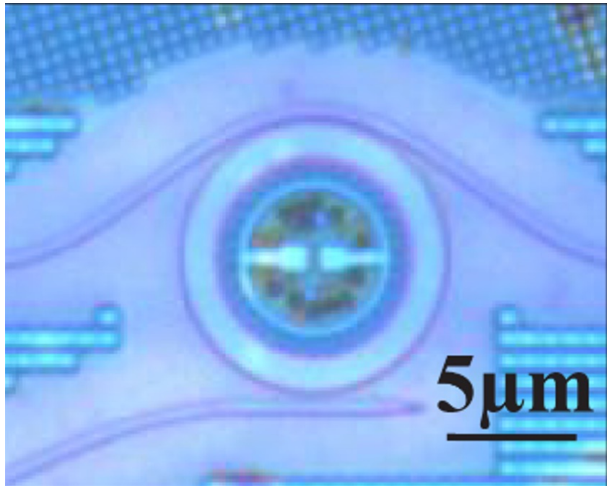
- MZM devices have …
  - Large footprints (mm-scale long) -> pF capacitive load!
  - Poor energy efficiency (5-10pj/b)
- ***Silicon Photonics***: Silicon based devices using CMOS foundries (GF, AMF, AIM, …)

Micro-Ring Modulators (MRMs)



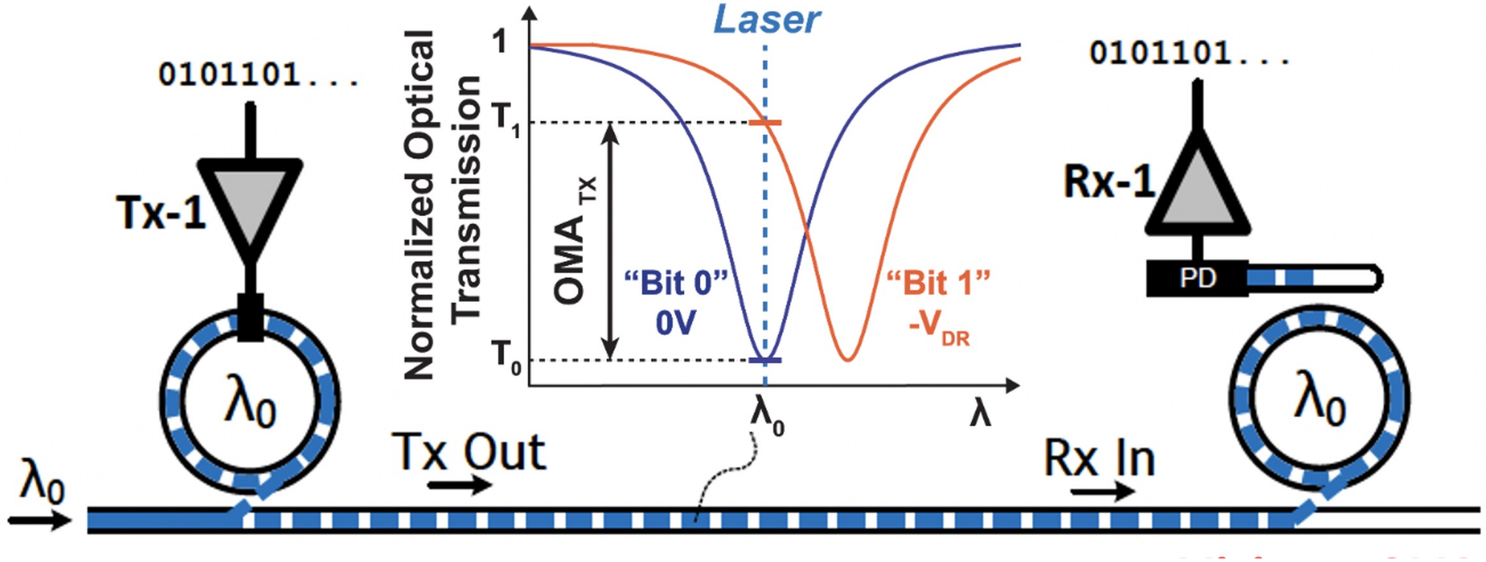


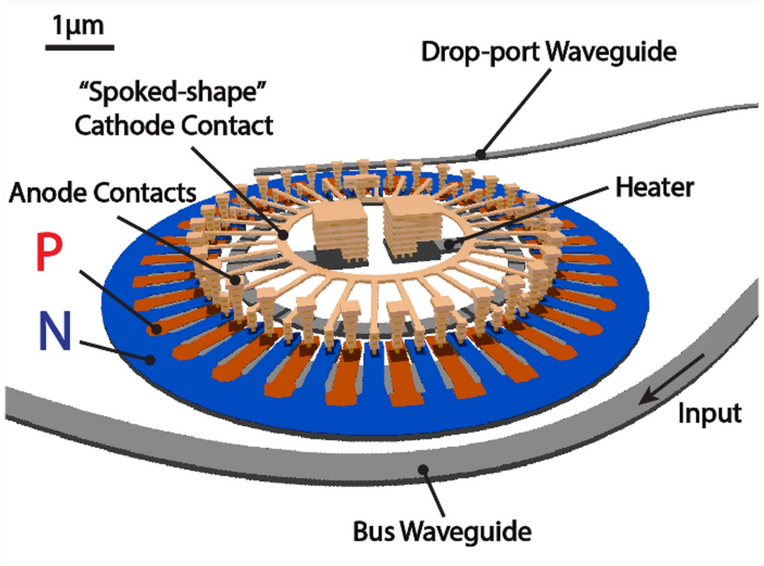
- Resonance wavelength: $\lambda_0 = n_{eff}\,L/m$, m = 1,2,3,...
  - Q-factor: $Q = \lambda_0 / \Delta\lambda$
- Compact device (radius of 5μm)
  - Energy & area efficient modulator/filter
- Supporting wavelength division multiplexing (WDM)



ELECTRICAL & COMPUTER ENGINEERING

Micro-Ring Modulators (MRMs)

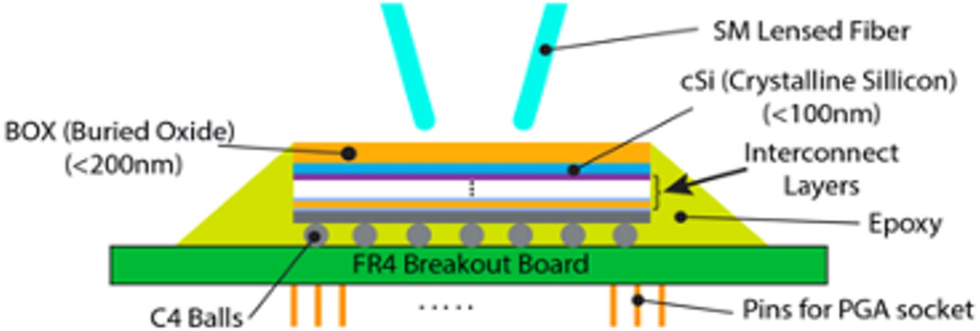


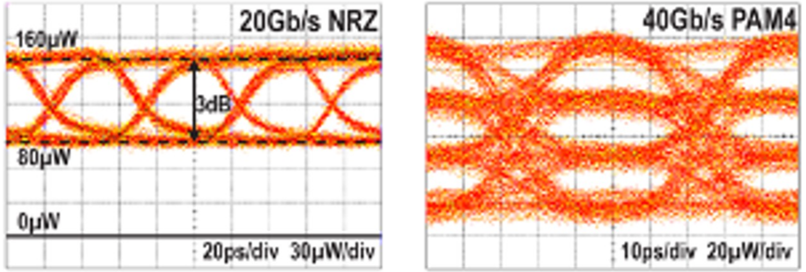


Modulation Scheme:

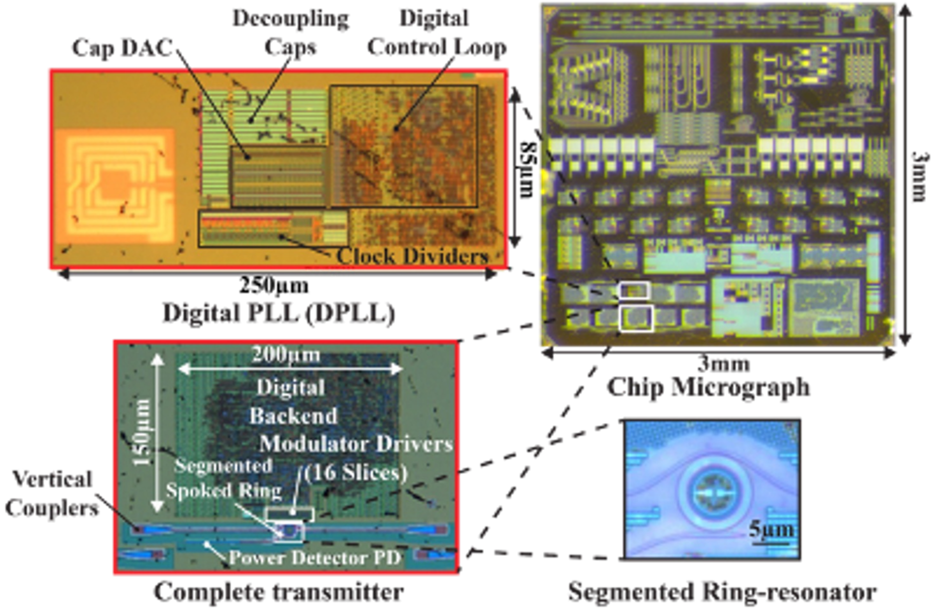
1. Deplete/Inject carriers using PN junctions
2. Δfree carriers -> Δindex of refraction [Carrier-Plasma Effect] -> Resonance shift
3. On-Off Keying (OOK) modulation (***OMA**: Optical Modulation Amplitude)

MRM in Advanced Silicon Photonics





GF 45nm SOI



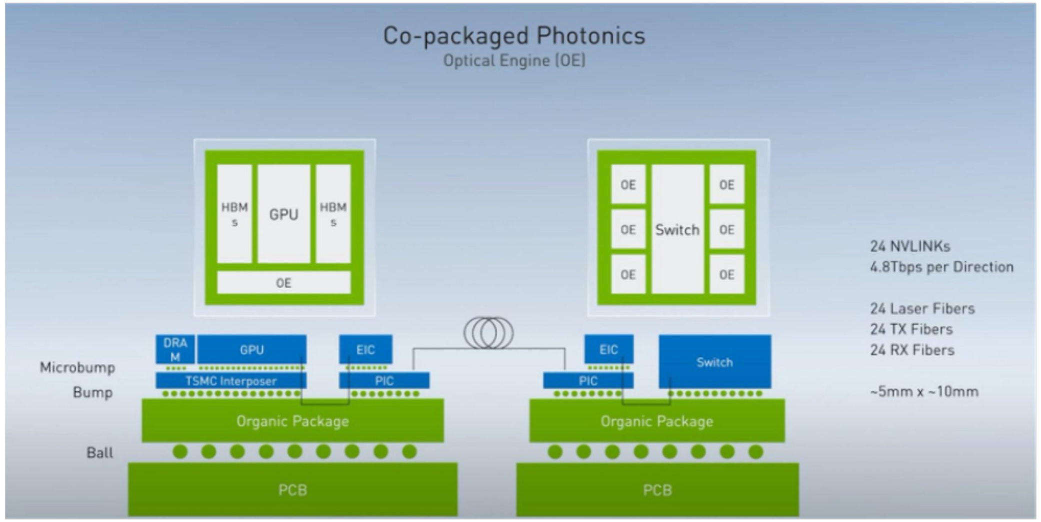
[Moazeni *et al.*, ISSCC/JSSC 17]

- Low-power (Sub-pJ/b) & high bandwidth (+50GHz) optical I/O
- GlobalFoundries Silicon Photonics + in-house post-processing & packaging
- Full photonic SoC design (clocking, driver, optical Rx, control feedbacks, ...)

Adoption in Commercial Applications

- Network Switches beyond 51.2T & interconnects for AI/ML in datacenters
- Co-packaged Optics (CPO)
  - Nvidia, Intel+AyarLabs, AMD+Ranovous
- State-of-the-art: ~5pJ/b (@1Tb/s per fiber)

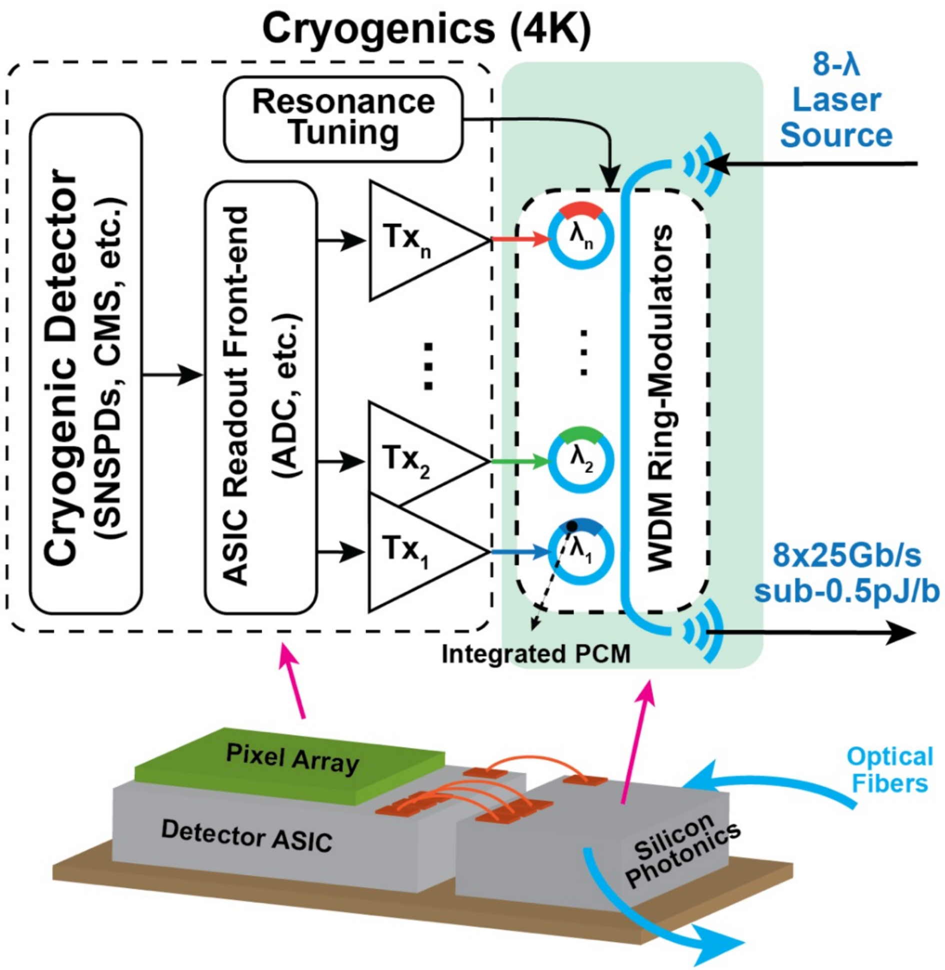
51.2T Broadcom Switch



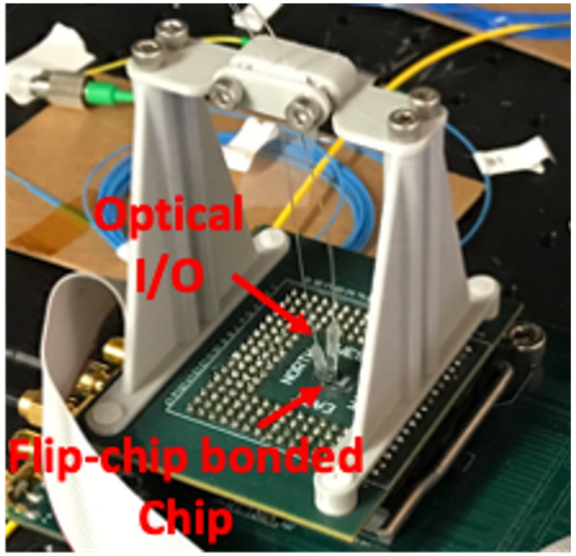
MRM Integration for HEP

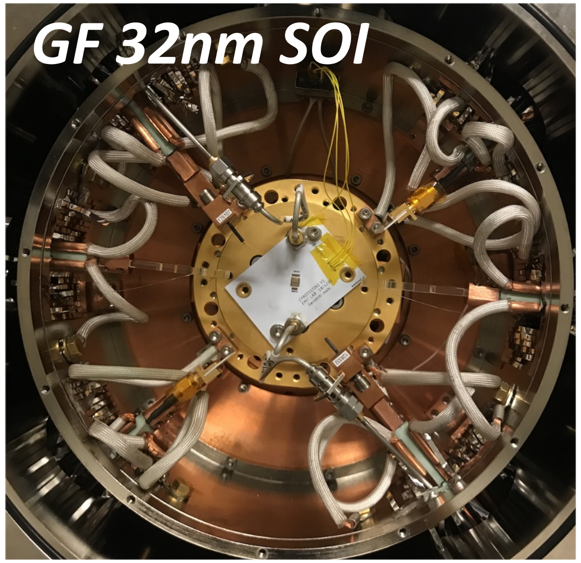
- Silicon photonics integration with CMOS (Monolithic, 3D, wire-bond)
- Integration with the detector chip
- Fiber/Optical packaging

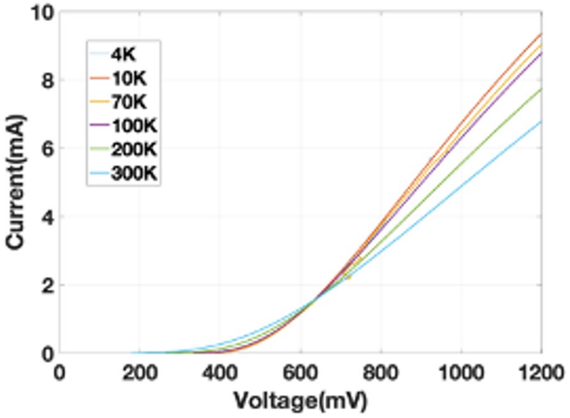
- Target specs for initial demo:
  - 4 Kelvin Operation
  - Wavelength-Division Multiplexing (target 4 wavelengths)
  - +100 Gb/s per fiber
  - < 1pJ/b @25Gb/s per wavelength

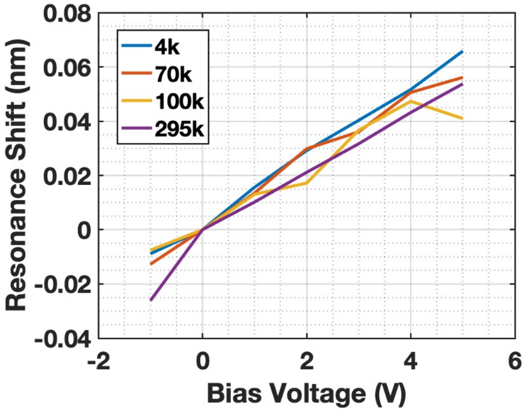


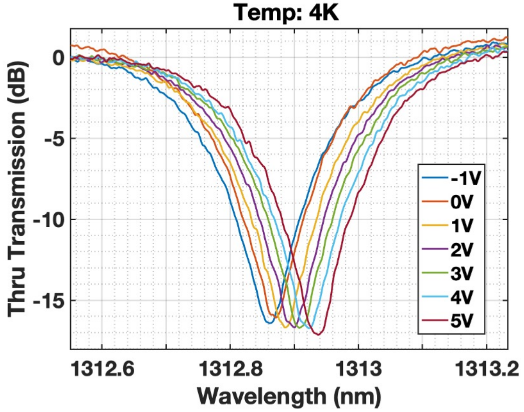
Cryogenic Silicon Photonics





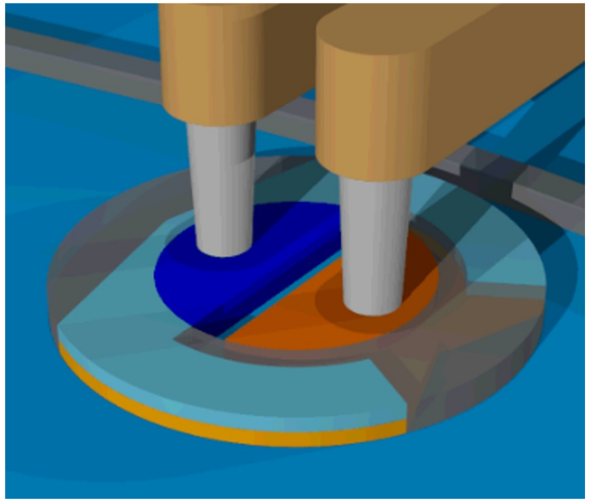


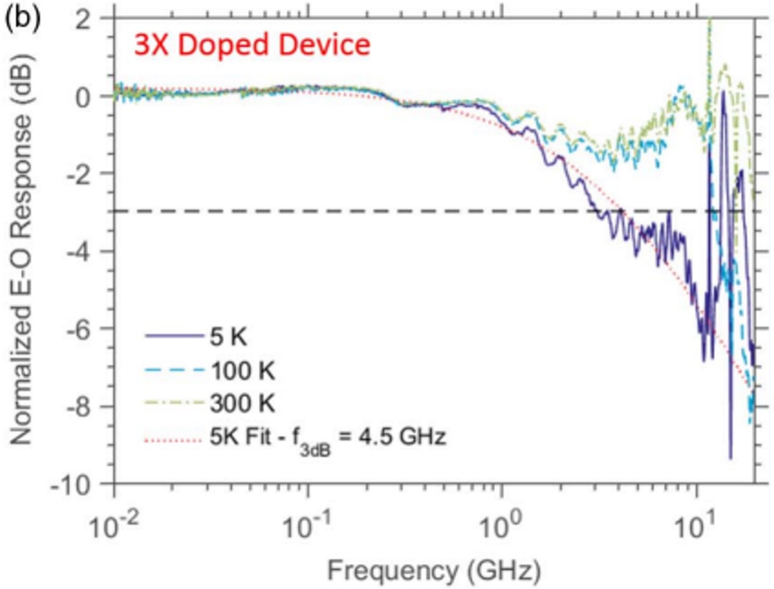


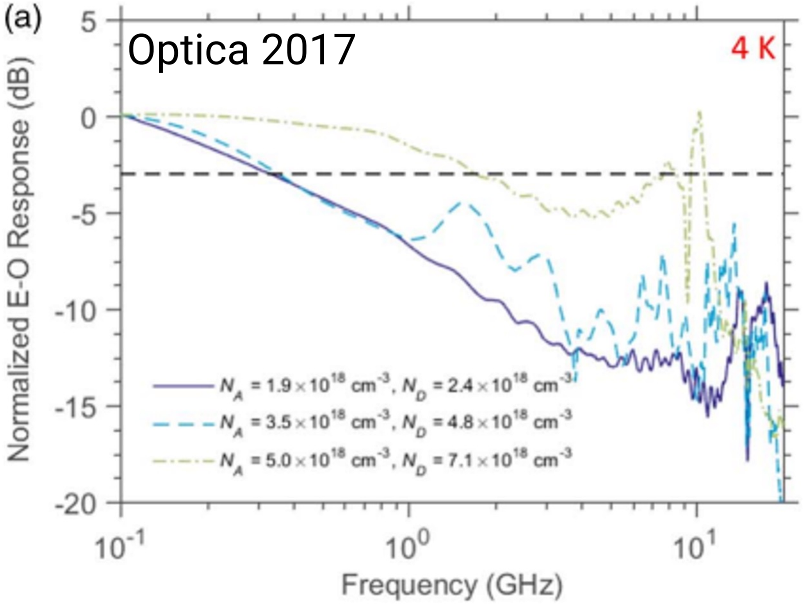


- Electro-optical packaging is very critical esp. in extreme edge conditions such as cryogenics
- CMOS & photonics are functional at 4K with no performance compromise!

Challenge 1: Limited Bandwidth of Cryo MRMs



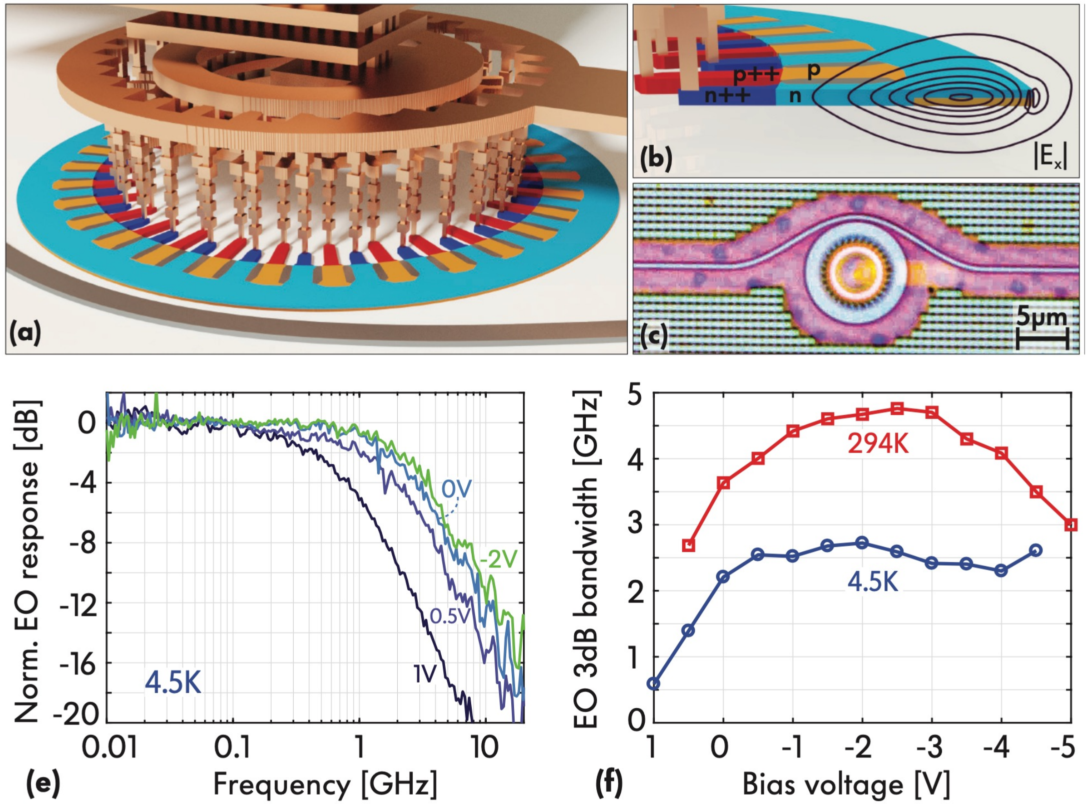




- Electro-optical (EO) BW depends on: (1) RC time-constant of PN junctions, (2) Optical FWHM
- MRM's EO BW reduces at 4K due to carrier freeze-out!

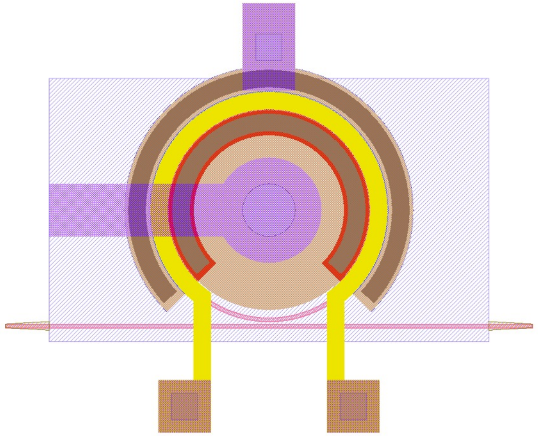
Need to optimize doping and reduce junction resistances

Challenge 1: Limited Bandwidth of Cryo MRMs

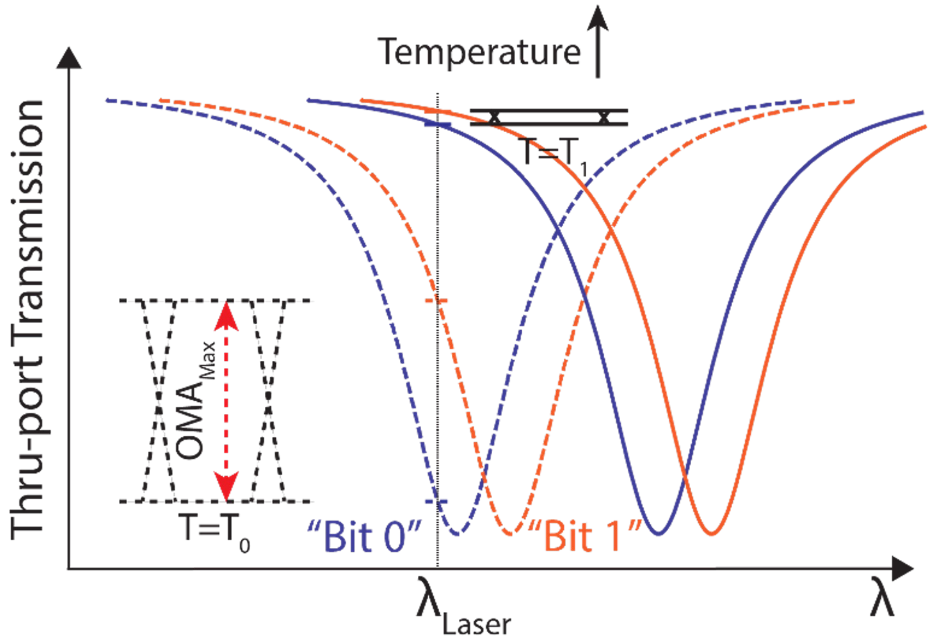


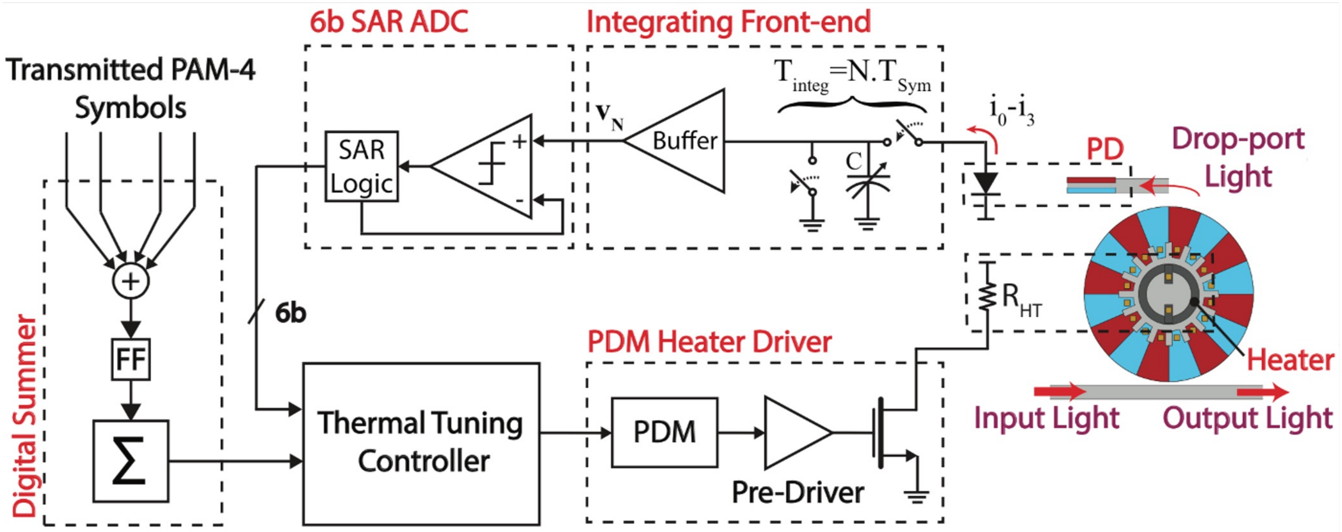
[Hayk Gevorgyan, et al., OFC 2021]

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



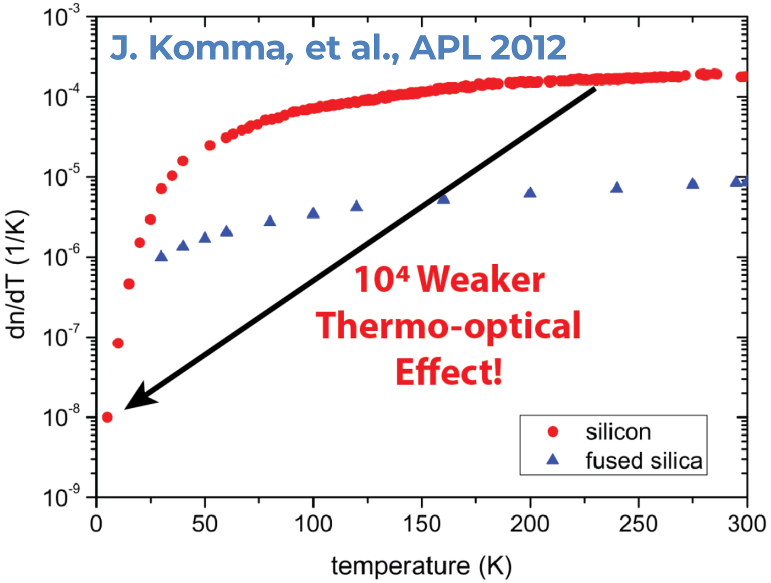
Challenge 2: Tuning Cryogenic MRMs

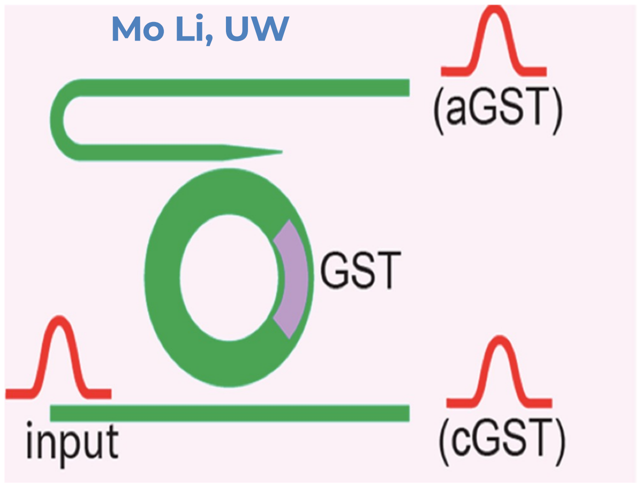


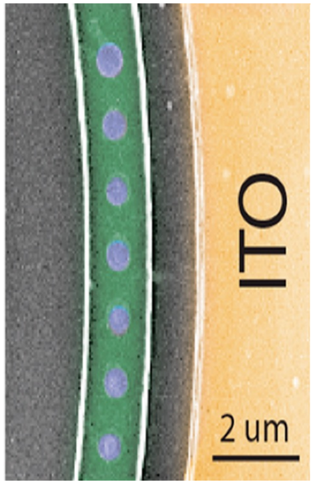


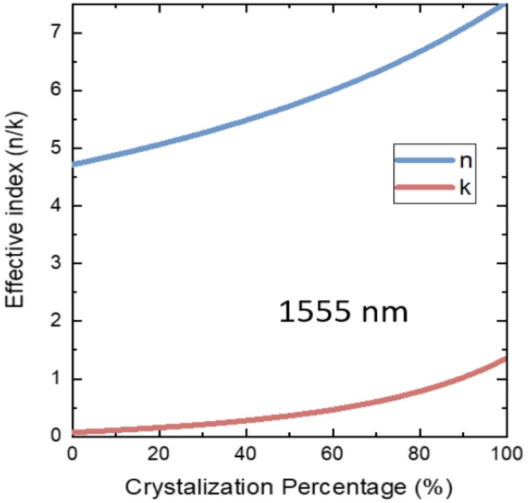
- Resonance wavelength and laser has to be precisely aligned
    - Process variations, temperature fluctuations (circuit blocks, etc.)
- Closed-loop thermal tuning has been demonstrated for this issue at room temperature

Challenge 2: Tuning Cryogenic MRMs



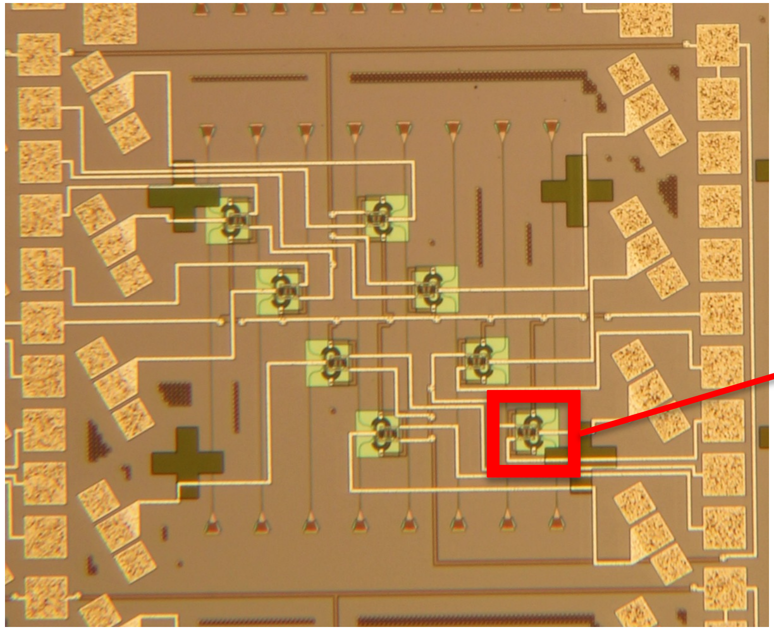


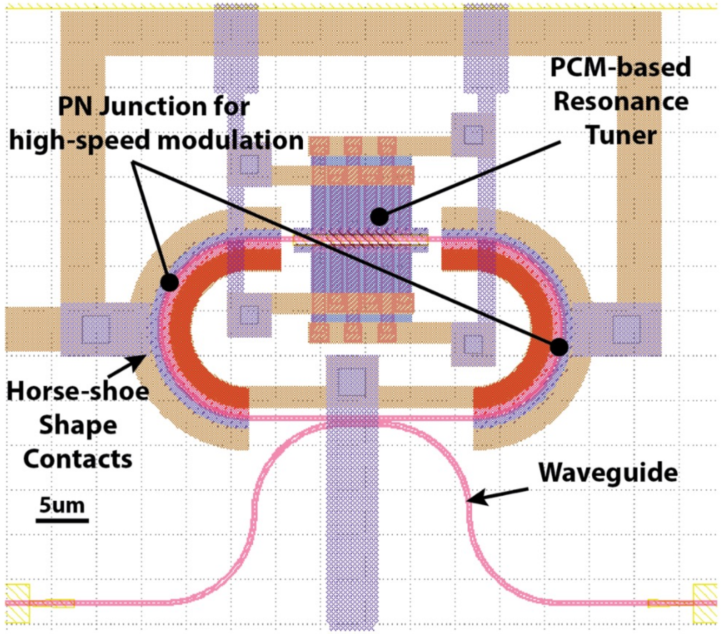


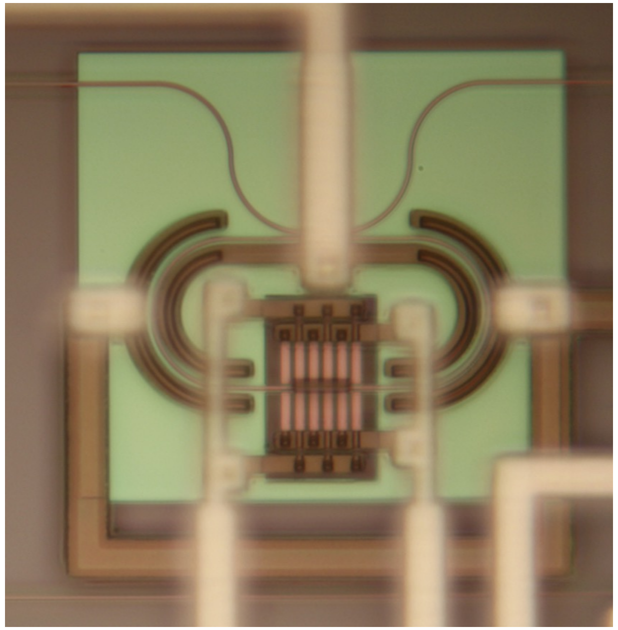


- Thermo-optical effect are extremely weak at 4K! (less challenging for 70K)
- Using tunable lasers is not a practical and scalable solution!
- Phase change materials (PCM) can be a solution for non-volatile refractive-index change
- We are currently working on characterizing PCM at cryo & show the proof-of-concept

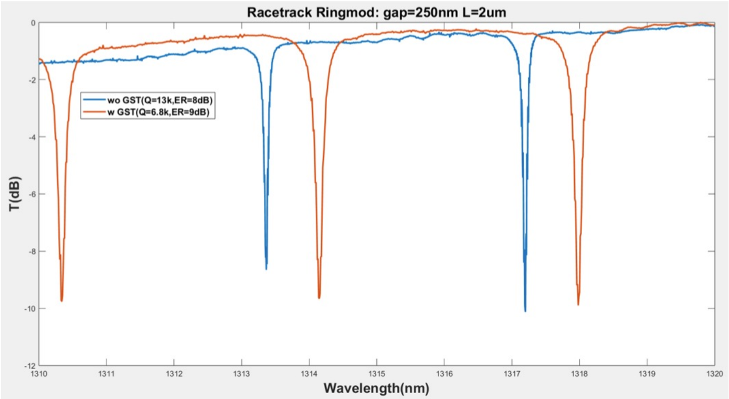
MRM with Integrated PCM





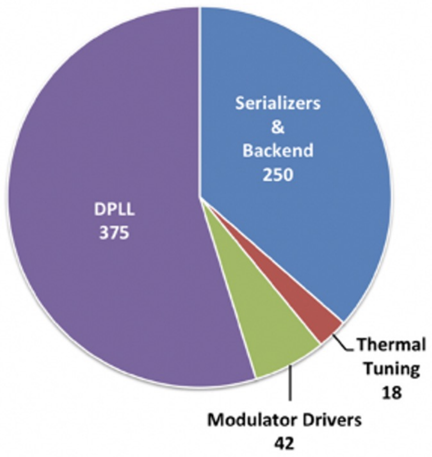


- AMF commercial foundry silicon photonics with post-processed PCM
- Highest BW MRM will be bonded to GF 22FDX (analog front-end of transmitter
- Open loop control of resonance at this phase

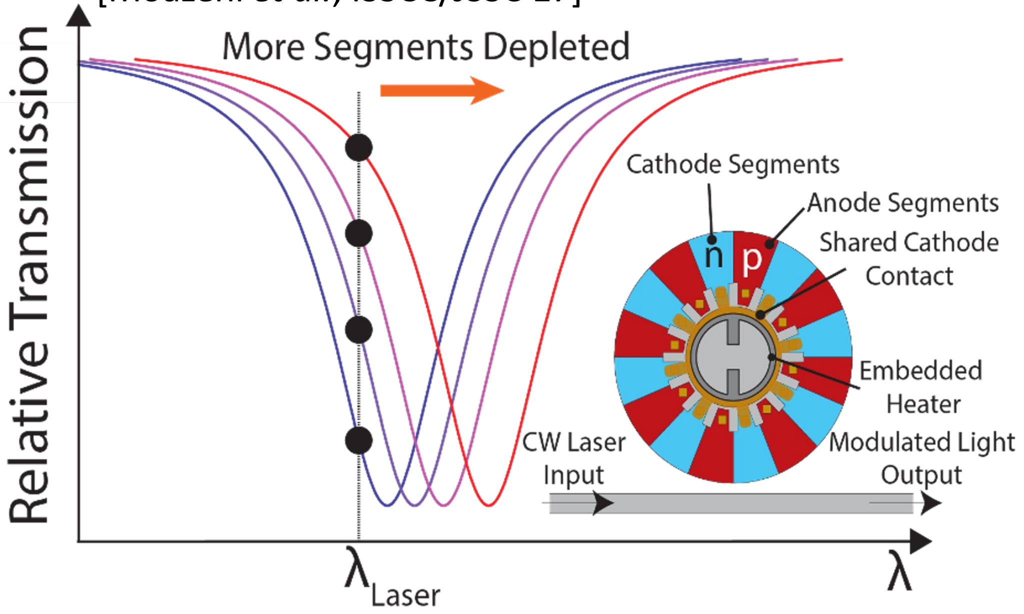


Challenge 3: Electronic/photonic Co-design

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



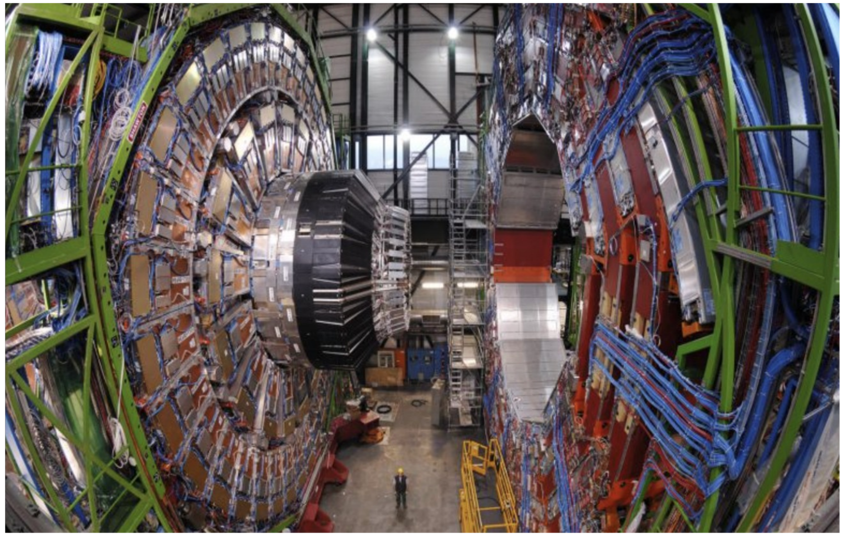
[Moazeni *et al.*, ISSCC/JSSC 17]



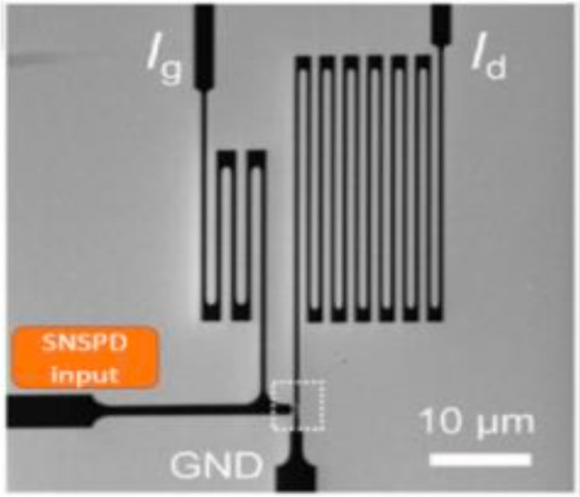
- Sub-0.5pJ/b energy-efficiency cannot be achieved by separately optimizing either electrical or optical blocks! (this might be critical for quantum applications)
- Co-design Examples: using optical DAC rather than electrical, trades on MRM Q-factor and OMA, etc.

Future Applications

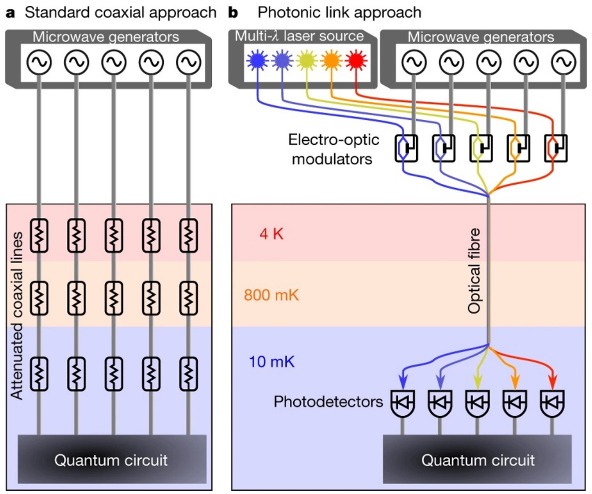
- Cryogenics and radiation-hard environments (DUNE, CMS, dark matter…)
- SNSPD Readout from 4K
- Supports analog/RF signals as well as digital I/O (can be used for SC quantum systems)



CMS detector @CERN LHC



Qing-Yuan Zhao *et al* 2017
Supercond. Sci. Technol. **30** 044002



NIST Nature 2022

Conclusion

- Ultra-low power MRM-based silicon photonic links is the most suitable communication link for HEP & Quantum applications

- Several challenges need to be addressed for cryogenic operations:
  - MRM’s tuning & limited EO bandwidth
  - Optical packaging
  - Integration with CMOS and Detector

- We are pursuing two directions currently with Fermi Lab …
  - SNSPD Readout at 4K: 22FDX CMOS + Silicon Photonics
  - CCD Detector Readout at 70K: 65nm + Silicon Photonics

Acknowledgment

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