Cryogenic Optical Links (CryOLink) and Application of Ring Resonator Modulators

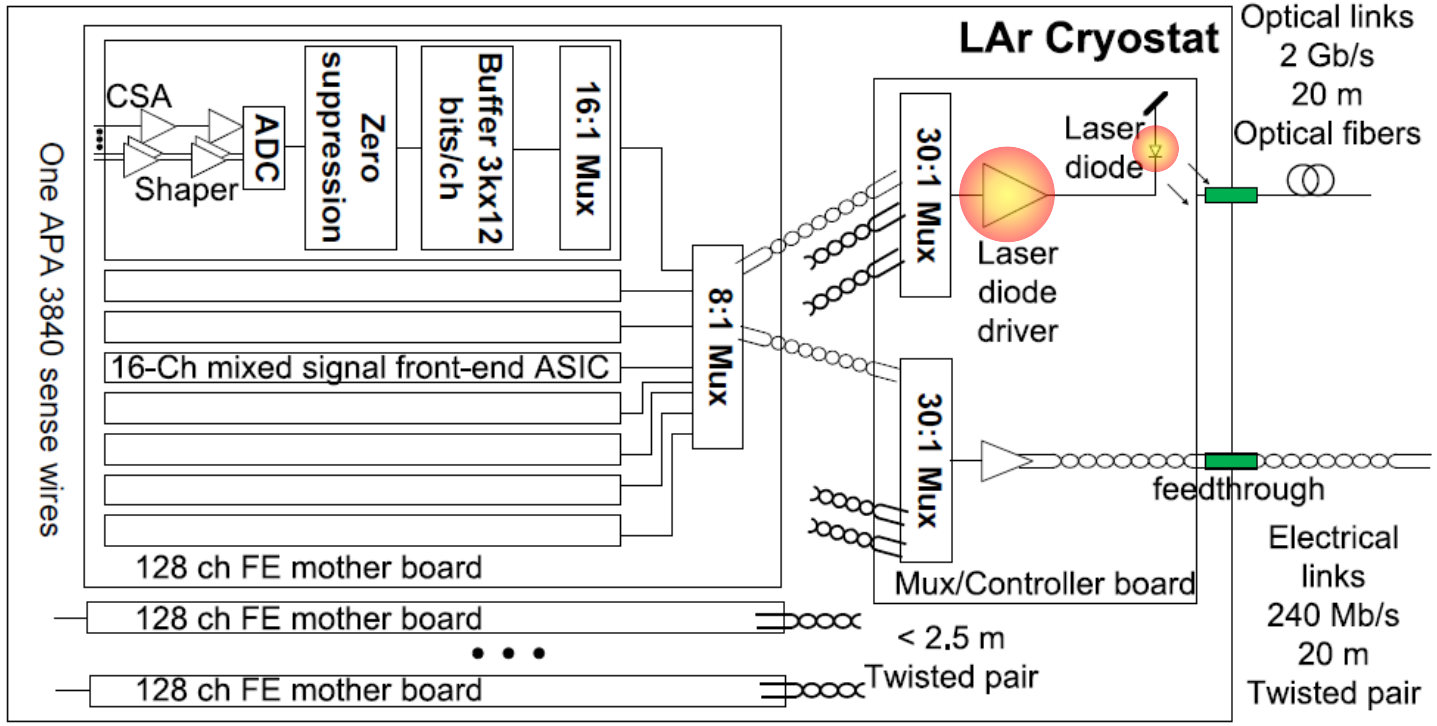
DUNE Vertical Drift Photon Detector Cold Electronics
(VD PhDet CE)

March 10, 2021

Steven Estrella
Freedom Photonics LLC
University of California Santa Barbara

41 Aero Camino
Santa Barbara, CA 93117
805-967-4900
steven@freedomphotonics.com
freedomphotonics.com

LAr TPC Cryogenic Link – Previous Vision



Liu, T., et al. "Cryogenic digital data links for the liquid argon time projection chamber." *Journal of Instrumentation* 7.01 (2012): C01091.

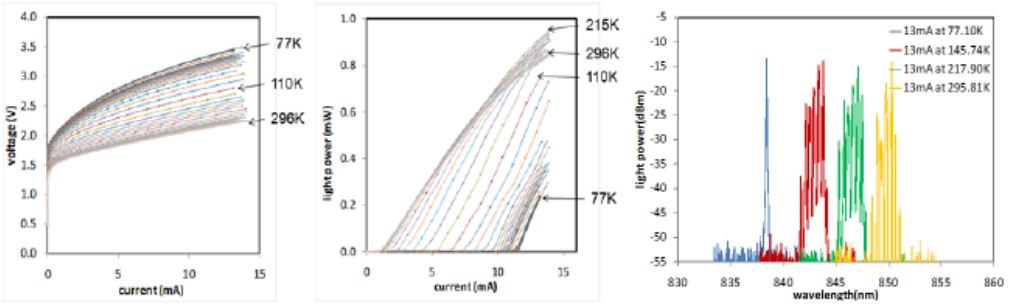


Figure 2. (from left to right) I-V curves (a), L-I curves (b) and optical spectra (c) of the VCSEL diode.

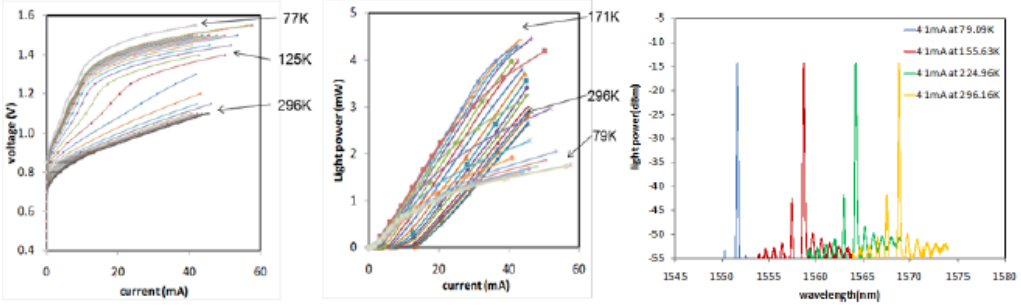


Figure 3. (from left to right) I-V curves (a), L-I curves (b) and optical spectra (c) of the DFB laser diode.

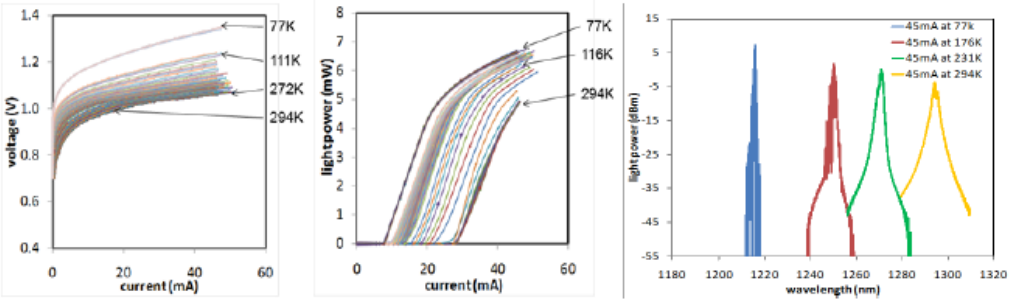


Figure 4. (from left to right) I-V curves (a), L-I curves (b) and optical spectra (c) of the FP laser diode.

- **Both LD & LDD are inside LAr cryostat**
  - Dissipates lots of heat, which impacts LAr needs
  - e.g. ~62 mW (DFB) + ~864 mW (LDD) = 926 mW (almost 1W)
- **Laser performance changes with wavelength**

LAr TPC Cryogenic Link – Current Vision

Abi, Babak, et al. "Volume IV. The DUNE far detector single-phase technology." *Journal of Instrumentation* 15.08 (2020): T08010.

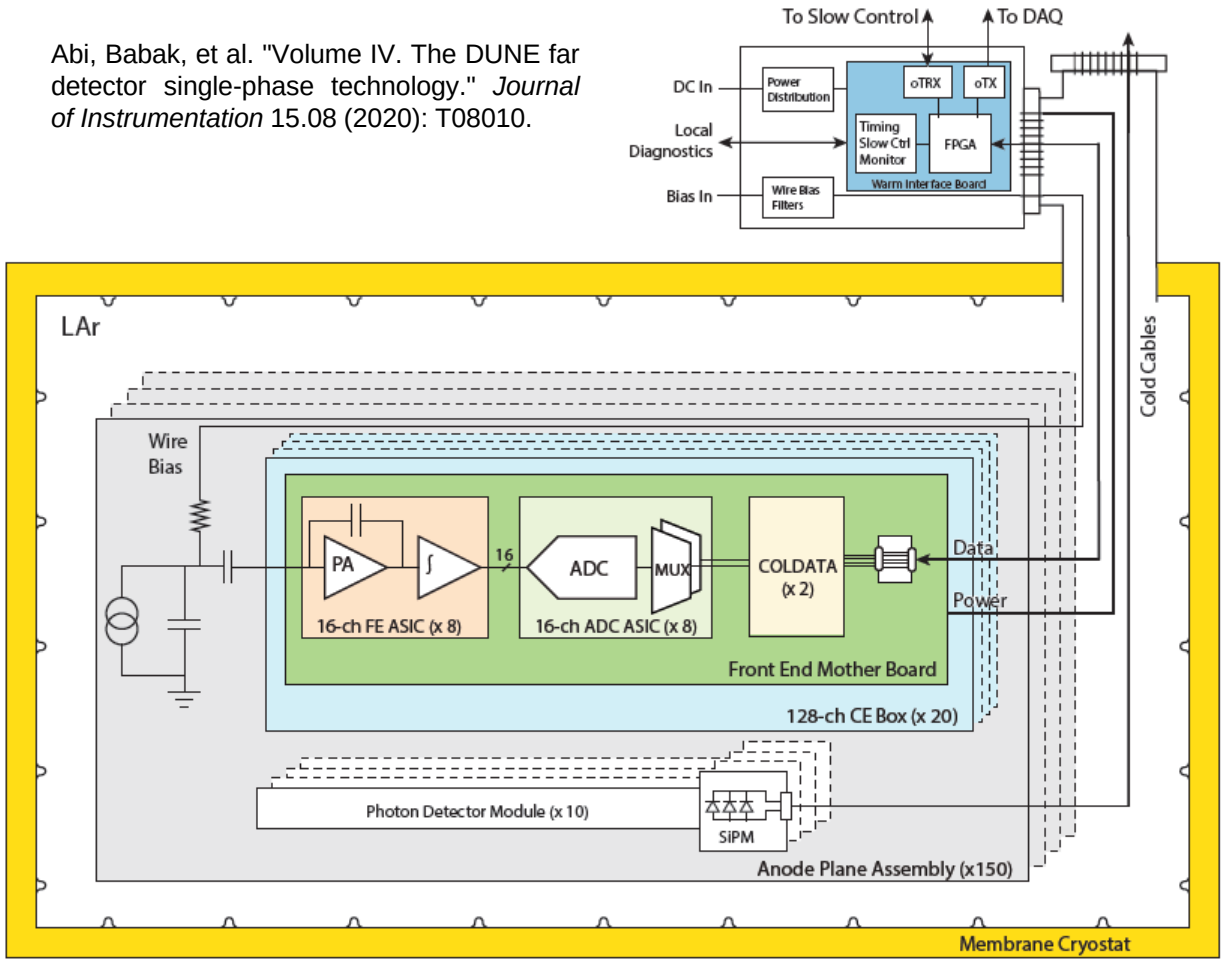


Figure 4.1. The reference architecture for the TPC electronics. The basic unit is the 128-channel FEMB. The scheme includes also the SiPMs used for the readout of the PDs, as discussed in chapter 5.

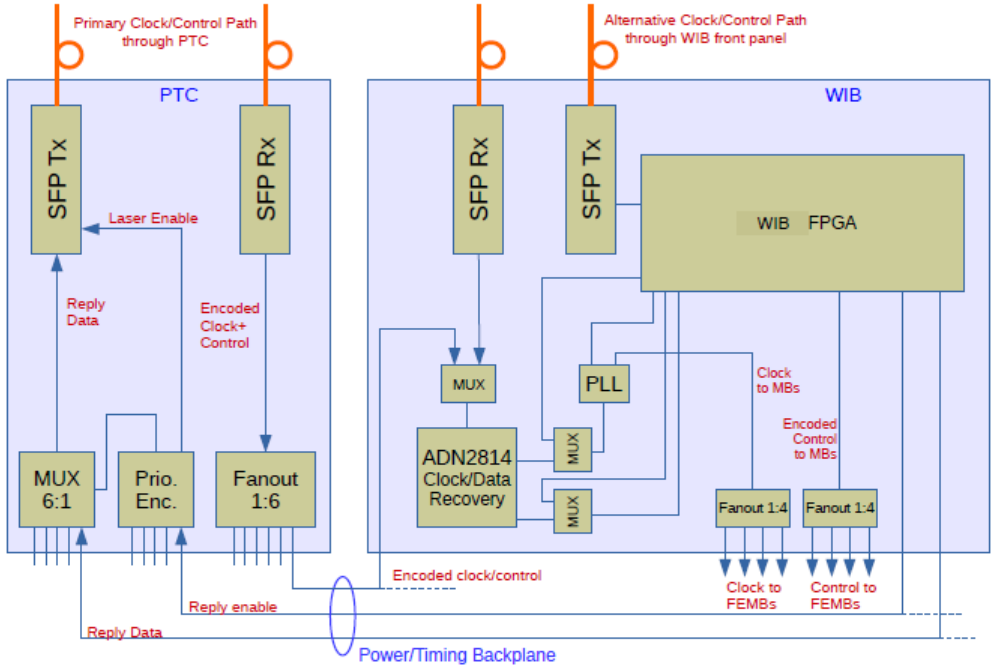
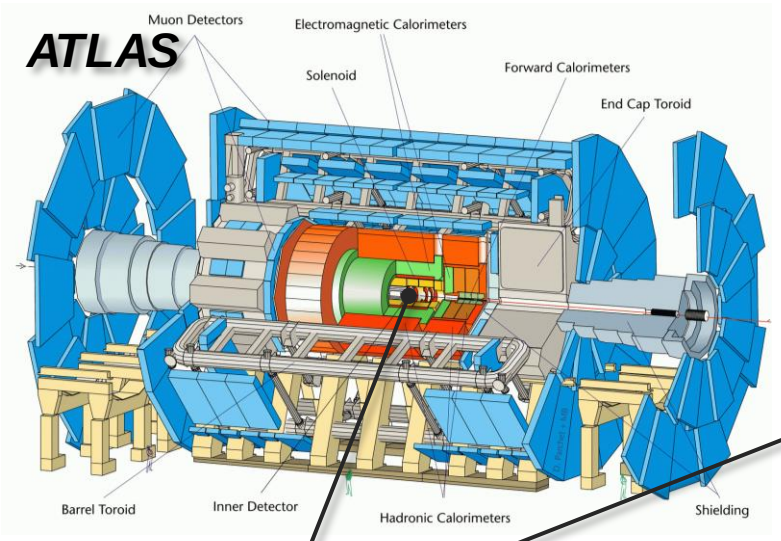
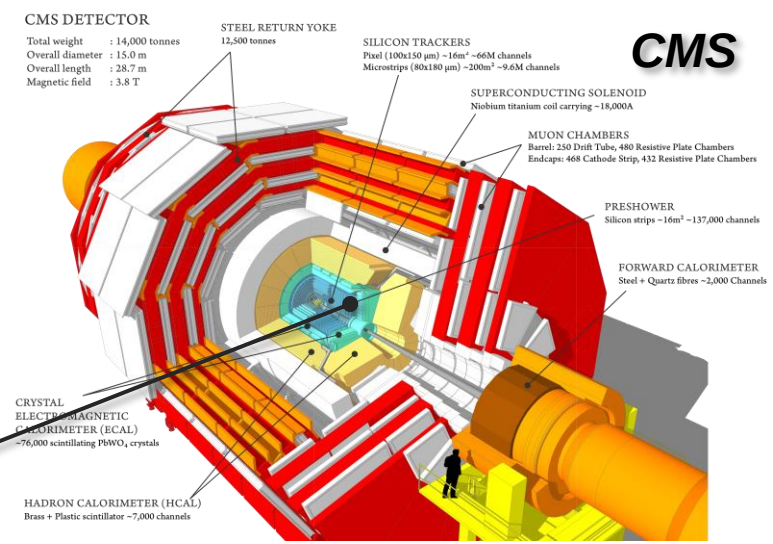


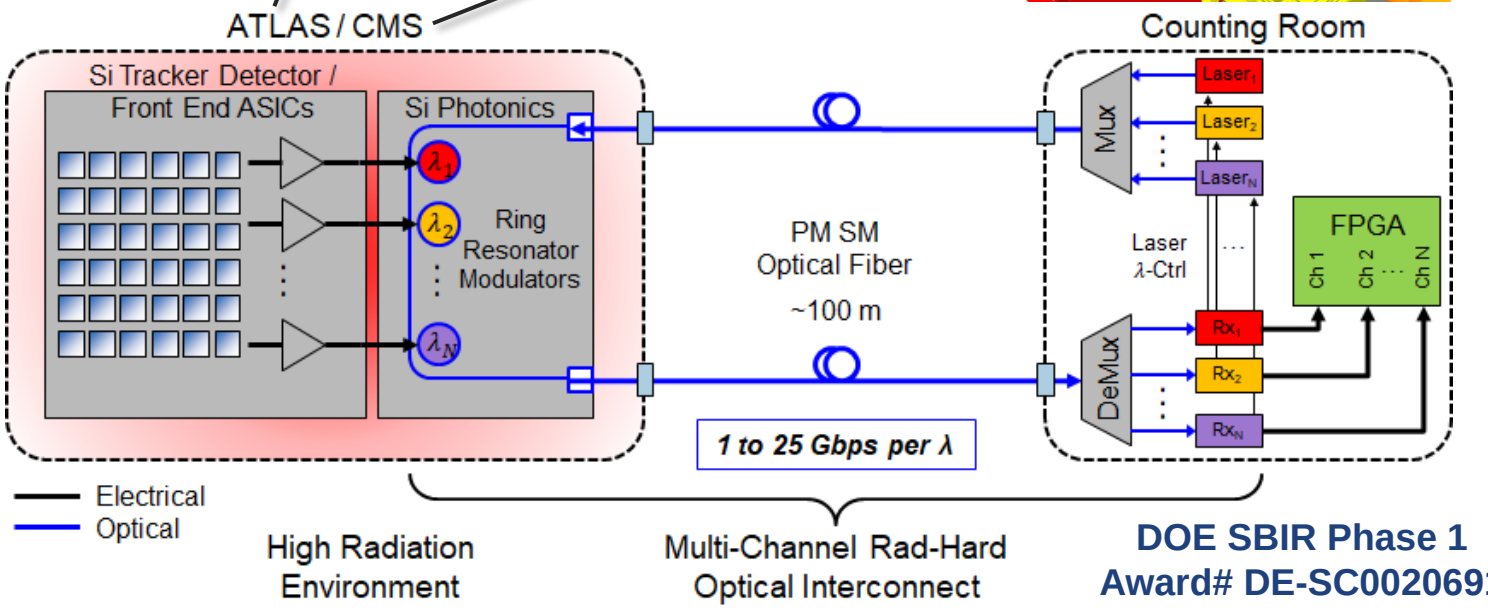
Figure 4.29. PTC and timing distribution to the WIB and FEMBs used in ProtoDUNE-SP. A similar design will be adopted for the DUNE SP module.

- **Utilize COTS SFP and/or QSFP TX/Rx modules**
  - Operate at LAr temperature or warmer (on WIB)?
- **10 Gbps optical link from WIB to DAQ backend**
  - Potential to reduce fiber plant by increasing bitrate

WDM Optical Link for HEP Applications



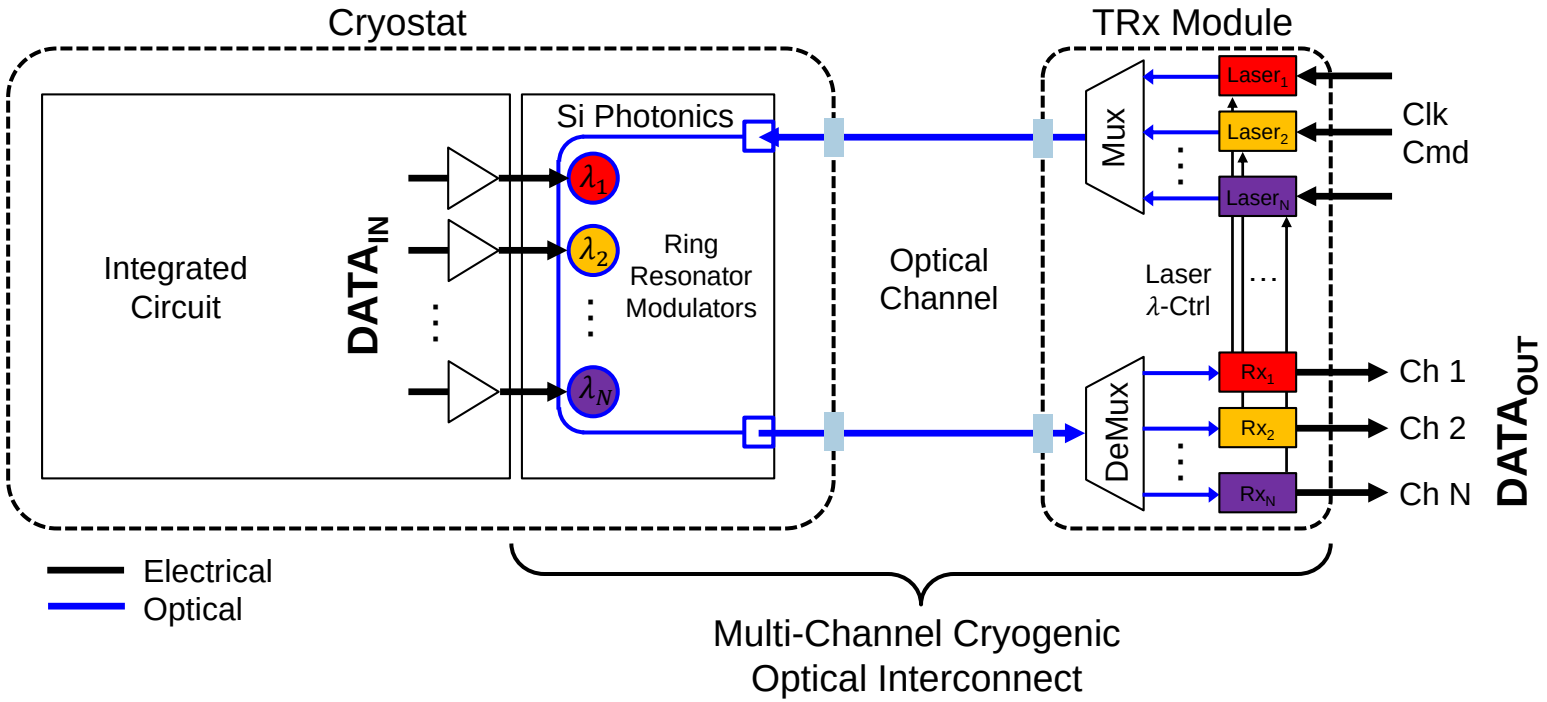


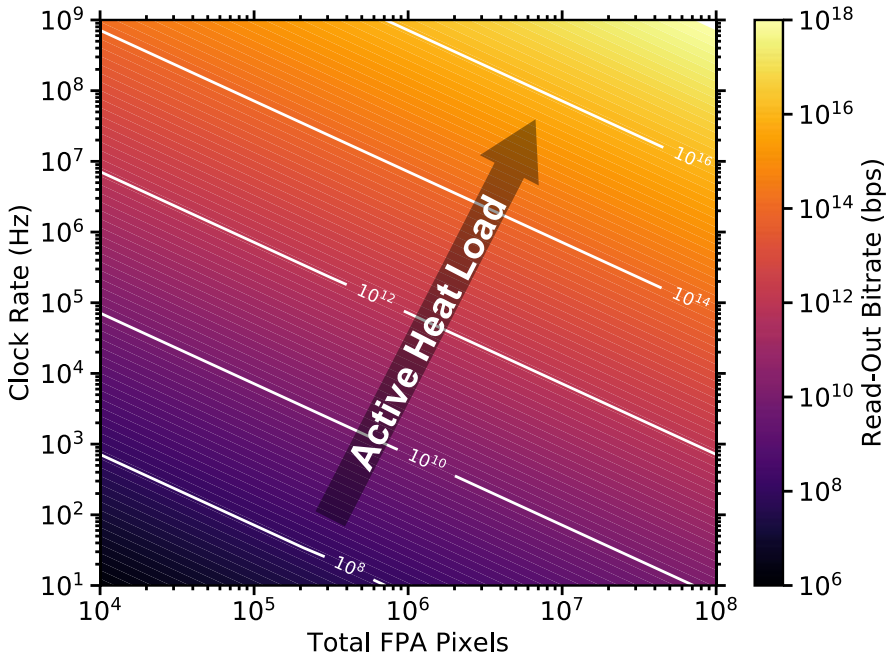


- **Developing optical link architecture for high-energy physics (HEP) applications**
- **Minimize components that are in the harsh environments**
  - Only the Si Photonic (SIPho) based electro-optic modulator (EOM) is subjected to high radiation
  - Lasers, receivers, and associated electronics are safely placed outside of radiation environment
- **EOM is a ring resonator modulator (RRM)**
  - Reduced switching voltage compared to traditional Mach-Zehnder Modulator (MZM)
- **Scalable via wavelength division multiplexing (WDM)**

DOE SBIR Phase 1
Award# DE-SC0020691

WDM Optical Link for Cryogenic Readout





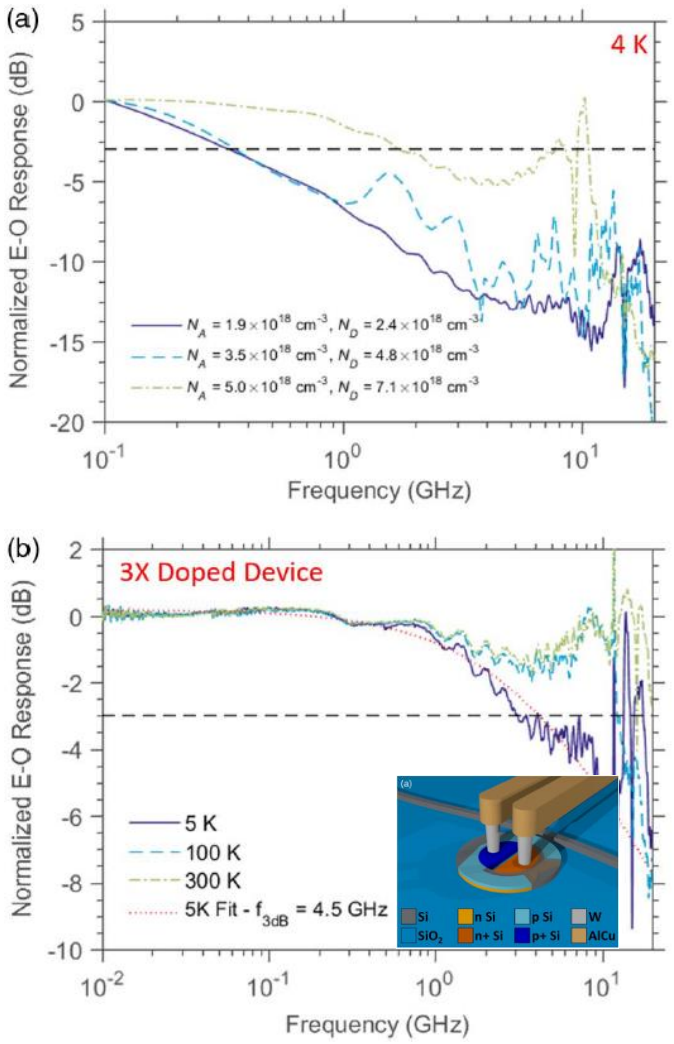
- **Optical interconnect with "remoted" Si photonic modulator**
  - Similar implementation of optical link for HEP: WDM scalable via SiPho RRMs
  - Temperature changes in RRM device performance are primary hurdle

ARO SBIR Phase II
Award# W911NF-18-C-0096

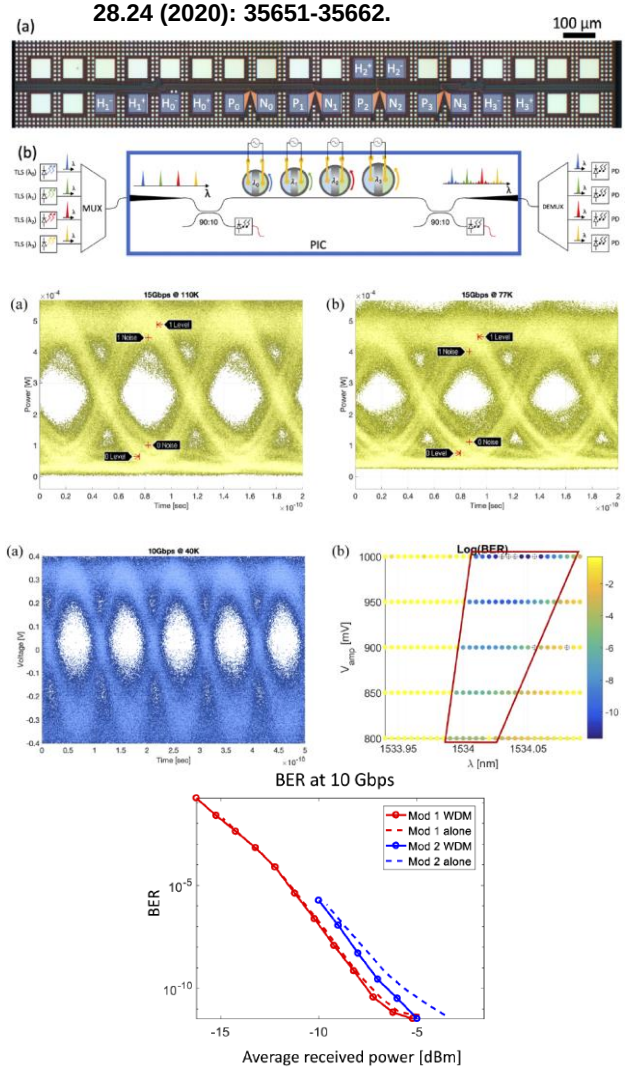
GOMACTech 2019 18.1; SPIE Photonics West OPTO 11286-9

Cryogenic RRMs: State-of-the-Art

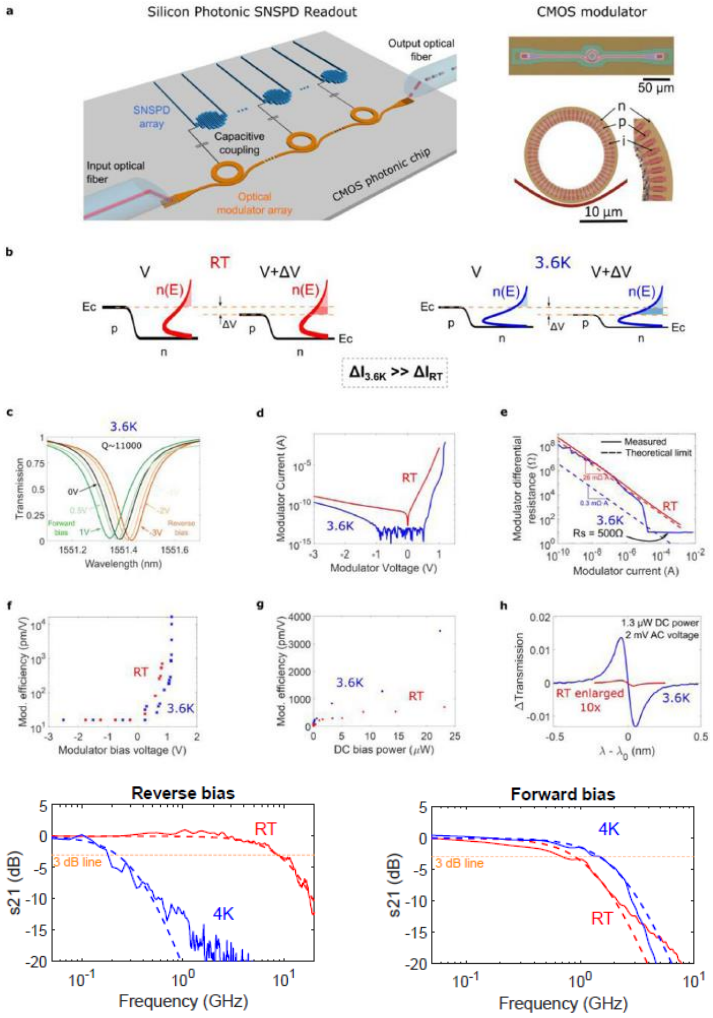
Gehl, Michael, et al. *Optica* 4.3 (2017): 374-382.



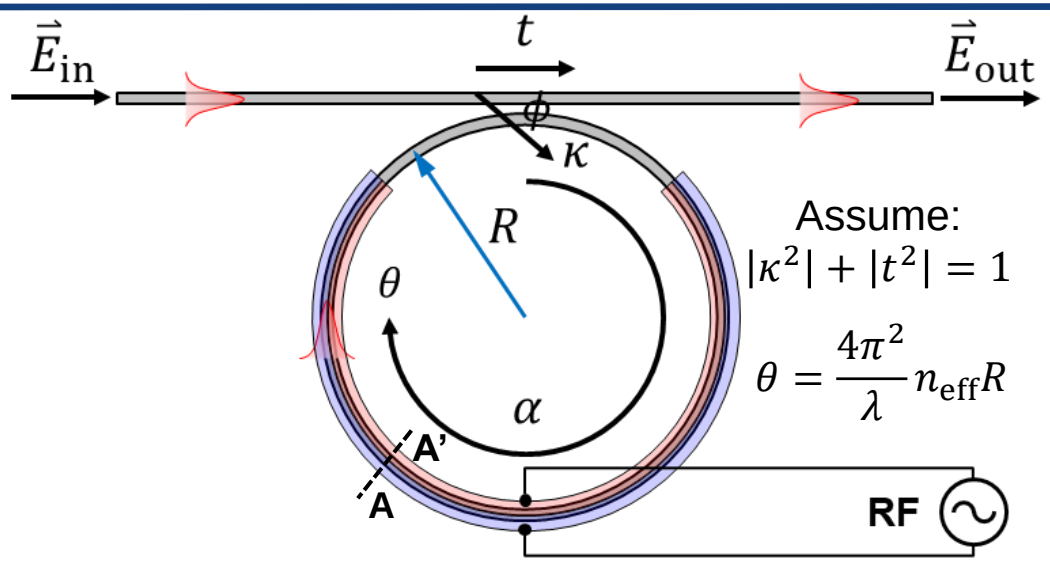
Fard, Erfan M., et al. *Optics Express* 28.24 (2020): 35651-35662.



de Cea, Marc, et al. *Scientific Reports* 10.1 (2020): 1-8.

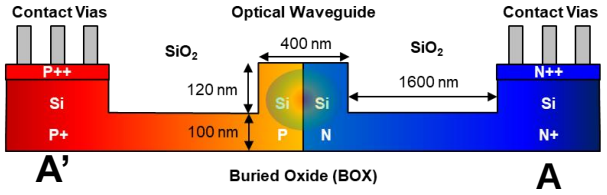


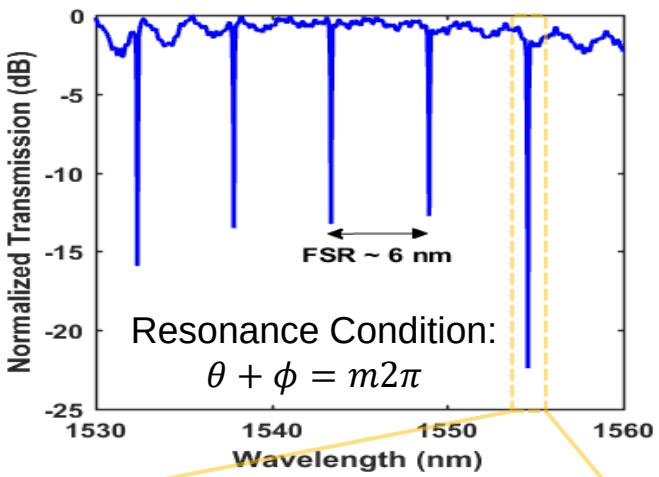
Ring Resonator Modulator (RRM) Principles



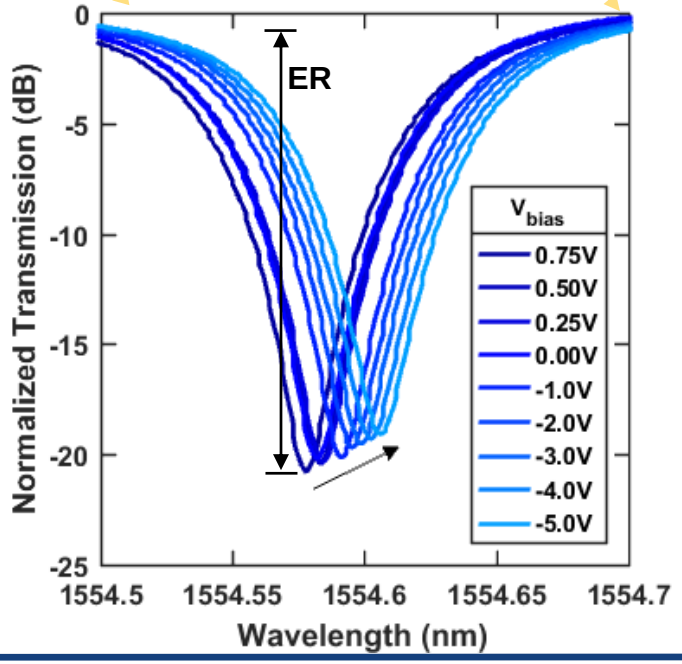
Assume:
$|\kappa^2| + |t^2| = 1$

$$\theta = \frac{4\pi^2}{\lambda} n_{\text{eff}} R$$





Resonance Condition:
$\theta + \phi = m2\pi$



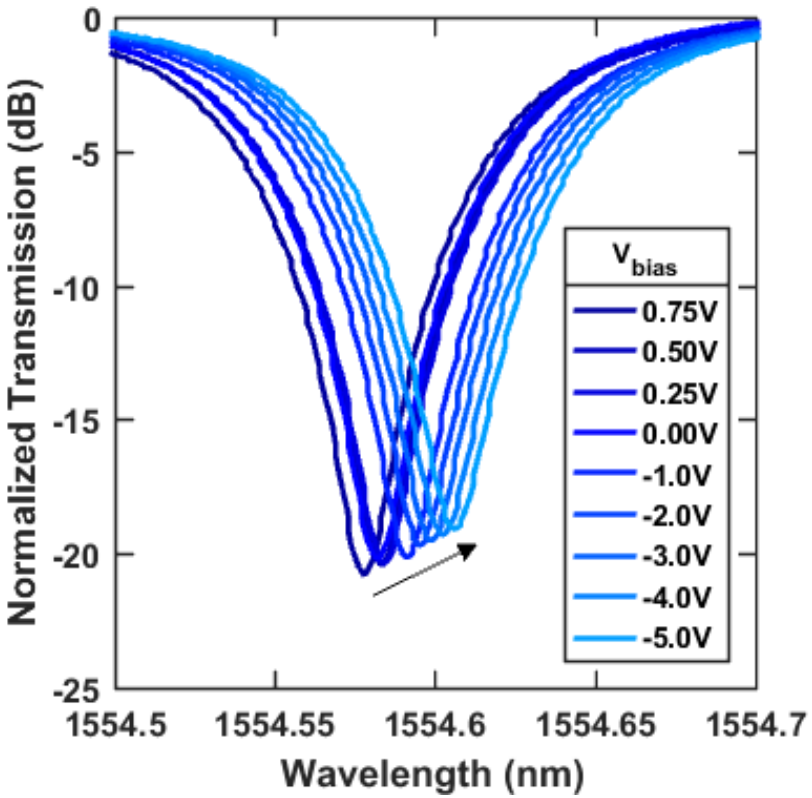
- **Ring Resonator Modulator (RRM)**
  - Essentially an RF tunable optical filter
  - Can modulate α, θ, or κ
  - FSR determined by cavity size
  - ER determined by cavity Q and tuning

Plasma Dispersion Effect:
$\Delta\theta \propto \Delta n_{\text{eff}} \propto \Delta N \propto \Delta V$
$\Delta\alpha \propto \Delta N \propto \Delta V$

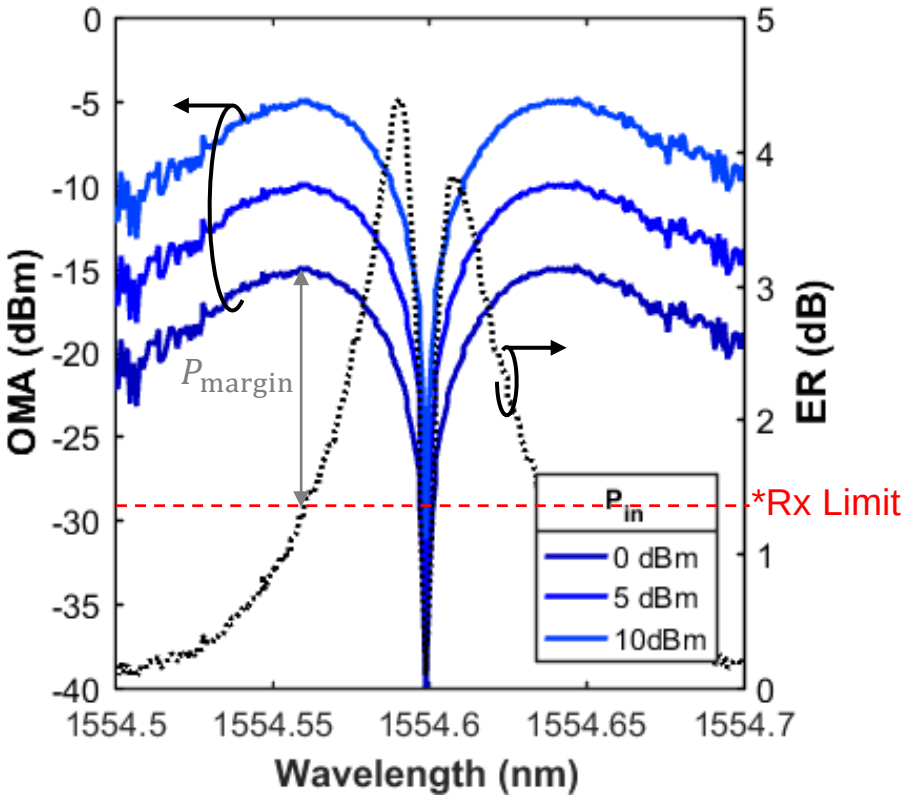
GOMACTech 2019 18.1; SPIE Photonics West OPTO 11286-9

RRM: ER vs OMA for Optimal Operation

$$OMA = 2P_{\text{avg}}\frac{ER-1}{ER+1}$$

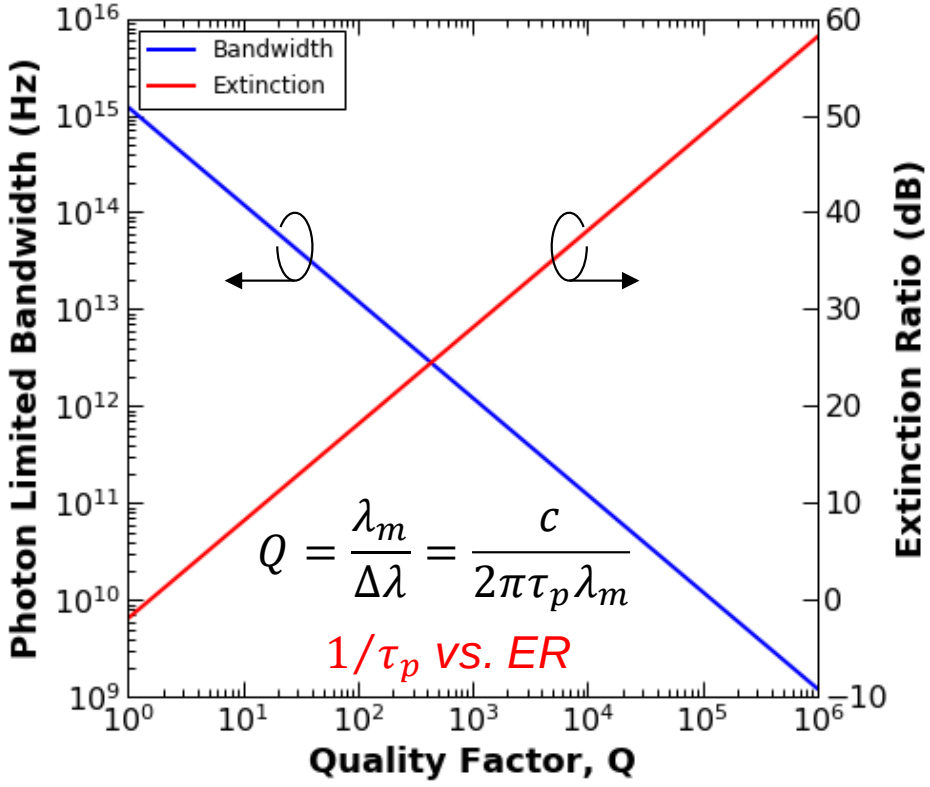


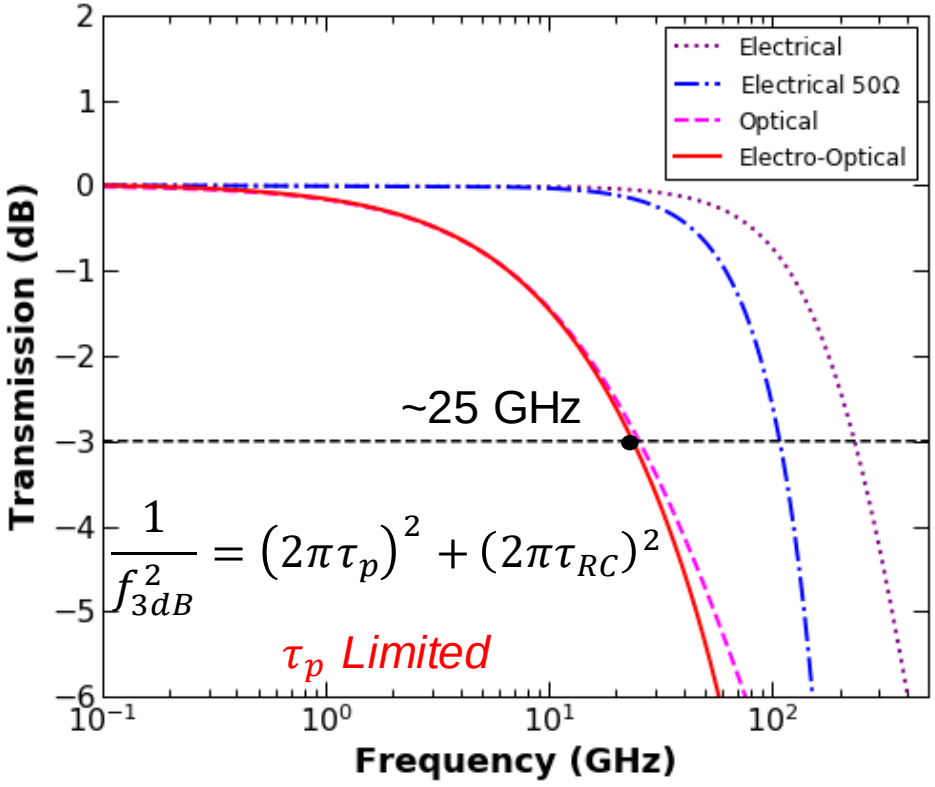
$$V_{DC} = -3\text{ V}$$
$$V_{AC} = 2\,V_{\text{pp}}$$



- **Si Ring Resonator Modulators (RRM) used for electro-optic conversion**
  - Resonant device that is wavelength & temperature sensitive
  - Maximize Optical Modulation Amplitude (OMA), not extinction ratio (ER)

RRM Performance Trade-Off

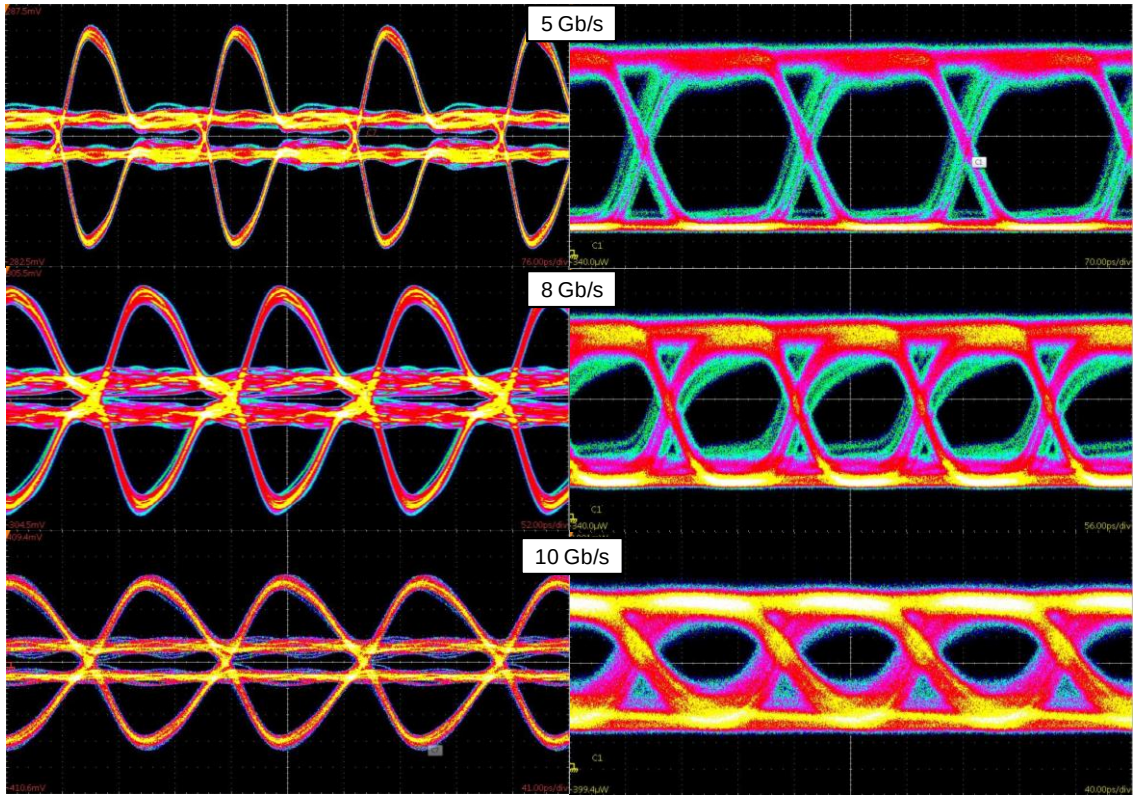




- **RRM electro-optical (E/O) response is the summed response due to both the RC- and photon-lifetime-limits, τ_{RC} and τ_p respectively**
  - Inherent trade-off in bandwidth and extinction ratio / switching voltage

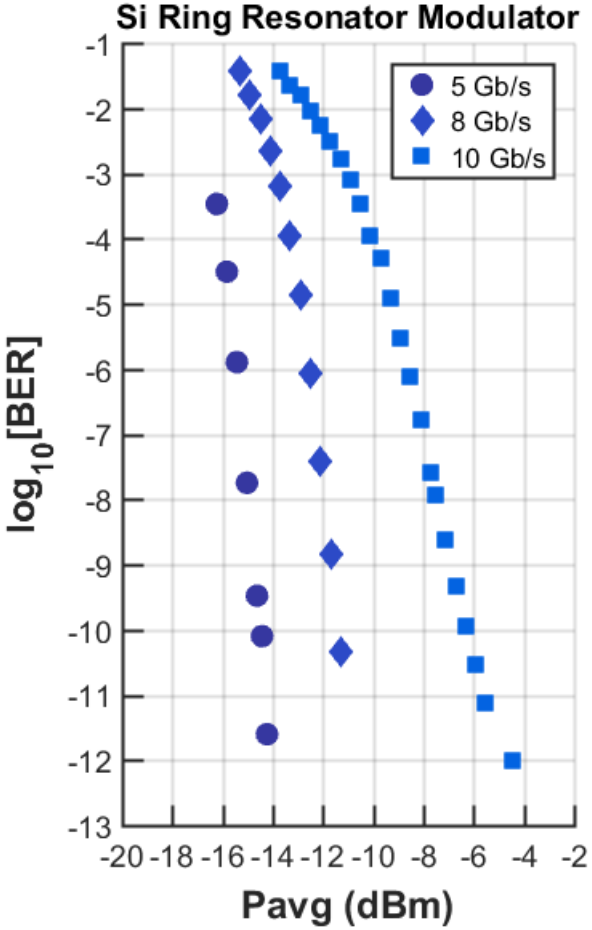
High-Speed Si RRM Characterization: Gen. 1

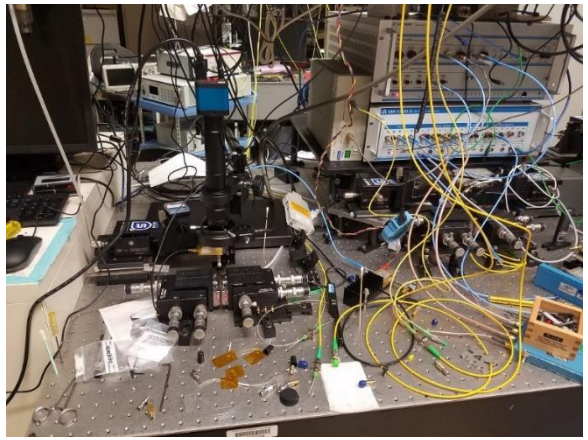
Electrical Input *Gen. 1* Optical Output

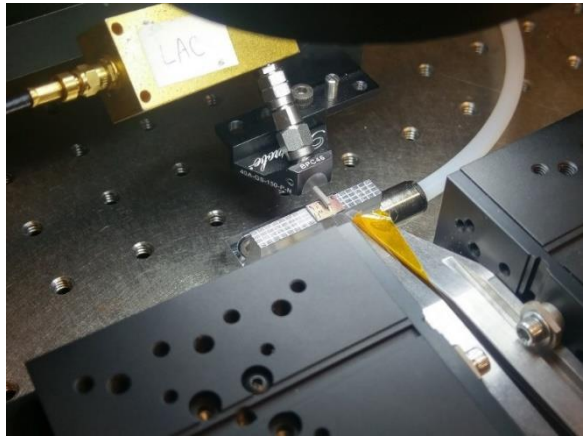


BER ≤ 1E-12 @ 10 Gbps

Room Temperature



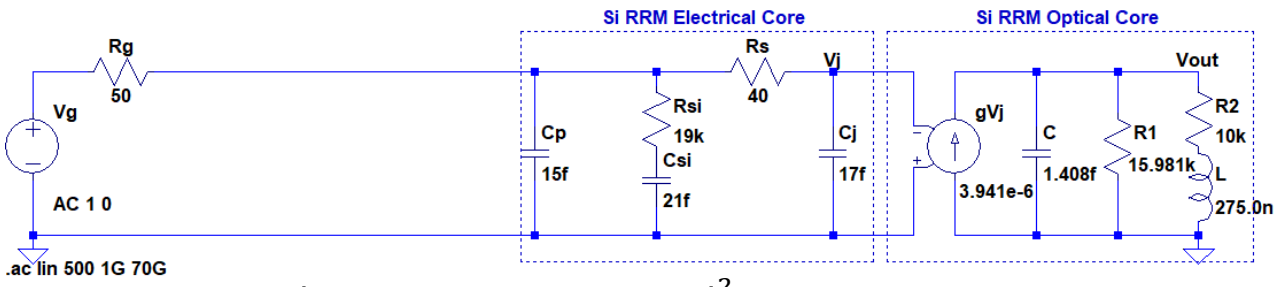




- **Pre-emphasis (equalization) of input drive signal compensates low bandwidth of device**

GOMACTech 2019 18.1; SPIE Photonics West OPTO 11286-9

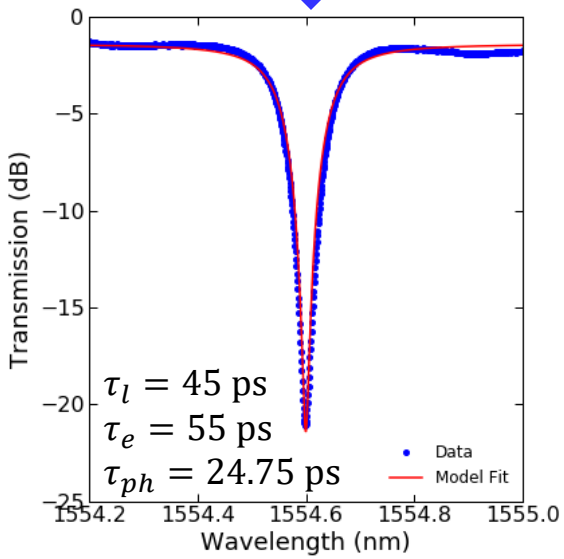
SiPho RRM Small-Signal Circuit Model

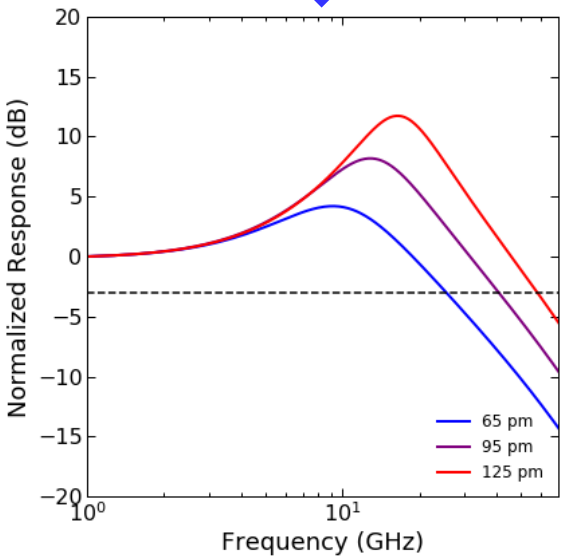


$$T = \frac{P_{\text{out}}}{P_{\text{in}}} = \left|\frac{j(\omega-\omega_r)+1/\tau_l-1/\tau_e}{j(\omega-\omega_r)+1/\tau_l+1/\tau_e}\right|^2$$

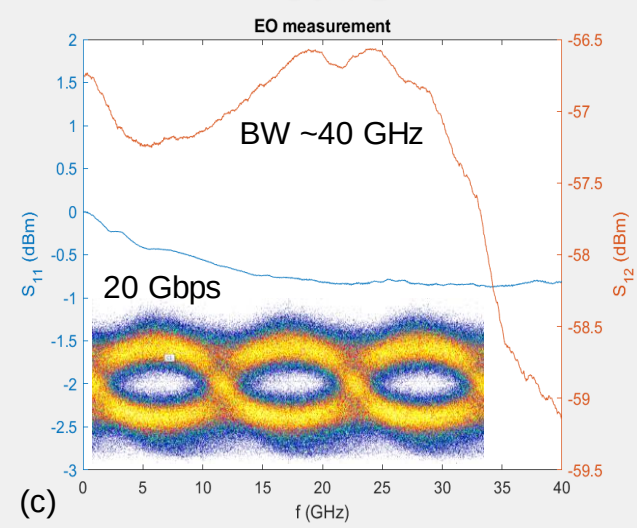
.step param g list 3.941e-6 1.597e-6 7.77e-7
.step param R1 list 15.981k 34.023k 58.831k
.step param C list 1.408f 0.661f 0.382f

$$\begin{cases} R_1 C = \dfrac{\tau_e}{2} \\ \dfrac{L}{R_2} = \dfrac{\tau_l}{2} \\ \dfrac{R_1}{R_2} = \dfrac{\tau_e \tau_l}{4}\left(\dfrac{1}{\tau_{ph}^2} + D^2\right) - 1 \\ g = \dfrac{2}{n_{\text{eff0}}} \cdot \dfrac{\delta n_{\text{eff}}}{\delta V} \cdot \dfrac{\omega_r D}{R_1\left(D^2 + \tau_{ph}^{-2}\right)} \cdot U \end{cases}$$





Gen. 2



$V_B = -6$ V
$\lambda = 1543$ nm

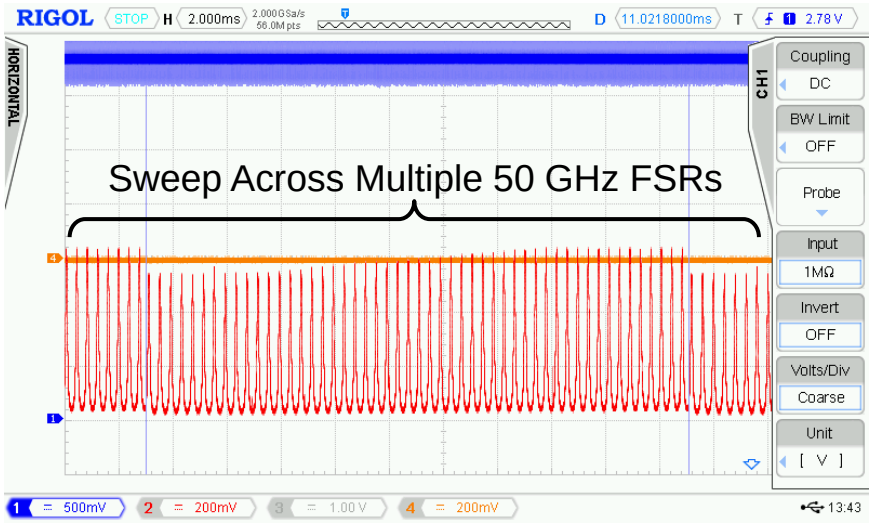
Shin, Myungjin, et al. *IEEE Transactions on Electron Devices* 64.3 (2017): 1140-1145.

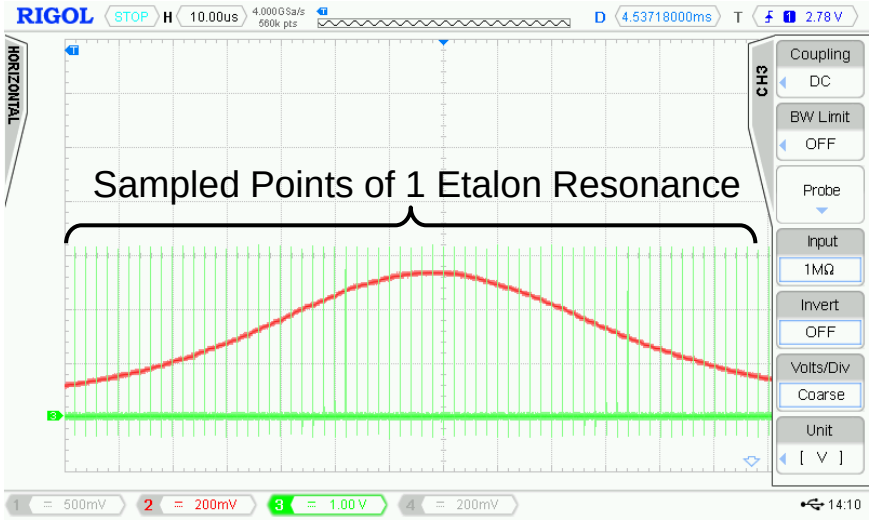
- **Model must consider both electrical <u>AND</u> optical dynamics**
  - Peaked response extends bandwidth, at cost of reduced ER/OMA

Widely and Rapidly Tunable Laser

FP4209 InstaTune

Available for O-, C-, U-Band



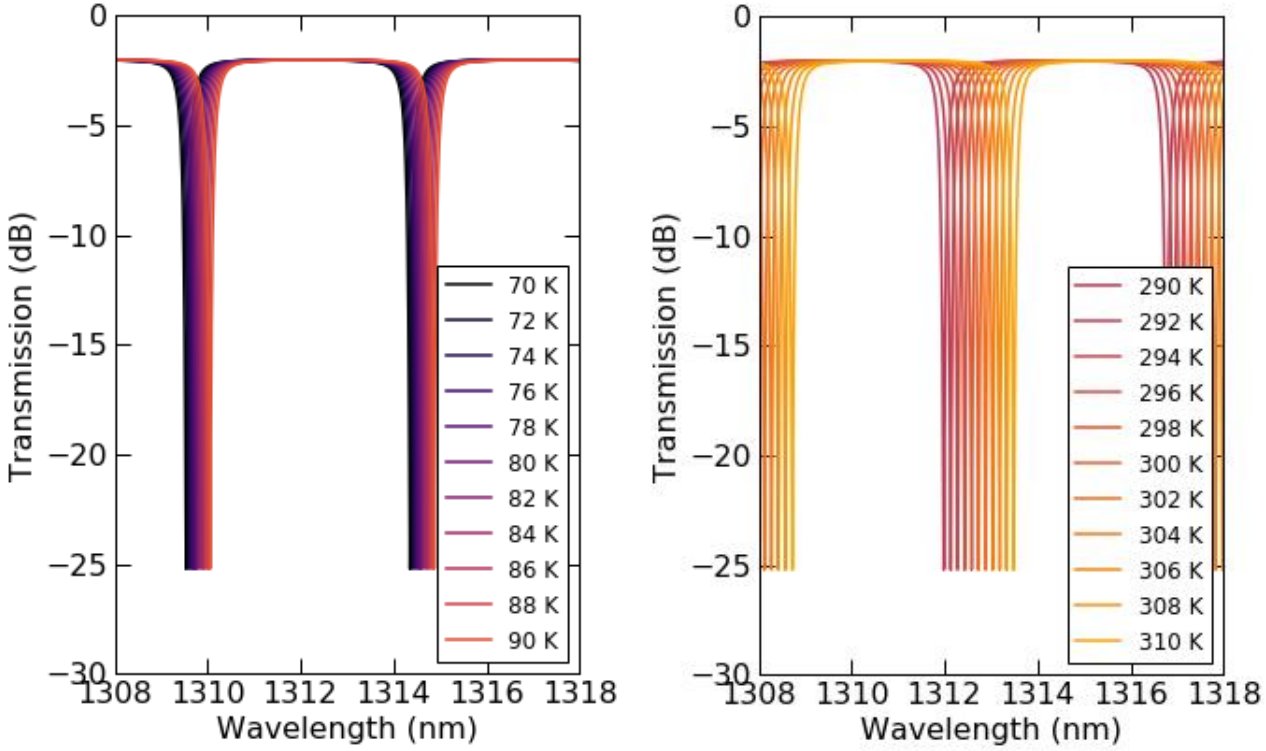


10k wavelengths @ 2us/pt. = 40nm (4pm/pt.) in 20msec

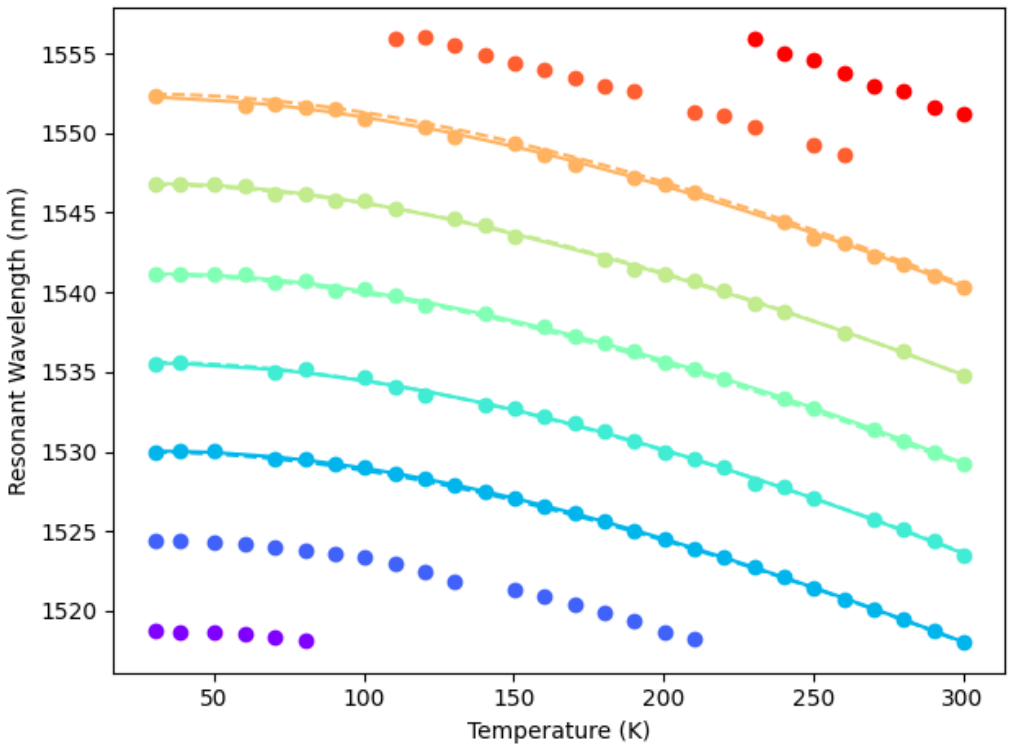
- **FP4209 based on Freedom Photonics widely tunable laser technology**
- **Fast tuning of the laser achieved by internal compensation**
  - Can be applied to tunable lasers for O-, C-, and U-bands
- **Tunes across 40 nm wavelength span in 20 ms**
  - 10k calibrated wavelengths
- **Capable of arbitrary wavelength sweeps (λ-AWG)**

Thermal Shift in SiPho RRM Resonance

Simulation



Measurement



Thermo-Optic Coefficient

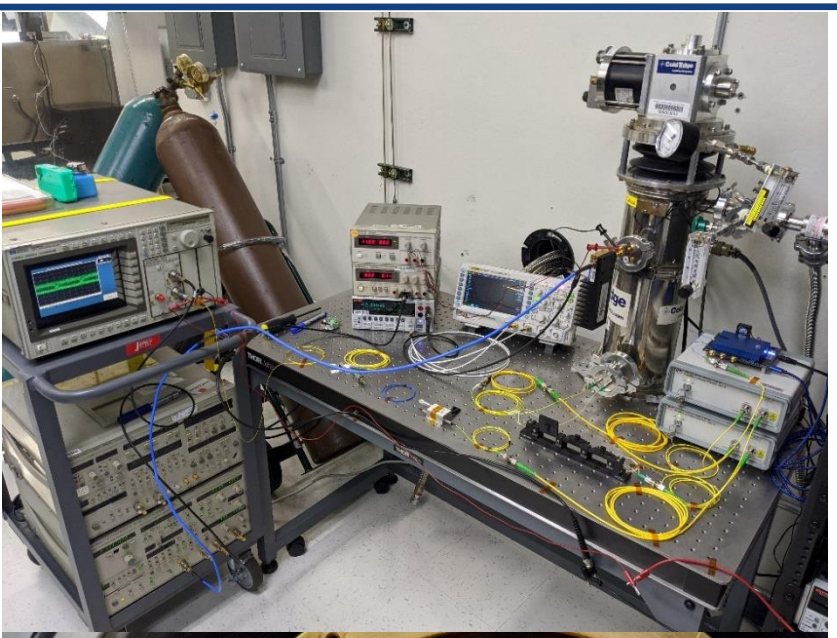
Change in Resonance → $\Delta\lambda \propto \boxed{\frac{\partial\lambda}{\partial T}}(\lambda, T)\Delta T$

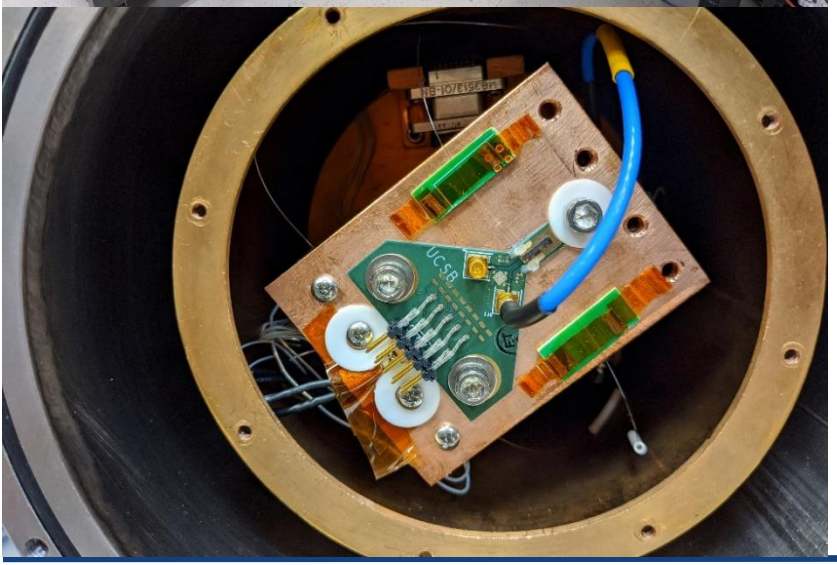
In Si, $\frac{\partial\lambda}{\partial T}$ coefficient <u>decreases</u> with decreasing T

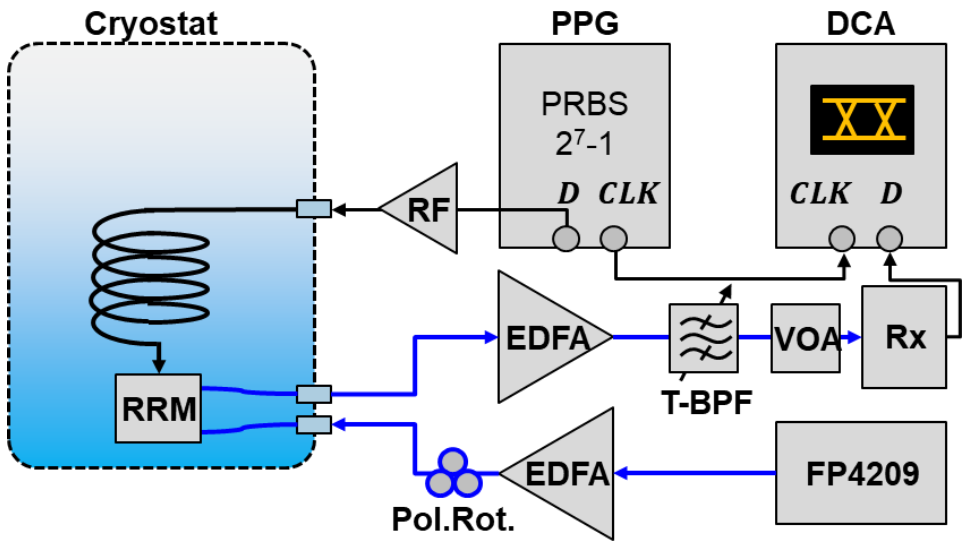
$$\frac{d\lambda}{dT}(1535\text{ nm}, 80\text{ K}) = -22.5\text{ pm/K}$$

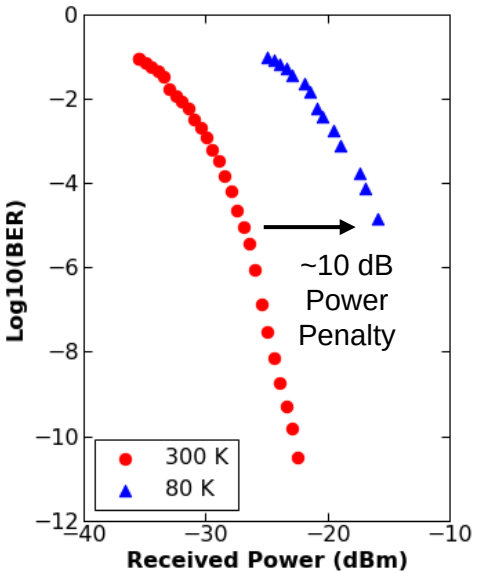
$$\frac{d\lambda}{dT}(1535\text{ nm}, 300\text{ K}) = -70.1\text{ pm/K}$$

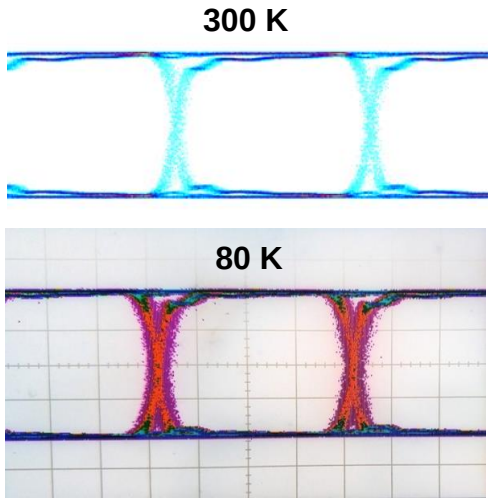
Cryogenic Characterization of SiPho RRM



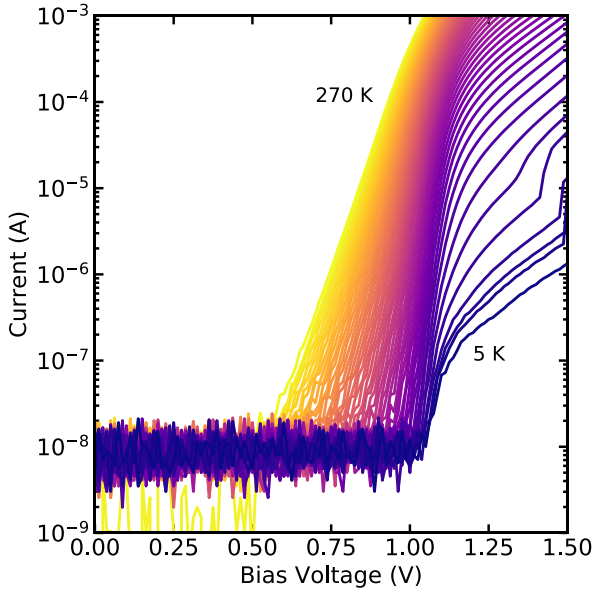








2.5 Gbps



Unpublished: To Be Presented at OFC 2021

Free-Carrier Dispersion / Absorption

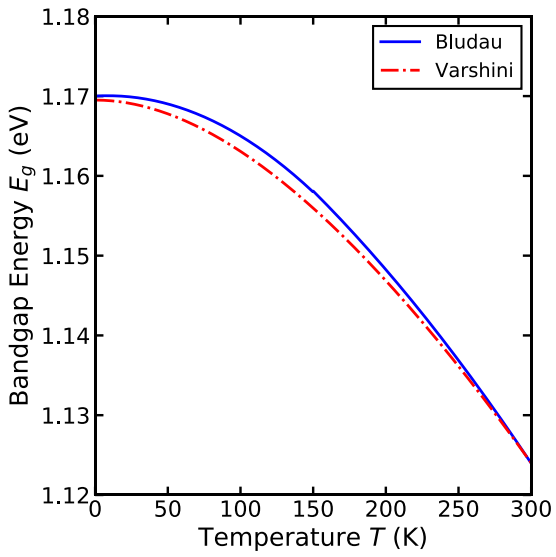
$$\Delta n = -\frac{q^2\lambda_0^2}{8\pi^2 c^2 \varepsilon_0 n}\left(\frac{\Delta N_e}{m_{ce}^*} + \frac{\Delta N_h}{m_{ch}^*}\right)$$

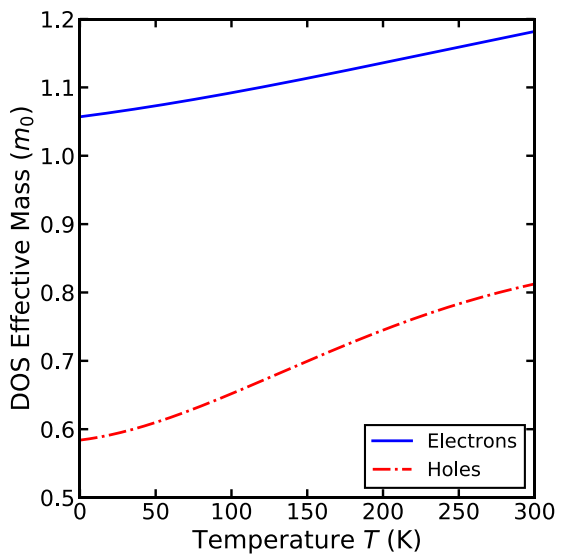
$$\Delta \alpha = \frac{q^3\lambda_0^2}{4\pi^2 c^3 \varepsilon_0 n}\left(\frac{\Delta N_e}{\mu_e {m_{ce}^*}^2} + \frac{\Delta N_h}{\mu_h {m_{ch}^*}^2}\right)$$

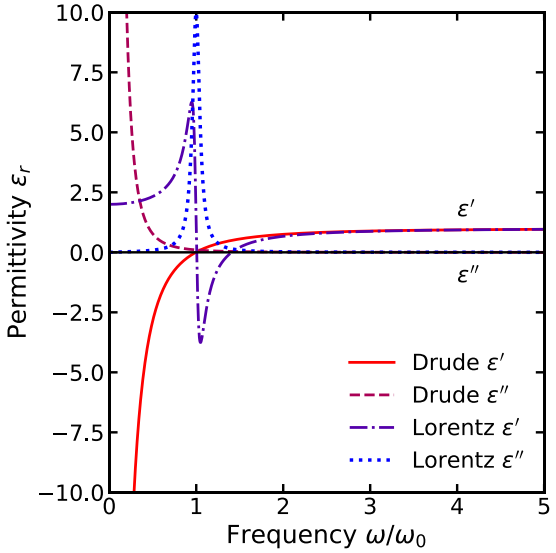
Soref, Richard A., and Brian R. Bennett. "Electrooptical effects in silicon." *IEEE Journal of Quantum Electronics* 23.1 (1987): 123-129.

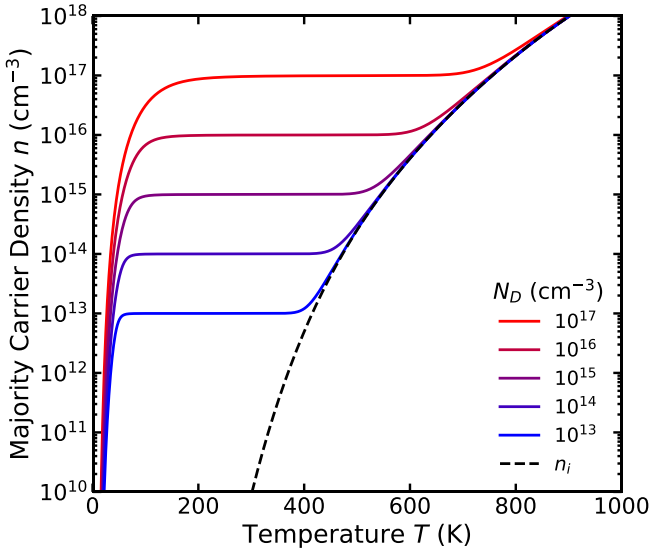
Nedeljkovic, Milos, Richard Soref, and Goran Z. Mashanovich. "Free-Carrier Electrorefraction and Electroabsorption Modulation Predictions for Silicon Over the 1–14-µm Infrared Wavelength Range." *IEEE Photonics Journal* 3.6 (2011): 1171-1180.

- **Typical expressions in literature assume RT**
- **Many parameters are in fact temperature dependent**
- **No low-temperature FCD / FCA model exists**

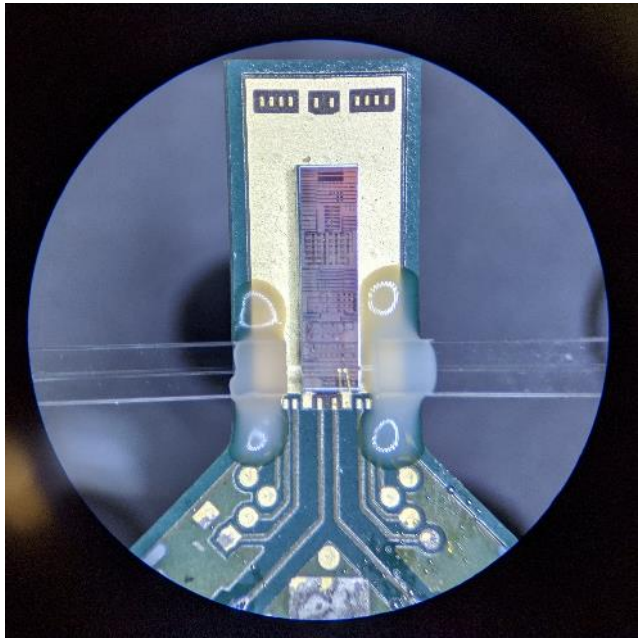


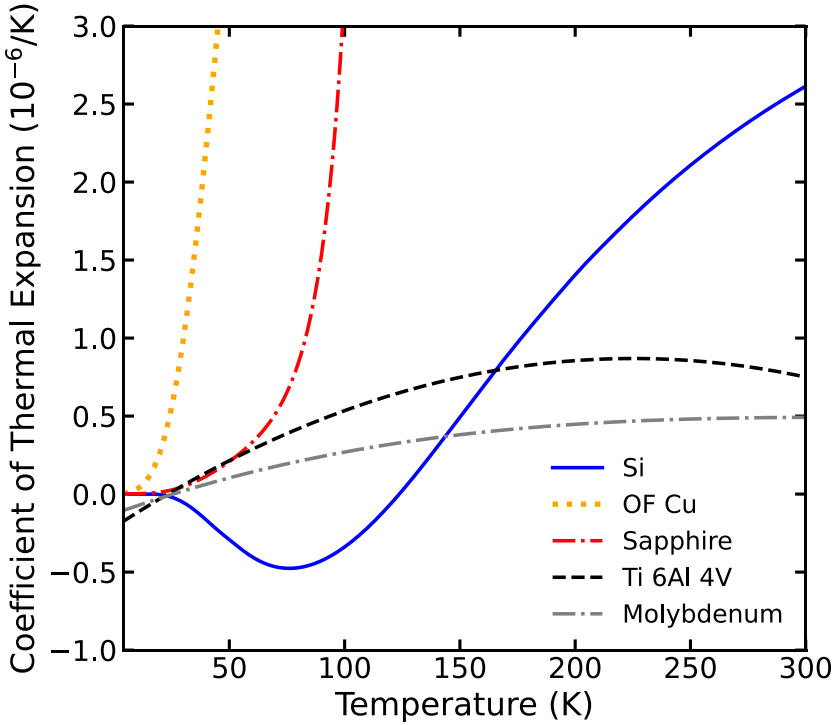


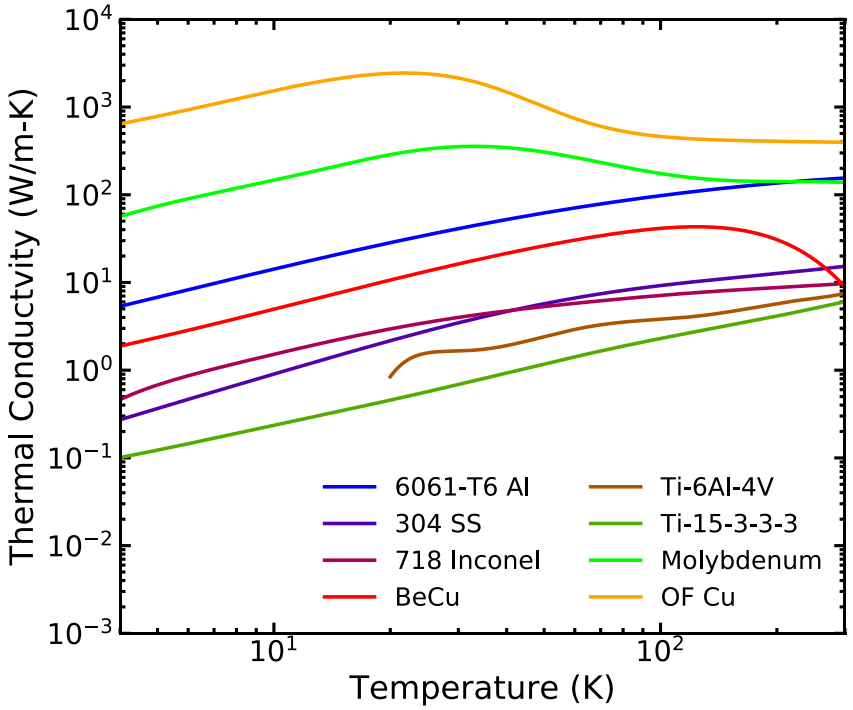




Cryogenic Packaging = CTE Engineering



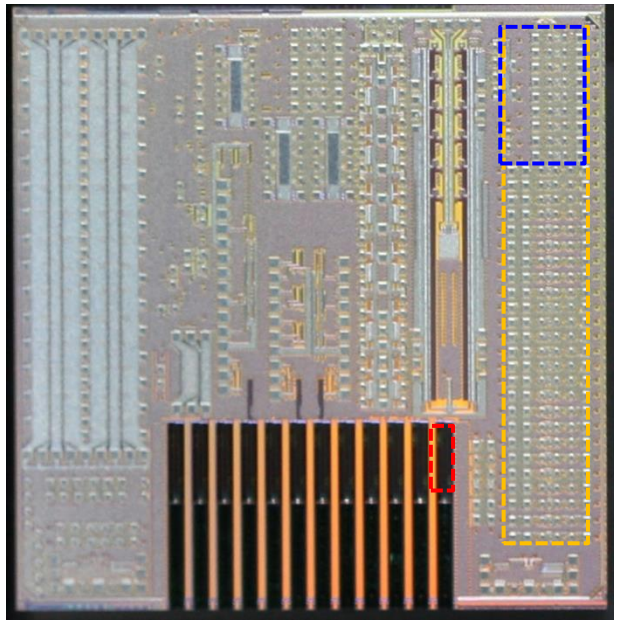


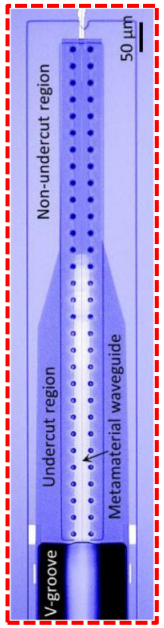


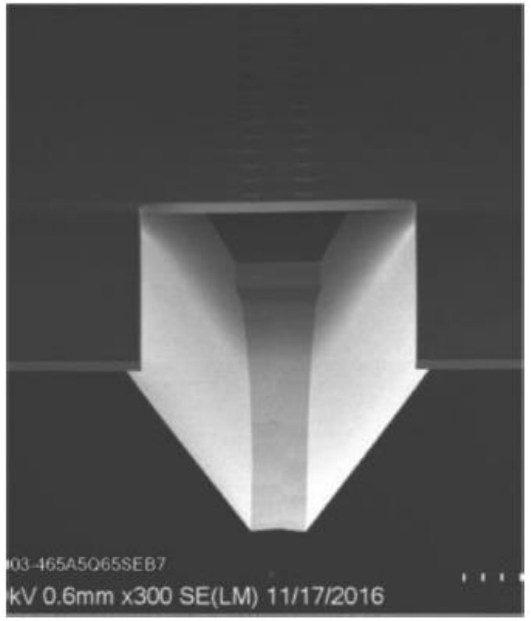
- **Optimal cryogenic photonic packaging materials have high thermal conductivity <u>AND</u> are CTE matched**
- **Models and methodologies for proper CTE engineering to SiPho devices will be developed**

GlobalFoundries 9WG

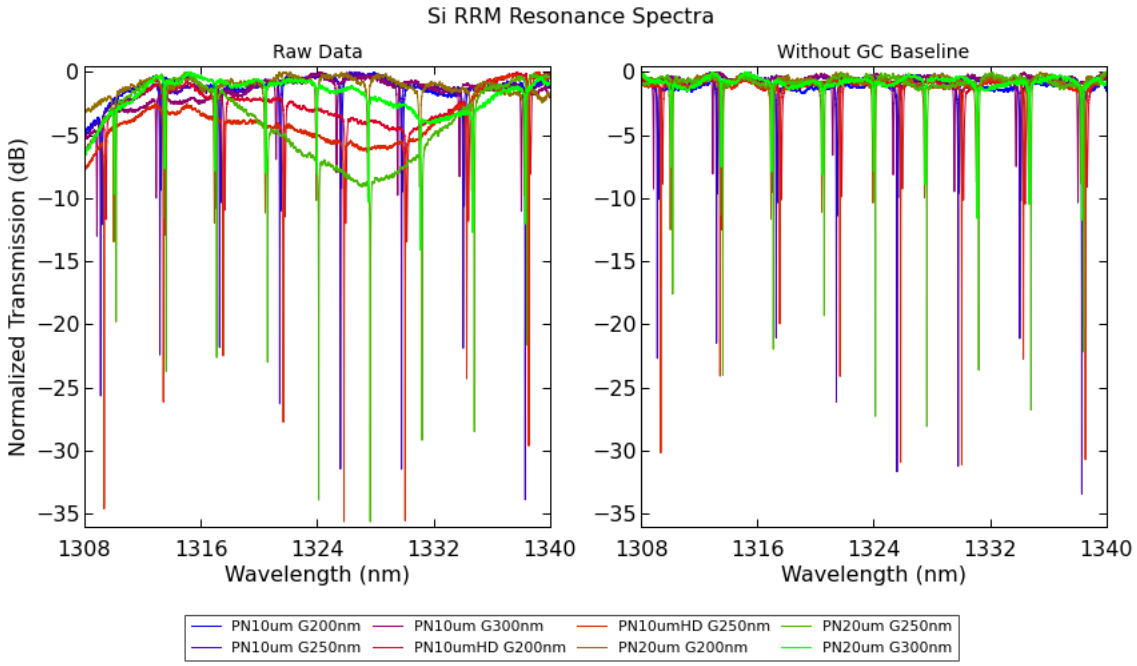
FEBRUARY 2019 / 2020

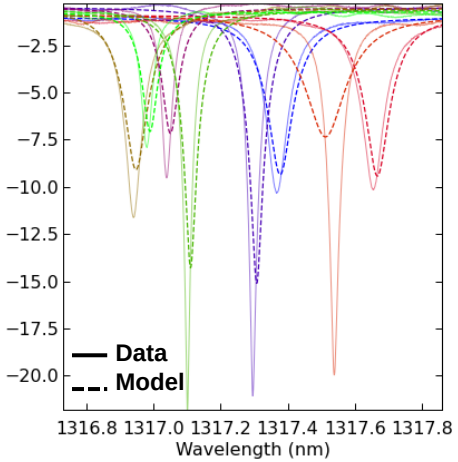


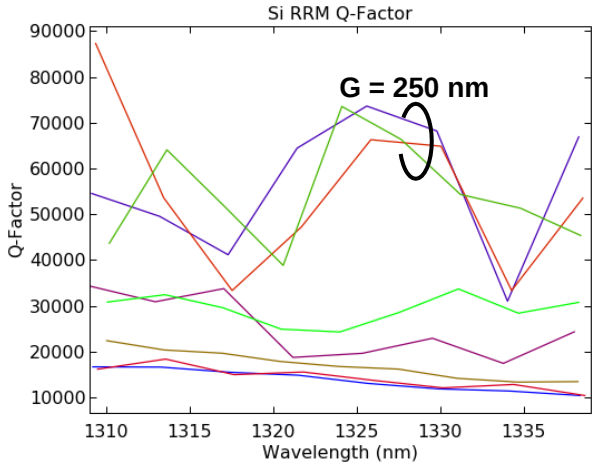




Giewont, Ken, et al. "300-mm monolithic silicon photonics foundry technology." *IEEE Journal of Selected Topics in Quantum Electronics* 25.5 (2019): 1-11.



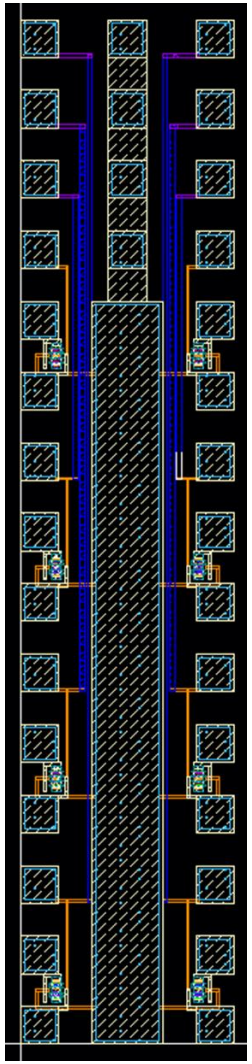




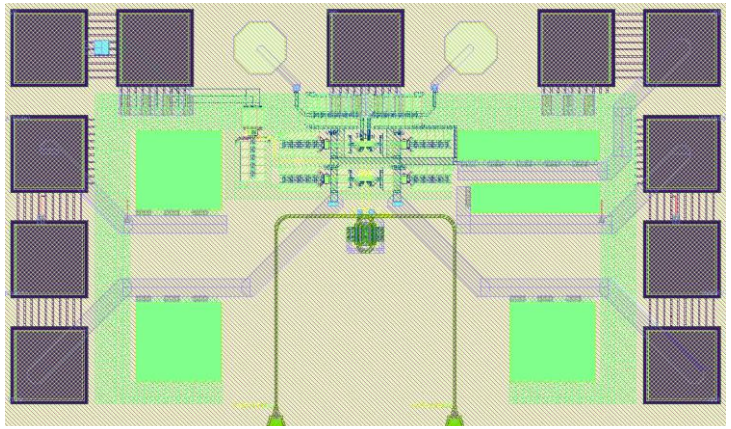
- **34 different RRM devices**
  - Single- and Double-ring RRMs, 200, 250, 300 nm gap
  - 10 and 20 µm PN junction phase shifter, Normal and Highly Doped, Lateral and Interdigitated

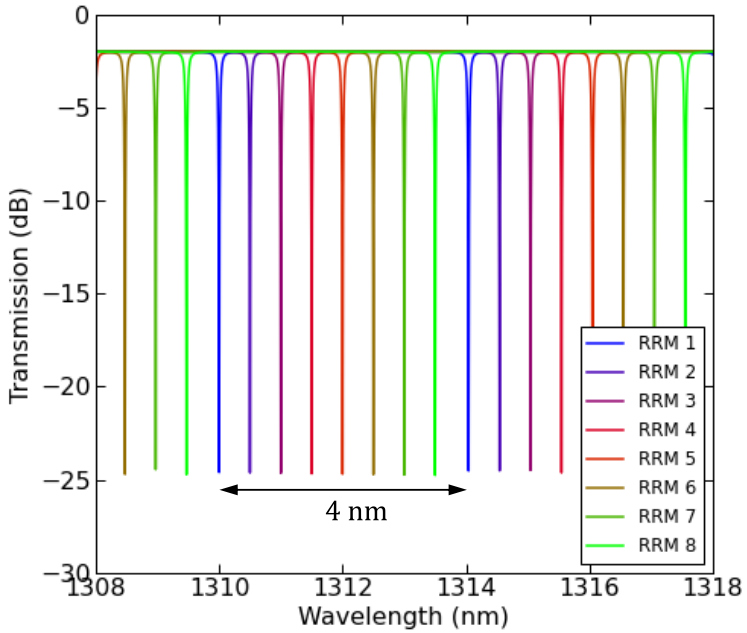
Monolithic RRM + Driver

8-Ch WDM RRM

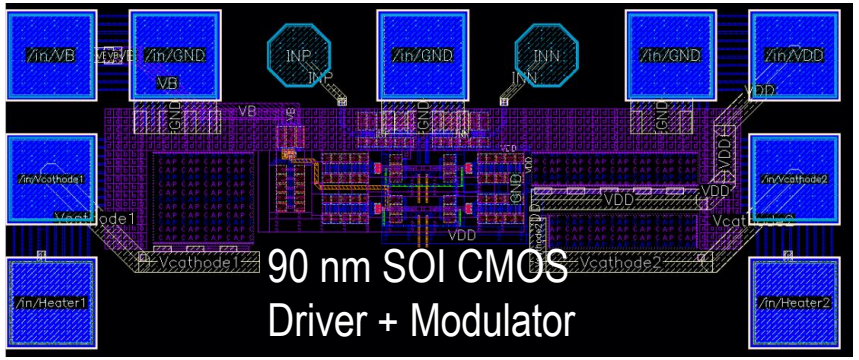


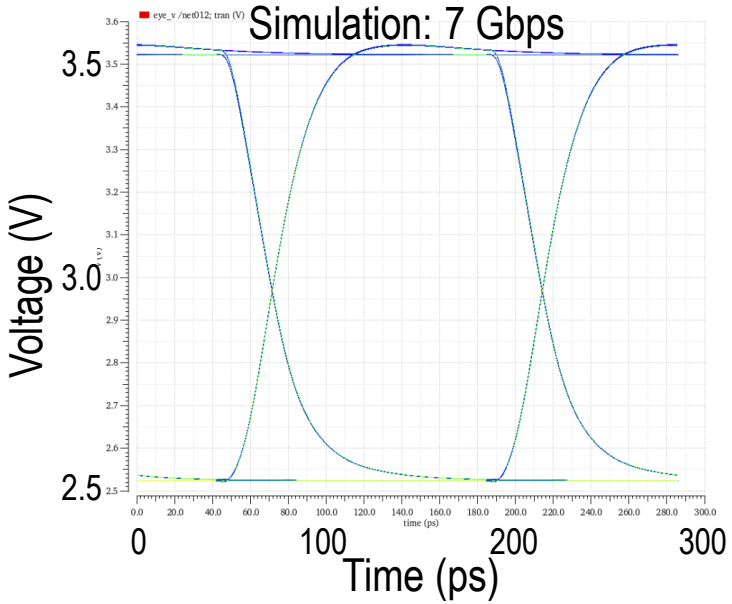
Single-Ring + Driver





Double-Ring + Driver





Thank You

Questions?