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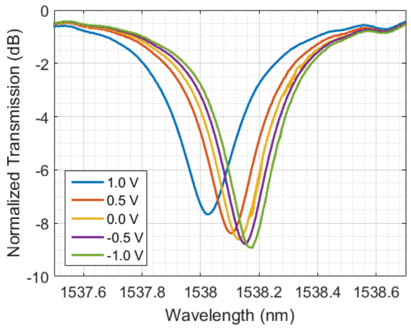

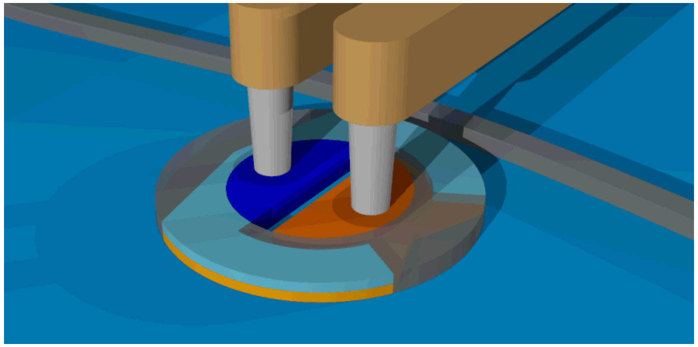

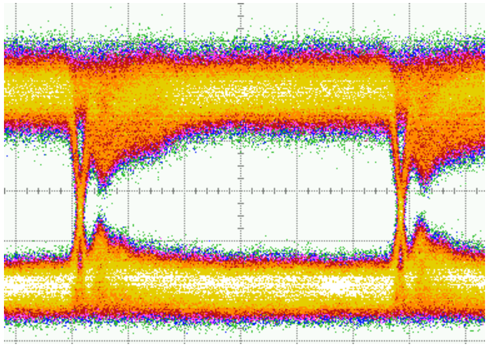

Operation of High-Speed Silicon Photonic Micro-Disk Modulators at Cryogenic Temperatures

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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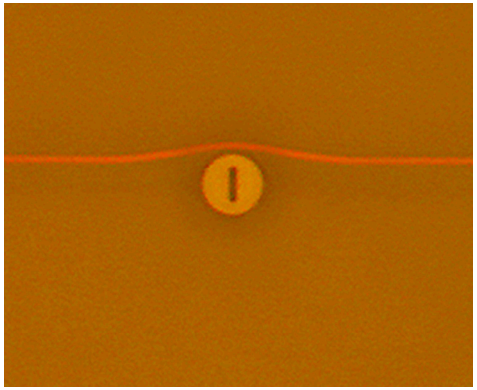
Silicon Photonics for Cryogenics

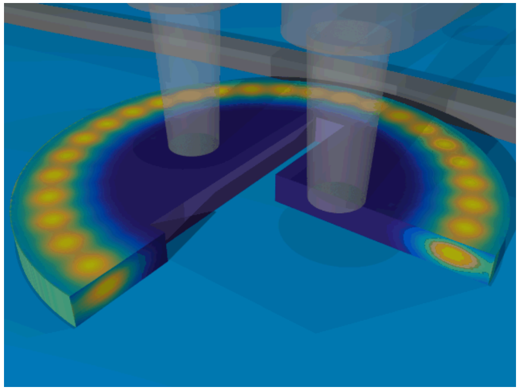
- Cryogenic systems have demanding constraints
  - Limited cooling power
  - Limited volume
  - Limited bandwidth connections
- Silicon photonics can meet demands of cryogenic environments
  - WDM – Multiple signals over single connection
  - High efficiency (1-3 fJ/bit [1,2])
  - CMOS compatible
  - High frequency (12-25 Gb/s at room temp [1,2])
- Applications
  - Focal plane arrays
  - Superconducting electronics
    - Superconducting nano-wire single photon detectors
    - Superconducting digital logic
  - Space/Satellite

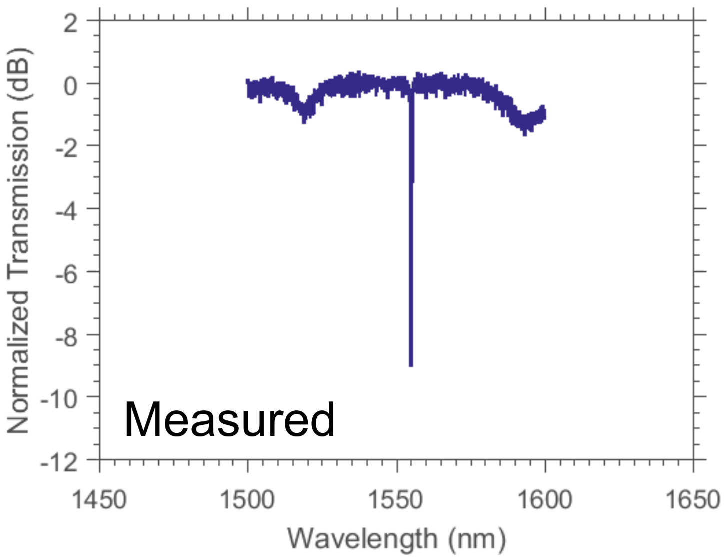
[1] *Optics Express* **19**, 21989 (2011), [2] *Nat. Comm.* **5**, 4008 (2014)

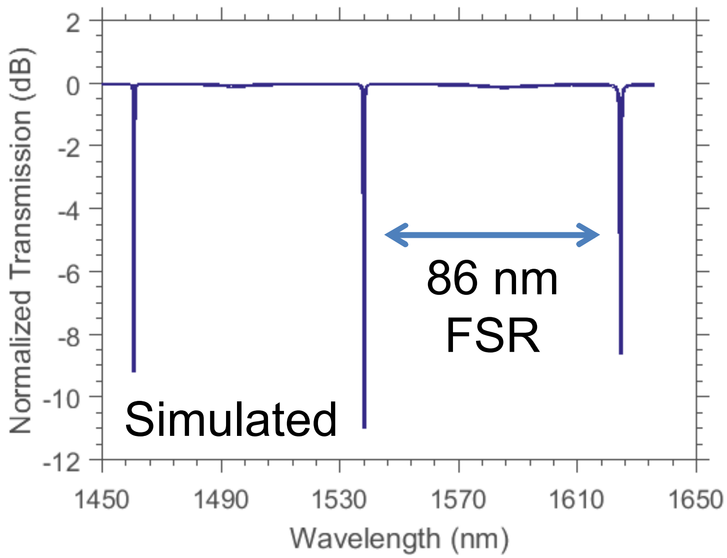
Modulator Optical Design

- 3.5 μm diameter disk
  - Large FSR (>80 nm)
- Serpentine coupling region
  - Minimal coupling to other modes



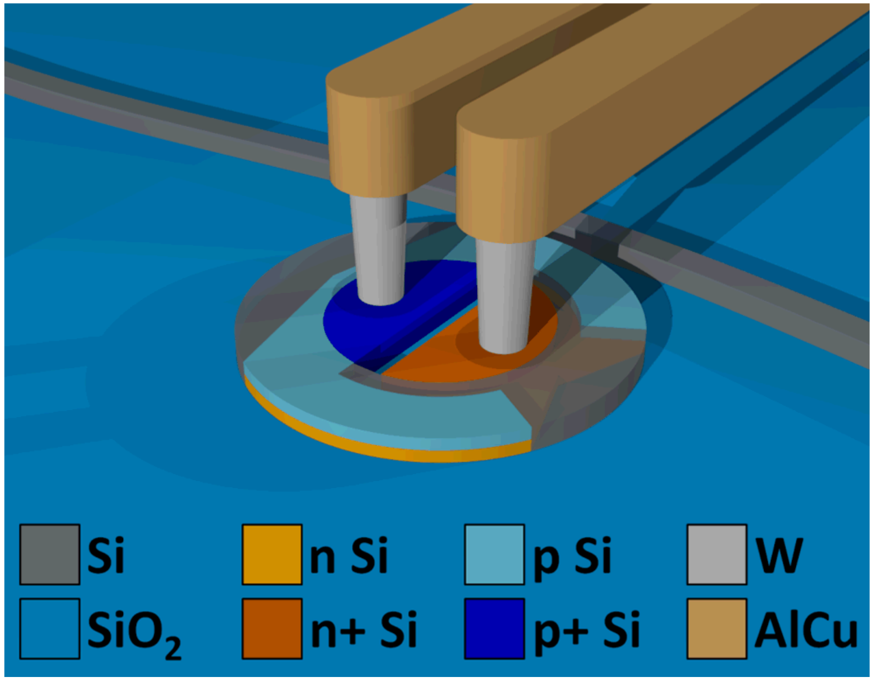






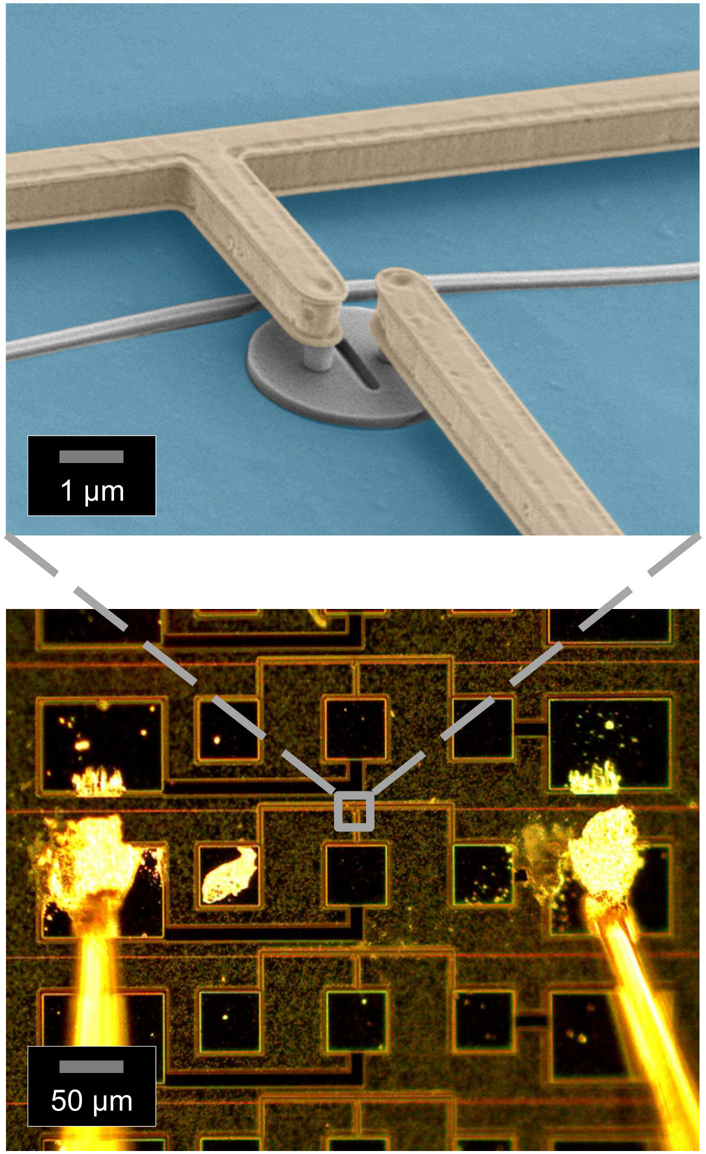
Modulator Electrical Design

- Vertical Junction
  - Index modulated by free-carrier concentration
- Partially Doped
- Forward Bias
  - Large resonance shift (>100 pm/V)
  - Frequency limited by free carrier lifetime
- Reverse Bias
  - Small resonance shift (~40 pm/V)
  - Frequency limited by device capacitance (~10-20fF)



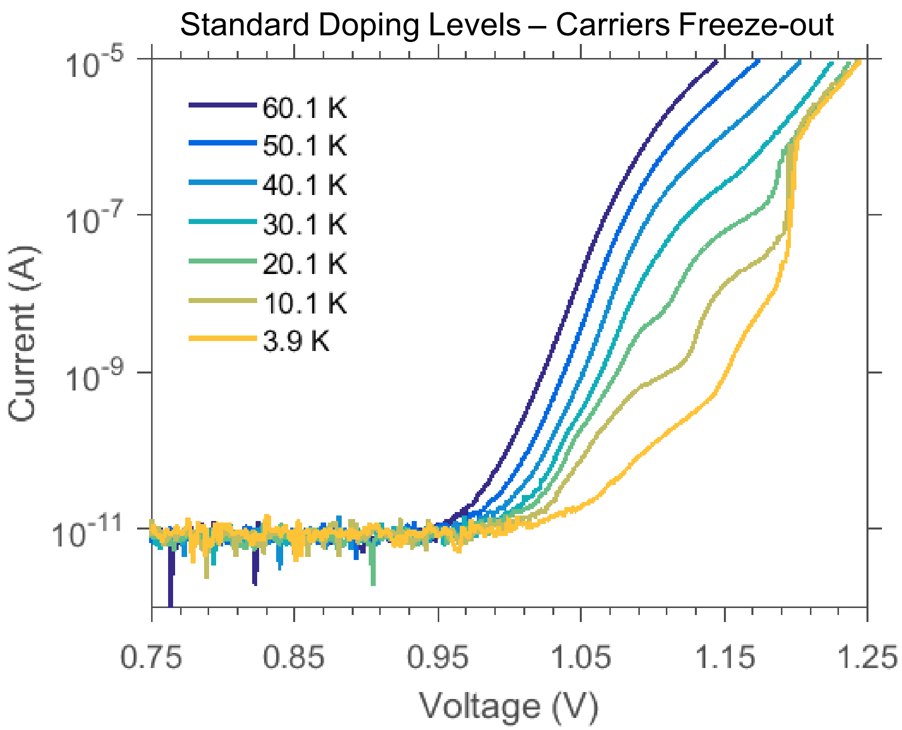
Device Fabrication/Mounting

- Sandia MESA Fab
  - Silicon Photonics Platform
  - CMOS Compatible
  - SOI – 3 µm BOX
- Low Temperature Testing
  - Recirculating He Cryostat (3.8-5 K)
  - End-fire tapered Si waveguide coupling
    - 5-8 dB I.L. per taper
  - RF feed-throughs to wirebonds
    - Low loss up to ~10GHz



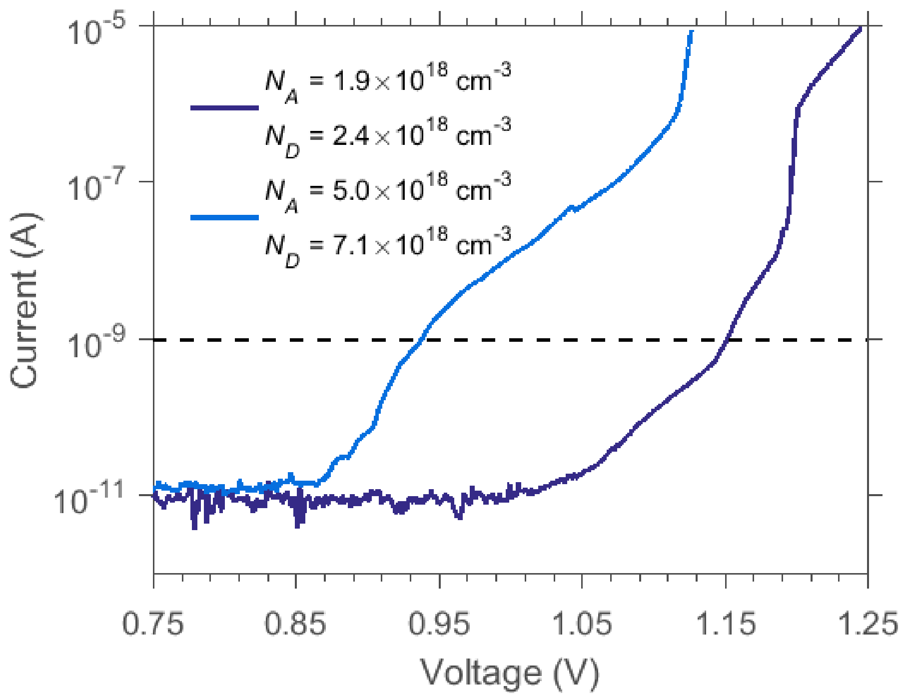
Carrier Freeze-Out

- Free carriers generated through thermal ionization
- Low temperatures leads to incomplete ionization
- Fermi level shifts towards impurity energy levels (near valence/conduction bands)
  - p-n junction built-in voltage increases
- Carrier concentration quickly drops
  - Series resistance increases



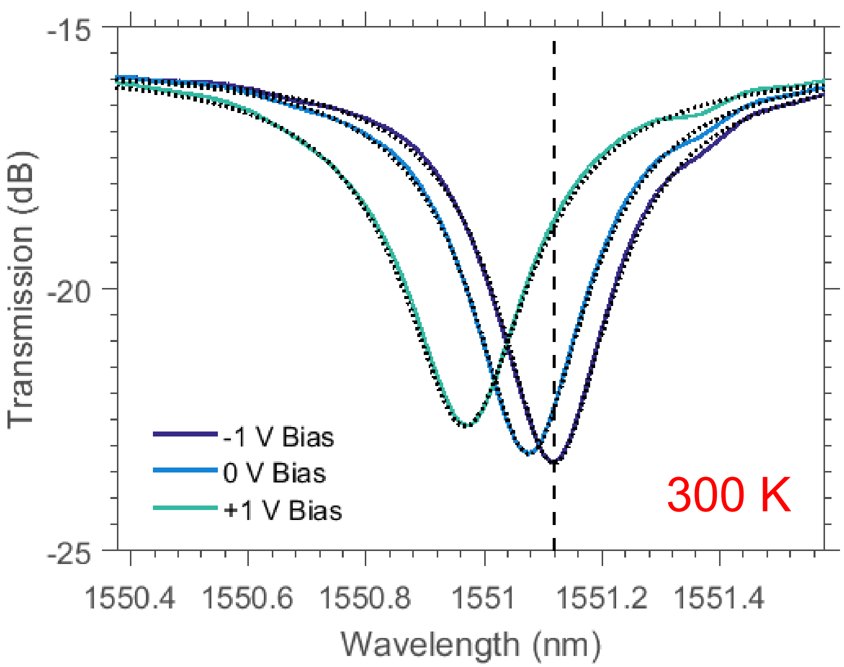
Doping Concentration

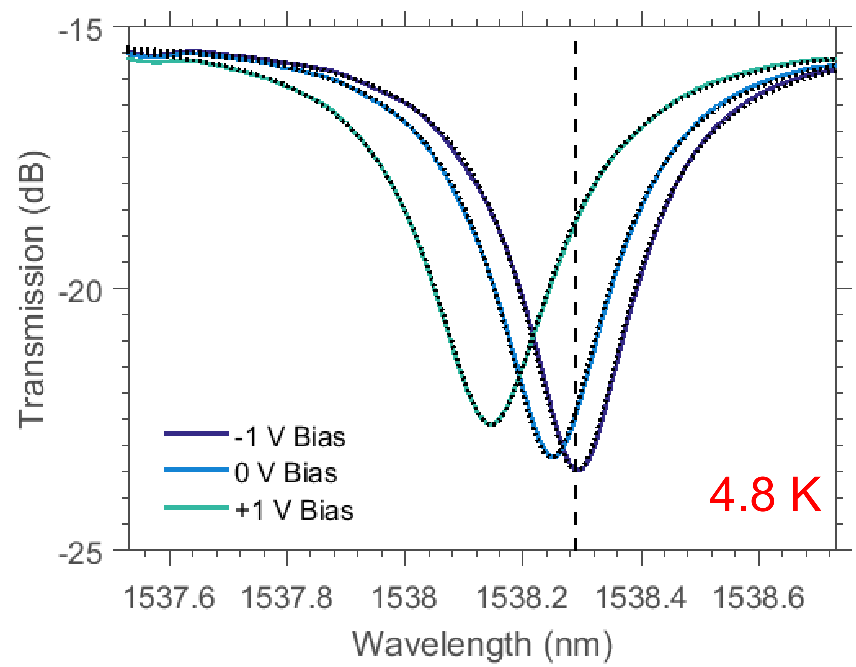
- Increase Doping
  - Increases carrier concentration
    - Decreased freeze-out temperature
  - Semiconductor to metal transition ~4×10^{18} /cm^3
- Standard Doping
  - $N_A \sim 1.9 \times 10^{18}$ /cm^3
  - $N_D \sim 2.4 \times 10^{18}$ /cm^3
- Implant doses increased by a factor of 2 and 3.



Steady State Optical Characterization

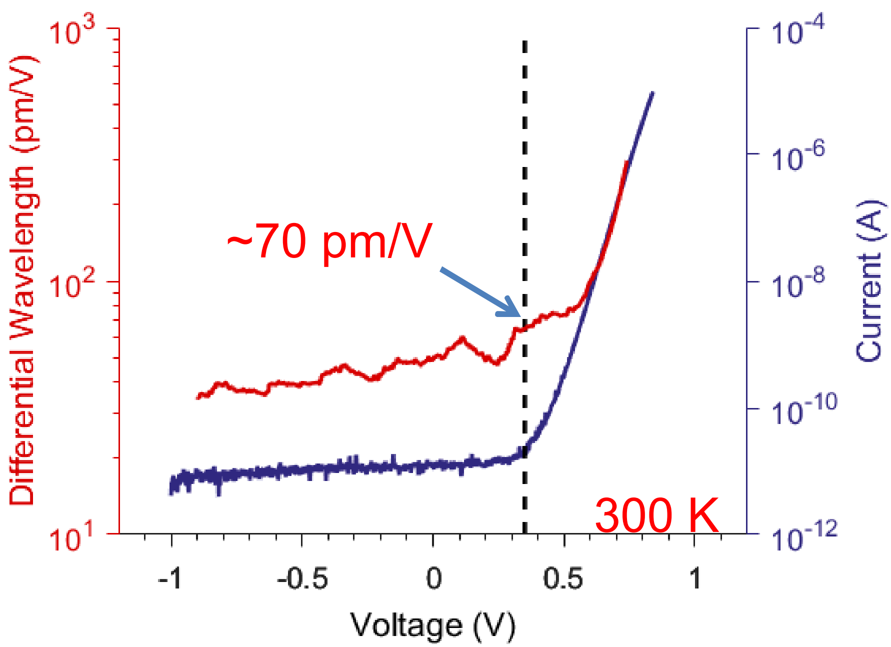
- Modulator resonance measured as a function of DC voltage
  - Similar spectral shift at room temperature and 4.8 K
  - 146pm shift from -1 V to 1 V (9 GHz/V)

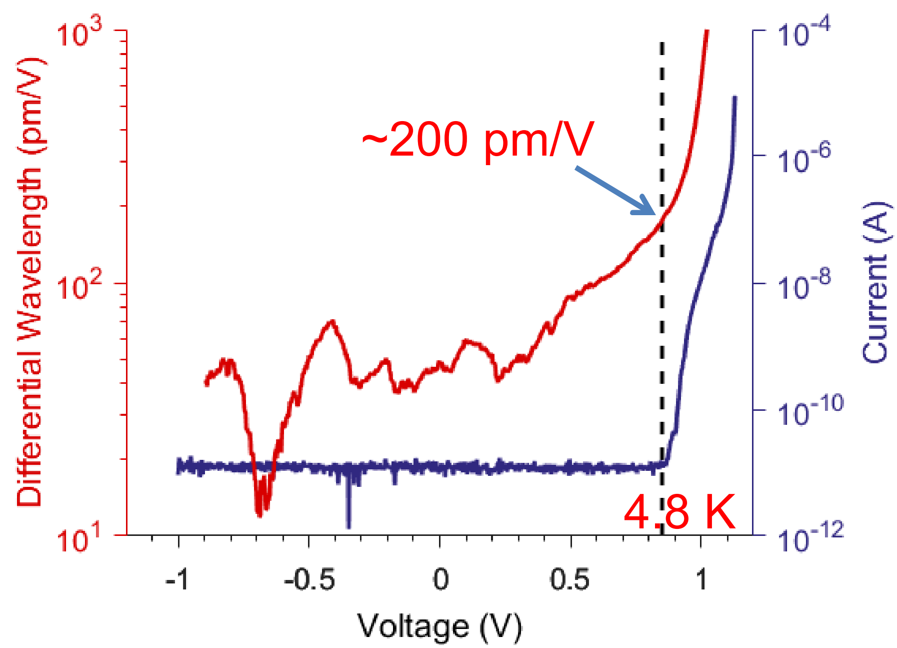




Steady State Characterization

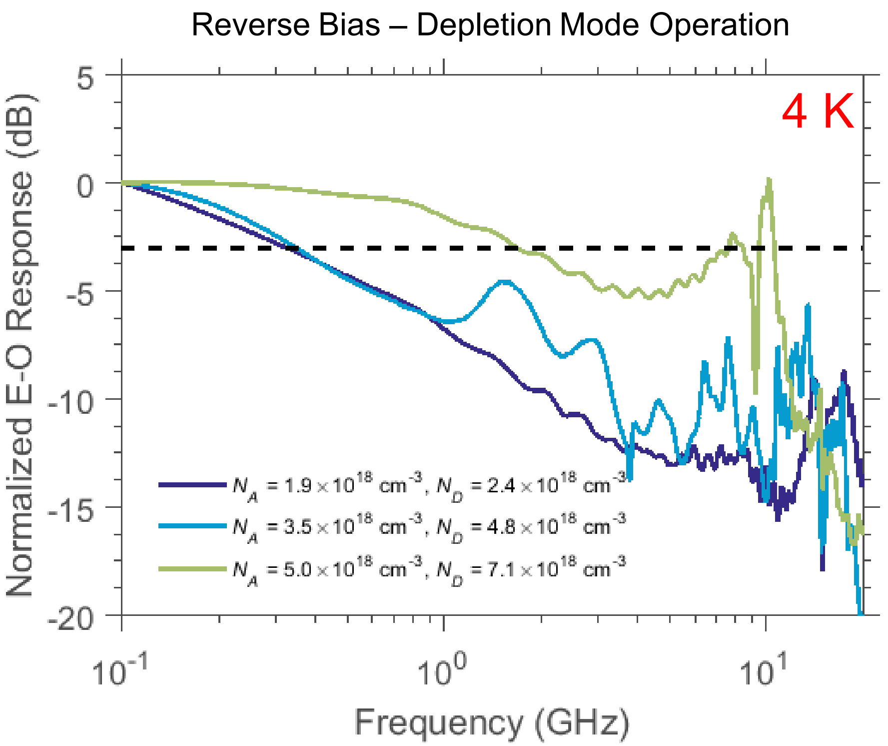
- Differential wavelength shift showed a similar magnitude from 300 K to 4.8 K
- Increased turn-on voltage allows larger shift with almost no forward current
  - Less current means less heating





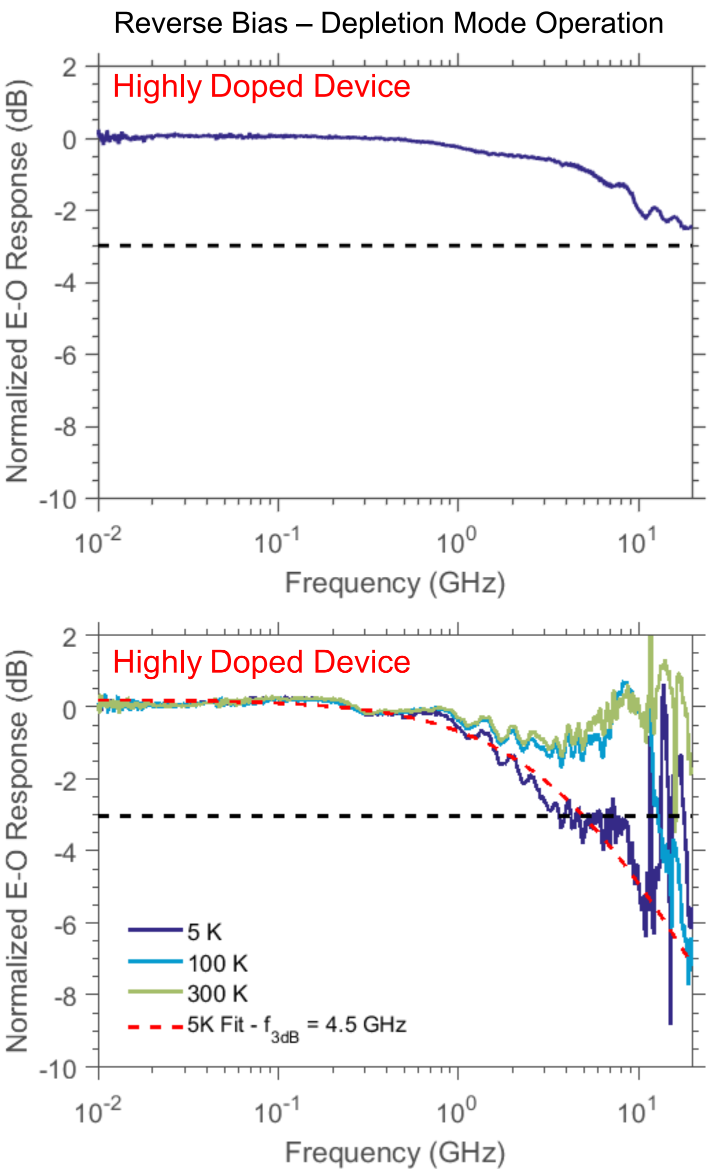
Frequency Response

- Small signal electro-optical response measured with a network analyzer
- Normal doped devices freeze out
  - Increased series resistance
  - Increased RC constant
  - Decreased frequency response
- Highly doped device showed improved response
  - 3 dB cut-off of 1.7GHz for this device



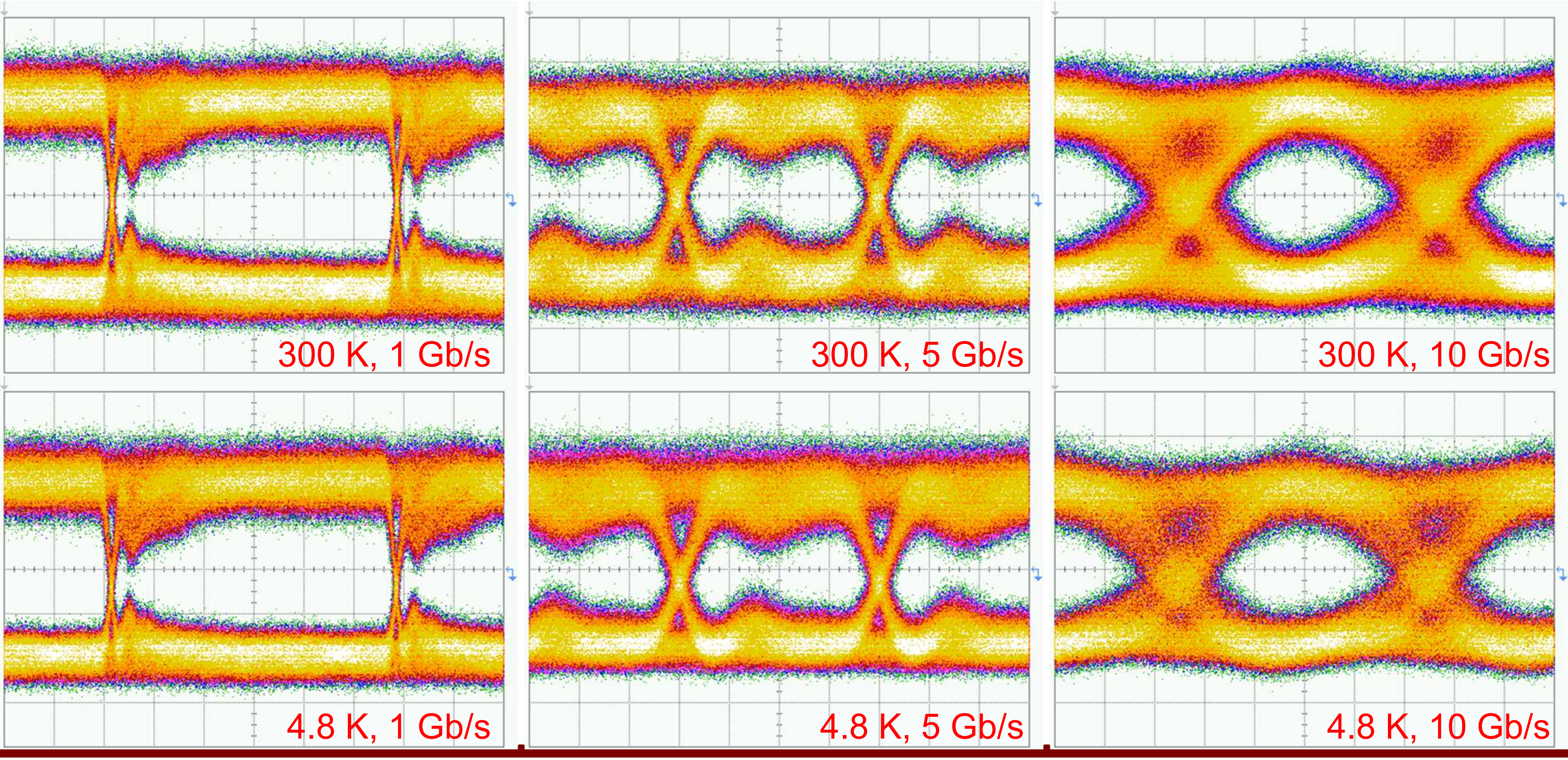
Frequency Response

- Device performance with RF probes at 300 K > 20GHz
- Device performance in cryostat similar from 300 K down to 100 K
- Frequency response drops below 100 K
  - 3dB cutoff of 4.5 GHz at 4.8 K for best device



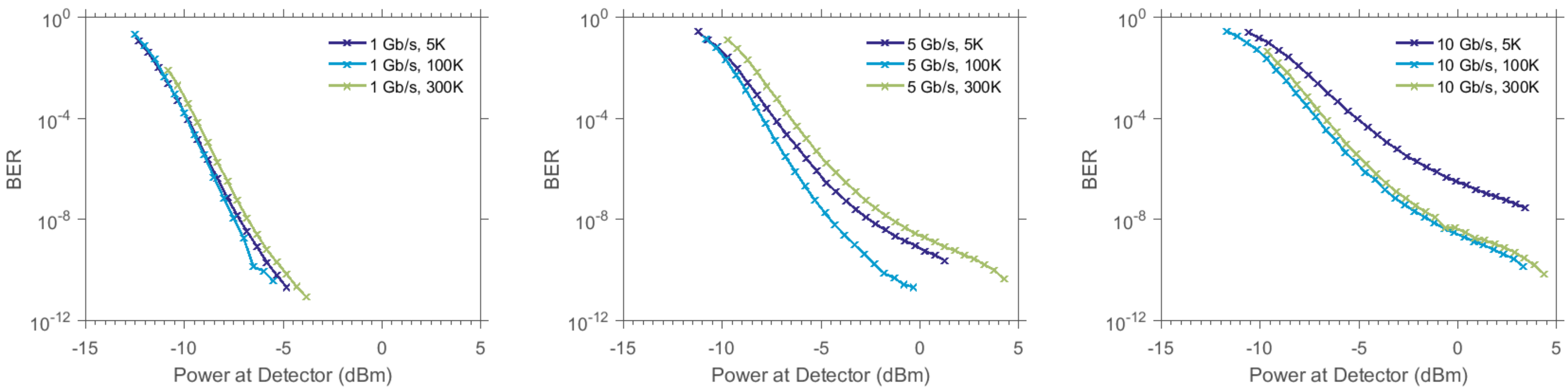
High Speed Data Transmission

- Performance demonstrated with eye diagrams
  - V_{DC} = -1.8 V, V_{AC} = 1.8 V_{pp}
  - Very little change from 300 K down to 4.8 K
  - Excess noise from signal amplification (~15 dB I.L. inside cryostat)



High Speed Data Transmission

- Bit error rate performed at 1, 5 and 10 Gb/s
  - Very little temperature dependence at 1 and 5 Gb/s
  - Degraded BER at 10 Gb/s below 100 K
  - Measurements limited by
    - Low extinction ratio (~4-5 dB)
    - Large amplifier noise (SNR ~ 7)
    - Can be improved with optimized micro-disk coupling and end-fire coupling



Conclusion

- Silicon photonics – promising for high frequency data transmission to and from cryogenic environments
- Operation of a micro-disk modulator demonstrated up to 10 Gb/s at 4.8 K
- Increased doping necessary to offset incomplete ionization
- Optimization of doping, optical coupling and increased integration will lead to improved performance