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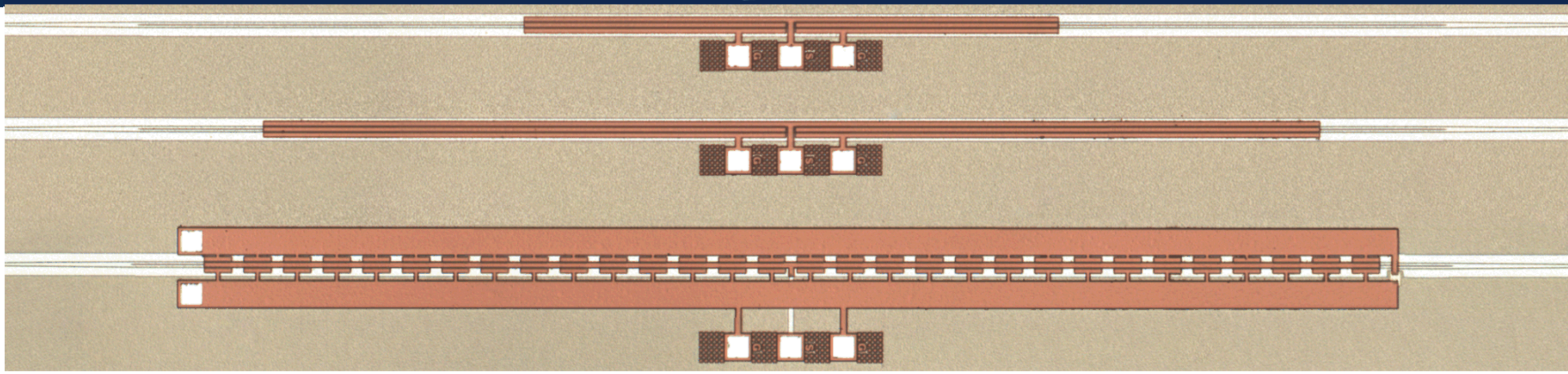

Integrated RF Silicon Photonics from High Power Photodiodes to Linear Modulators

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*cderose@sandia.gov

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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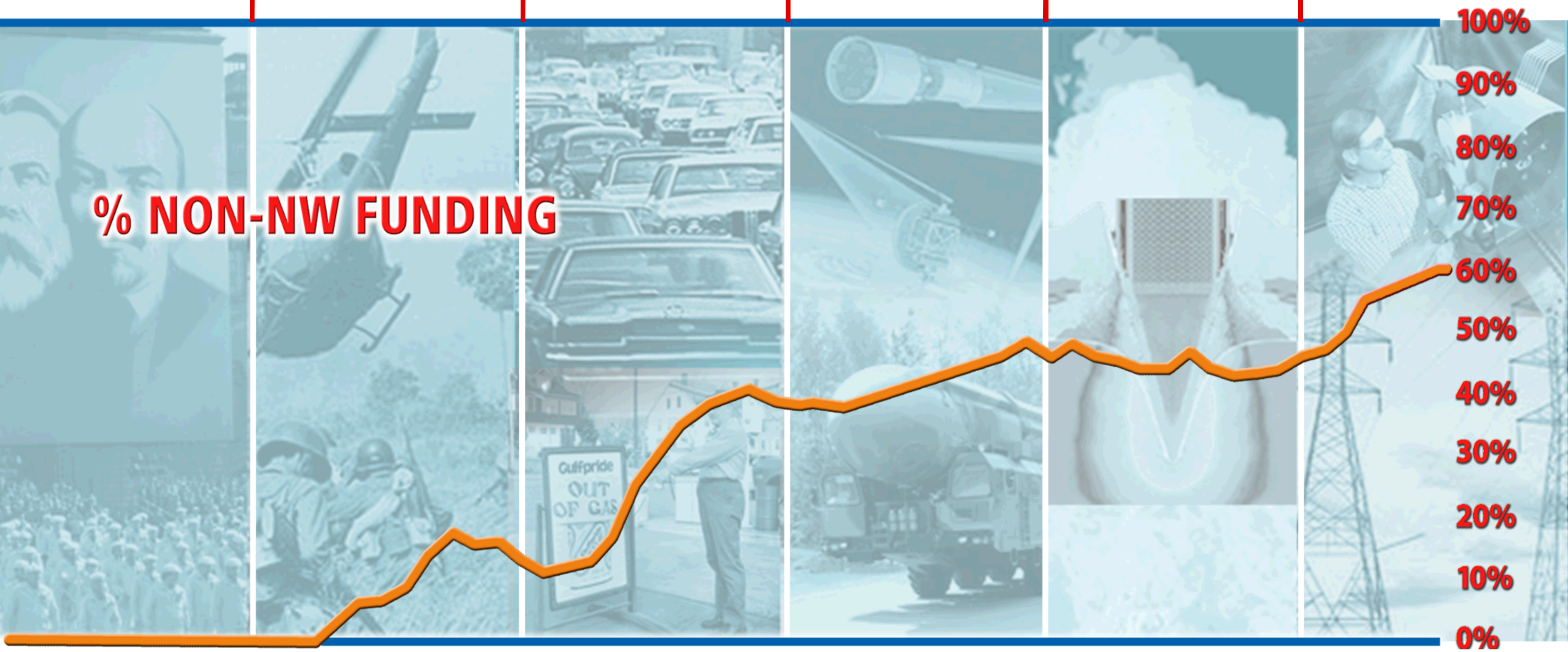
The Mission Has Evolved for Decades

Sandia National Laboratories

1950s	1960s	1970s	1980s	1990s	2000s
Production engineering & manufacturing engineering	Development engineering	Multiprogram laboratory	Research, development and production	Post-Cold War transition	Broader national security challenges



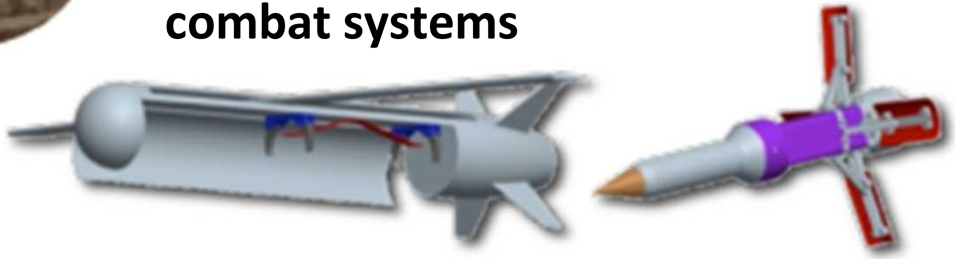
Defense Systems & Assessments

Synthetic aperture radar

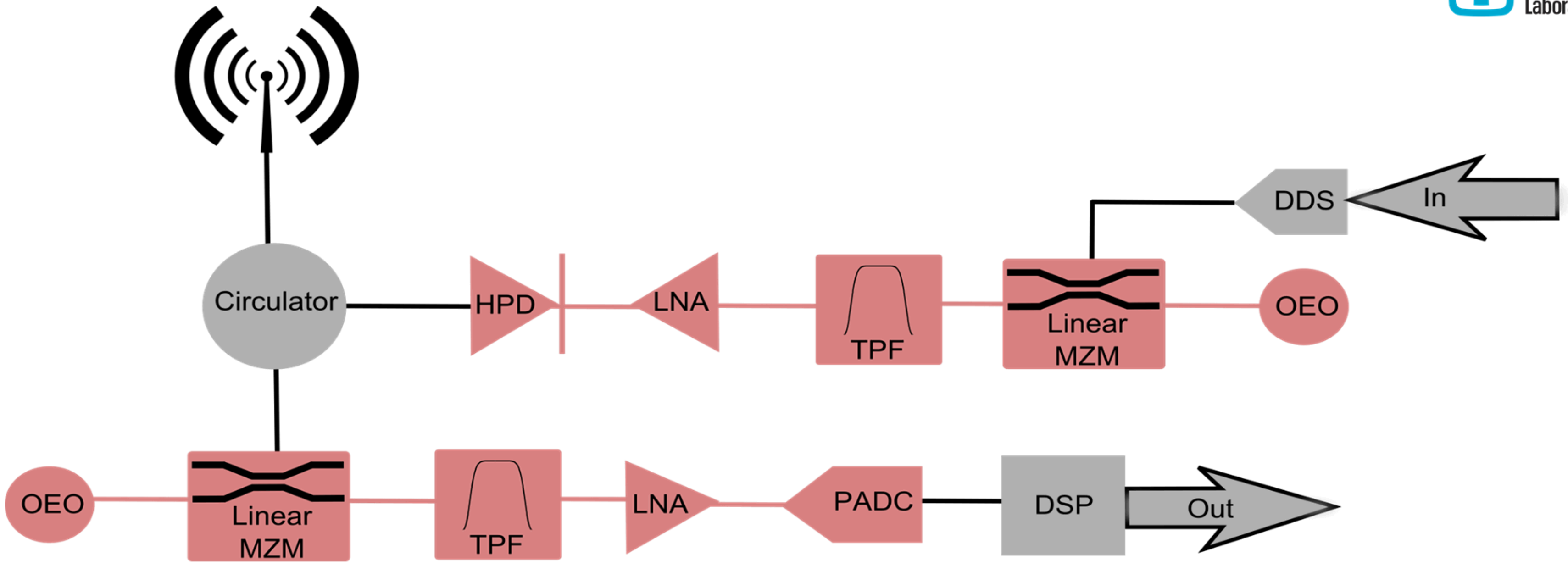
Support for NASA

Support for ballistic missile defense

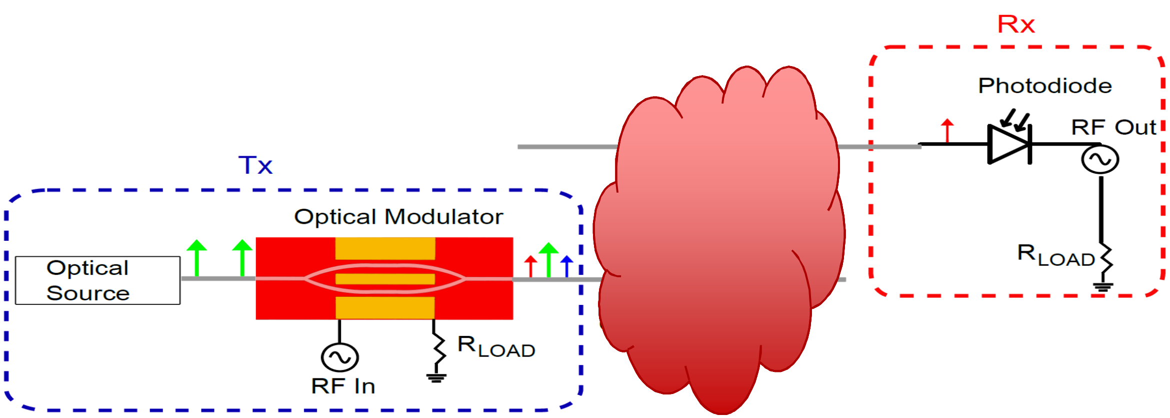
Ground sensors for future combat systems



Silicon Photonics Enabled Radar



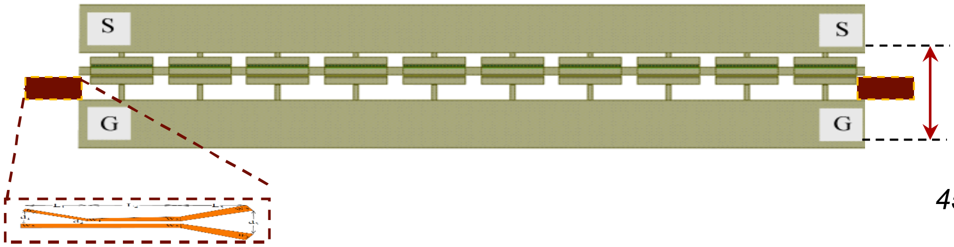
Photonic Enabled RADAR



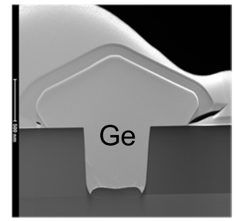
Hypothetical RF photonic functional system

Silicon Photonics at SNL

Broadband Mach-Zehnder

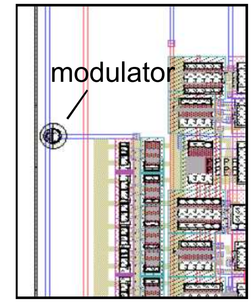


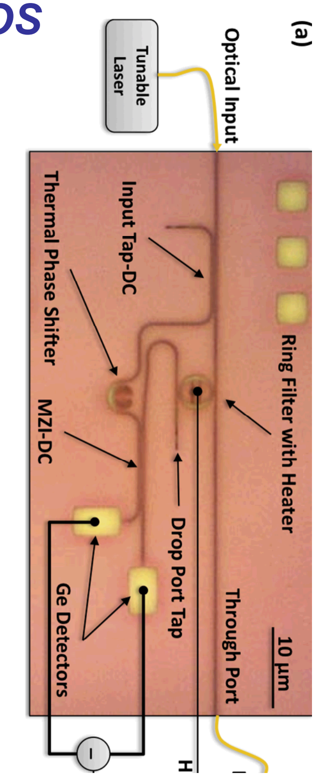
High-speed Ge Detector

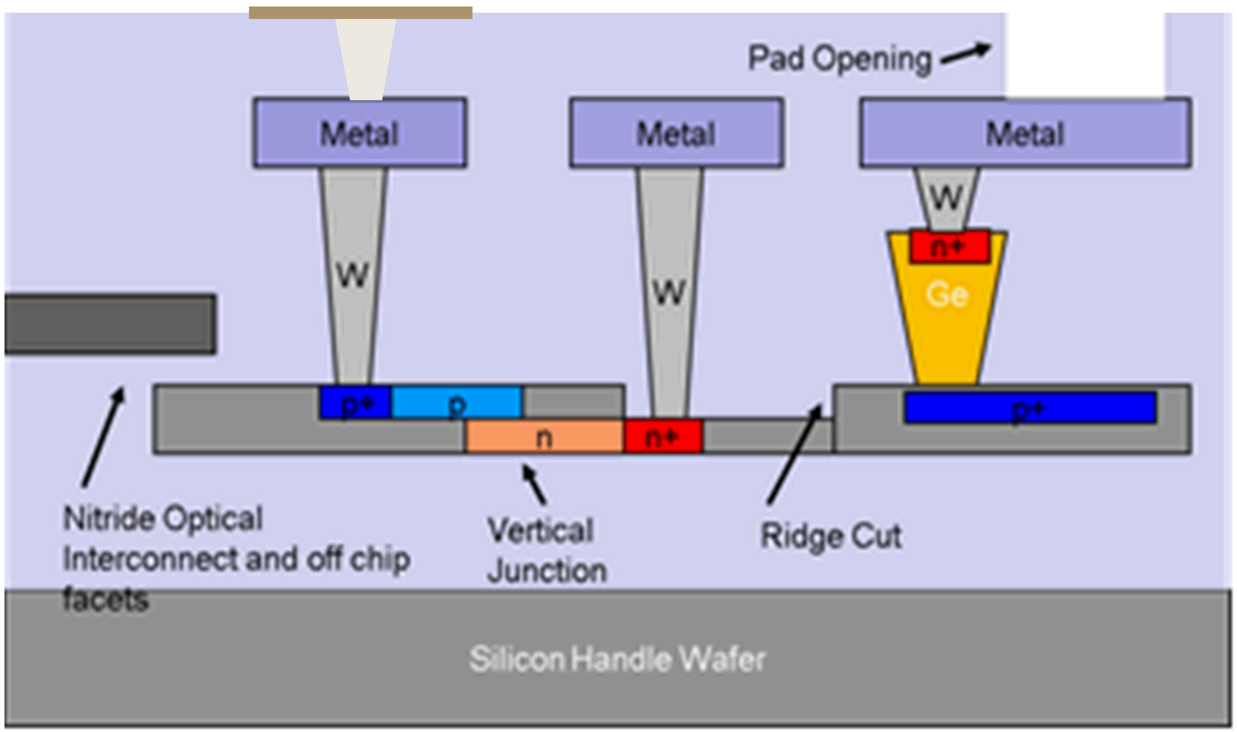


45GHz, 3nA dark current

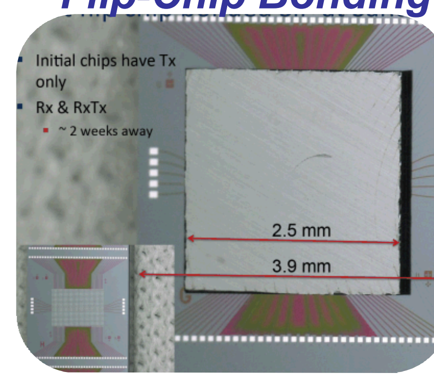
Photonics-CMOS Integration







Flip-Chip Bonding



Sandia's MESA Complex

Microsystems Design, Fabrication and Test

- Microfabrication
- Packaging
- Rad-Hard CMOS
- Si Micromachining
- III-V Semiconductors
- Silicon Photonics
- Nanotechnology
- Advanced Modeling
- Design
- Test & Characterization
- Failure Analysis

650 people
380,000 sq ft

III-V and Si Fabs

Part I: Modulators

TW Mach-Zehnder Modulator (MZM)

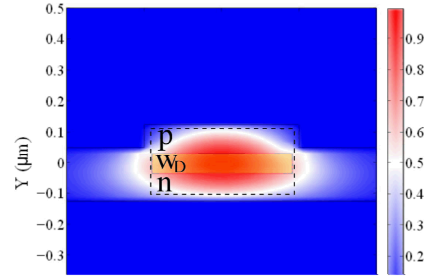
Problem: Require high speed low voltage MZM

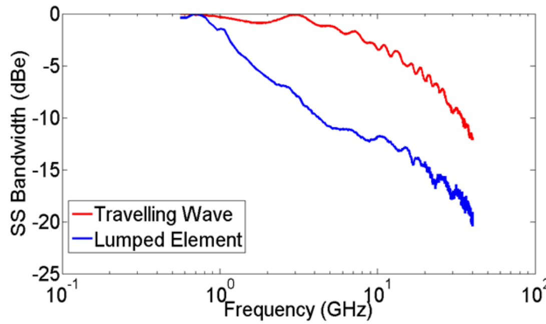
Solution: Capacitively loaded travelling wave design with vertical pn junction

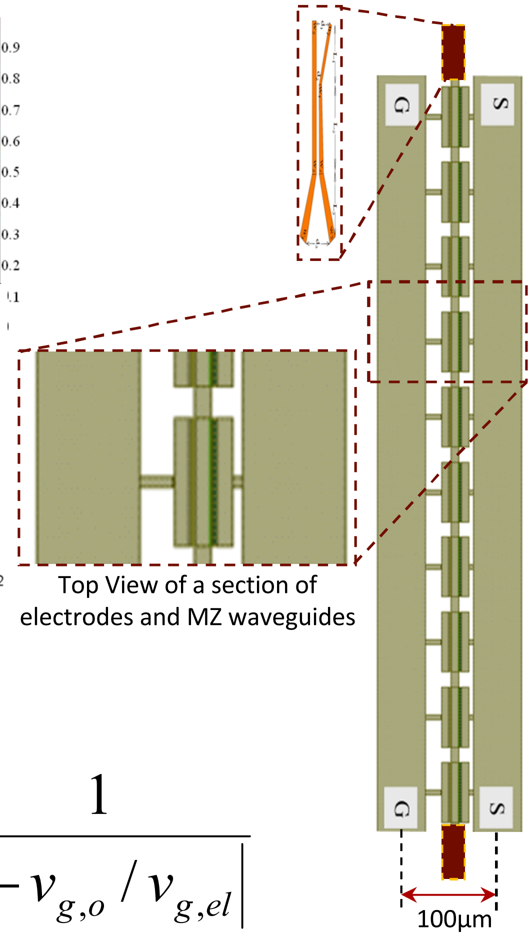
- Travelling wave design improves bandwidth
- Vertical junction enhances mode overlap

Results to Date:

- 23 GHz Bandwidth (0.5 mm device)
- V_π = 0.9 V (4mm device)

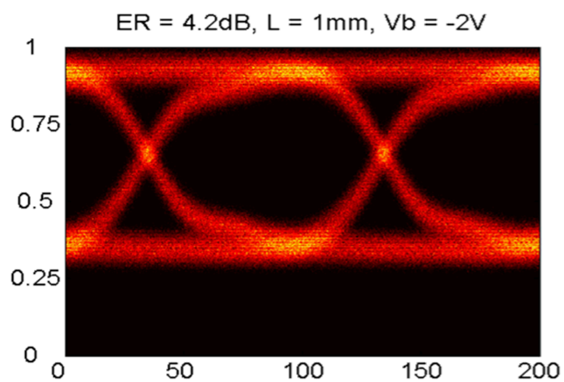






Top View of a section of electrodes and MZ waveguides

Traveling Wave Mach-Zehnder Modulator



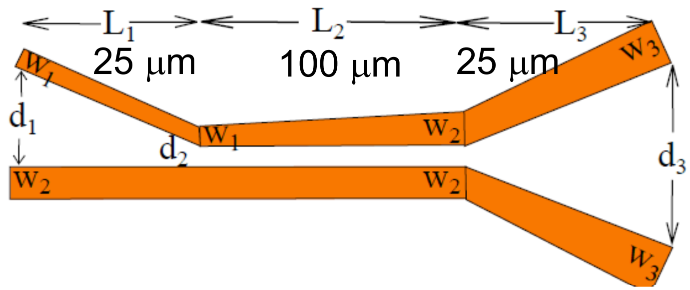
$$f_{3-dB} = \frac{0.5 v_{g,o}}{L} * \frac{1}{\left|1 - v_{g,o} / v_{g,el}\right|}$$

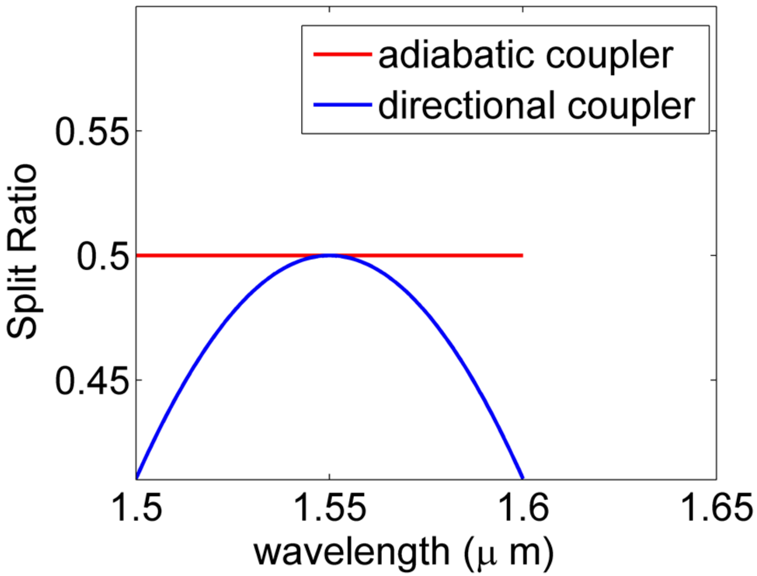
C.T. DeRose, et al. "High Speed Travelling wave carrier depletion silicon Mach-Zehnder modulator" OIC 2012

M.R. Watts, et al. "Compact Low Voltage Depletion Mode Modulators" JSTQE 2010

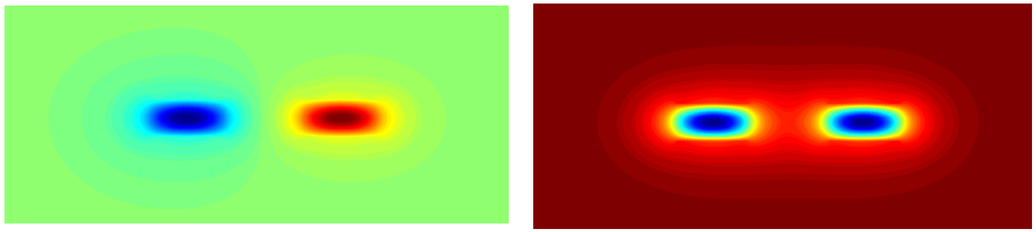
Adiabatic Coupler

Adiabatic 3-dB Splitter



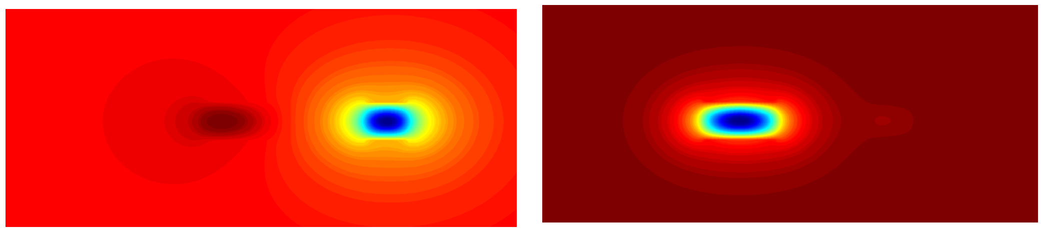


Symmetric Waveguide Coupling

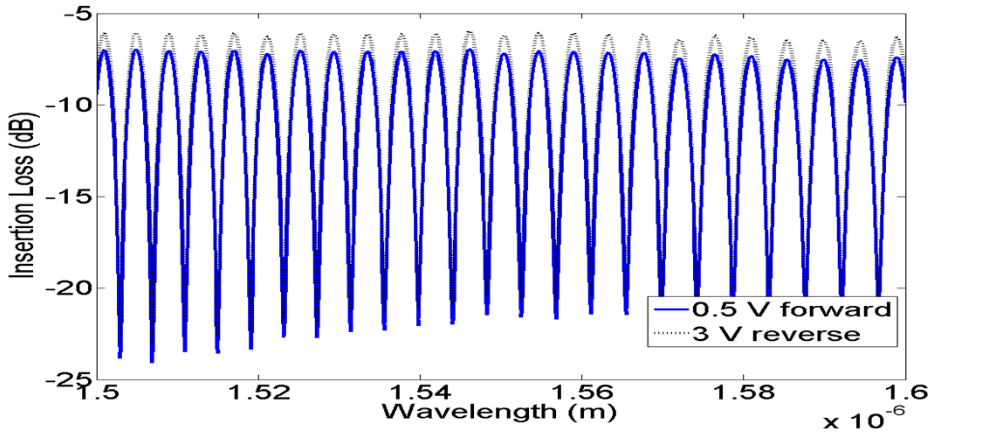


n_{eff} = 1.9745 n_{eff} = 1.9417

Asymmetric Waveguide Coupling

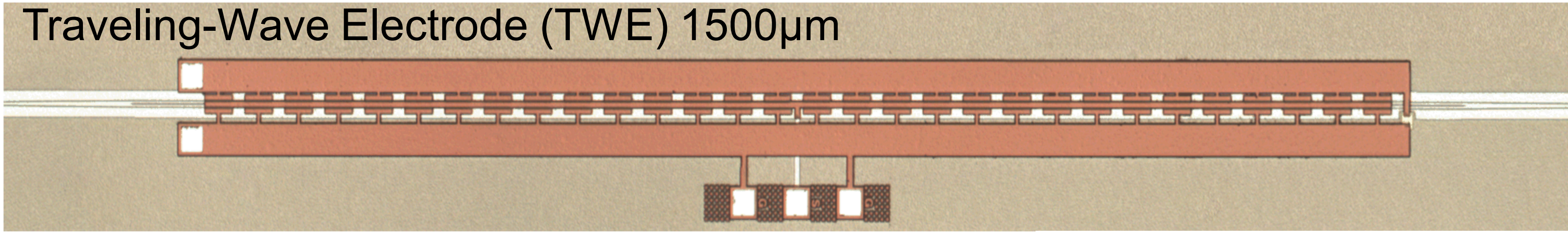


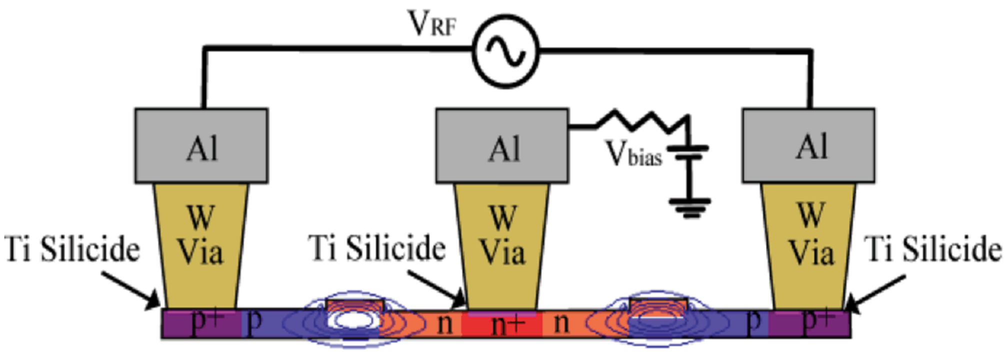
n_{eff} = 1.6248 n_{eff} = 1.9592

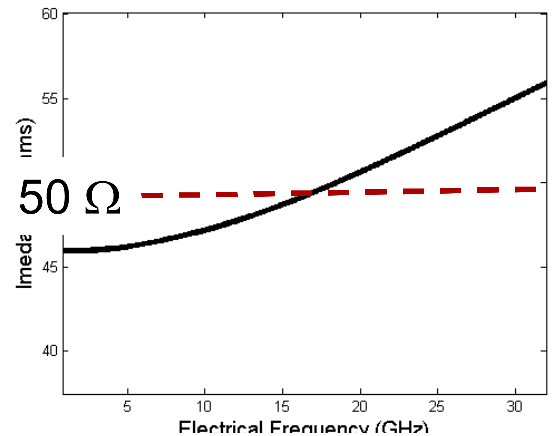


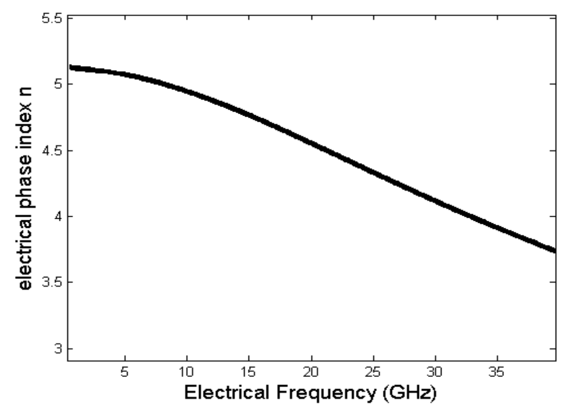
C.T. DeRose, M.R. Watts, et al., "Low Power 2X2 Thermo-Optic switch" OFC (2009)

Capacitively Loaded TW MZM







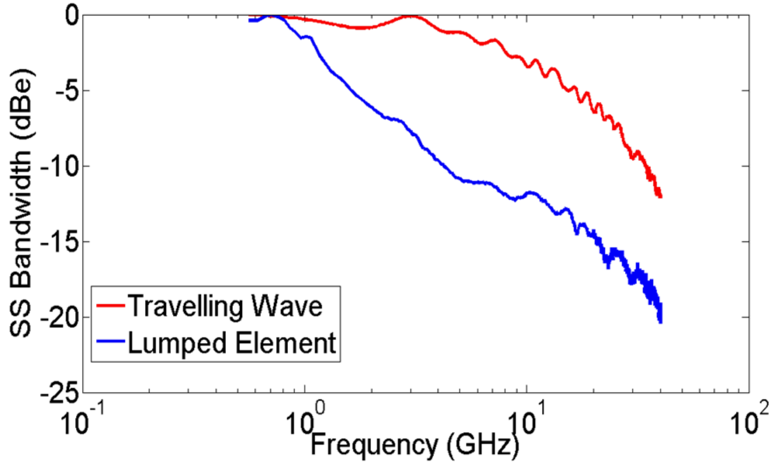


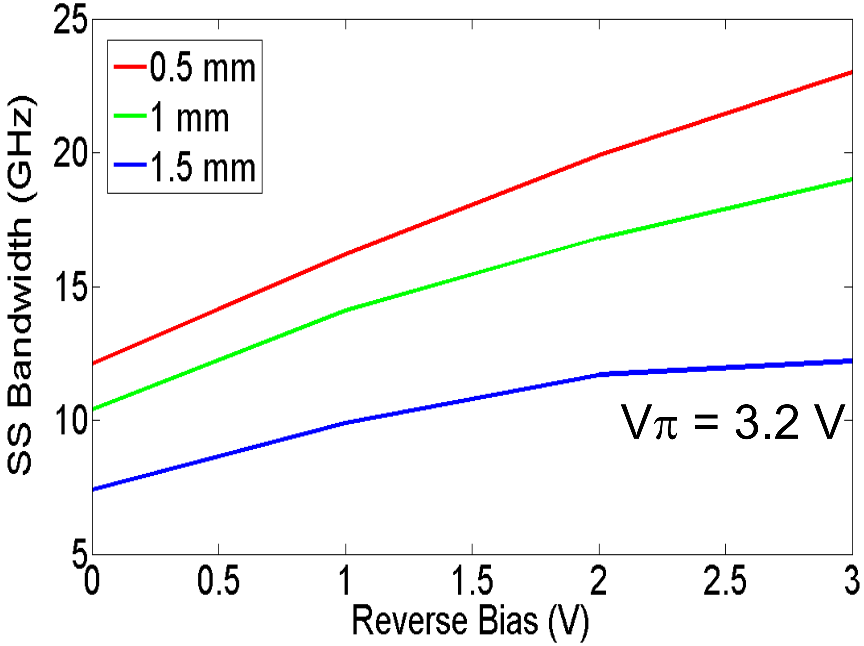
$$Z_0 = \sqrt{\frac{L_0}{C_0}} \qquad n_L = \sqrt{L_0(C_0 + C_L)}$$

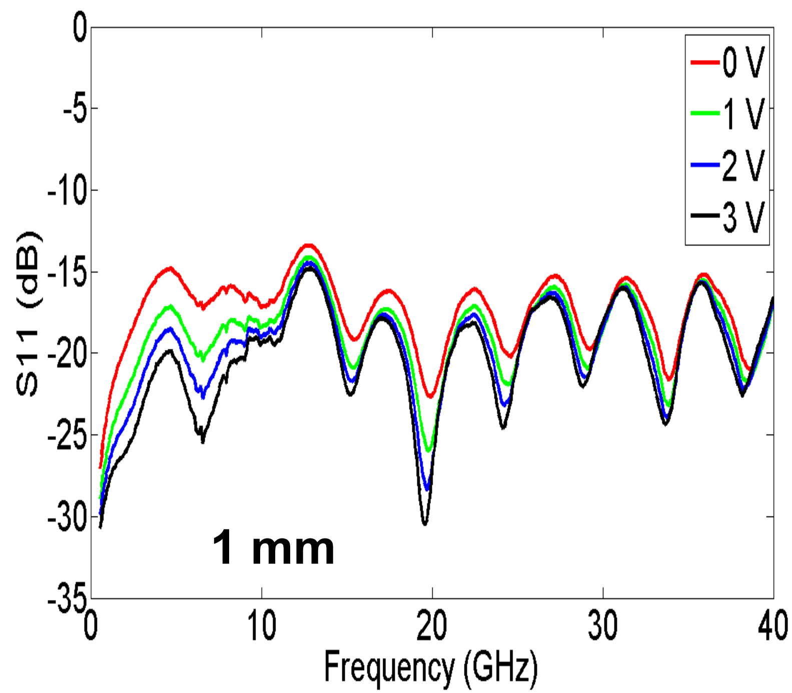
$$Z_L = \sqrt{\frac{L_0}{(C_0 + C_L)}}$$

Modulator RF characteristics

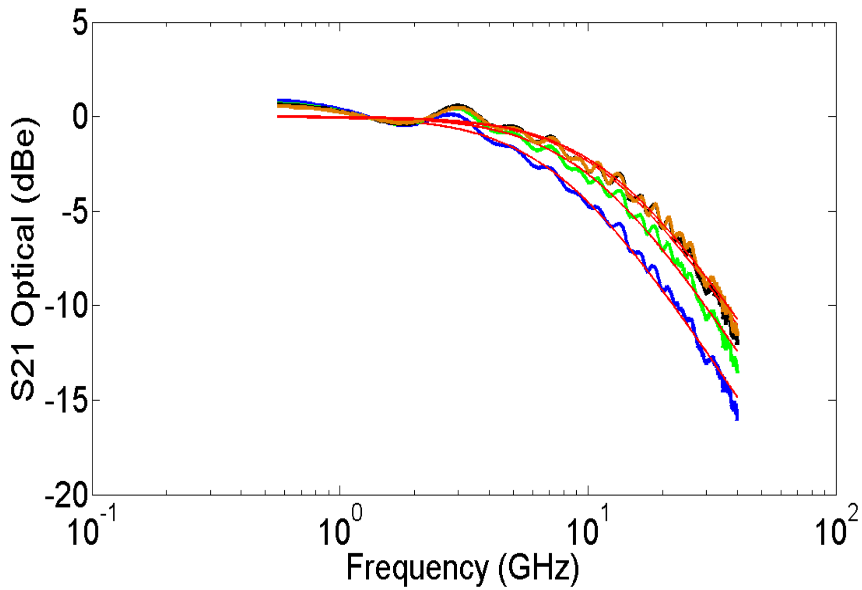
- Traveling wave design shows:
  - good impedance matching
  - enhanced bandwidth
  - low halfwave voltage operation

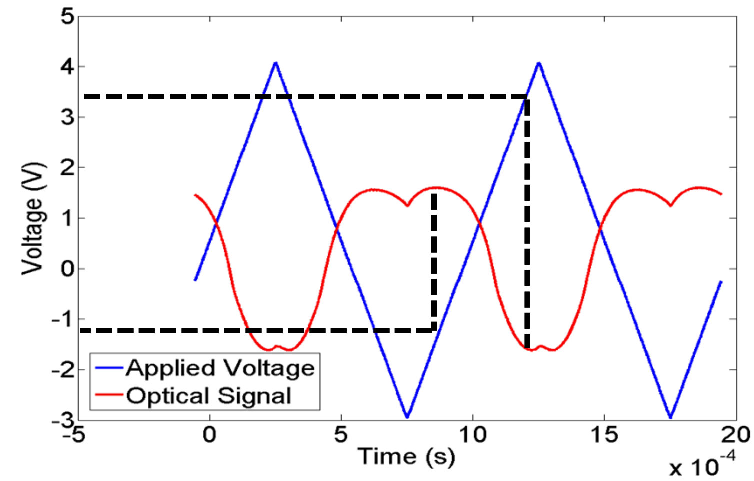






TW Modulator Performance



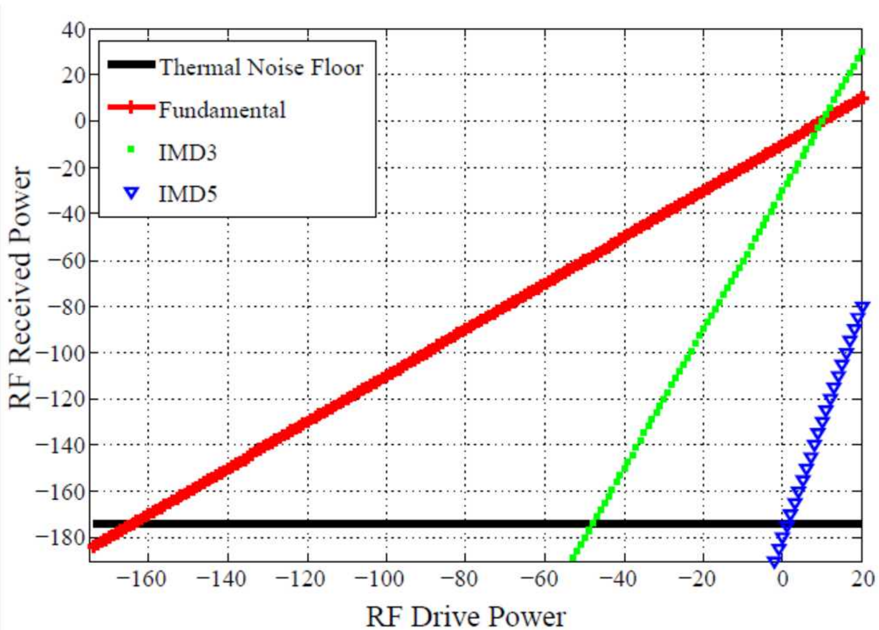


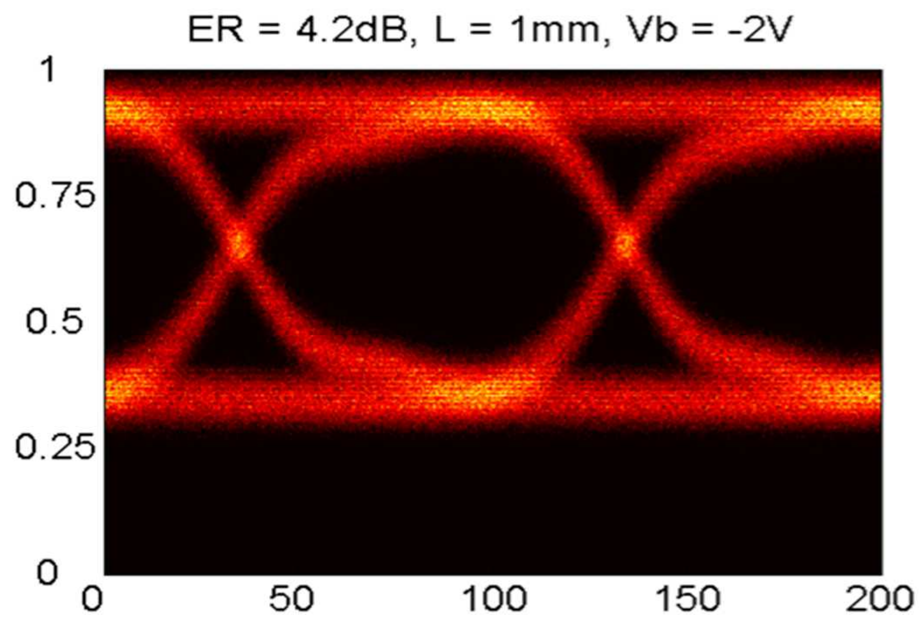
Bias Voltage	Insertion Loss	Extinction Ratio (3Vpp)	Vpi	Small Signal Bandwidth
0	7.9 dB	12.3 dB	3.2 V	7 GHz
-1	7.8 dB	9.3 dB	x	10 GHz
-2	7.6 dB	7.3 dB	x	12 GHz

Modulator requirements: Microwave vs. Digital

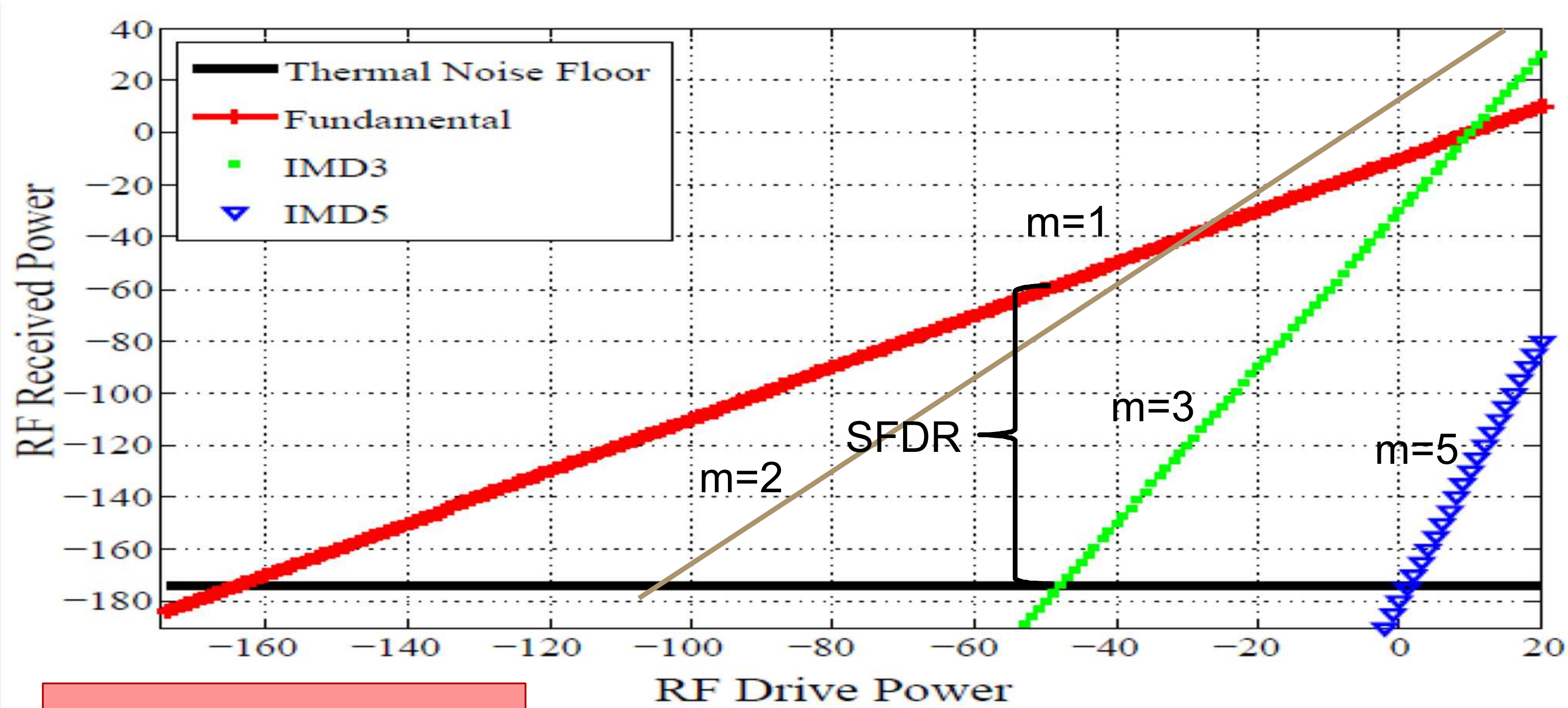
- High Dynamic range
- Low noise figure
- High Sensitivity
- High Bandwidth

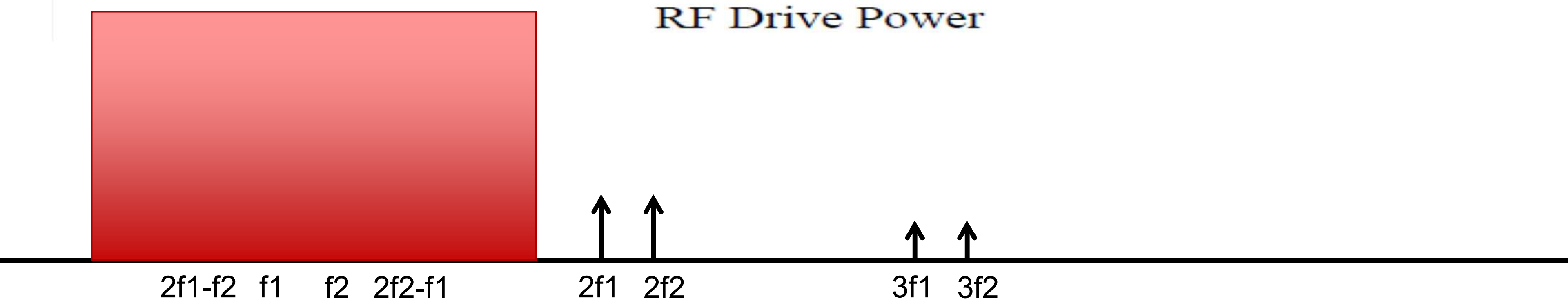
- Low Power
  - Forward Error Correction
  - Multiple bits per symbol
  - Just enough bandwidth





Spurious Free Dynamic Range (SFDR)





Intermodulation Distortion

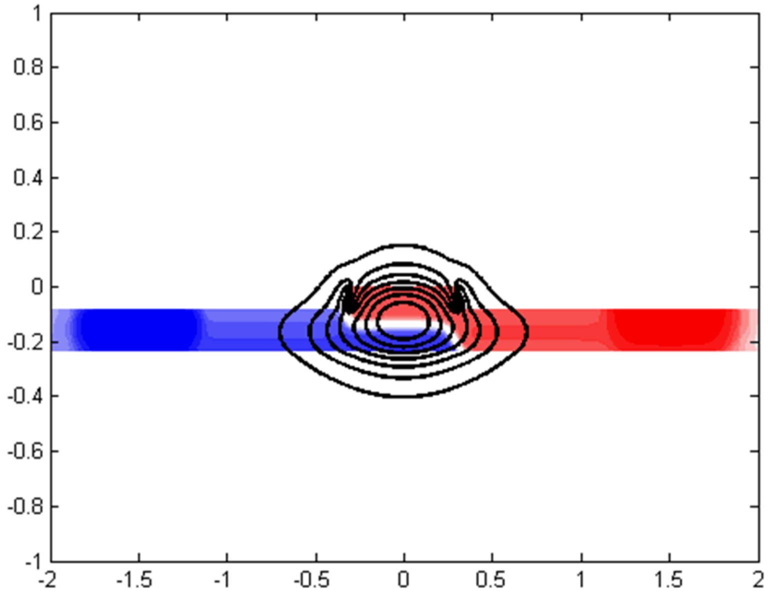
$$I(V) = I_0 \frac{1 + \cos\left(\frac{2\pi}{\lambda} n_{eff}(V_{RF}) L + \phi_0\right)}{2}$$

$$I(V) = I(V_0) + \frac{\partial I}{\partial x}\frac{\partial x}{\partial V} V_{RF} + \frac{1}{2}\left\{\frac{\partial^2 I}{\partial x^2}\left(\frac{\partial x}{\partial V}\right)^2 + \frac{\partial I}{\partial x}\frac{\partial^2 x}{\partial V^2}\right\} V_{RF}^2$$

$$+ \frac{1}{6}\left\{\frac{\partial^3 I}{\partial x^3}\left(\frac{\partial x}{\partial V}\right)^3 + 3\frac{\partial^2 I}{\partial x^2}\frac{\partial x}{\partial V}\frac{\partial^2 x}{\partial V^2} + \frac{\partial I}{\partial x}\frac{\partial^3 x}{\partial V^3}\right\} V_{RF}^3 + \ldots$$

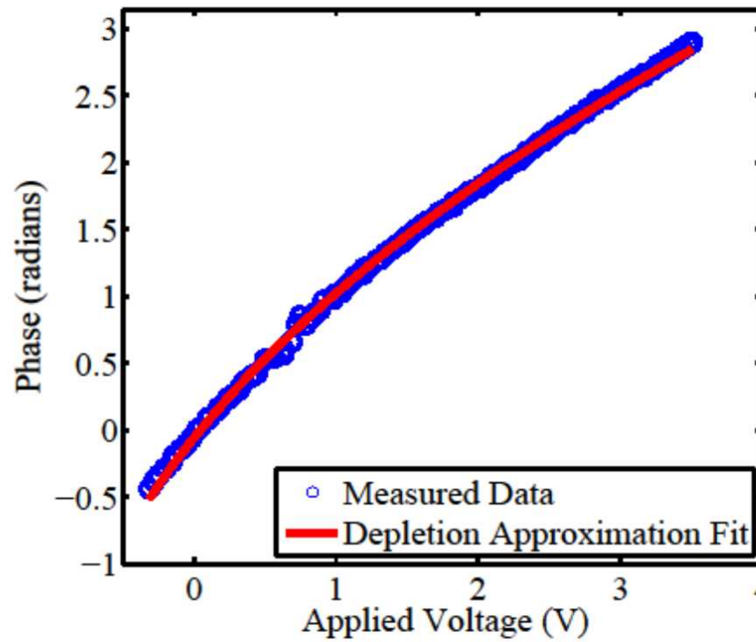
Would like to suppress this term for wide dynamic range operation

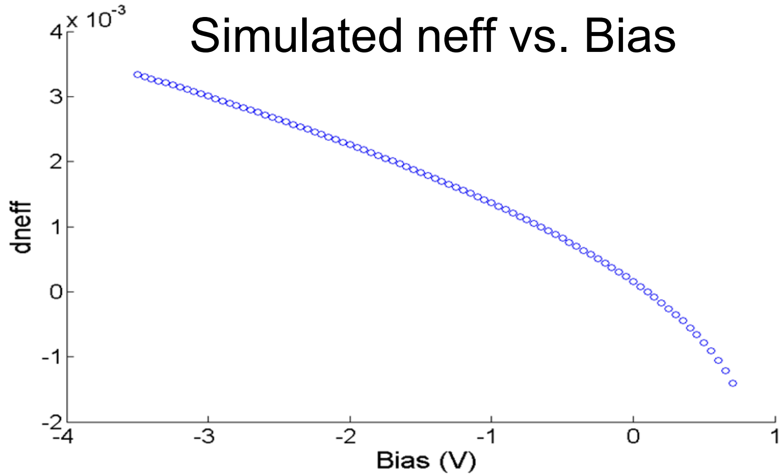
Nonlinear Phase Shift



$$\delta\beta = \frac{\omega n_g}{2c}\frac{\iint \Delta\varepsilon_{12}\left|E\right|^2 dA}{\left\langle E\middle|\varepsilon\middle|E\right\rangle}$$

Measured phase vs. bias

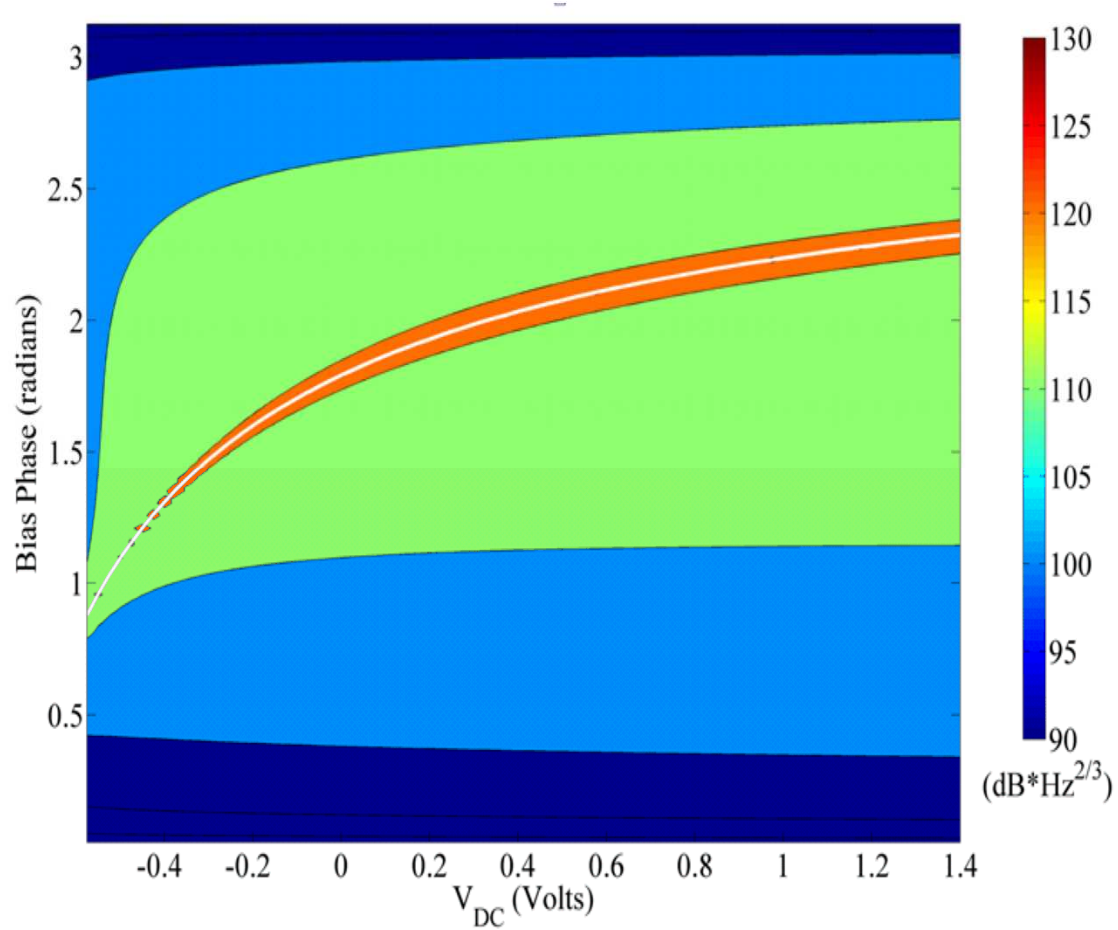




$$n_{eff}(V) = n_{eff,0} + r\sqrt{V + \phi_B}$$

Effect of nonlinear phase shift on modulator SFDR

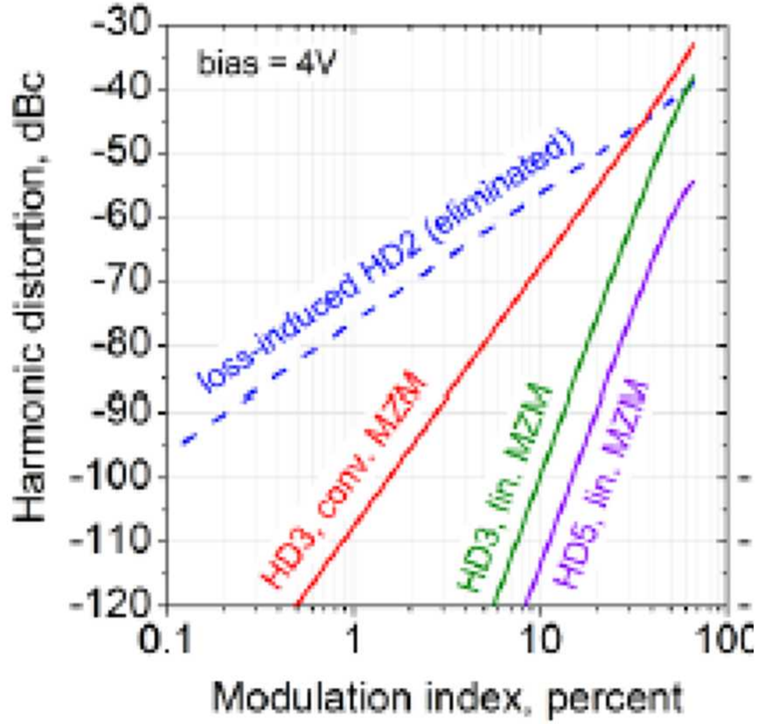
- IMD3 suppression possible
- SFDR depends on *both* bias phase and reverse bias voltage
- Wide range of 'good operation'
- Model does not include loss modulation
- Best operating point depends on other system parameters



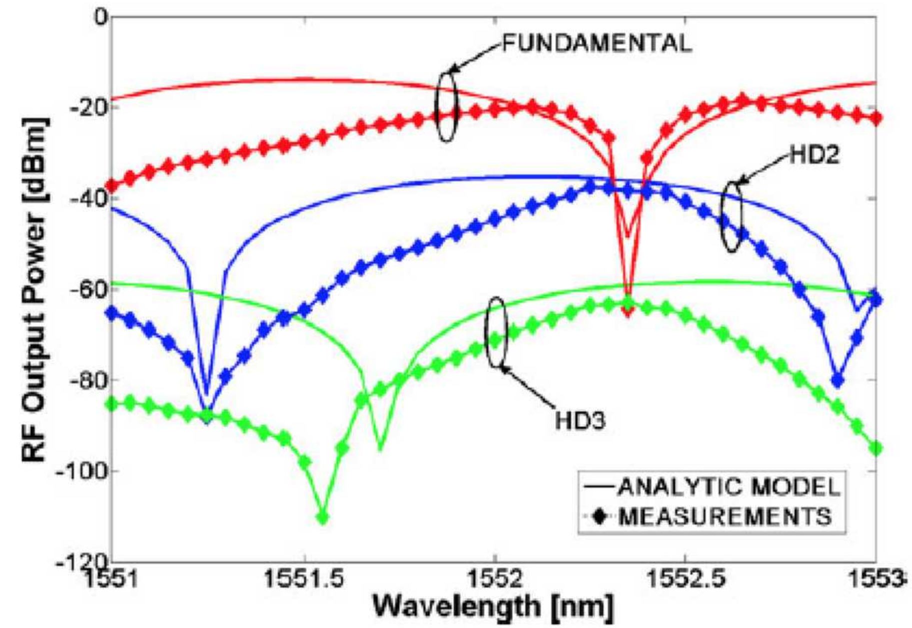
Calculated SFDR for 10 mW output power

Confirmation in the literature

[1]



[2]



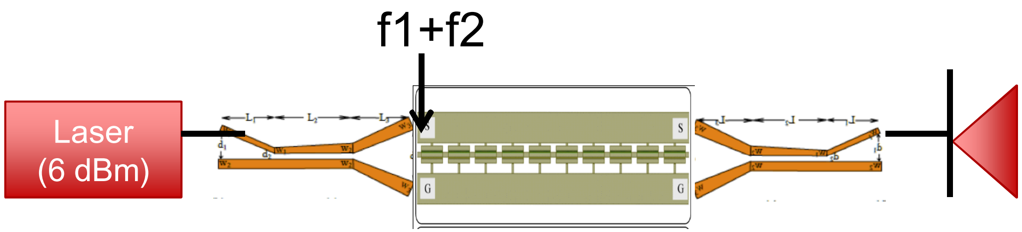
$$\phi(v) \sim \sqrt{v_{DC} + v}\ .$$

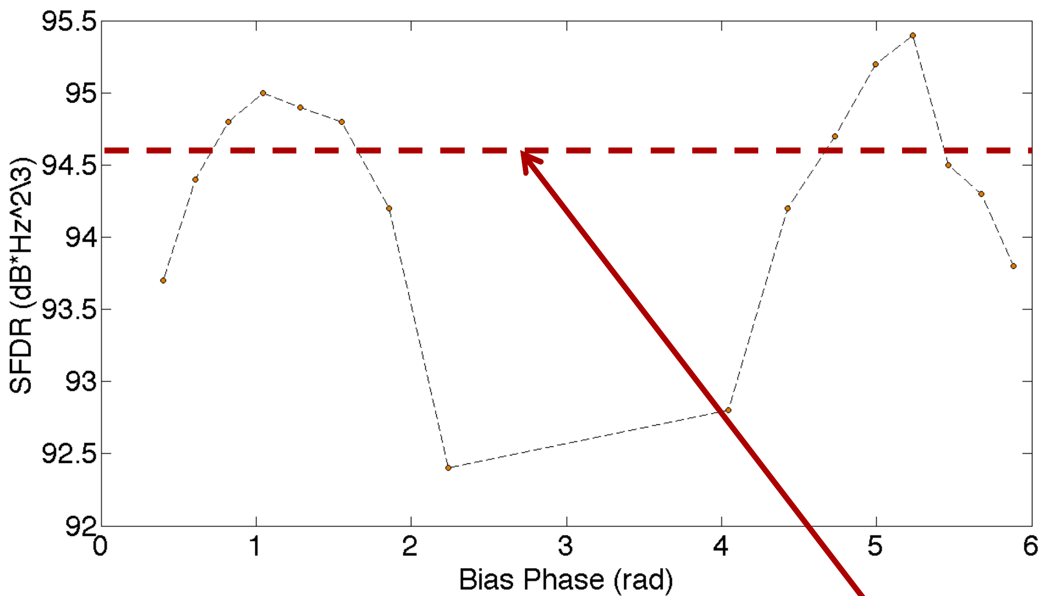
$$\Delta n_{\text{eff}} = k \ln\left(1 + \frac{V_{\text{app}}}{V_b}\right)$$

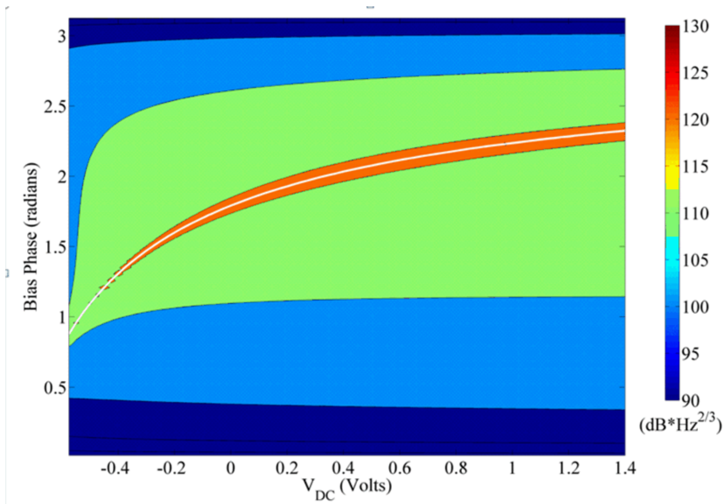
[1] A. Khilo, C.M. Sorace, and F.X. Kartner, "Broadband linearized silicon modulator" OPEX 4485 (2011)

[2] A.M. Gutierrez, A. Brimont, J. Herrera, M. Aamer, D.J. Thomson, F.Y. Gardes, G.T. Reed, J-M Fedeli and P. Sanchis "Analytical Model for Calculating the Nonlinear Distortion in Silicon-Based Electro-Optic Mach-Zehnder Modulators" JLT 3603 (2013)

SFDR measured results





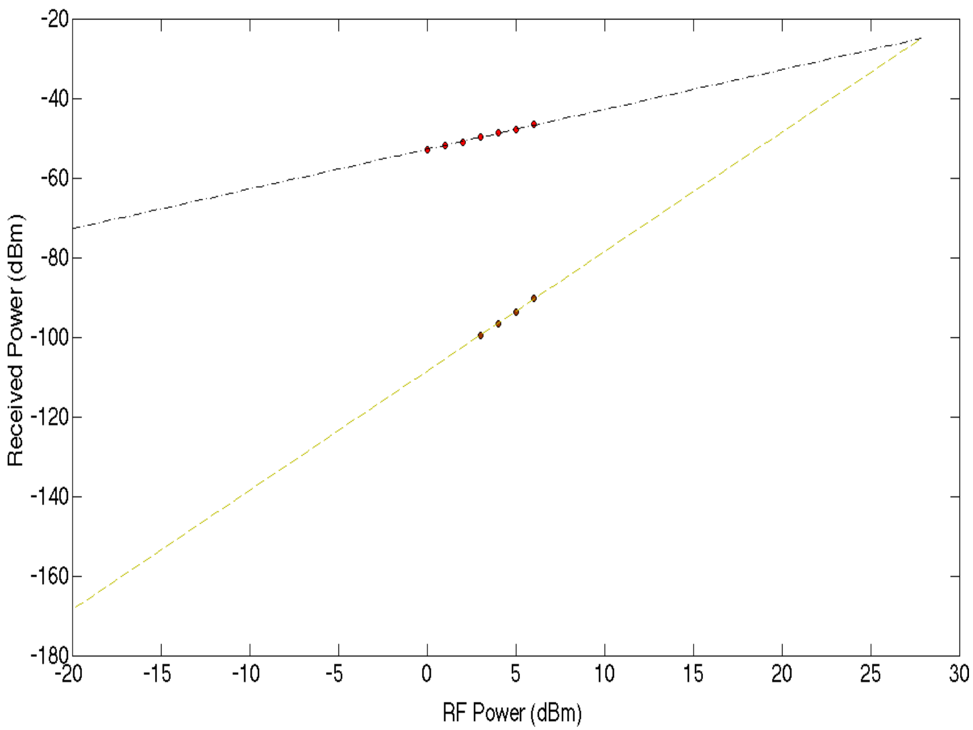


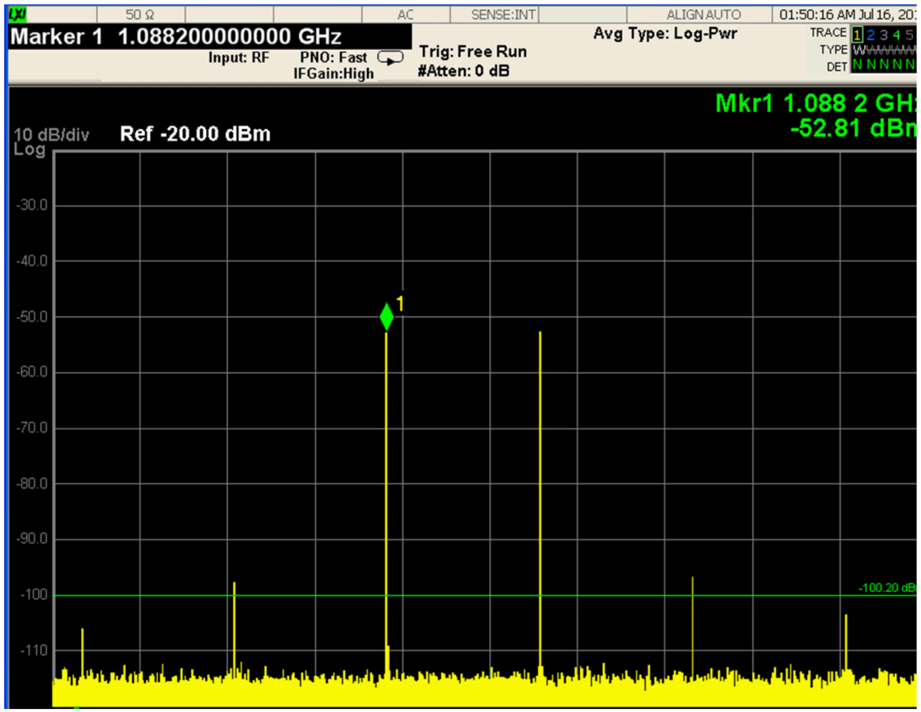
- 1mm travelling wave modulator
- 1 Volt reverse bias
- 7 dB insertion Loss
- 0.5 mA peak photocurrent
- within 2 dB of best reported si MZM result [3]

10 Gbps, 5V commercial LiNbO3 biased at quadrature measured with the same peak photocurrent!

[3] M. Streshinsky, et al., “Highly linear silicon traveling wave Mach-Zehnder carrier depletion modulator based on differential drive” OPEX 3818 (2013)

SFDR measured results





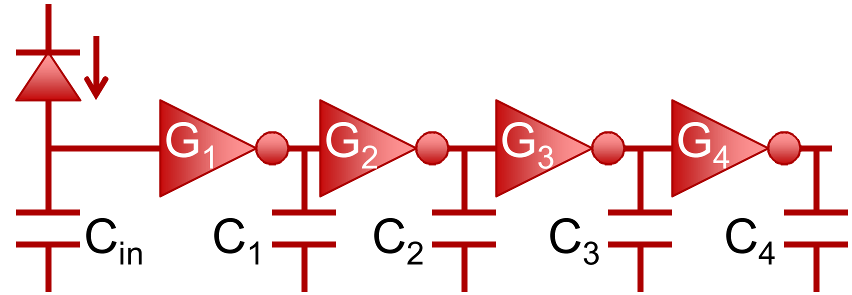
Measured points on RF spectrum analyzer then fit with lines of slope m=1 and m=3. OIP3 intercept is found and SFDR is calculated from measured noise floor or -166 dBm/Hz.

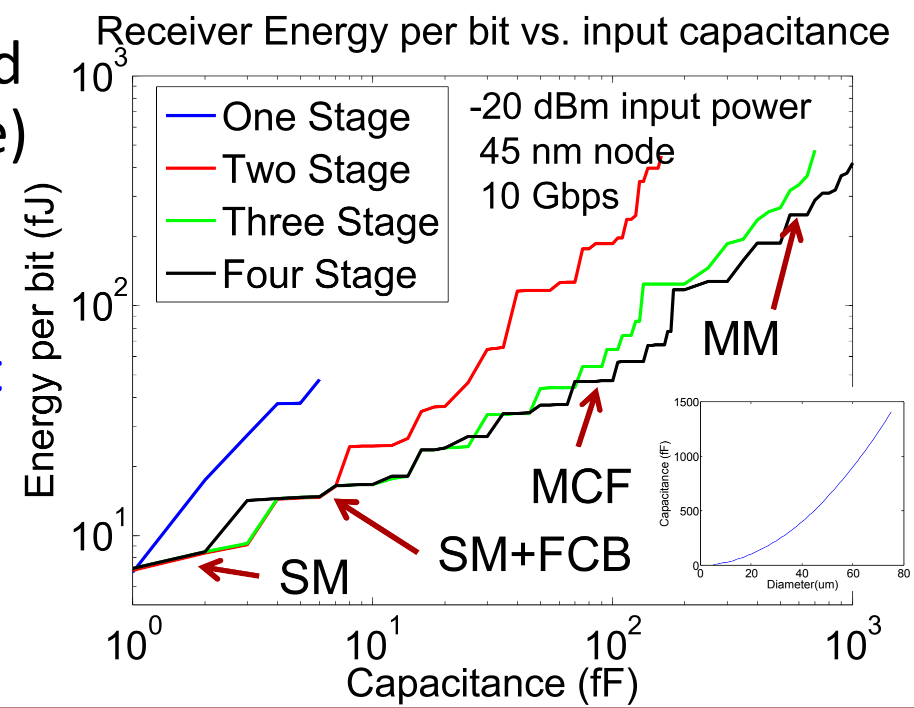
Did not observe complete suppression of IMD3 saw evidence in one case that IMD5 could become limiting distortion in SFDR

Part II: Photodiodes

Detectors for digital communications: Rx energy/bit vs. input capacitance

- No previous analysis comparing Rx power to receiver capacitance for multistage receivers
- Existing analyses comparing technologies focus on transmit power
- Receiver power greatly influenced by input capacitance (fiber choice)
- Analysis here is over simplified, provides lower bound
- Uses gain stage chains: i = CdV/dt
  - Current/Capacitance Ratio (f_T)
  - Gain (Constant gain-bandwidth)
  - Sizing (Drive capability)

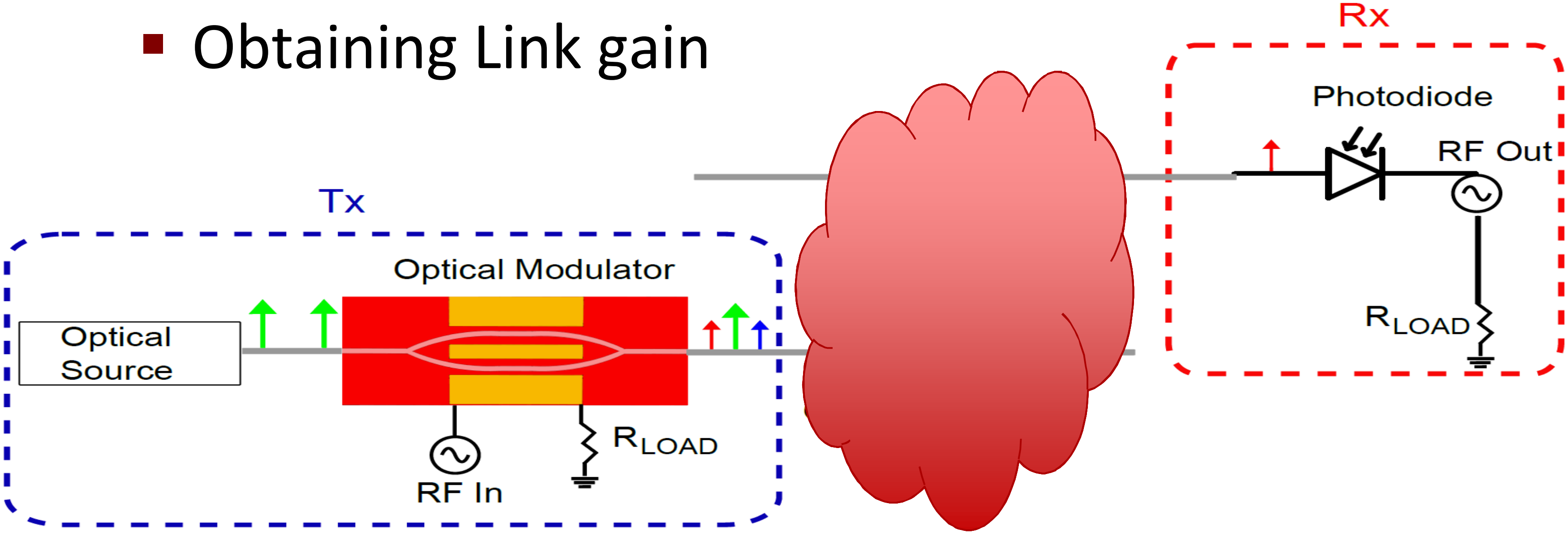




* calculation courtesy of A.L. Lentine

Detector requirements for RF

- Require as much photocurrent as possible for:
  - Improved dynamic range
  - Low noise figure
    - Working in the quantum limited noise regime
  - Obtaining Link gain

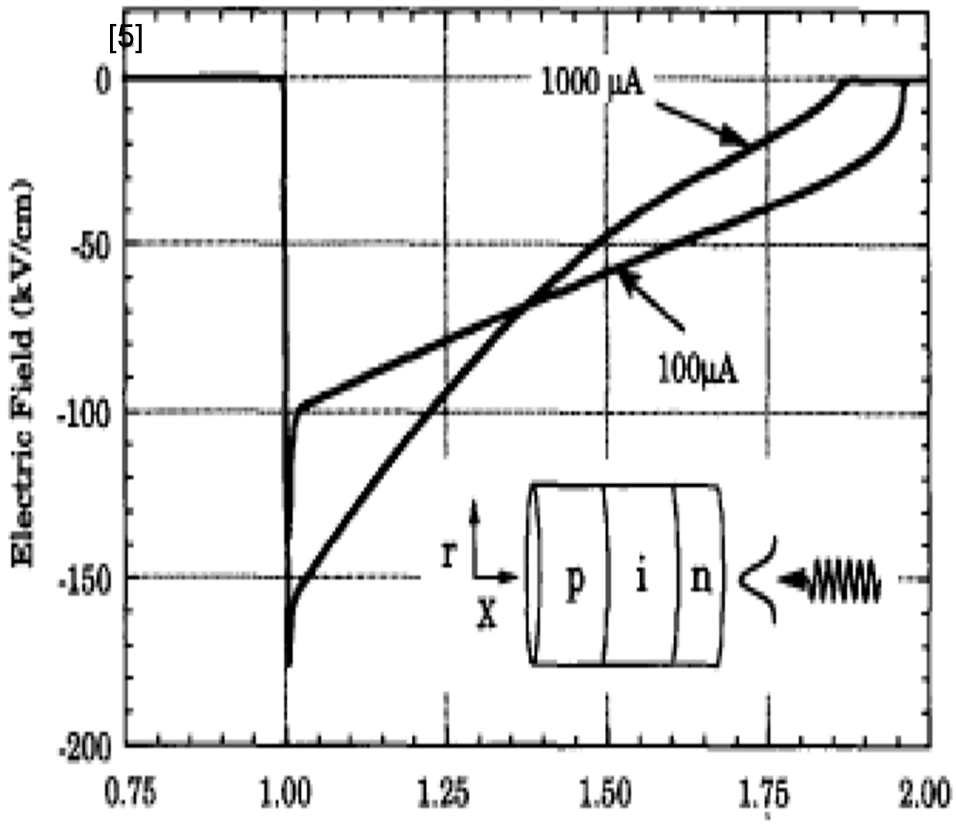


Nonlinearities in detectors

- Carrier screening effects
- Thermal runaway
- Series impedance effects
- Effects are all dependent

on carrier densities. Can be partially mitigated with nove detector structures.

[5]



[5] K.J. Williams, et al., "Effects of high space-charge fields on the properties of microwave photodetectors" PTL (1994)

Ge in Modern CMOS

Germanium old semiconductor technology.

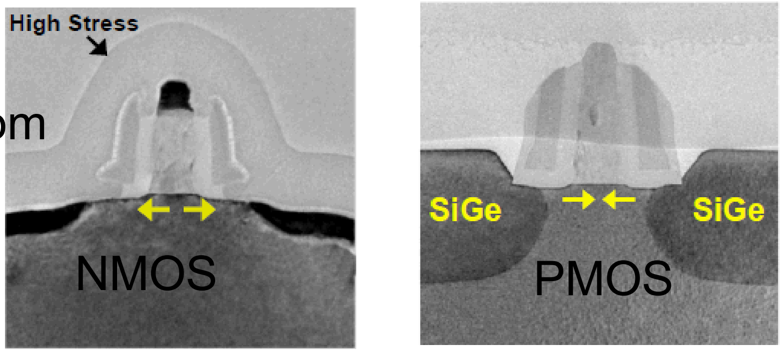
- Indirect Bandgap at 0.66 eV.
- Direct Bandgap at 0.8 eV (1550 nm) in telecom band.
- Not efficient optical emitter.

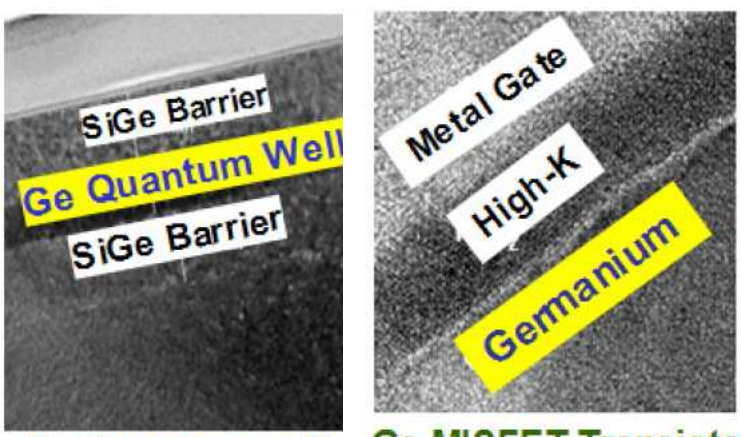
Selective epitaxial growth of Ge on Si has enabled advanced strain engineering in modern CMOS.
Fully CMOS Compatible.
High electron and hole mobilities.

Ge optoelectronics: direct bandgap at 1550nm implies good absorption.

Strain engineering in CMOS

Intel 45nm



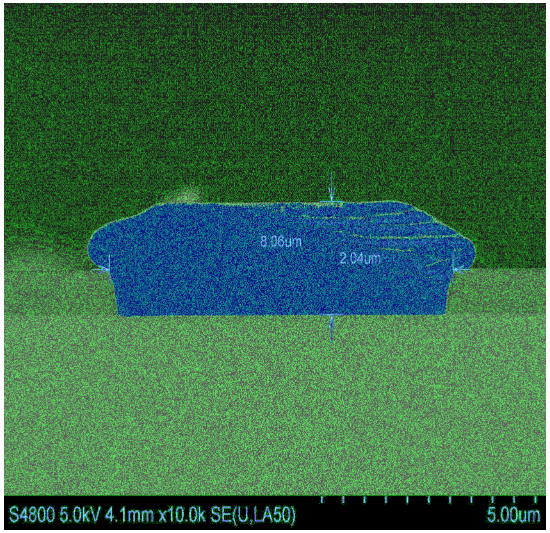


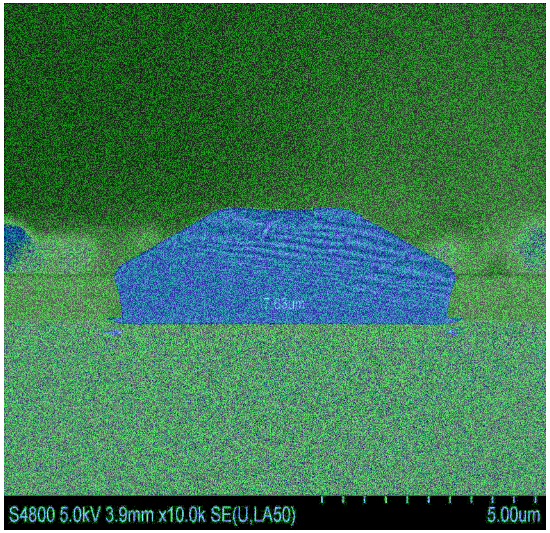
Ge Quantum-well Ge MISFET Transistor

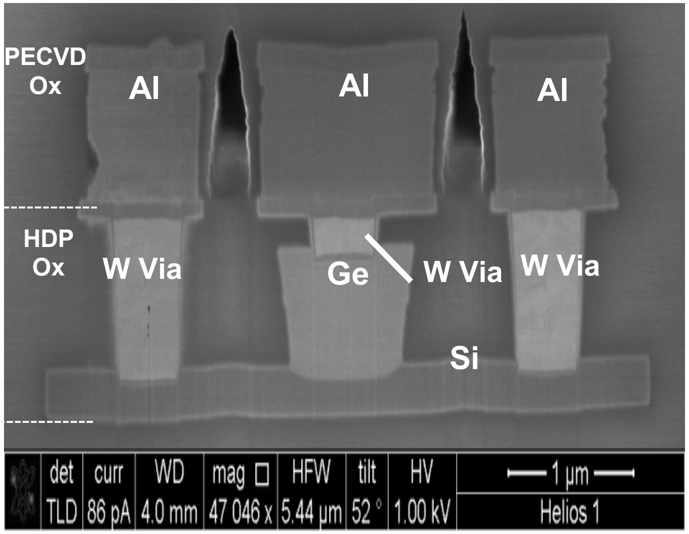
Sources: (1) ESSDERC 2008, (2) www.intel.com/silicon research/R&D pipeline

Selective Area Growth

- All silicon processing and high temperature anneals are performed first
- Trench opened in oxide
- Germanium epitaxy with low fill factors occurs in oxide window
- Epitaxy conditions designed to allow lateral overgrowth
- Germanium CMP and planar processing continue



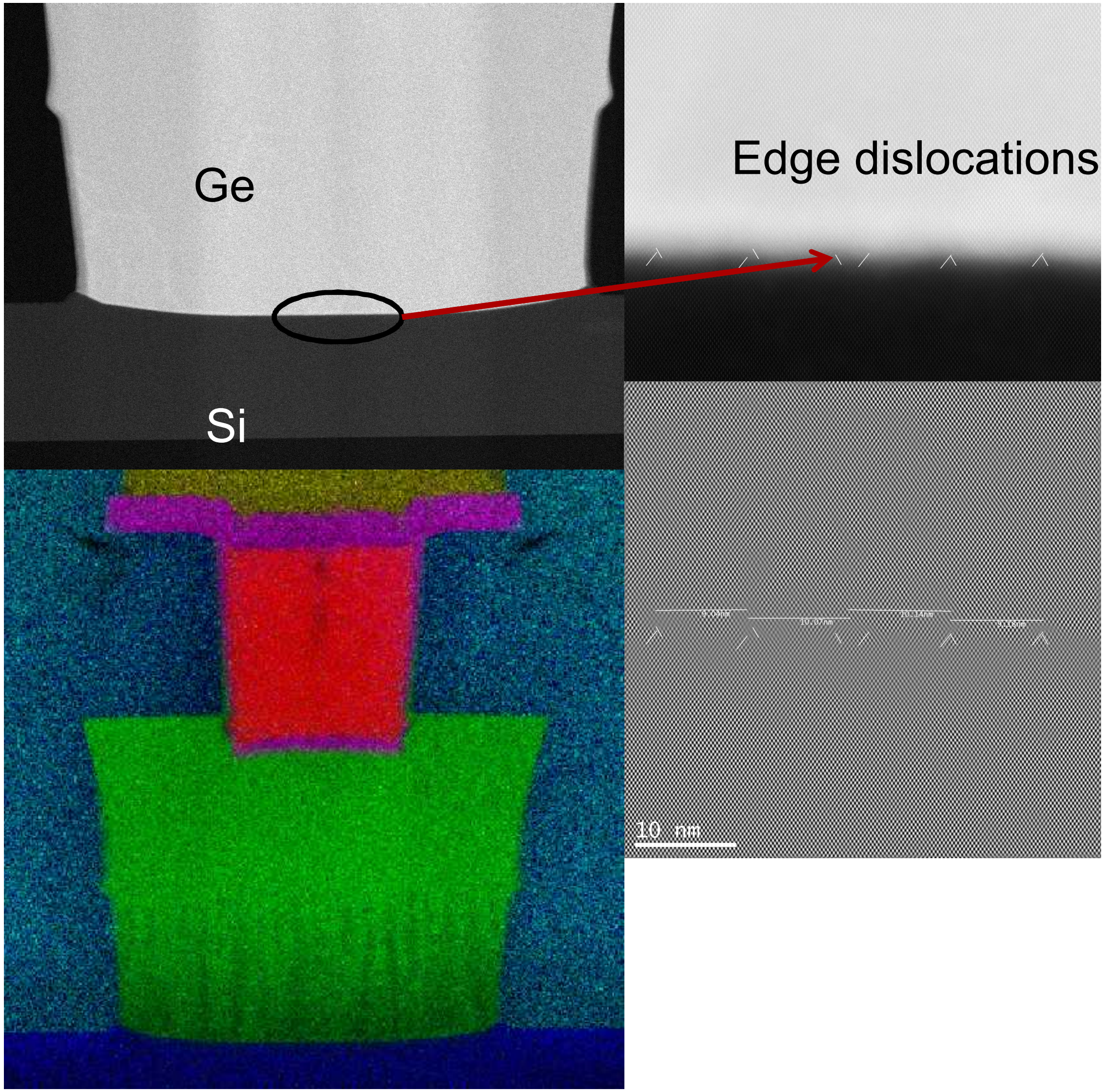




Low Dark Current Detection

- Our Selective Ge on Si gives low defect count at Si/Ge interface.
- Leverages CMOS compatible processing
- Apply analytic tools to reduce defects at interface.
  - Very low threading dislocations.
- Selective growth enables aspect ratio trapping

Our Ge device



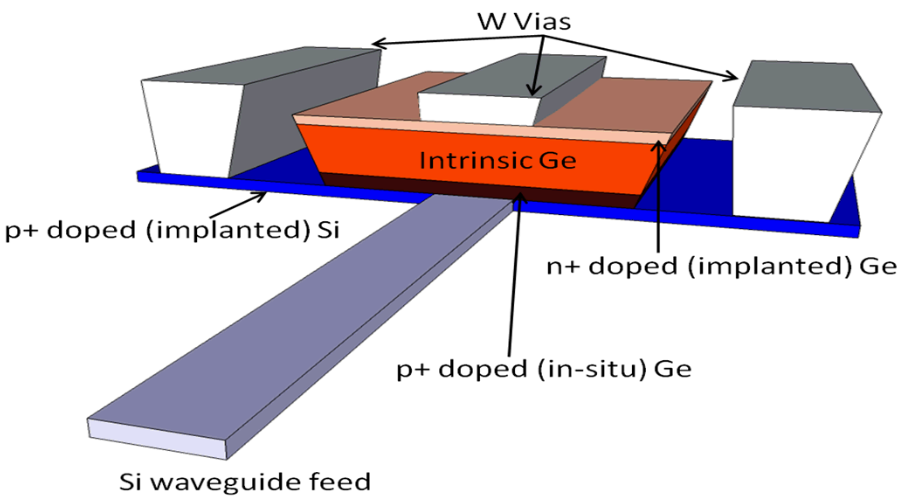
Digital Germanium Optoelectronics

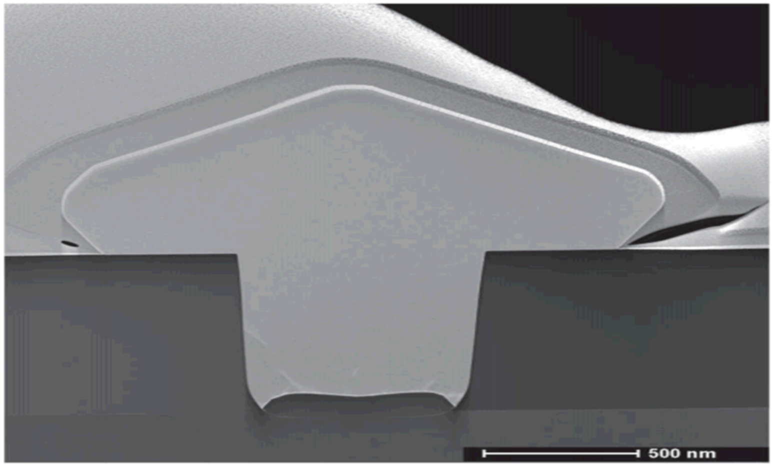
Applications: Low power receivers for data communications

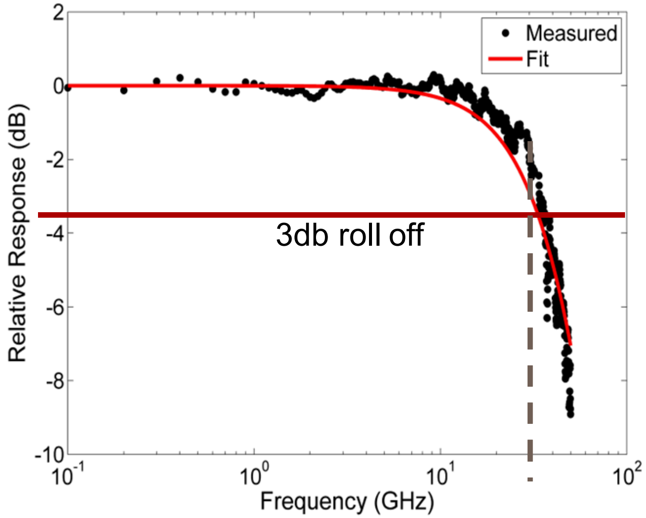
Accomplishments:

Demonstrated CMOS compatible Ge photodiode with

- Record low capacitance (~1 fF)
- Best-in-class dark current (3 nA)
- Best-in-class bandwidth (45 GHz)
- High responsivity (0.8 A/W)
- Small footprint (1.3μm x 4.0μm)
- High-power detector designs next



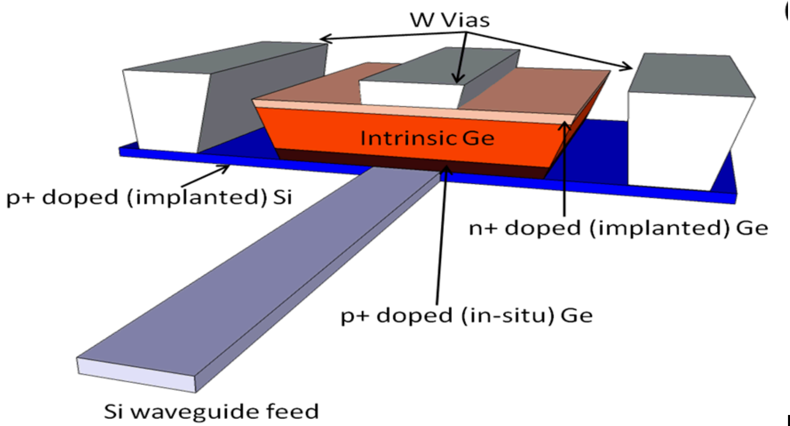


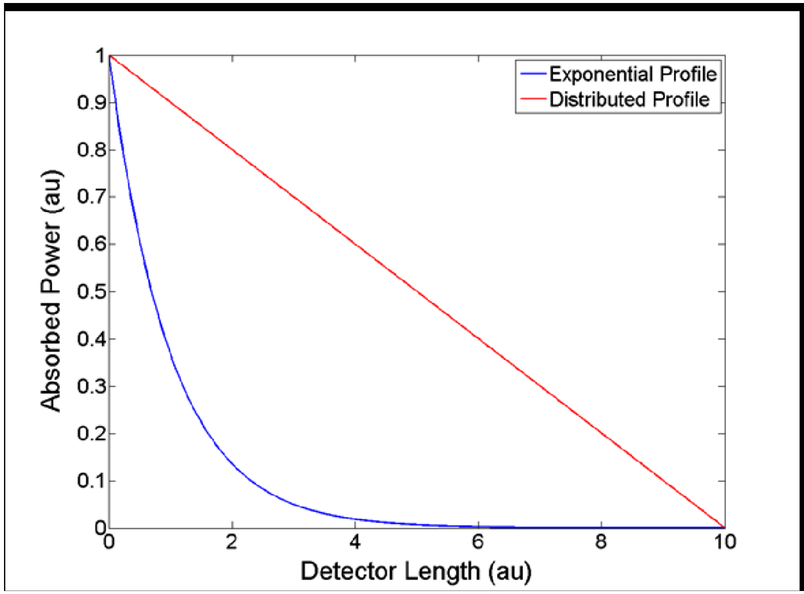


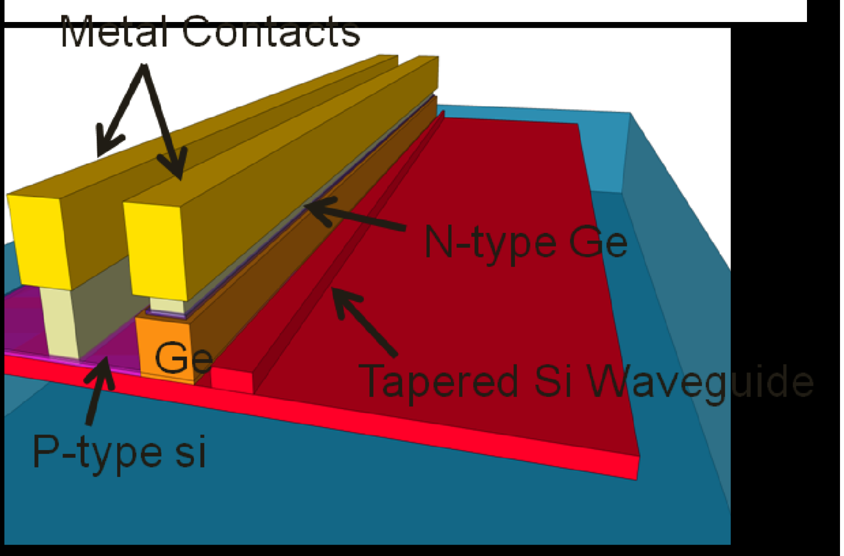
C.T. DeRose, et. al., OPEX, 19, pp. 24897-24904 (2011)

Distributed absorption Ge photodiode

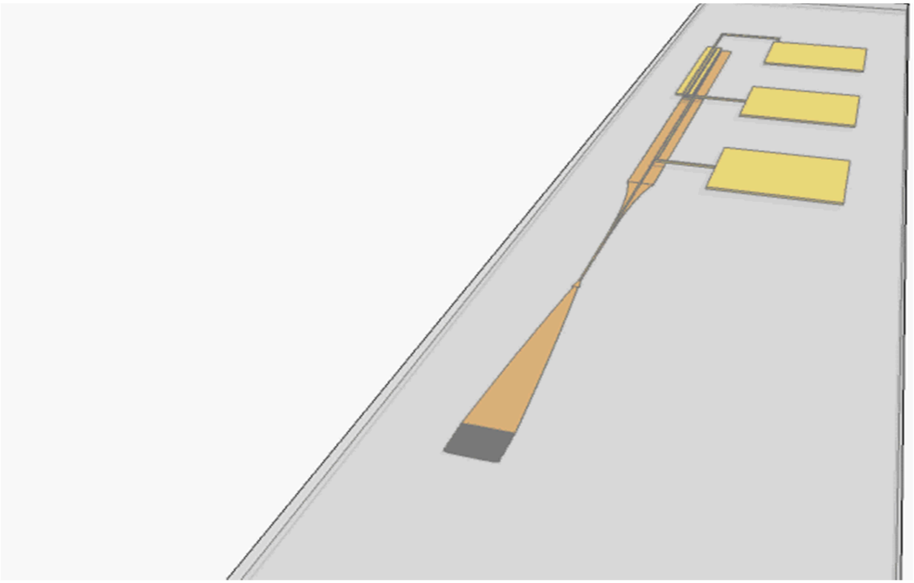
- Desire a linear absorption profile to minimize localized high carrier densities
- Selective area growth eliminates typical III-V designs
- Use tapered coupler structure

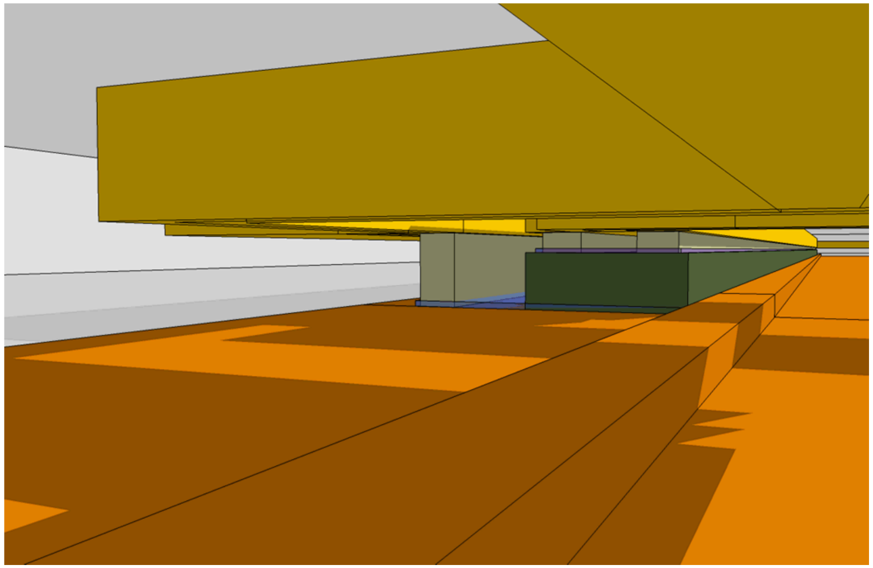




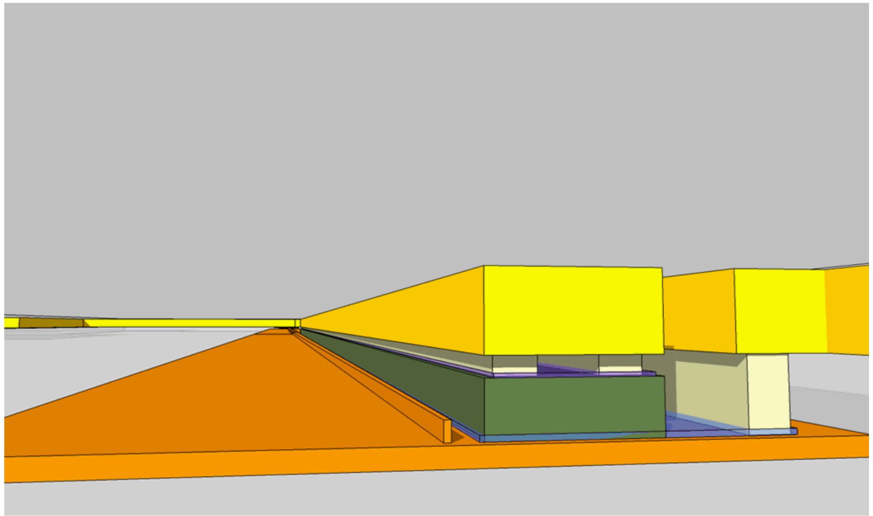


Distributed absorption Ge photodiode

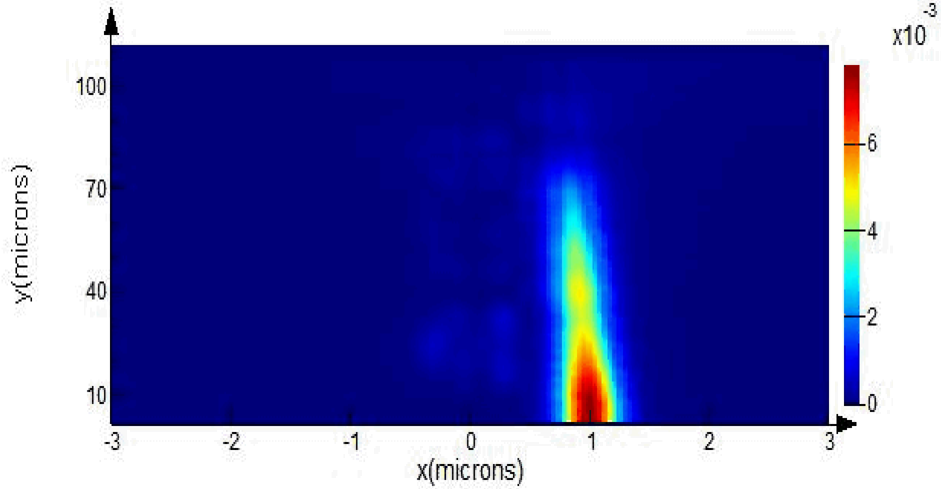




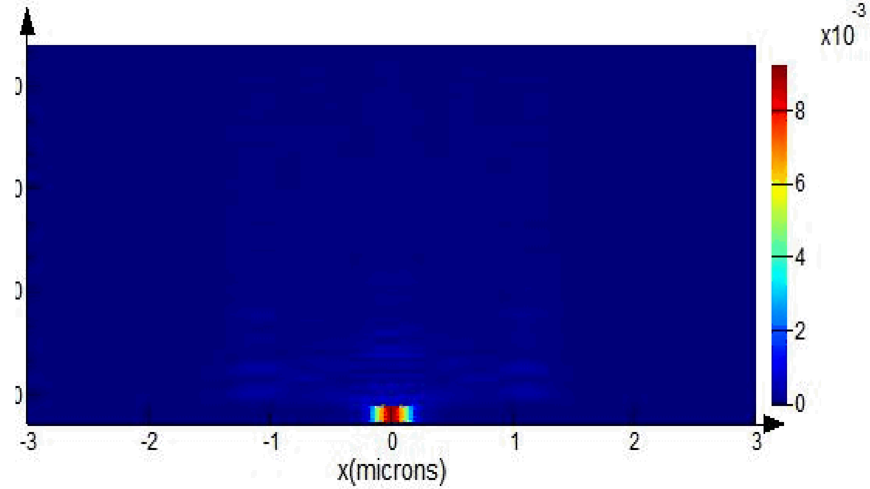
- Nonadiabatic transfer of power to Ge waveguide structure
- Requires growth on partially etched silicon for fabrication
- Gap = 350 nm, Width = 2um, Thickness = 700 nm



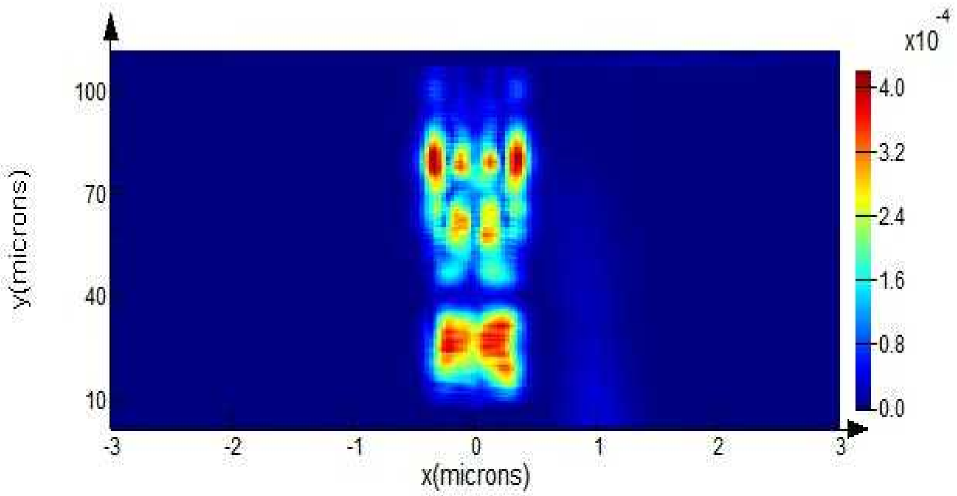
FDTD Simulations



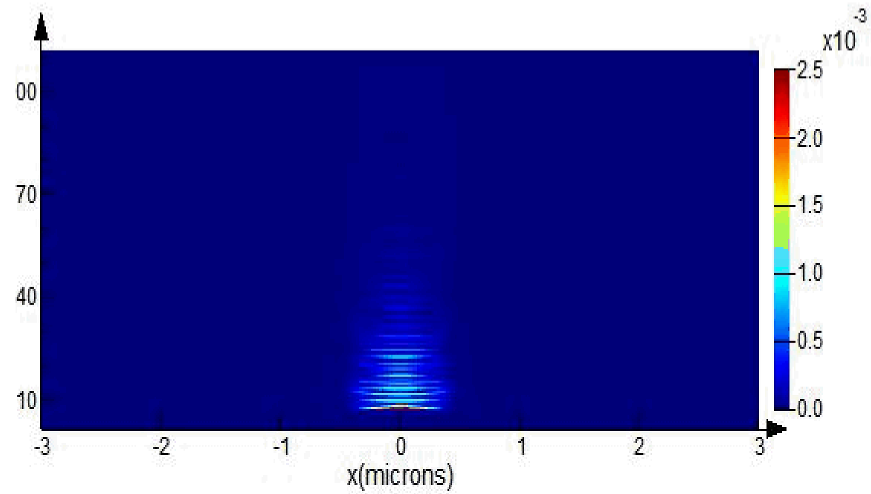
Dist. Abs. Si Cut



End Fire Si Cut



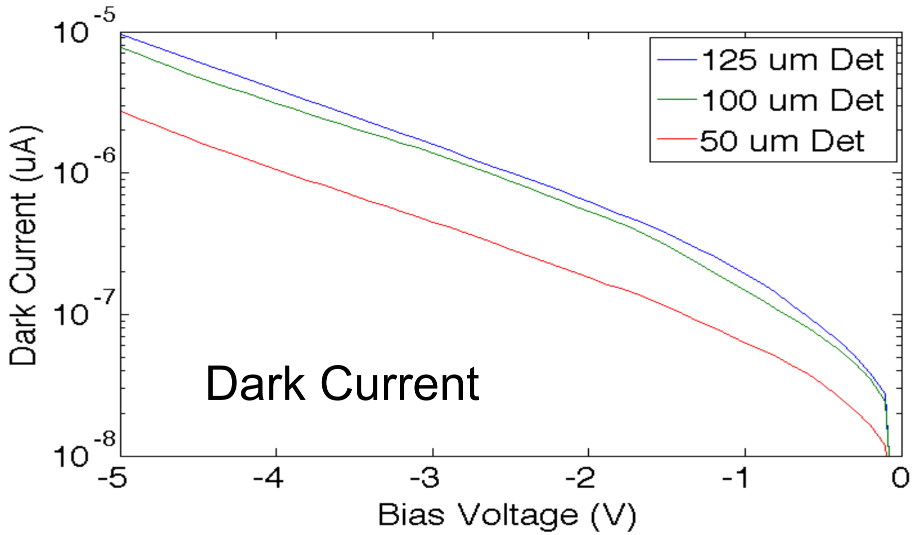
Dist. Abs. Ge Cut

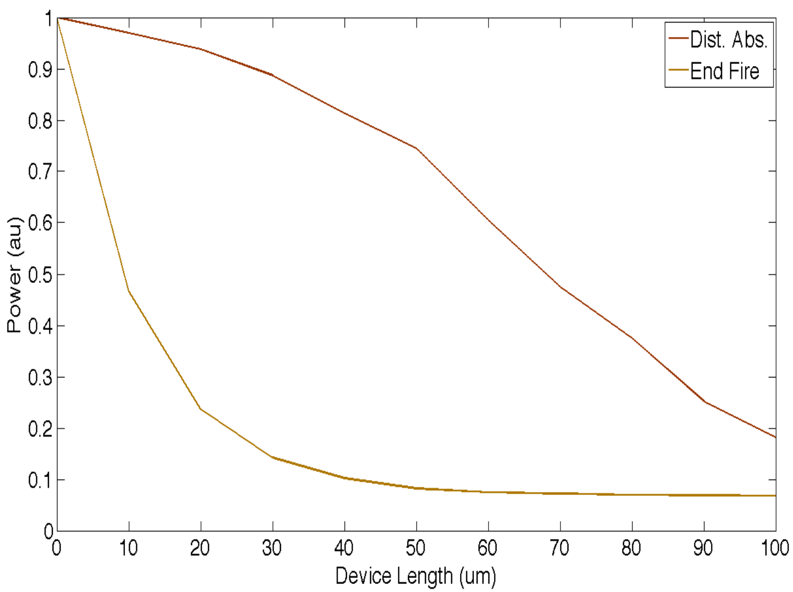


End Fire Ge Cut

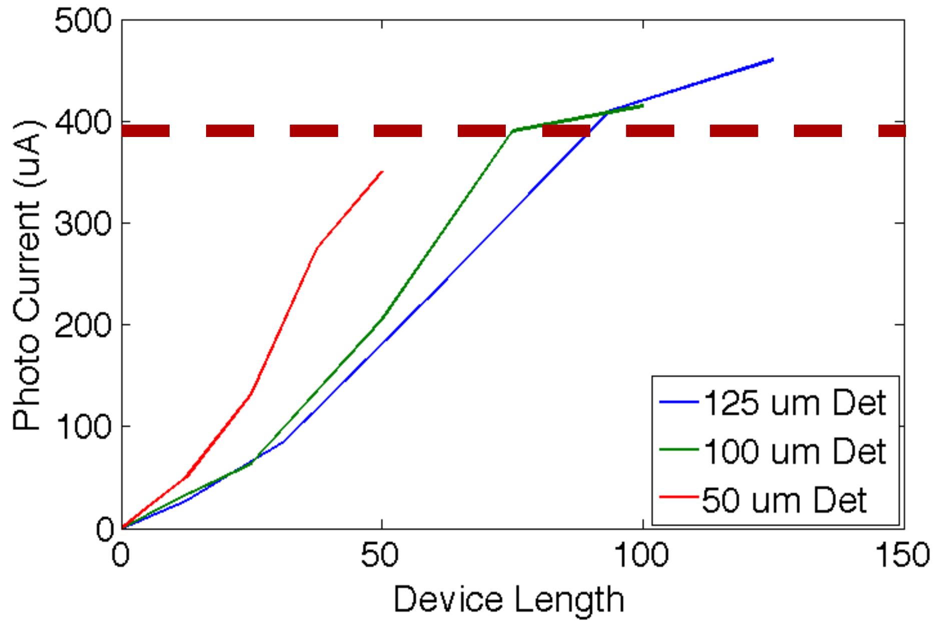
Distributed Absorption

- Simulation and measurement are in qualitative agreement
- Able to maintain low dark currents on partially etched substrate





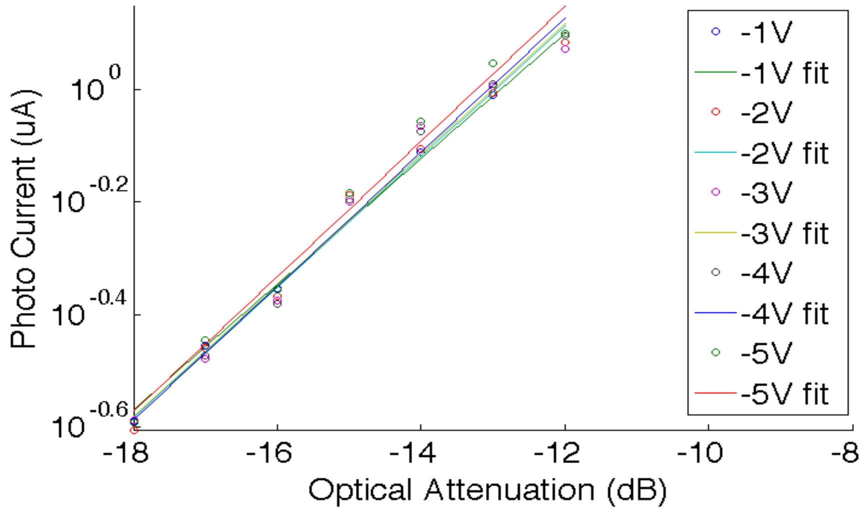
Simulated Absorption Profile



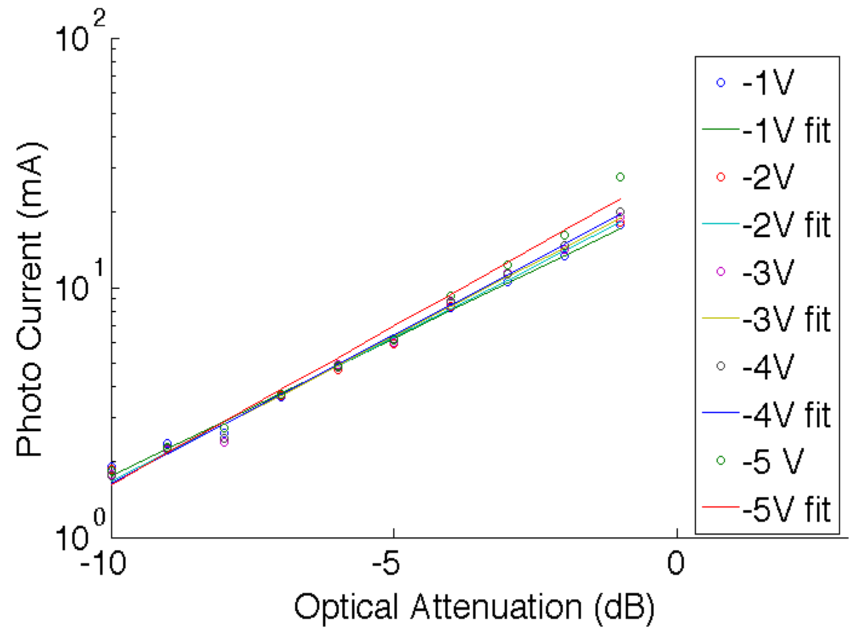
Measured Absorption Profile

Power Handling

- 10 X improvement in DC current operation over initial end fire coupled design demonstrated
- Measurements indicate that thermal runaway is main limiter
- Increase in area and improvements to thermal management needed to reach state of the art 125 mA in waveguide Ge photodiode [4]



End Fire Detector



Distributed Absorption

[4] A. Ramaswamy, et al., “High Power Silicon-Germanium Photodiodes for Microwave Applications” IEEE Microwave (2010)

Summary

- Silicon photonics is a promising platform for pursuing RF photonics
- High speed travelling wave MZMs with 95.5 $dBHz^{2/3}$ SFDR were presented

  -- Can be further optimized
- Initial results on a novel distributed absorption germanium photodiode for improved power handling ~20 mA photo current was presented

  -- Expect significant improvement with thermal management and improved geometry

Acknowledgements: M.R. Watts for initial designs and helpful discussions

Questions?

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