SAND2012-4254C

High Speed Travelling Wave Carrier Depletion Silicon Mach-Zehnder Modulator

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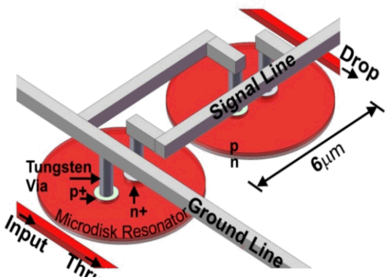
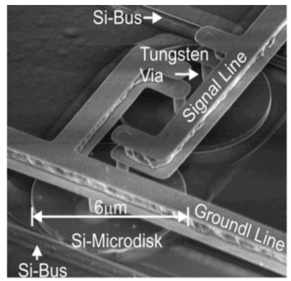
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Silicon Photonics At Sandia

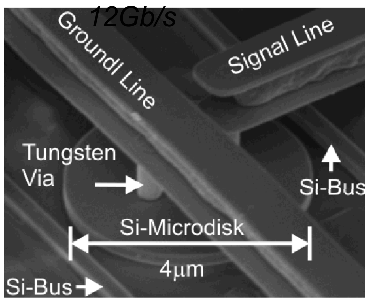
Free-carrier Effect (high-speed)

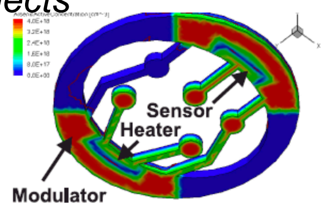


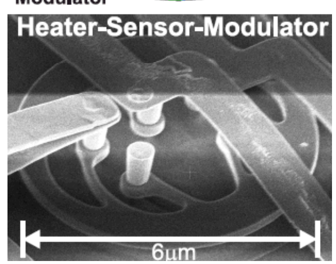


Fast Reconfigurable Interconnects

3.2fJ/bit at 12Gb/s





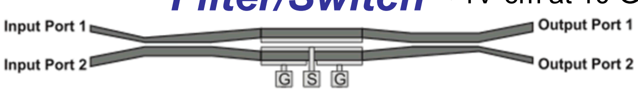


Resonant Optical Modulator/Filter

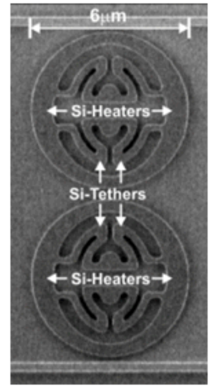
Thermally stabilized modulator

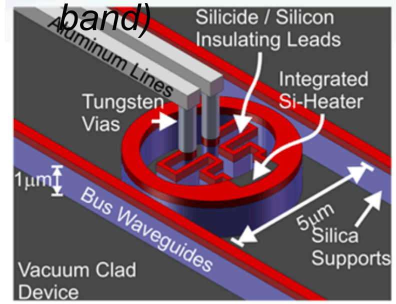
Broadband Mach-Zehnder Filter/Switch

< 1V-cm at 10 Gb/s

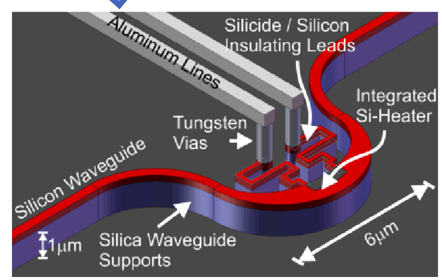


Thermal Optic Effect (wide-band)

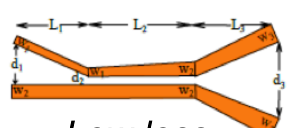




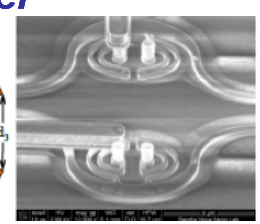
Tunable Resonant Filter



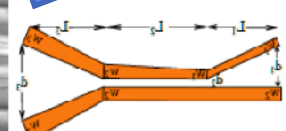
Thermo-optic Phase Shifter



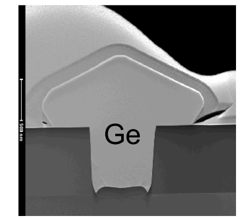
Low loss optical coupler



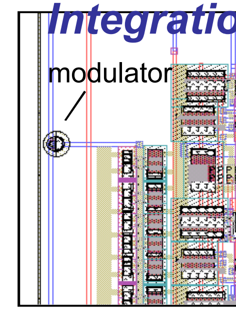
Switch Arrays



High-speed Ge Detector in



Si Photonics-CMOS Integration



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Sandia's MESA Fabrication

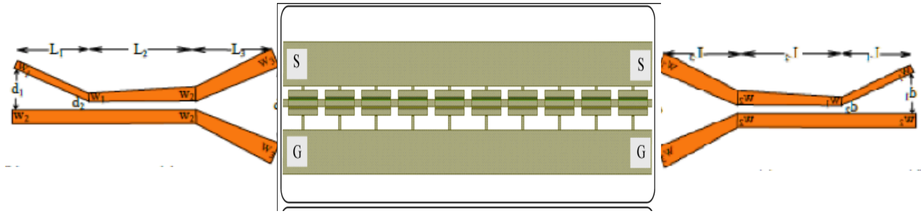
Microsystems Design, Fabrication and Test

- Microfabrication
- Packaging
- Si Micromachining
- Advanced Modeling
- 3D Simulation
- Photonics
- III-V Semiconductors
- Nanotechnology
- Electronics

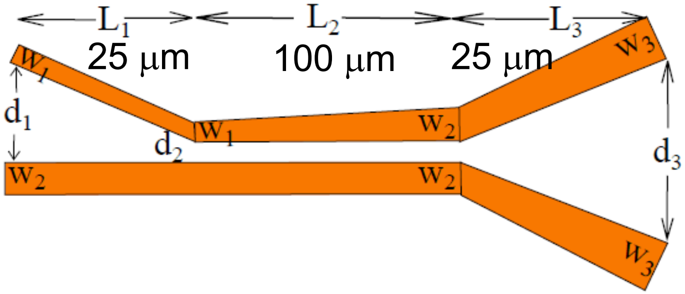
$400M total investment.

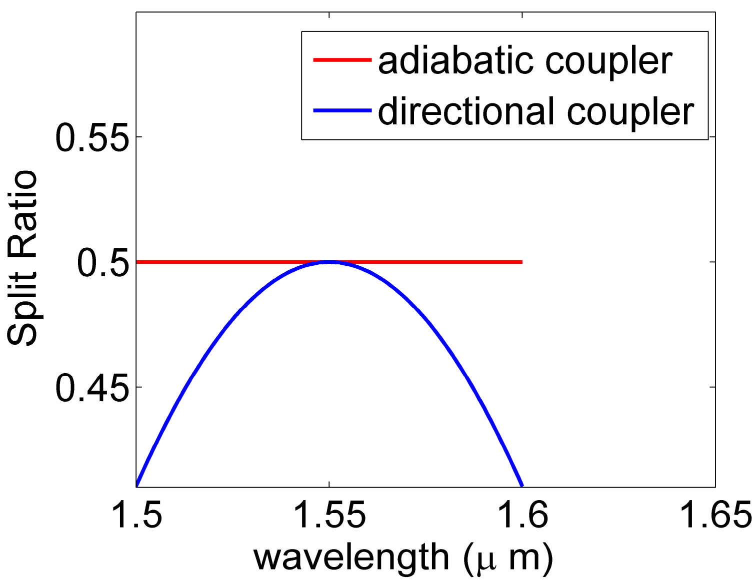
650 people
380,000 sq ft

Adiabatic Coupler

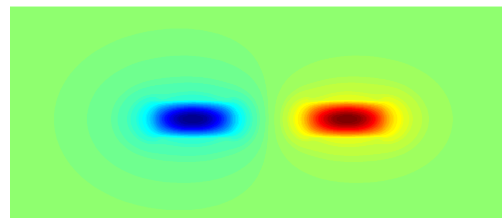


Adiabatic 3-dB Splitter

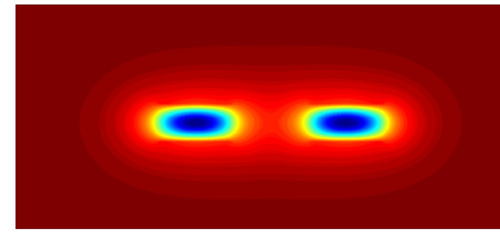




Symmetric Waveguide Coupling

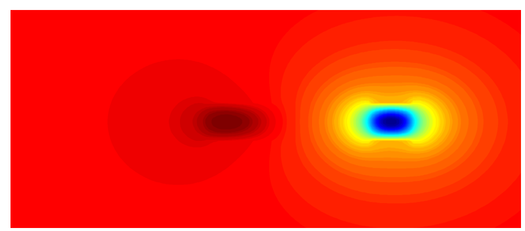


n_{eff} = 1.9745

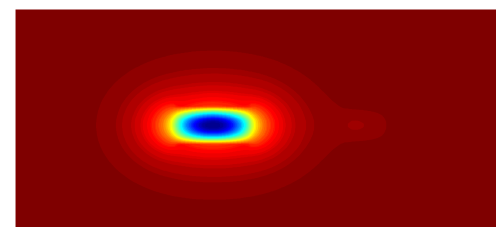


n_{eff} = 1.9417

Asymmetric Waveguide Coupling



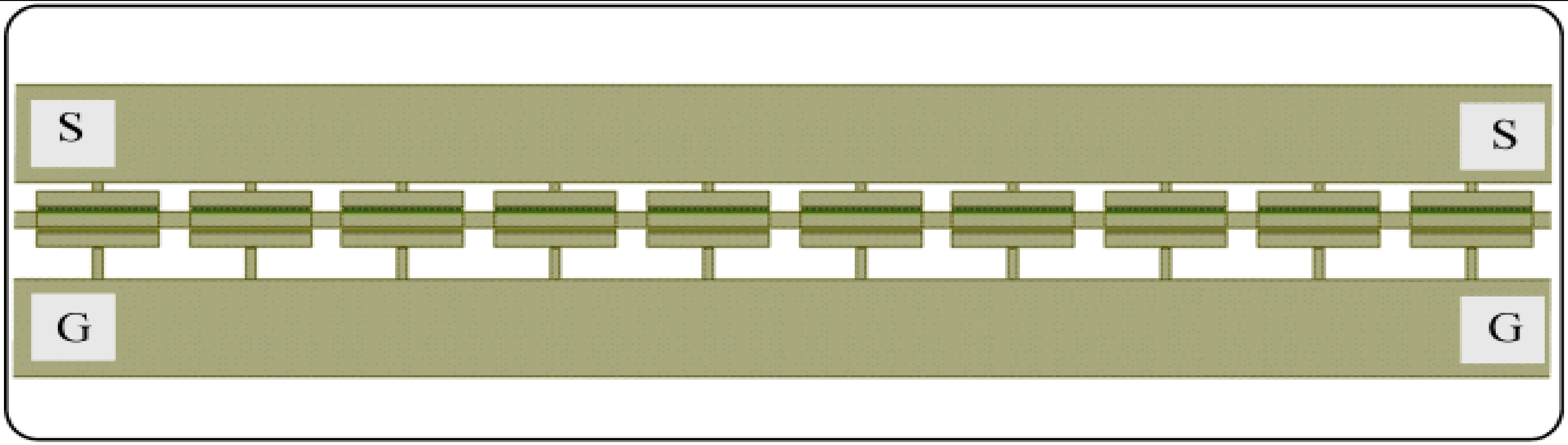
n_{eff} = 1.6248

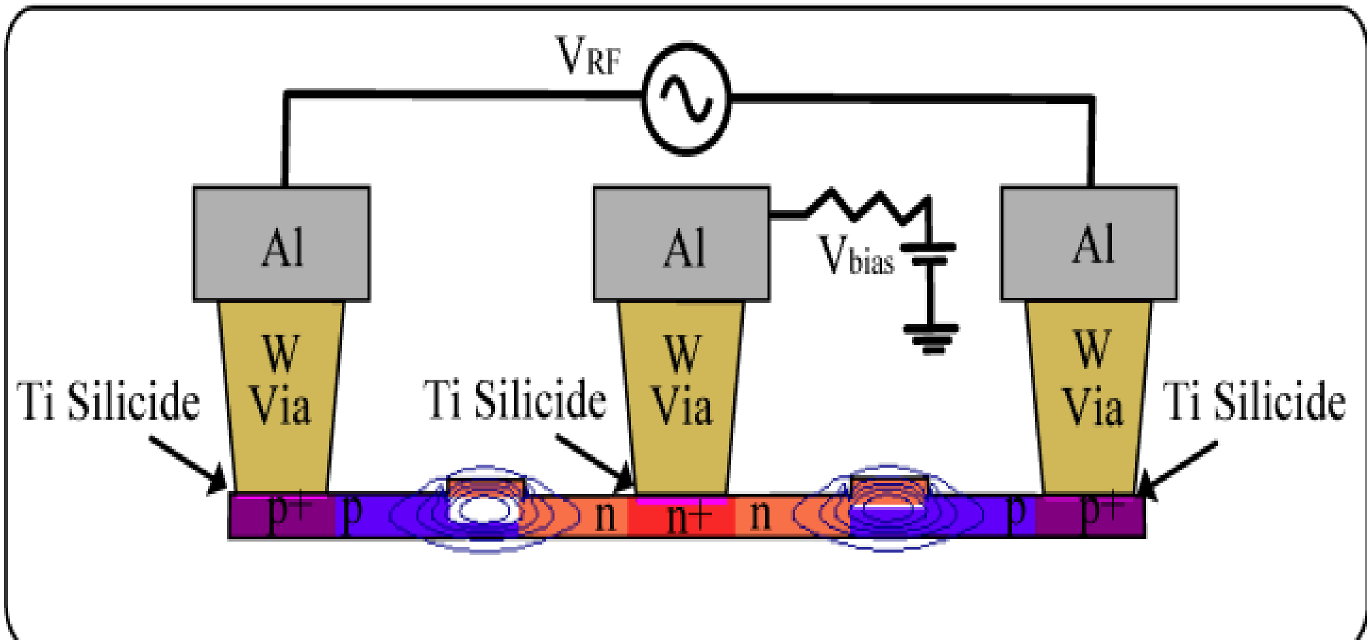


n_{eff} = 1.9592

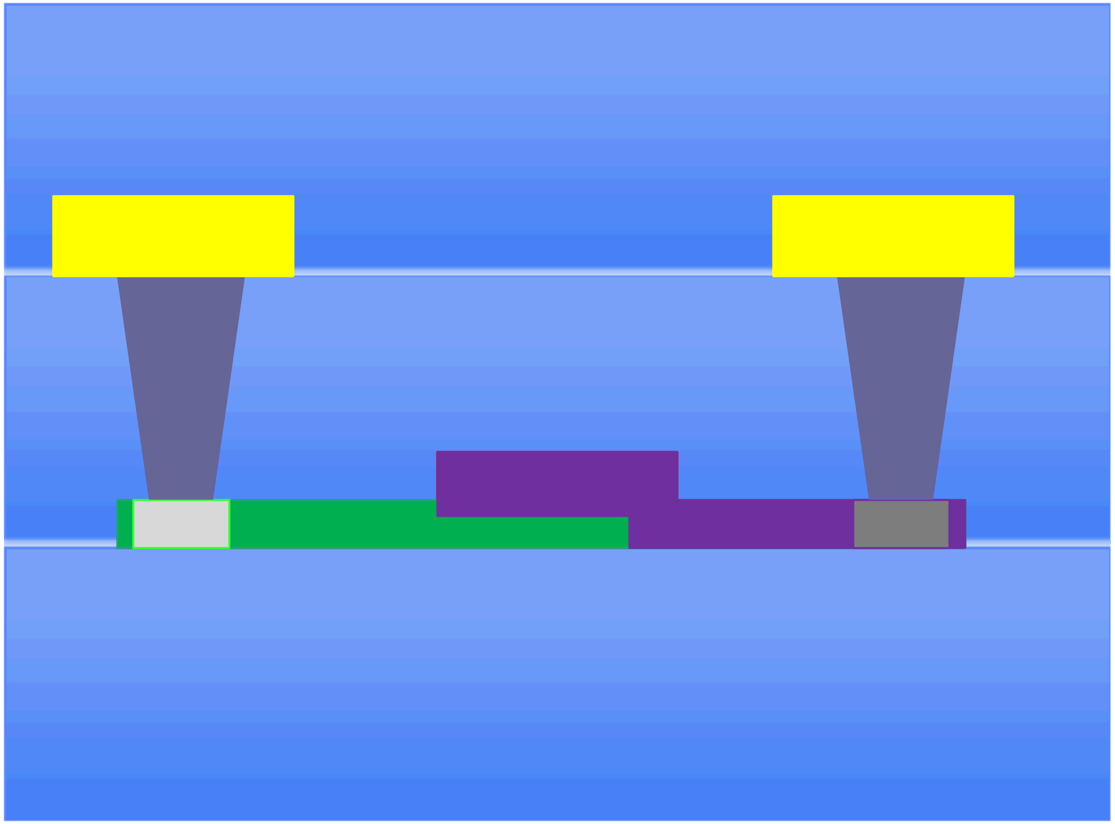
Y. Silberg, *et. al*, Appl. Phys. Lett. , 51(16), 1230 1232, (1987)

Device Schematic

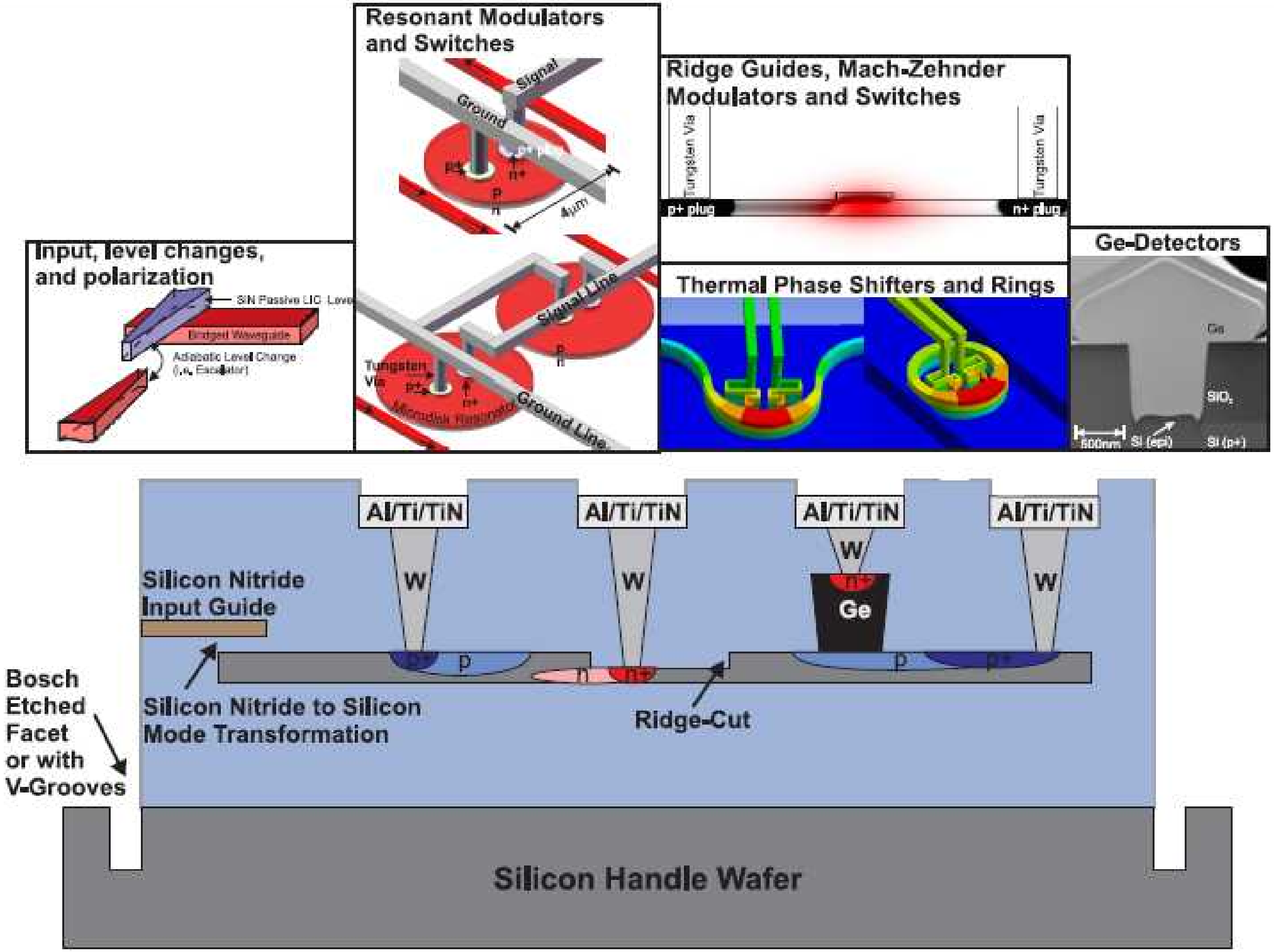




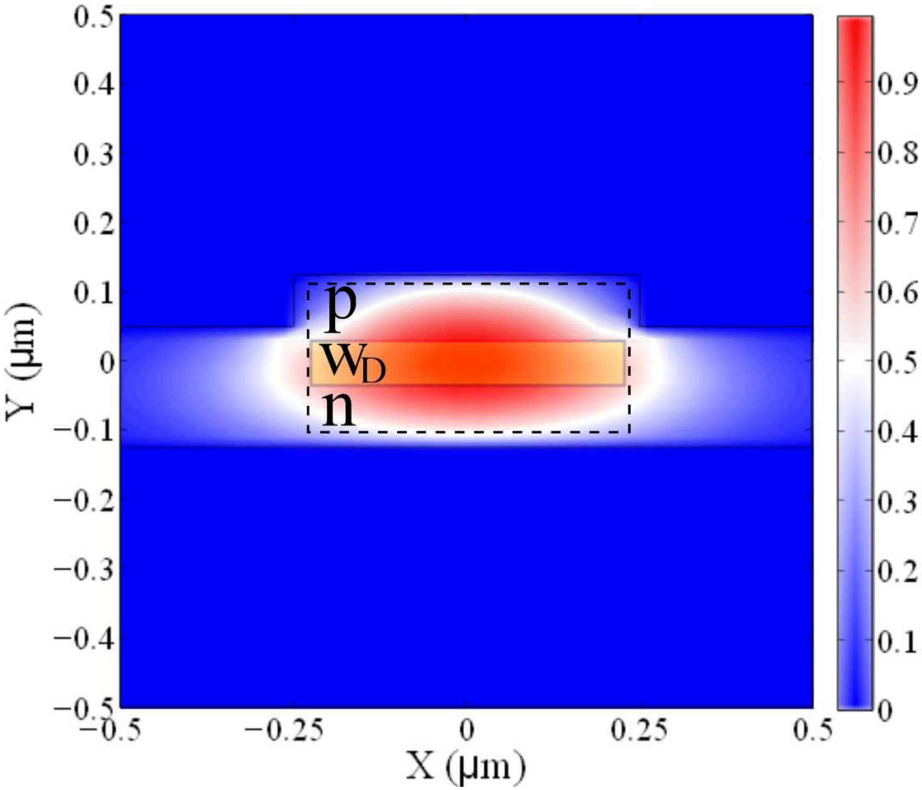
Process Flow

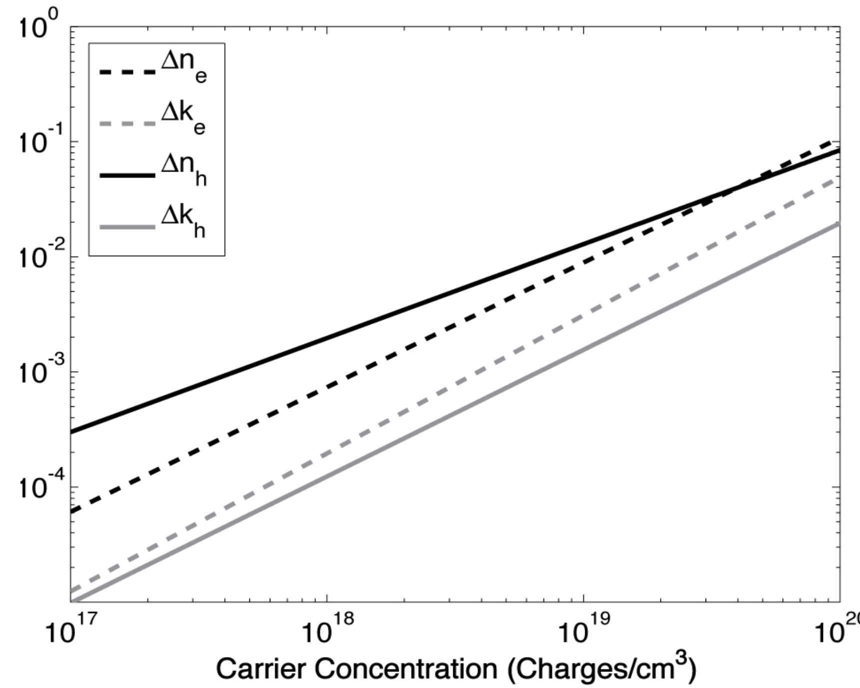


SNL Si Photonics Platform



Free Carrier Dispersion Effect





$$\Delta n = A \cdot N^{B} + jC \cdot N^{D}$$

Soref and Bennet JQE Vol. 23 pp.123-9 (1987)

Xu, *et al.* Nature (2004)

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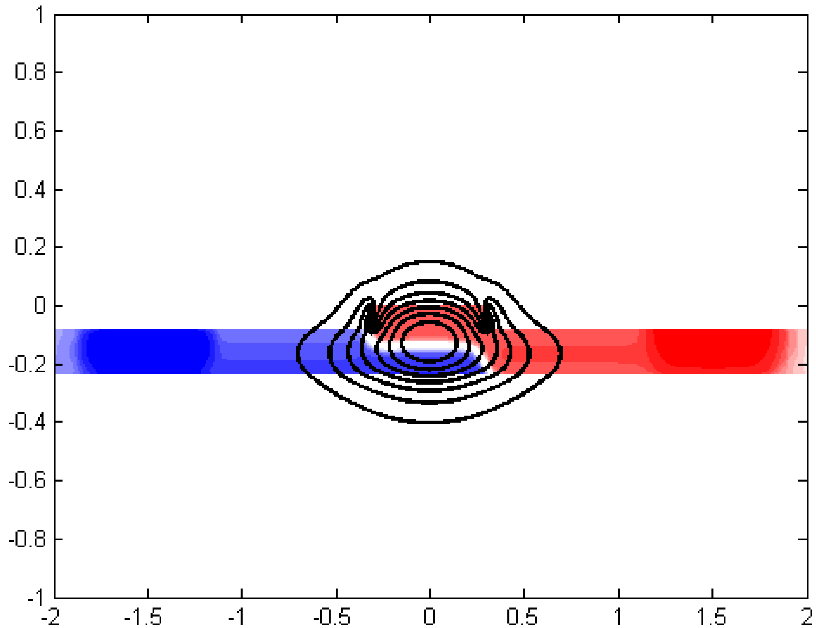
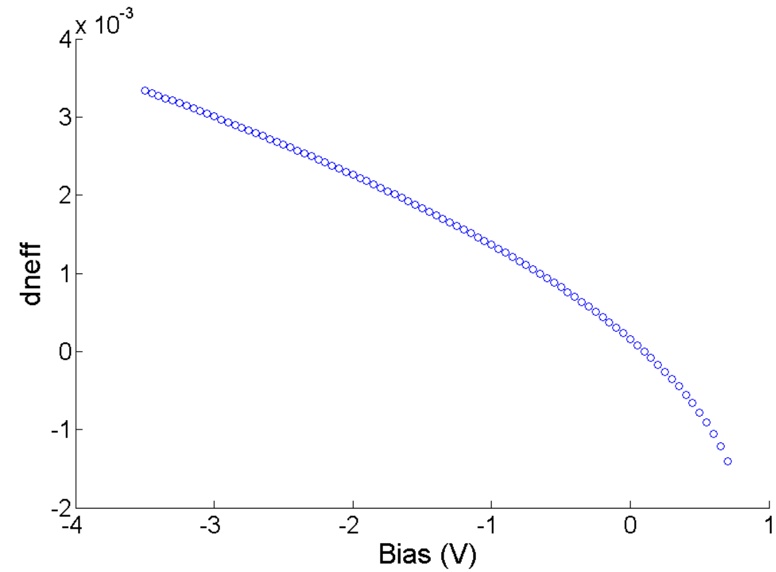
Device Model





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

C = 0.53 fF/um
R = 3.2 kOhm-um

Need δn of ~ 1e-3 for 1 mm device

Watts et al. JSTQE (2010)
Watts et al. Optics Express (2012)

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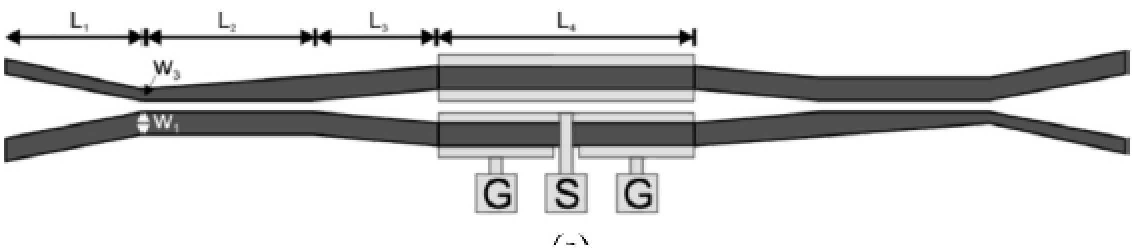
Why Travelling Wave ?



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

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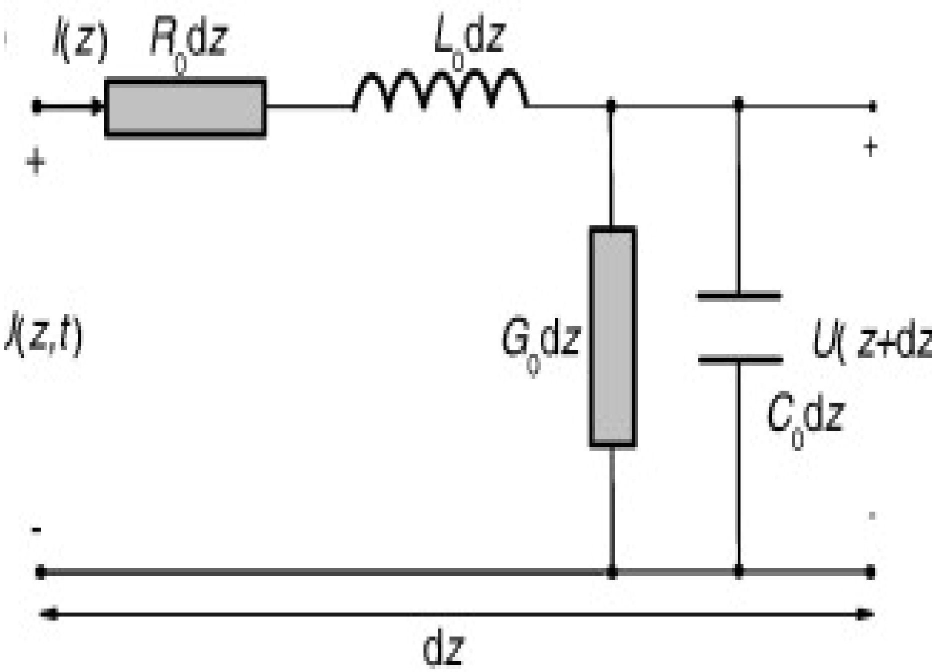
Circuit Model of Segmented Inductors TW Modulator



$$Z_0 = \sqrt{\frac{Lo}{Co}} \qquad Z_L = \sqrt{\frac{Lo}{Co + C_L}}$$

$$n_0 = c\sqrt{LoCo}$$

$$n_L = c\sqrt{Lo(Co + C_L)}$$

Z_L = 50 Ω and n_L matched to group index of waveguide

$$C_L = \frac{n_L^2 - n_L^2}{cZ_L n_L}$$

G.L. Li, et al., *J. Lightwave Technol.* **22** 1789-1796 (2004)

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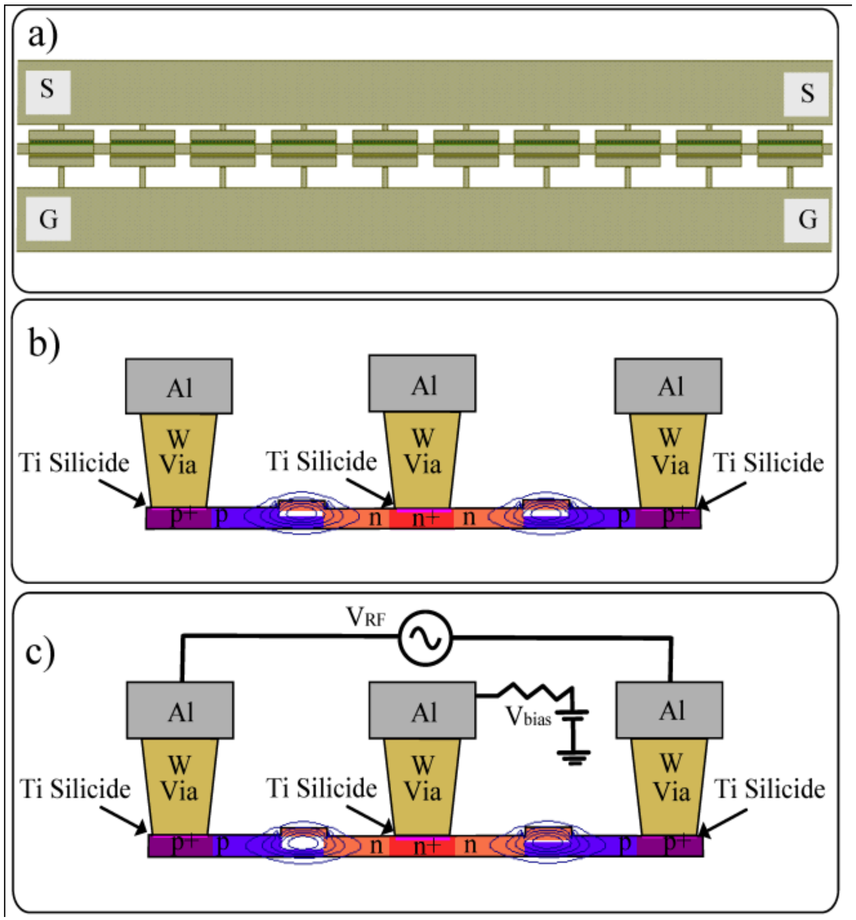
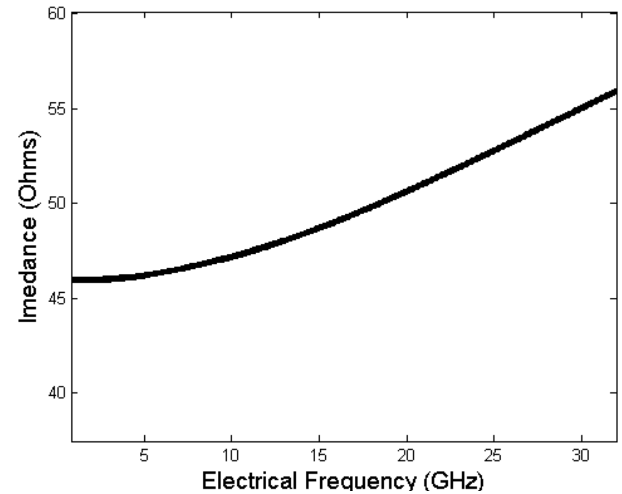
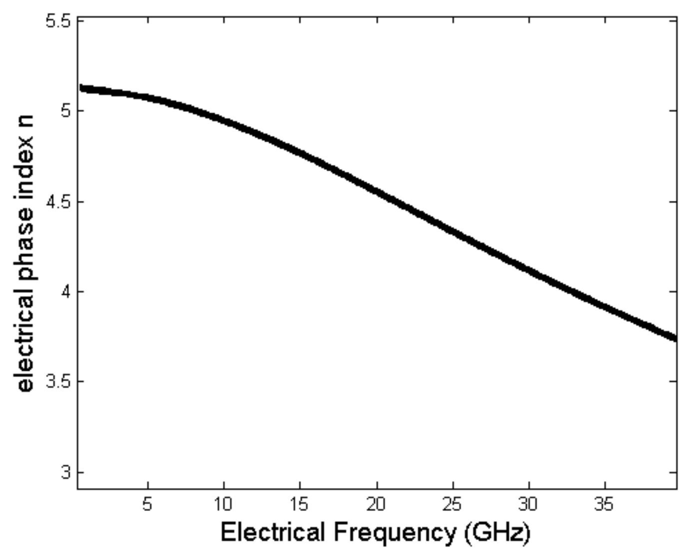
Travelling Wave Design

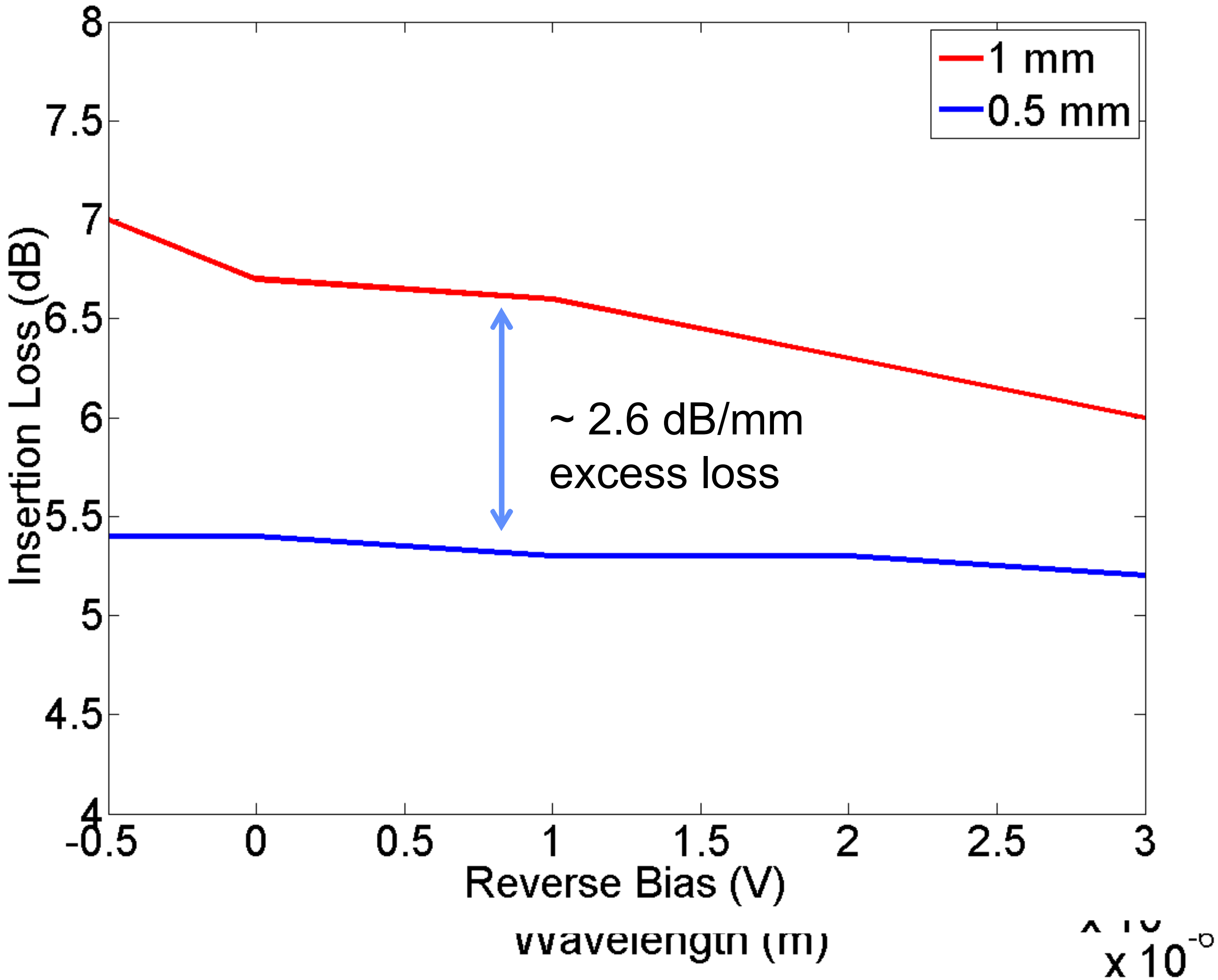






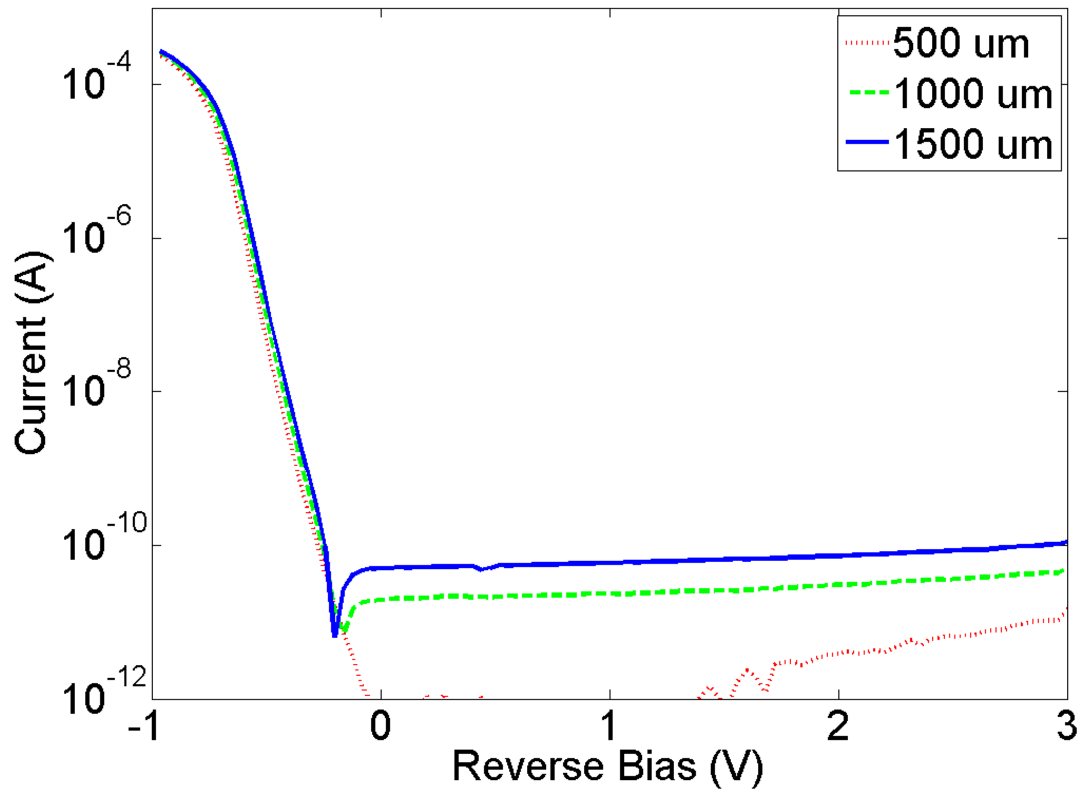
Z0 = 95 Ohms
N0 = 2.3

Passive Device Characteristics

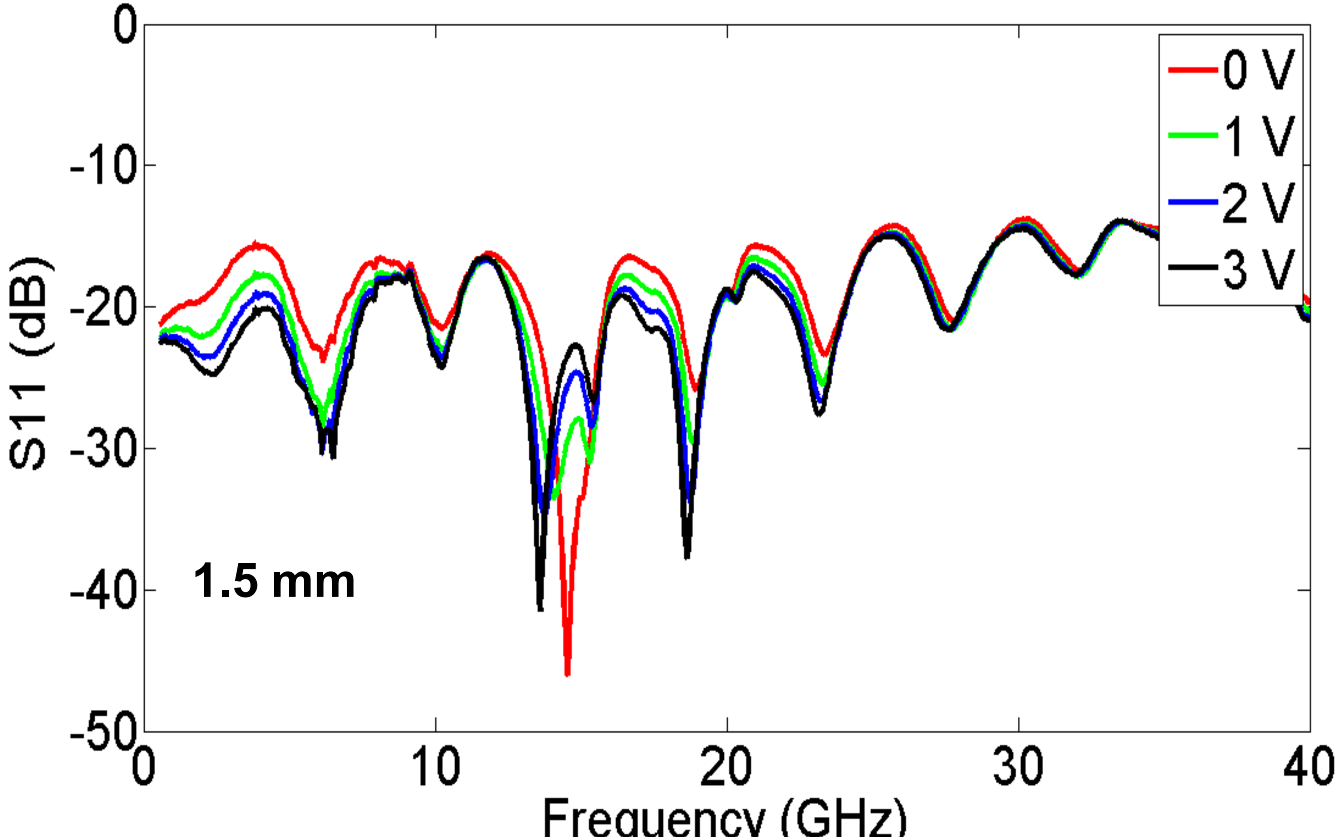


DC device performance

Low leakage current in reverse bias



RF Device Performance



S11 < -15 dB
up to 40 GHz

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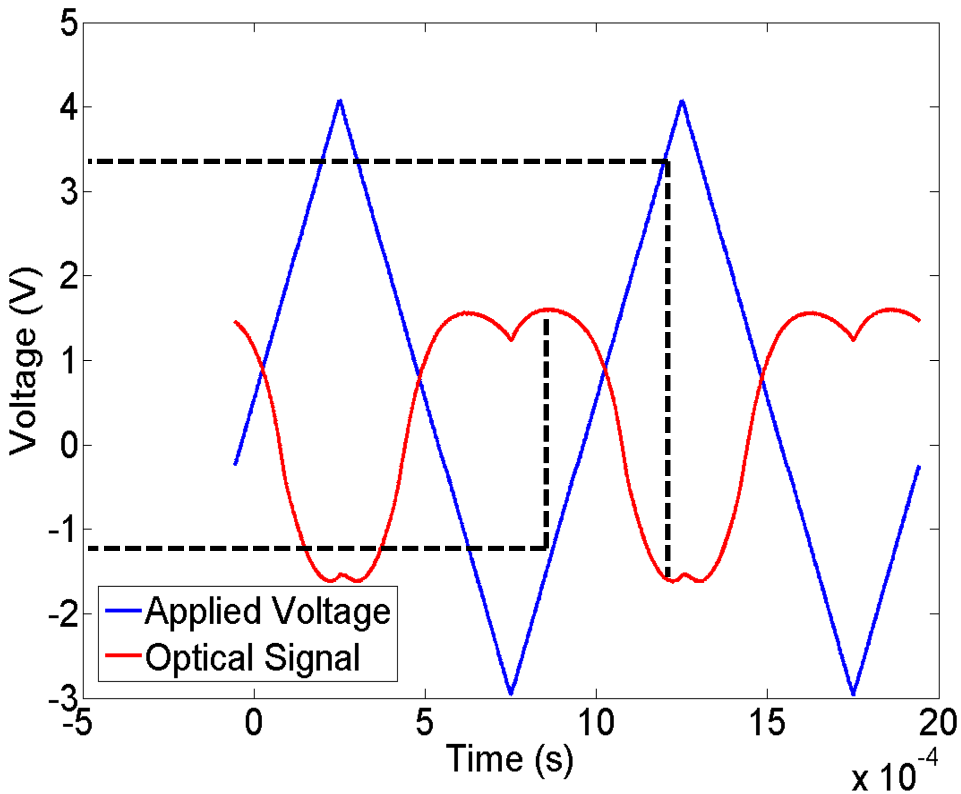
Halfwave Voltage Measurement



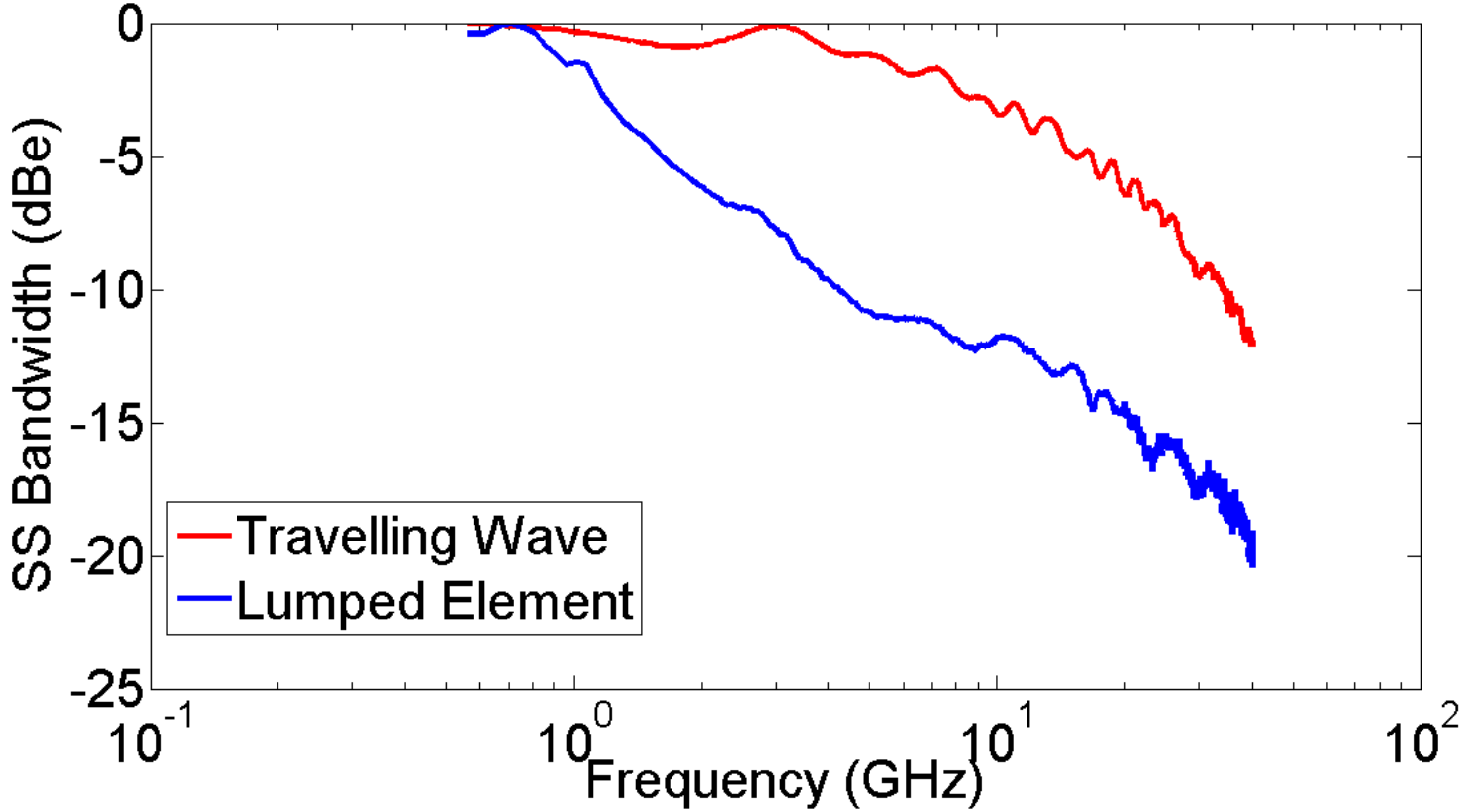
5 V $V\pi$

Leff = 1 mm

$V\pi$ L = 0.5 V-cm

Efficiency due to vertical junction

Small Signal Bandwidth



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Conclusions

• Vertical junction allows for efficient modulation

•Segmented approach enables simultaneous impedance and velocity matching

• There is a large trade-off space left to be further explored for further device improvement