Electrostatic Doping Assisted Push-Pull Mach-Zehnder Modulator For Optical Interconnects

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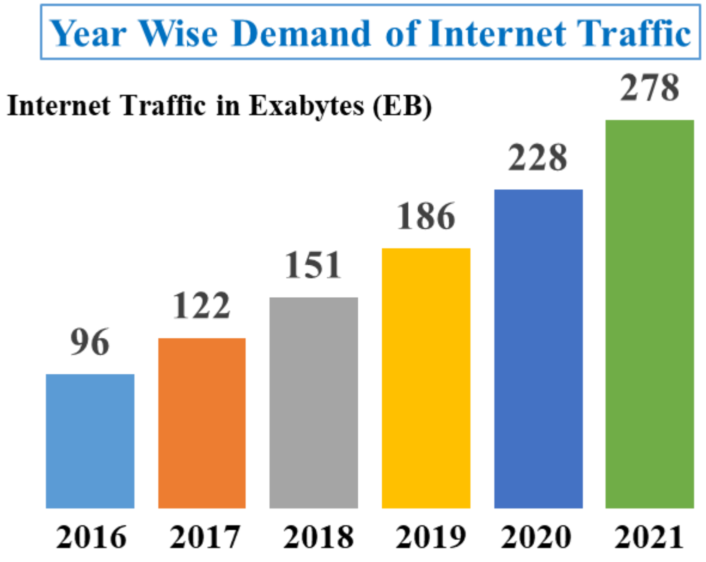
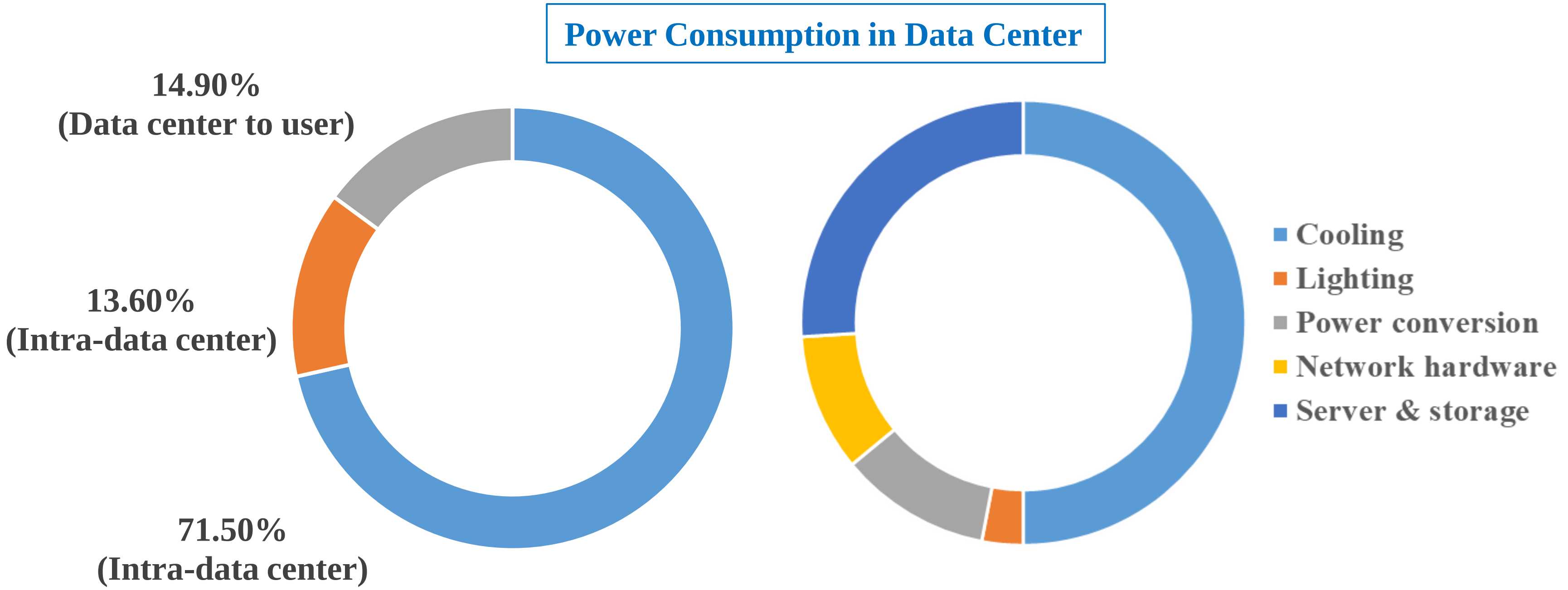
Why Silicon Photonics?





Problems in Present Design

- Fixed bandwidth capability.
- High power consumption.
- Scaling limitation.

Solution(s)

- Replacement of copper based interconnects by photonic interconnects.
- Integration of electronic and photonic circuits.

Why Silicon Photonics?

Advantages of Silicon

- Stable and well understood material.
- Mature fabrication technology.
- High optical confinement and refractive index.
- Optically transparent at 1.3 μm to1.5 μm.
- Electro-refraction and electro-absorption: dual method for optical modulation.
- Offers electronic and optical integration.

Requirements of Silicon Based Interconnects

- Power Requirement[1]: Inter-chip: ≤100 fJ/bit; Intra-chip: ≤ 50-200 fJ/bit.
- Photodetectors integrated with transistors.
- Total time delay: 180-270 ps.
- Total power consumption: 18-20 mW.

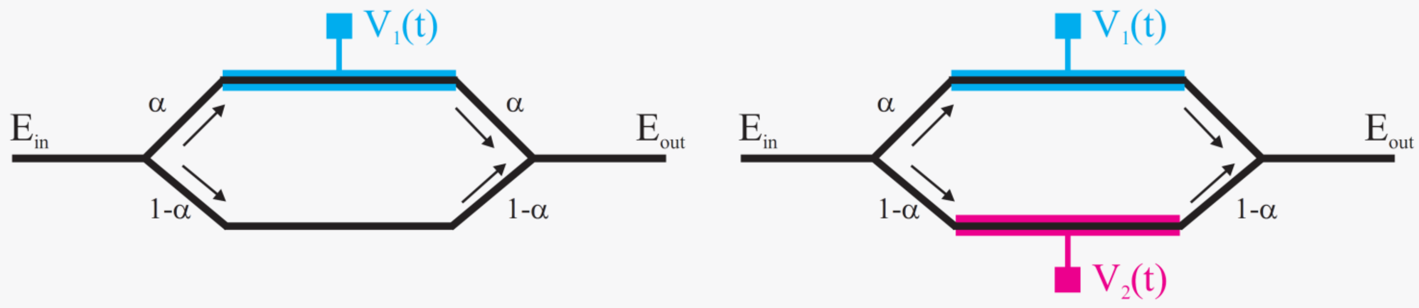
1. D. Miller, Proc. IEEE, vol. 97, no. 7, pp. 1166-85, 2009.

Optical Modulators in Photonic Integrated Circuits

Optical Phase Shifters and Modulators

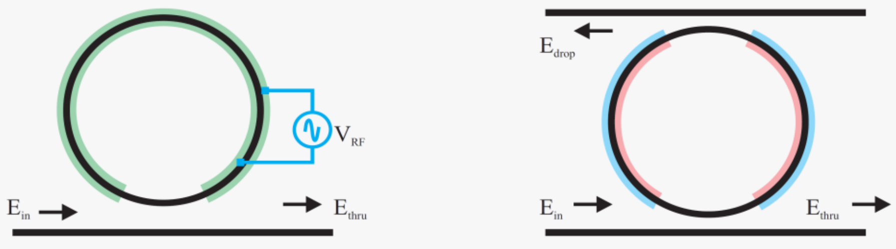
- Phase shifter introduces additional phase shift in guided-light.
- Additional phase shift: $\Delta\phi = (2\pi L \Delta n)/\lambda$
- Δn: Electro-optic effect (via free carrier plasma dispersion effect) or thermo-optic effect.
- Most common structure: PN/PIN diode or MOS Capacitor in a rib waveguide.

Different Modulator Structures



Single MZM

Push-Pull MZM

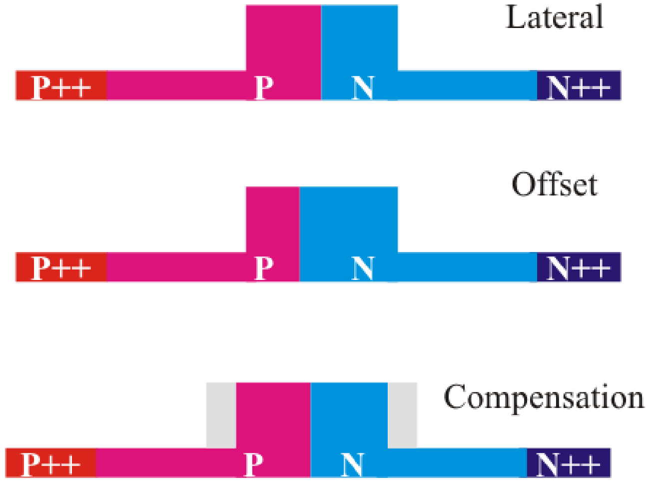


All-Pass MRM

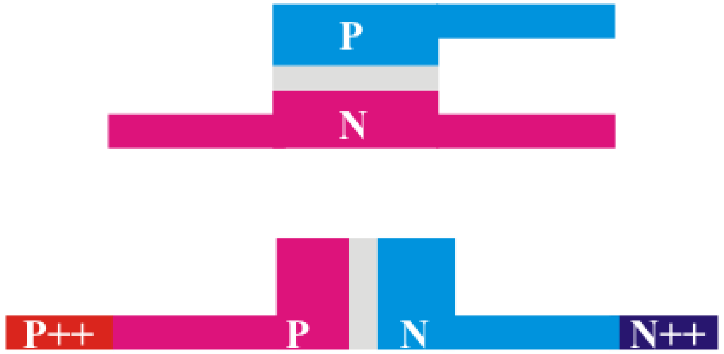
Add-Drop MRM

Different Optical Modulator Structures

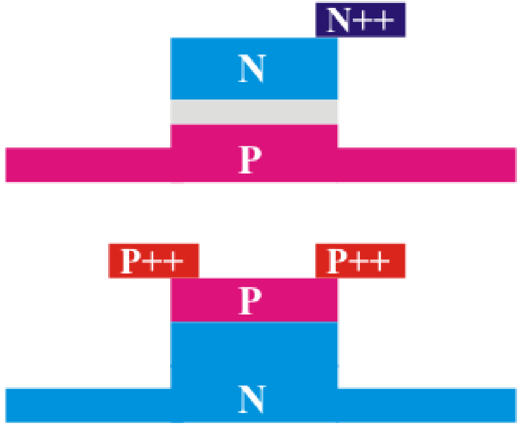
PN Junction



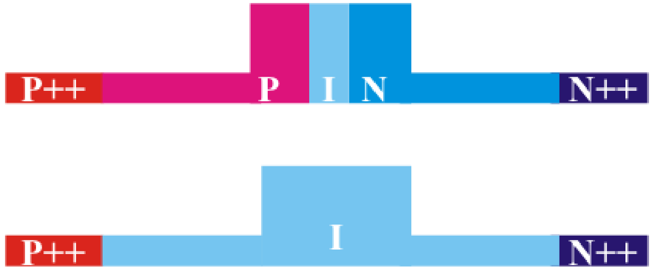
MOS Junction



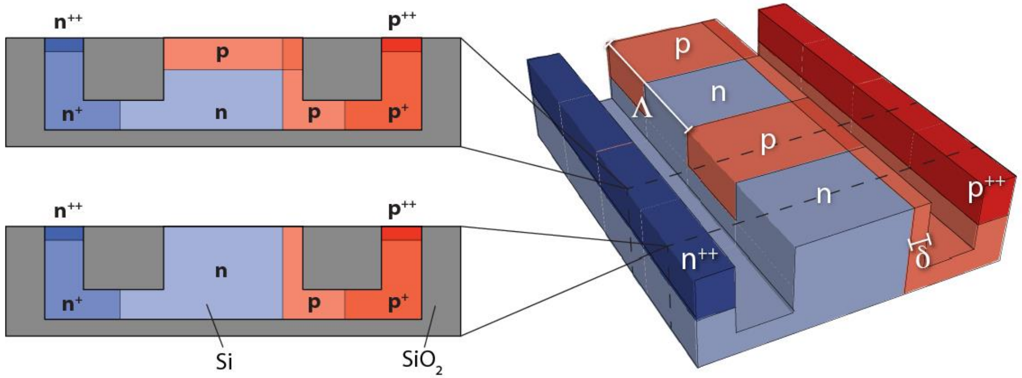
Vertical PN Junction



PIN Junction

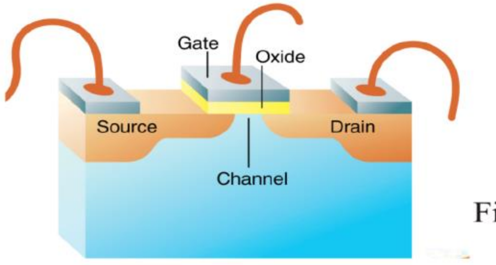


Interleaved PN Junction

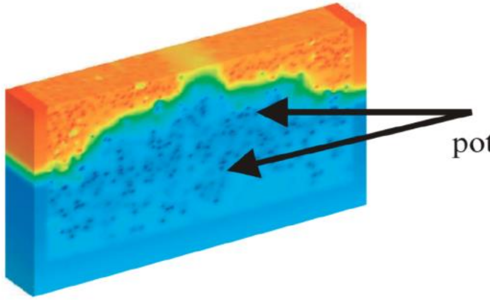


Source: Opt. Express **20,** 26411-26423 (2012)

Random Dopant Fluctuations

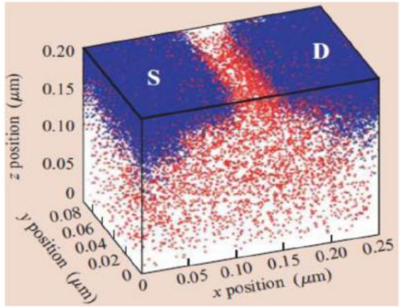


30 nm x 30 nm
Field Effect Transistor

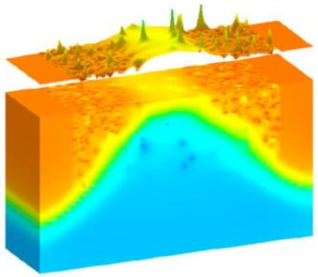


RDF induced
potential fluctuations

Source: Roy et al., Science Magazine, vol. 309, pp.388-389, July 2005.

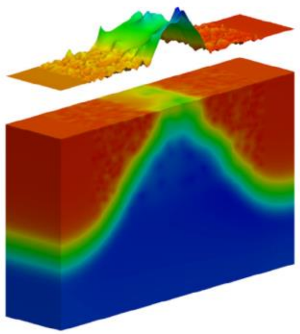


Dopant distribution in a
32 nm MOSFET



RDF induced
potential fluctuations

Source: Gabriele Tocci, Masters Thesis, KTH, 2010.



RDF induced local rise
of channel acceptors in a
typical 25 nm MOSFET

Source: L. Gerrer et al., Microelectronics Reliability, vol. 52, pp. 1918-1923, 2012.

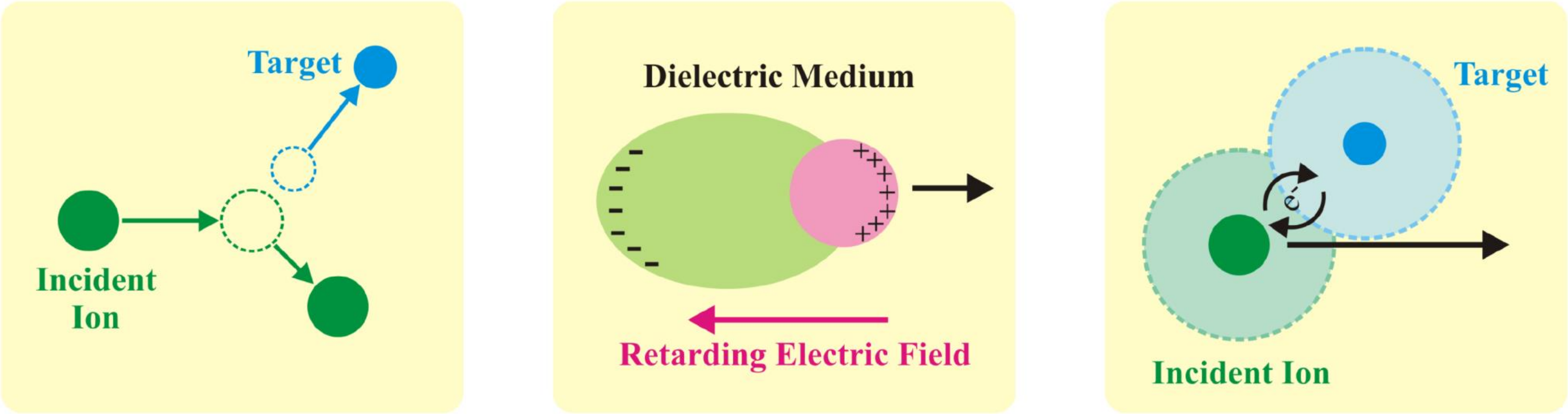
Insertion loss in MZM as a function of doping[1]:

$$\mathrm{IL} = 2\alpha_{sp} + \left(A \cdot \sqrt{N_{dop}} + \frac{\alpha_{wg}}{\sqrt{N_{dop}}} \right) \cdot B$$

where α_{sp} : splitter loss; A, B: two coefficients related to length and light overlap factor; N_{dop}: doping concentration; and α_{wg}: optical propagation loss.

[1] Xi Xiao et.al., *Optics Express*, vol. 21, no. 4, pp. 4416-4125, 2013.

Origin of Random Dopant Fluctuations



(a) Nuclear stopping (b) Non-local electronic stopping (c) Local electronic stopping

Plausible Solution?

Use of Electrostatic Doping (ED)

Concept of Electrostatic Doping (ED)

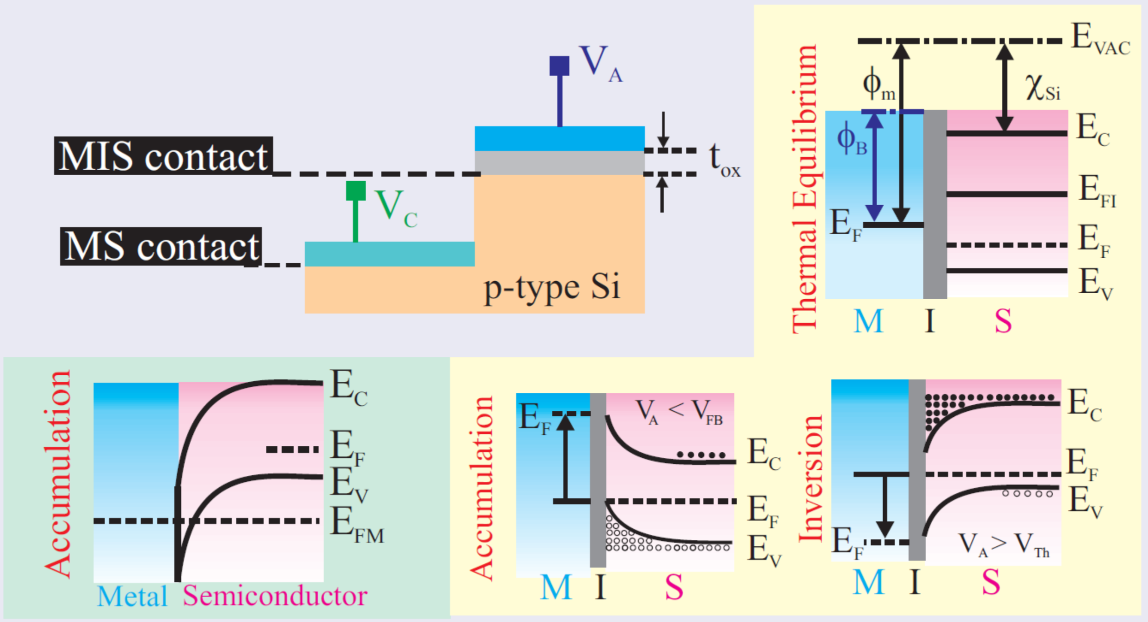


Figure: Concept of ED in metal-semiconductor and metal-insulator-semiconductor junction.

Types of ED in Semiconductor Devices

- **Schottky Barrier Based Doping**
  SB-MOSFET, SB-FinFET, CNT
- **Work-function Induced Doping**
  CP-PN/PIN diode, CP-BJT, CP-TFET
- **Bias Induced Doping**
  Lateral/ vertical PN junction, DG-TFET

Plausible ED in Si-Ph Devices

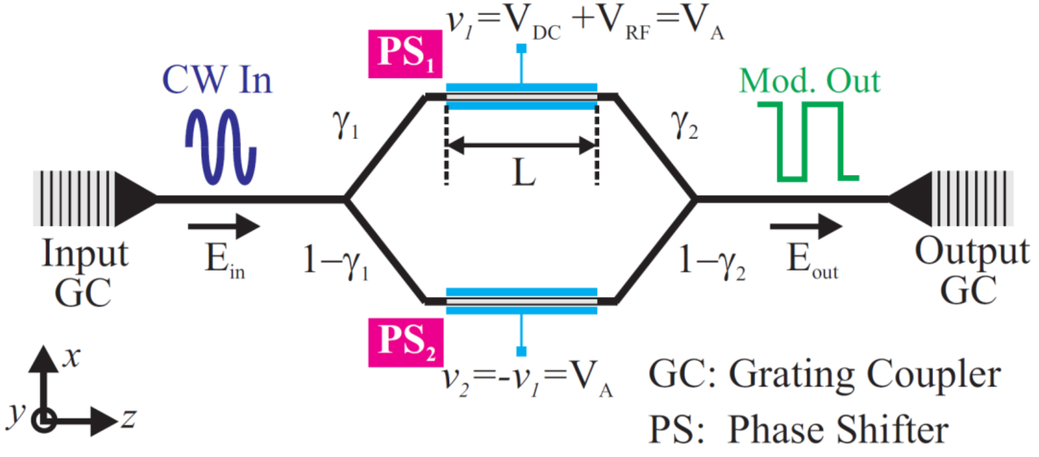
- **Work-function induced doping**
  Utilizes different metal as electrodes.
- **Bias induced doping**
  Use of proper bias voltages.

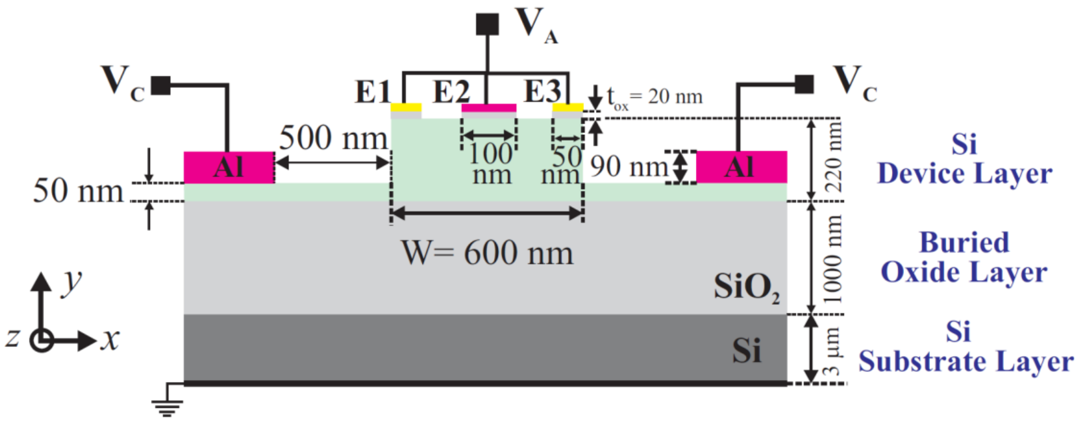
Design Objectives

- ED assisted optical phase shifter based Push-Pull Mach-Zehnder Modulator (MZM).

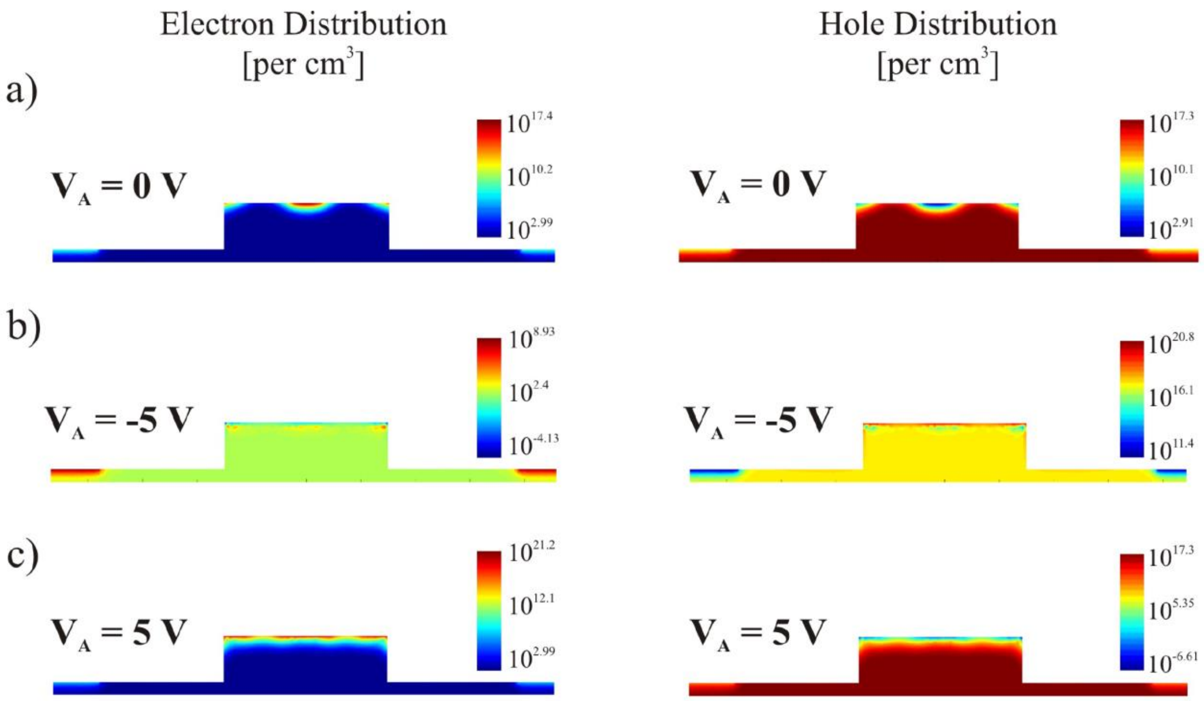
Proposed ED Assisted Push-Pull MZM

Proposed Modulator Structure





Carrier Distribution Across ED Assisted Optical Phase Shifter



Mathematical Model of Proposed Modulator

Referring to the device structure, the output electric field of the modulated signal (E_{out}) can be expressed as:

$$E_{out} = \left[\sqrt{\gamma_1\gamma_2}e^{-j\Delta\phi(v_1)}e^{-\Delta\alpha(v_1)L}\right]e^{-(j\phi_0+\alpha_0 L)}E_{in} + \left[\sqrt{(1-\gamma_1)(1-\gamma_2)}e^{-j\Delta\phi(v_2)}e^{-\Delta\alpha(v_2)L}\right]e^{-(j\phi_0+\alpha_0 L)}E_{in}$$

For symmetric power splitting and combining i.e. $\gamma_1 = \gamma_2 = ½$, the above equation reforms to:

$$E_{out} = \frac{E_{in}}{2}\left[e^{-j\Delta\phi(v_1)}e^{-\Delta\alpha(v_1)L} + e^{-j\Delta\phi(v_2)}e^{-\Delta\alpha(v_2)L}\right]e^{-(j\phi_0+\alpha_0 L)}$$

where, $\Delta\phi(v) = \frac{2\pi L}{\lambda}\Delta n(v)$: bias voltage induced phase change in the optical phase shifter

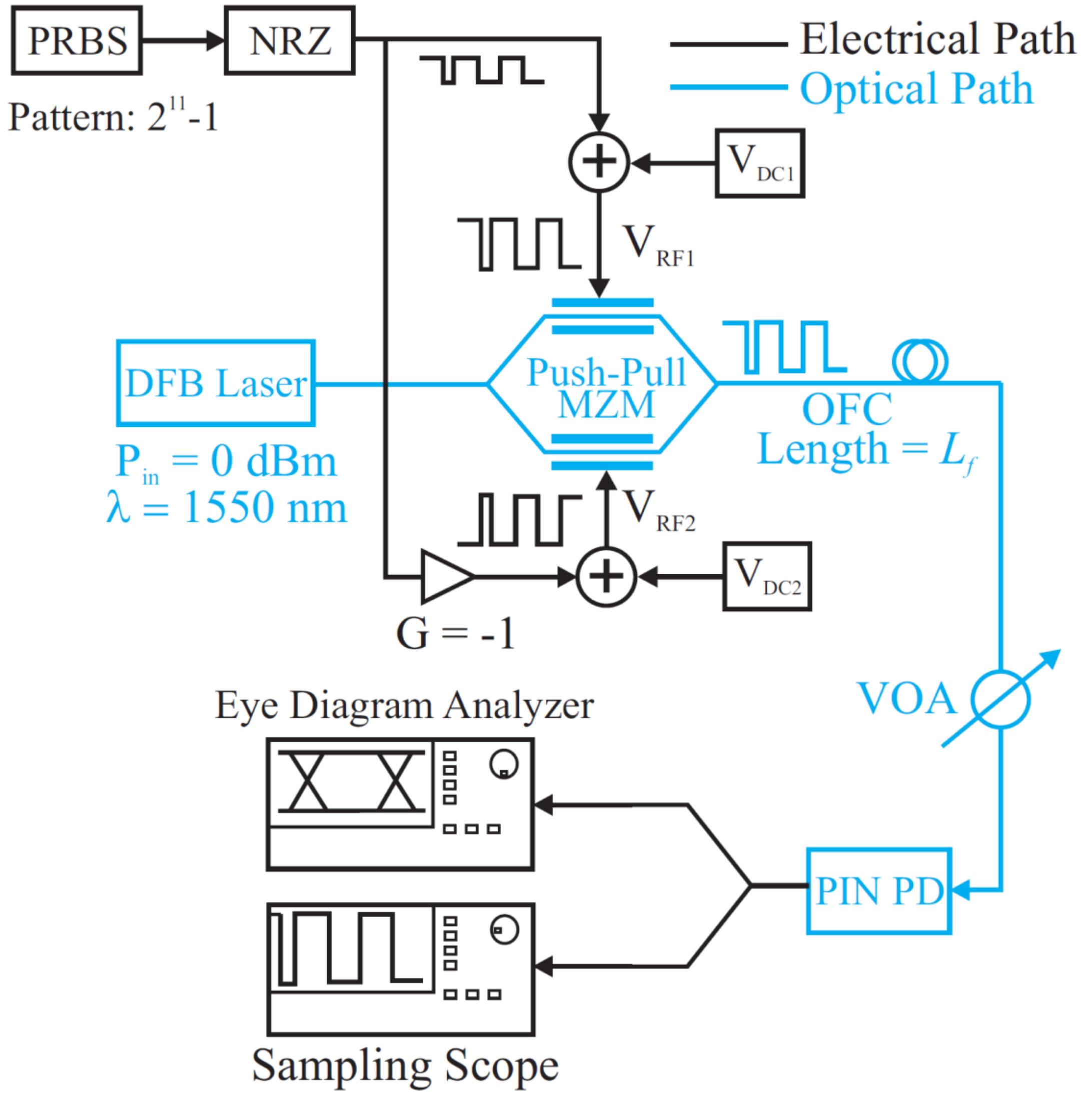
λ = operating wavelength;

ϕ_0 = phase shift at zero bias voltage;

α_0 = loss coefficient at zero bias voltage;

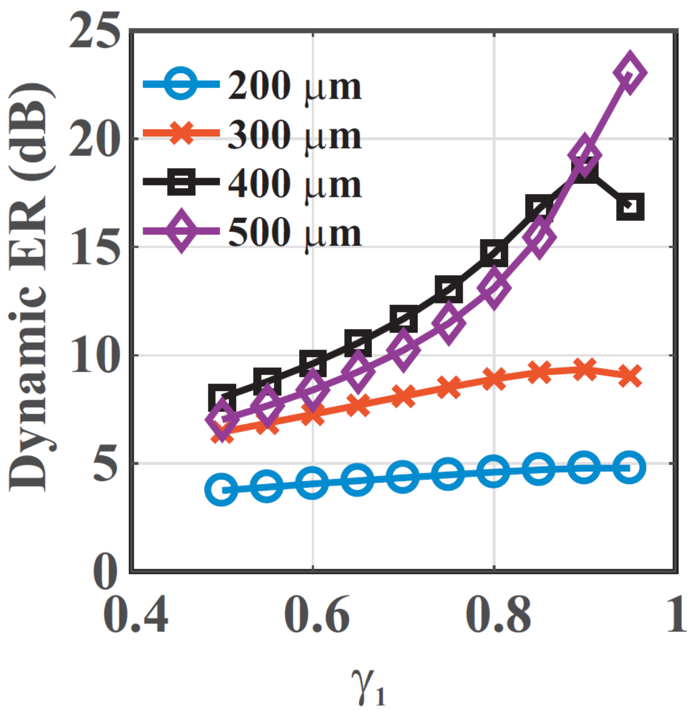
L = length of the phase shifter.

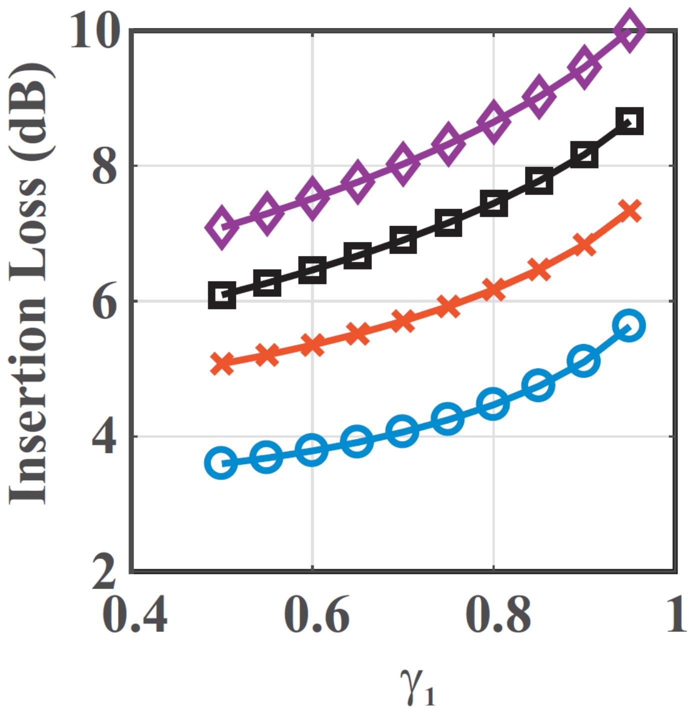
Simulation Setup for the Proposed Modulator



Used Simulation Platform
Carrier Dynamics: Lumerical Device CT
Modal Calculation: Lumerical Mode Solutions
Transmission System: Lumerical Interconnect

Simulation Results: Dynamic Performance Metrics





Performance Metrics: Design 1

L = 200 µm

3-dB EO Bandwidth: 28 GHz

Maximum operating frequency: 35.2 GHz

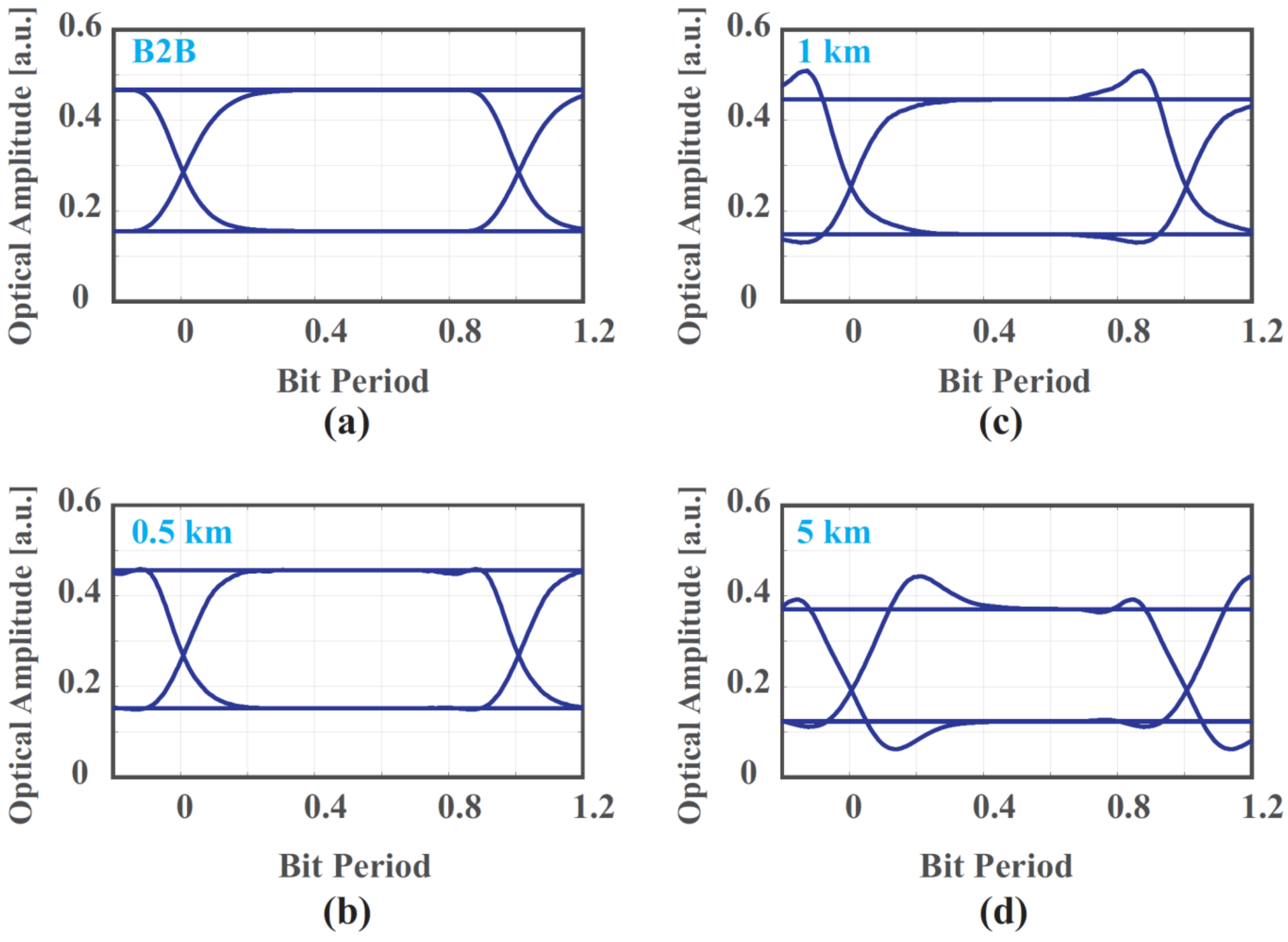
Performance Metrics: Design 2

L = 400 µm

3-dB EO Bandwidth: 22.7 GHz

Maximum operating frequency: 30.3 GHz

Simulation Results: Eye Diagram After Different Fiber Length at 10 Gb/s Data Rate



Fiber Length (km)	Dynamic ER (dB)
B2B	5.93
0.5	5.26
1.0	4.68
5.0	3.64

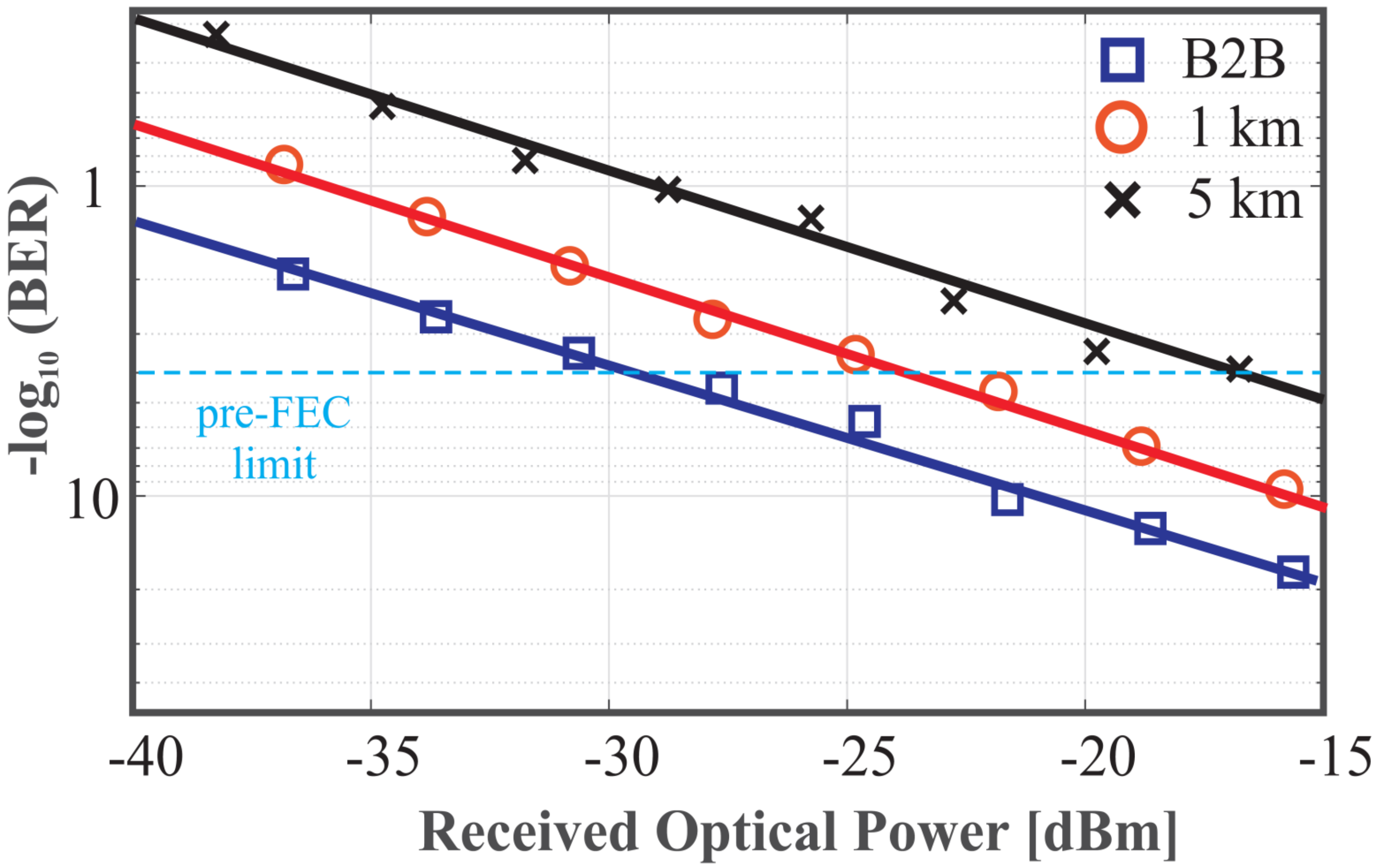
Transient Performance Metrics

L = 200 μm

3-dB EO Bandwidth: 28 GHz

Maximum operating frequency: 35.2 GHz

Simulation Results: BER Performance



Simulation Parameters
Data Rate: 25 Gb/s
Input Data: 2^{11}-1, PRBS
Thermal Noise: -410 dBm/Hz
Dark Current: 5 nA
Responsivity: 0.85 A/W

Comparative Performance Study

Reference	Year	Material	L [mm]	ER [dB]	IL [dB]	f_{max} [GHz]	$V_\pi L_\pi$ [V.cm]
[10]	2019	Si	3	3.6	9.1	32	0.55
[11]	2019	$Si-LiNbO_3$	3	5.0	2.5	112	2.20
[19]	2019	AlGaAs	10	3.0	7.5	-	1.00
This work	2020	Si	0.2	4.7	5.1	30.3	0.36-0.74

[10] G. Zhou, L. Zhou, Y. Guo, L. Liu, L. Lu, and J. Chen, “High Efficiency Silicon Mach-Zehnder Modulator With U-shaped PN Junctions,” in CLEO: Applications and Technology. Optical Society of America, 2019, pp. JTh2A–42.

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Conclusions

- Push-Pull Mach-Zehnder intensity modulator with electrostatic doping assisted optical phase shifter for photonic integrated circuits is plausible.
- For 200 µm long proposed MZM, estimated dynamic ER is 4.7 dB with 5.1 dB of IL at 10 Gb/s data rate.
- 3-dB electro-optic bandwidth of MZM with L = 200 µm: 28 GHz.
- Maximum operating frequency of MZM with L = 200 µm: 35.2 GHz.
- Transmission over 5 km SSMF fiber also plausible.
- Power penalty at 25 Gb/s data rate over 1 km and 5 km SSMF: 5 dB and 13 dB, respectively.

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Thank You