# *High-speed optical modulation based on carrier depletion in a silicon waveguide*

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*by*
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## *Outline of the Presentation*

1. *Introduction to Silicon based Optical Modulator*
2. *Proposed Design*
3. *Figure of Merits*
4. *Results & Discussion*
5. *Conclusion & Future Outlook*

# *Introduction*

***What the communication & Computing industries are looking for in modulators?***

*Bandwidth*
*Energy Efficiency*
*Low Deployment Cost*
*Fast Speed*

***To meet these need devices for optical modulators are based on technology platform like***

*Indium phosphide*
*gallium arsenide and*
*electro-optic crystals such as lithium niobate (LiNbOs)*

***However, there exist some limitations with them, like***

*High cost*
*Large size*
*Low yield*
*Lack of integration*

***SOLUTION - Si based modulator***

*Low optical absorption loss*
*CMOS compatibility*
*Ease of Integration*
*Low Cost*
*Size Reduction*

***However there exist some limitation with Silicon***

*No linear electro-optic coefficient (Pockel's effect)*
*Weak Kerr and Franz-Keldysh effects*

***Alternatives,***

***Strained Si***
*but electro-optic coefficient is very small*

***Strained Ge/SiGe quantum well structures***
*- Show strong electro-optic absorption due to the QCSE*
*- However, critical strain engineering is needed*

***This leaves only two physical effects for optical modulation in Si***

***Thermo-optic effect***

***Basic Idea behind the effect***
*Refractive index of silicon is varied by applying heat to the material*

*This effect is too slow for the high frequencies required by modern telecommunications applications*

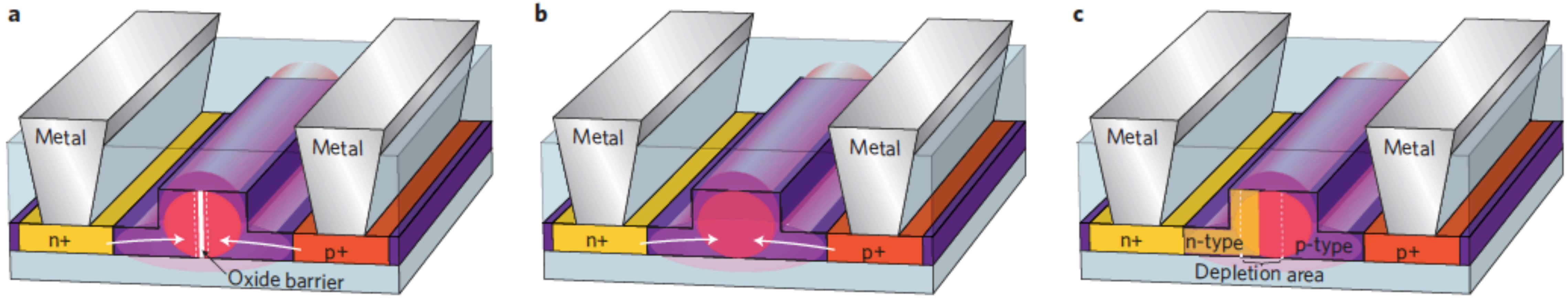
***Free carrier plasma dispersion effect***

***Basic Idea behind this concept***
Refractive index is varied by changing concentration of free charges in the material

*The change in RI occurs over a wide range of wavelength*

*Enable the fabrication of CMOS compatible active devices in silicon, where a relatively low carrier concentration change bring significant change in Index of the material*

# *Study of Different Mechanisms*




***Carrier Accumulation Model*** ***Carrier Injection Model*** ***Carrier Depletion Model***

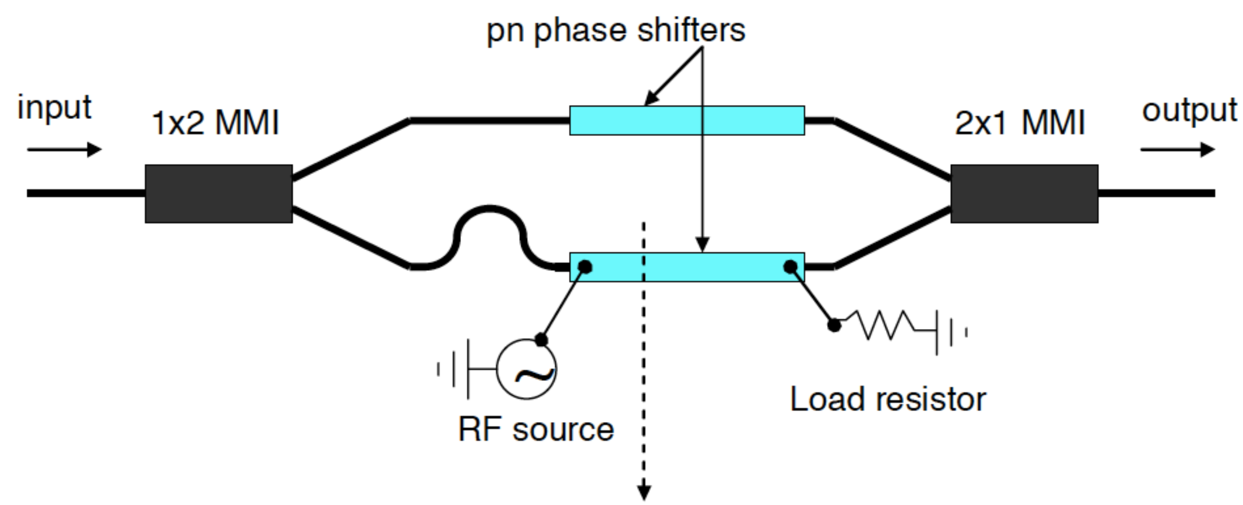
*Cross-sections of typical device structures implementing the three different mechanisms commonly used to electrically manipulate the free carrier concentrations in* ***plasma-dispersion-based silicon optical modulators***

*Reed, G., Mashanovich, G., Gardes, F. et al. Silicon optical modulators. Nature Photon* ***4,*** *518–526 (2010). https://doi.org/10.1038/nphoton.2010.179*

| ***Modulation Mechanism*** | ***Structure*** | *Extinction Ratio* | *Speed* | *Bandwidth* | *Modulation Efficiency* |
|---|---|---|---|---|---|
| *Carrier Injection (forward biased p-i-n diode) [Ref. 1]* | *Phase Modulator* | - | - | *100 MHz* | *21.2 Vcm* |
| *Carrier Injection (forward biased p-i-n diode) [Ref. 2]* | *Phase Modulator* | - | - | *100-500 MHz* | *21.5 Vcm* |
| *Carrier Injection (forward biased p-i-n diode) [Ref. 3]* | *MZI* | *16 dB* | *1 Gbps* | *1 GHz* | - |
| *Carrier Accumulation (MOS Capacitor) [Ref. 4]* | *MZI* | *3.8 dB* | *6-10 Gbps* | *10 GHz* | - |
| *Carrier Depletion (reverse biased p-n junction) [Ref. 5]* | *MZI* | - | - | *50 GHz* | - |
| *Carrier Depletion (reverse biased p-n junction) [Ref. 6]* | *MZI* | *>20 dB* | *30 Gbps* | *20 GHz* | *4 Vcm* |

# *Proposed Design*

*based on a Mach-Zehnder interferometer (MZI) with reverse biased pn diode embedded in each of the two arms*



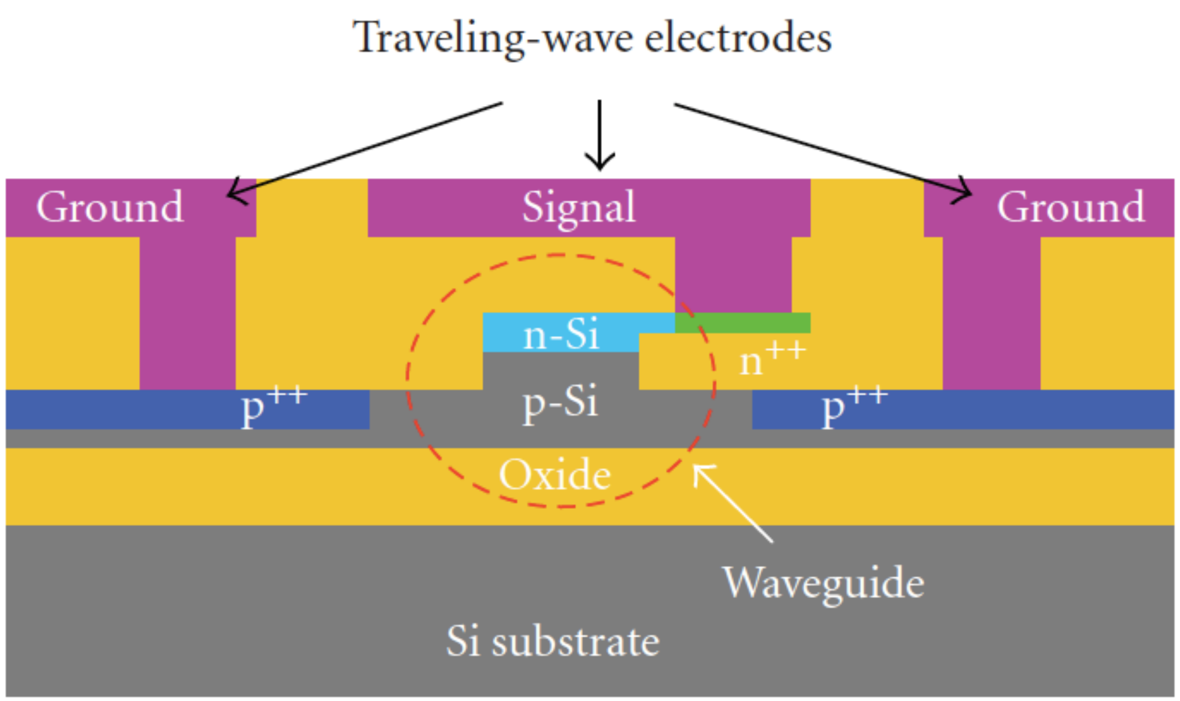

*Proposed high-speed silicon modulator based on a Mach-Zehnder Interferometer (MZI) with a reverse biased pn diode*

## *USP of the Proposed Design*

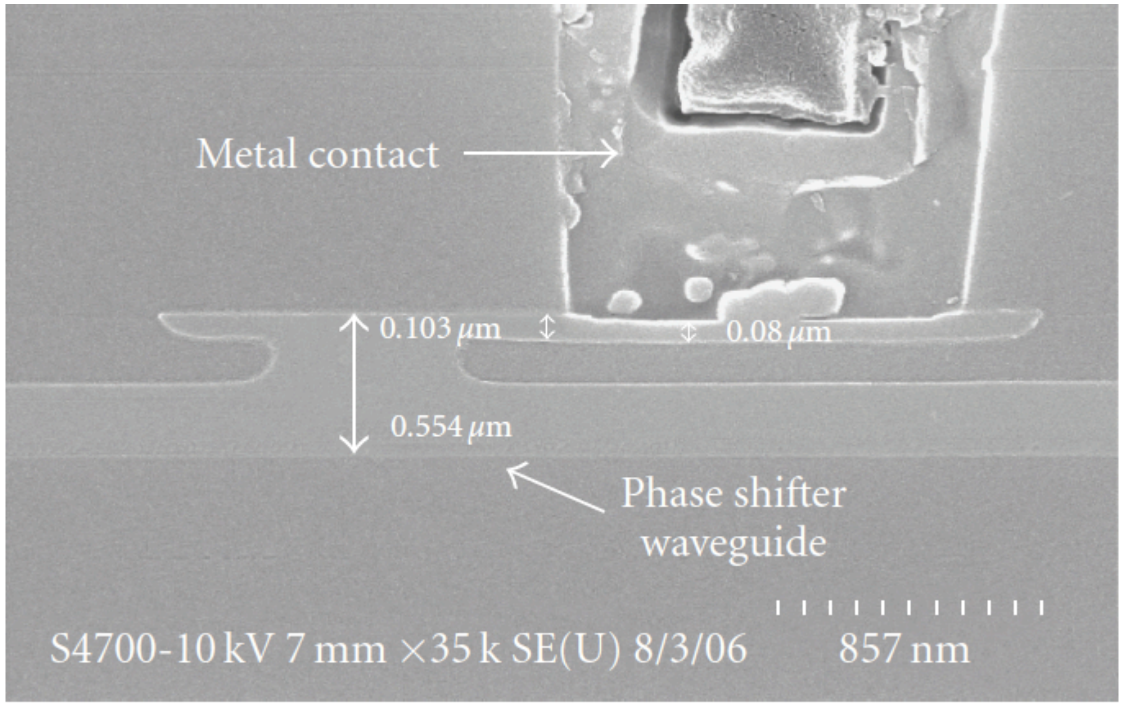
- *better phase modulation efficiency*
  - *due to submicrometer size waveguide*
  - *which offer single mode behaviour for wavelengths around 1.55 $\mu m$*

- *Use of multi-mode interference (MMI) couplers*
  - *provide broader range of operating wavelengths*
  - *larger fabrication tolerance*
  - *low losses in comparison to other coupler types*

# Proposed Design




*Schematic cross sectional view of the proposed phase shifter*

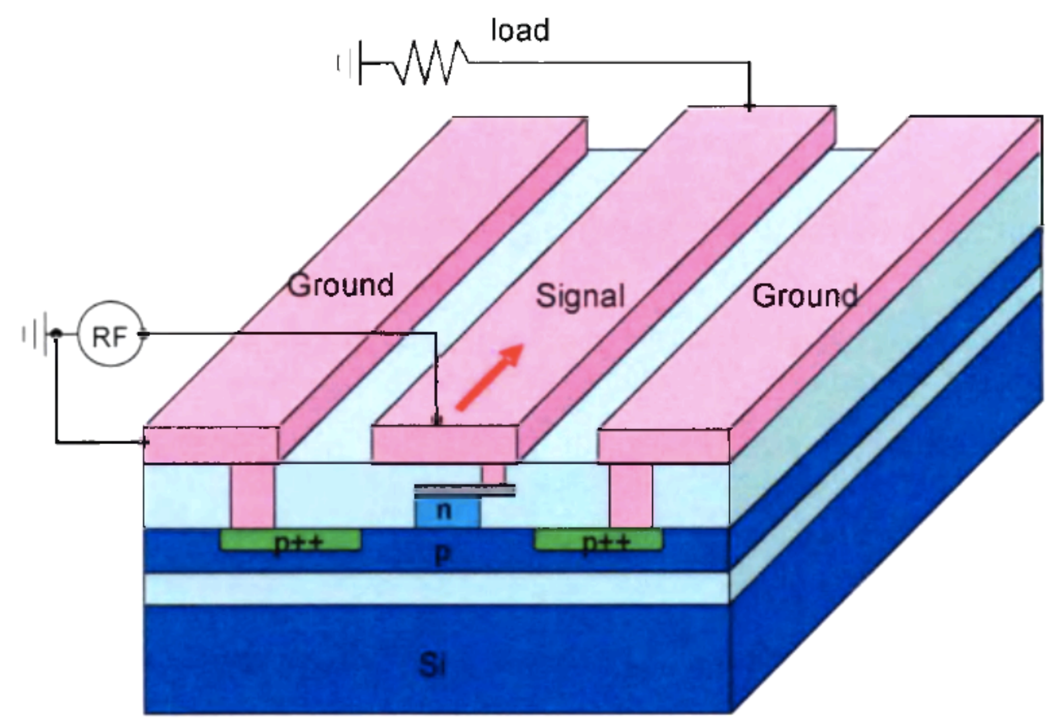



*Scanning electron microscope (SEM) image of a pn diode phase shifter waveguide.*

## *Building blocks of proposed phase shifter*

- *Rib waveguide with p-type doped Si on the bottom*
- *Wide n-type doped Si cap layer (the Si wing)*
- *Heavily p-doped two slab regions*
- *Travelling wave electrode based on coplanar waveguide structure*
  *- consist of metal for ground and RF Signal propagation*

# Figure of Merits




Schematic 3-D view of the proposed phase shifter

### Modulation bandwidth (MHz / GHz / THz)

- *on of the important figure of merit for an optical modulator*
- *define as the frequency at which the modulation is reduced to 50% of its maximum value*

### Modulation Speed (Gbps)

- *The speed of a modulator is commonly characterized by its ability to carry data at a certain rate*

### Footprint ($\mu m^2$/ $mm^2$)

### Insertion loss (dB)

- *Define as the lost optical power when the modulator is added to a photonics circuit*

### Power consumption (pJ/bit)

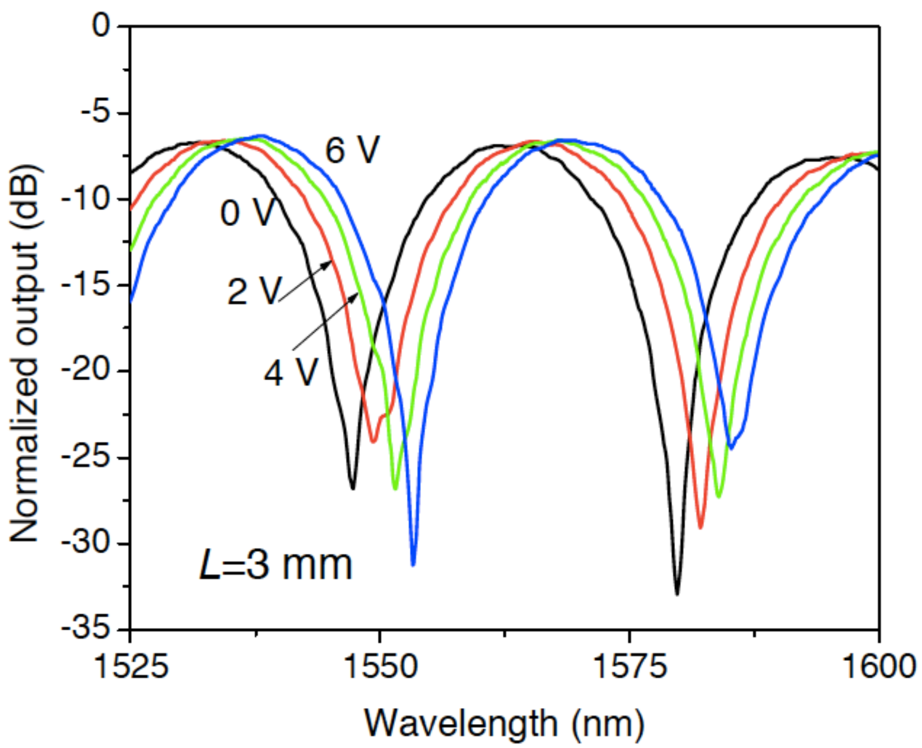
- *The energy expended in producing each bit of data*

### Modulation depth (dB)

- *also known as the* ***extinction ratio***

- *defined as* $10log\frac{I_{max}}{I_{min}}$

# Results



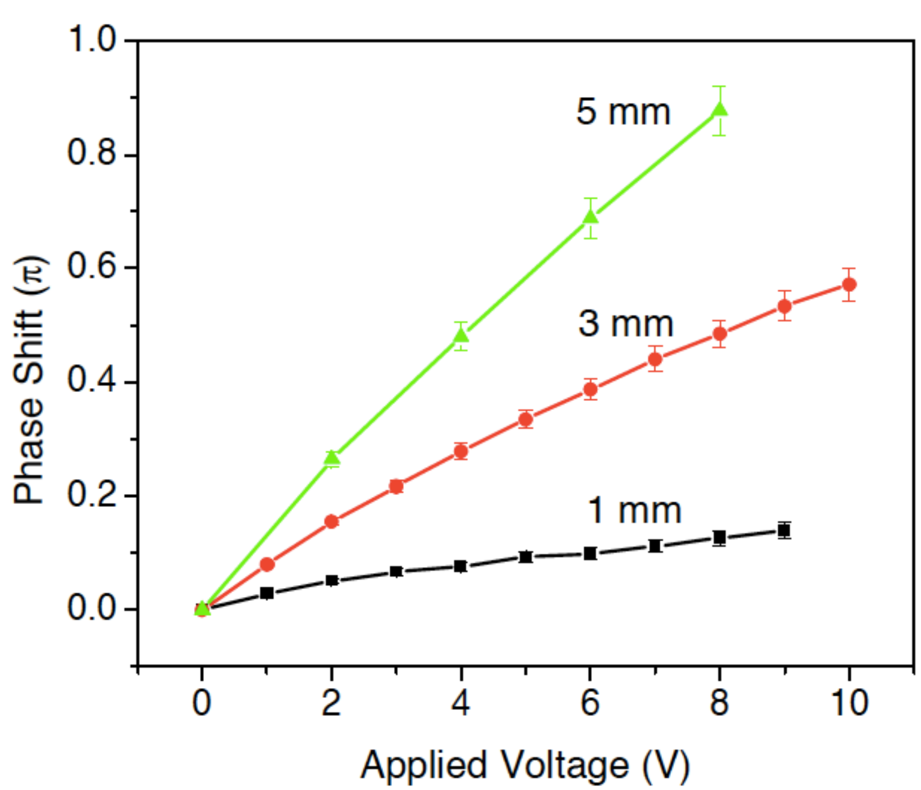

*The output spectra of a MZI modulator having 3 mm long phase shifters for various voltages applied to one of the arms*

*The MZI output spectrum shows a red-shift with increasing applied voltage*

*For the asymmetrically doped pn junction the doping width can be expressed by*

$$W_D = \left(\frac{2\epsilon_o \epsilon_r (V_{Bi} + Vapp)}{eN_A}\right)$$

| | |
|---|---|
| $W_D$ | *Depletion width* |
| $\epsilon_o$ | *vacuum permittivity* |
| $\epsilon_r$ | *low-frequency relative permittivity of silicon* |
| $V_{Bi}$ | *built-in voltage* |
| $V_{app}$ | *applied voltage* |
| $e$ | *electron charge* |
| $N_A$ | *acceptor concentration* |

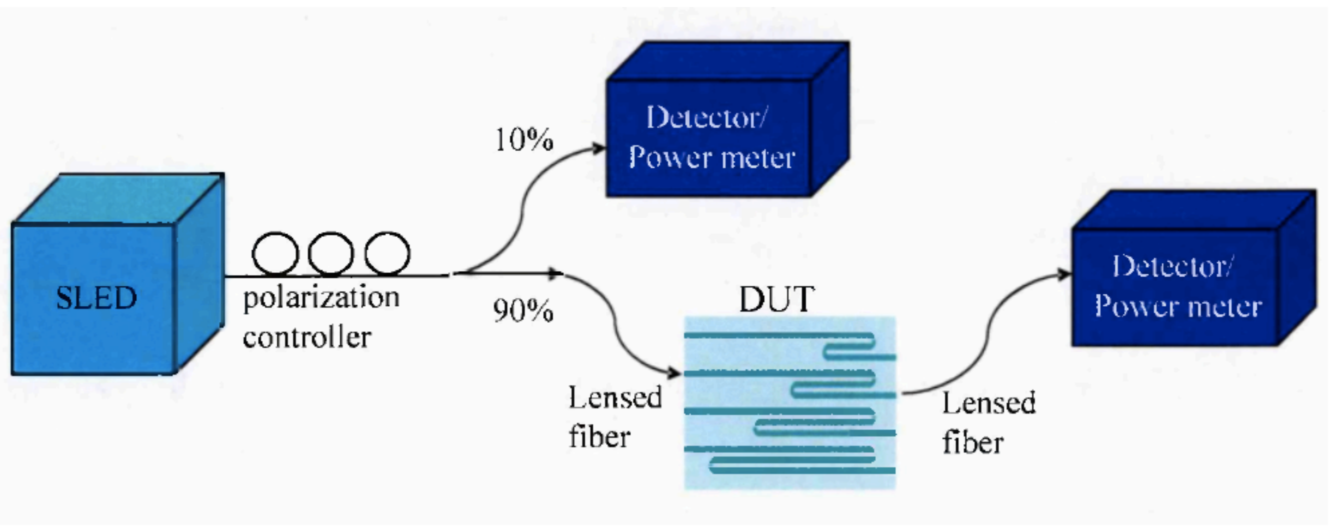



*The phase shift of an individual phase shifter vs. the drive voltage for the wavelength round 1550 nm for different phase shifter lengths*

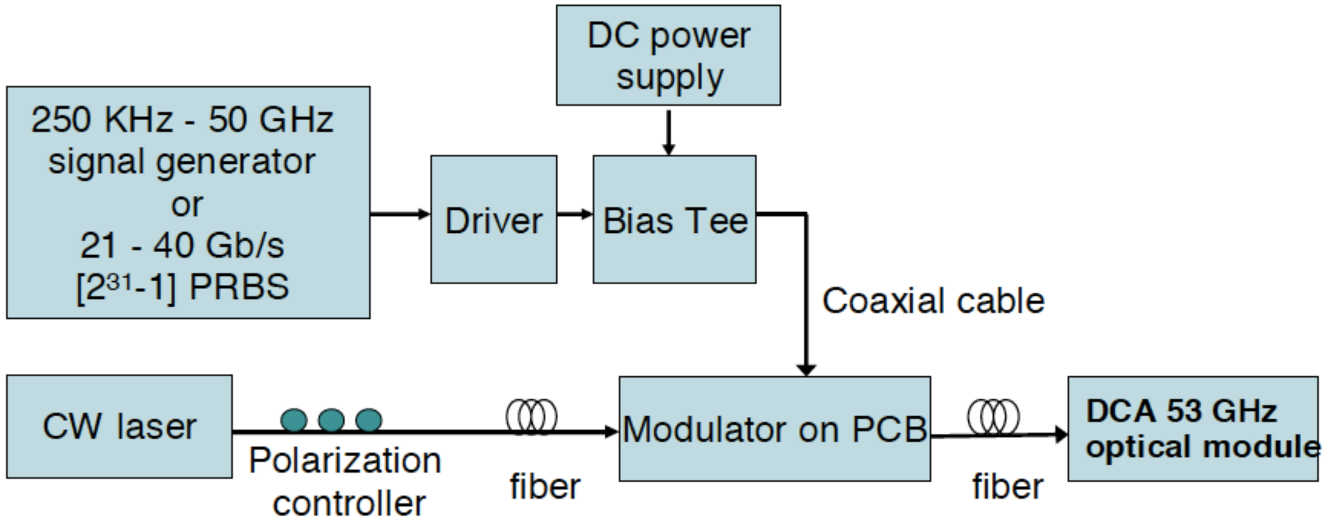
*As expected, phase shift increases with both device length and applied voltage*

*The phase voltage curves are not perfectly linear partly because the depletion width does not increase linearly with voltage*

# Device Characterisation Setup




*Schematic of the optical test setup for* ***cutback measurement***

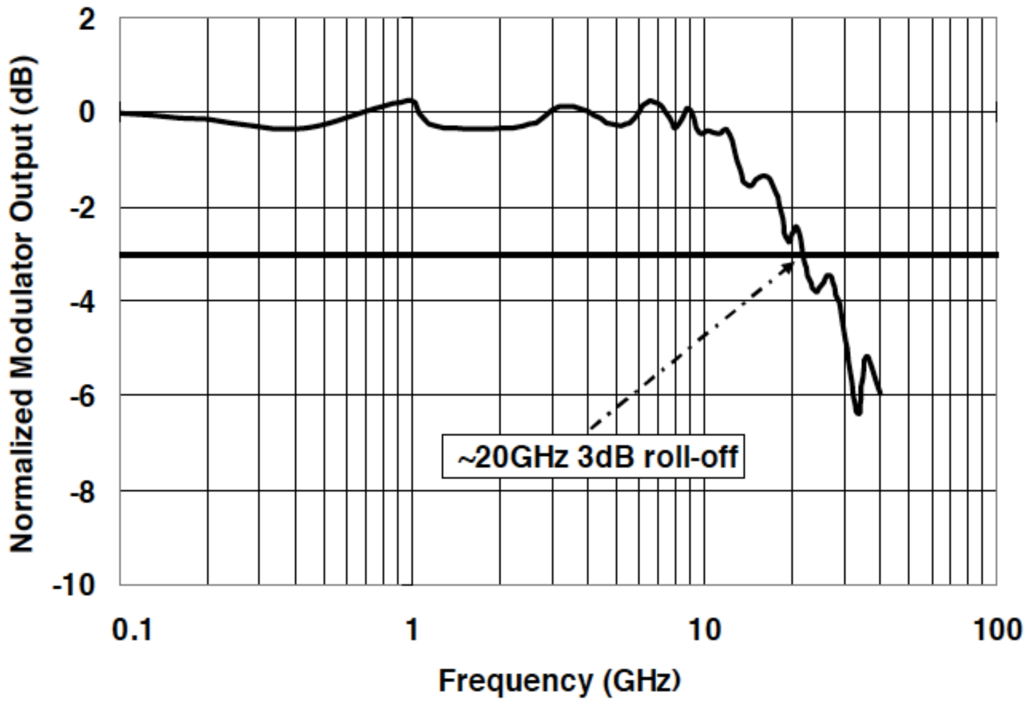



*Experimental setup for measuring the 3-dB roll-off and data transmission of the p-n diode modulators*

*Yield accurate data for coupling and transmission loss*
*- coupling loss*
*- passive waveguide loss*
*- phase shifter loss*
*- MZI loss*
*- extinction ratio (ER).*

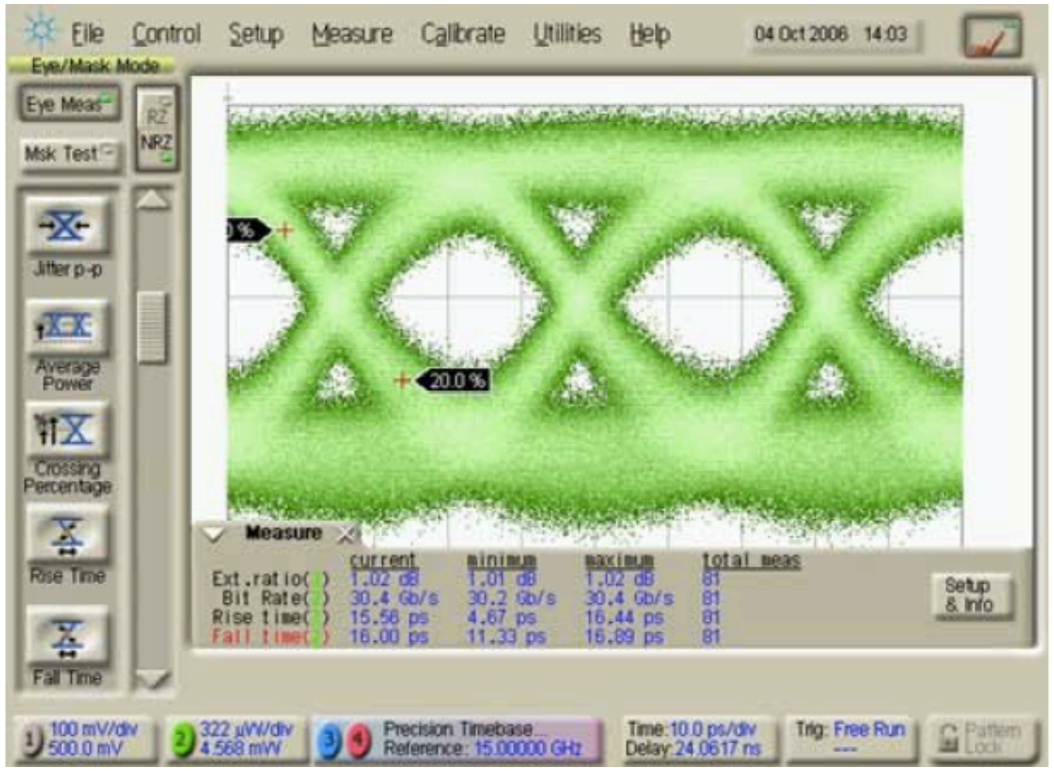
*Characterisation of high frequency performance of Si modulator*
*- 3 dB frequency roll-off (modulator bandwidth )*
*- data transmission capability*
*using*
*Single ended drive scheme depicted int the figure above*

# Optical Testing




*Optical response of a silicon modulator as a function of the RF frequency for a MZI having 1 mm long phase shifter.*

*This optical data is the normalised response of the modulator, obtained by dividing the measured optical signal by the corresponding input electrical drive for all frequencies*




*Optical eye diagram of the MZI modulator having a 1 mm long phase shifter*

*The open eye diagram suggests that the modulator is capable of transmitting data at 30 Gb/s, which is consistent with the 3 dB roll-off frequency of ~20 GHz*

# *Conclusion*

- *The paper presented design, fabrication, and characterization of a* ***high speed silicon optical modulator*** *based on*
  *-* ***electric-field-induced carrier depletion effect*** *in a SOI waveguide* ***containing a reversely biased pn junction***

- *The proposed design of the Si modulator successfully demonstrated high speed operation with a*
  *- 3 dB roll-off frequency (Bandwidth) of ~**20 GHz***
  *- Data transmission of* ***30 Gb/s***
  *- Extinction Ration* ***>20 dB***
  *- Modulation Efficiency* ***4 V cm***

# *Scope for Further Improvement*

- *Increase phase efficiency by*

*- Modelling pn junction placement in the waveguide by operating the MZI in a push-pull configuration*

- *Scaling Bandwidth by*

*- Lowering the RF loss of the travelling-wave electrode with proper termination resistor usage*

- *Reducing Insertion Loss by*

*- Using selective epitaxial growth of silicon for the n-type silicon cap*

### *Fun Fact*

*Same year another paper published by the same authors become a key milestone for Si modulation by demonstrating 30 GHz bandwidth and 40 Gb/s data transmission*
*They addressed all the limitations discussed above*



*Liao, L., Liu, A., Rubin, D., Basak, J. A. B. J., Chetrit, Y. A. C. Y., Nguyen, H. A. N. H., ... & Paniccia, M. A. P. M. (2007). 40 Gbit/s silicon optical modulator for high-speed applications. Electronics letters, 43(22), 1196-1197.*

# Future Outlook

***Modulator based on Graphene shows a future potential in getting GHz regime high speed modulator***

**Table 1 | Comparison of modulators based on different material platforms**

| Material | $V_{\pi}L$ (V mm) | Insertion loss ($dB\ mm^{-1}$) | $FOM_{PM}$ (V dB) | Refs |
|---|---|---|---|---|
| $LiNbO_3$ (E) | 50–100 | 0.4 | 20–40 | 36 |
| $LiNbO_3$ (E)[a] | 18 | 0.3 | 5.4 | 37 |
| InGaAsP/InP (E) | 5–10 | 0.7 | 3.5–7 | 38,39 |
| Si photonics (E) | 10–20 | 1–2 | 10–20 | 94–103,125 |
| Graphene (T) | 0.7–2.8 | 0.1–1.2 | 1–2 | 72,79,87 |

E, experiment; T, theory; [a]Small-mode $LiNbO_3$ rib waveguide (width = 900 nm, rib height = 400 nm and slab thickness = 300 nm)

*Romagnoli, M., Sorianello, V., Midrio, M. et al. Graphene-based integrated photonics for next-generation datacom and telecom. Nat Rev Mater* ***3,*** *392–414 (2018). https://doi.org/10.1038/s41578-018-0040-9*

| *Modulation Principle* | *Footprint* | *Extinction Ratio* | *Speed* | *Bandwidth* | *Modulation Efficiency* |
|---|---|---|---|---|---|
| *electro-absorption [Ref. 7 ]Jan 2018* | *300* | *35 dB* | *10 Gbps* | *5 GHz* | *0.28 V cm* |
| *electrorefractive-absorpion [Ref . 8] Jan 2018* | *40* | *25 dB* | | | *0.129 V cm* |
| *electro-absorption [Ref. 9 ] 2015* | *45* | *28 dB* | *150* | *30 GHz* | |
| *electro-absorption [Ref. 10 ] 2011* | *25* | *4 dB* | *1.2* | *~35 GhZ* | |

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***Thank you for your attention !***

# *Appendix I*

***How Plasma Dispersion effect works***

$$\Delta N$$

$$\downarrow$$

$$\Delta n$$

$$\downarrow$$

$$\Delta n_{eff}$$

$$\downarrow$$

$$\Delta\phi = \frac{2\pi}{\lambda}\Delta n_{eff} L$$

*Using an interferometer or resonant device, this phase modulation is transformed into the desired intensity modulation.*

$\Delta N$ *concentration of free charges in silicon*

$\Delta n$ *change in the refractive index of the material*

$\Delta n_{eff}$ *change in the effective refractive index of the propagating optical mode*

$\Delta\phi$ *optical phase change*

# *Appendix II*

**Box 4 | Mechanisms of optical modulation**

In a photonic circuit, optical modulation is obtained either by varying the absorption of the material through which propagation takes place or by varying its refractive index ($n$). The former case is known as electro-absorption modulation[59,143,308–311] and the latter as electro-refractive modulation. Phase modulation can be turned into amplitude modulation using a Mach–Zehnder interferometer (MZI)[312–316].

**Modulation in silicon**

***Plasma dispersion.*** This occurs when Si absorbs a photon and an electron in the conduction band or a hole in the valence band is excited and occupies an available state in the same band[84]. This process may appear as absorption[108]. As a consequence of the Kramers–Kronig relations[317], both absorption and $n$ vary with carrier concentration, $N$. In the case of Si, the following equations apply for variations in absorption ($\Delta\alpha$) and refractive index ($\Delta n$) at 1.3 μm and 1.55 μm (REF.[108]):

$$\Delta\alpha = 8.5 \times 10^{-18}\Delta N_e + 6.0 \times 10^{-18}\Delta N_h \quad (12)$$

$$\Delta n = -8.8 \times 10^{-22}\Delta N_e - 8.5 \times 10^{-18}(\Delta N_h)^{0.8} \quad (13)$$

***Franz–Keldysh effect.*** In semiconductors, on application of an electrical field, the bands can be distorted, causing a shift in absorption[64,65,318], which can be used to modulate transmission[60,66]. In Si photonics, modulation through the Franz–Keldysh effect has been shown in GeSi alloys with <1% Si, grown on Si waveguides[60,66]. State-of-the-art GeSi electro-absorption modulators[319] integrated in Si photonics circuits operate at rates of up to 100 Gb s$^{-1}$.

***Quantum-confined Stark effect.*** This is observed when an electrical field is applied to a quantum well[67]. In the absence of such a field, electrons and holes occupy a discrete spectrum of energy bands. The electric field modifies the bands, causing variations in absorption and n, analogous to the Franz–Keldysh effect[68].

**Modulation in graphene**

In graphene, $\alpha$ and $n$ depend on $E_F$ and the intraband and interband transitions of electrons and holes excited by impinging photons[73,82,320,321]. In undoped SLG, the absorption of photons of any wavelength is allowed[69]. However, if $E_F$ is increased above half the photon energy, because of Pauli blocking[83], carrier excitation is inhibited, and SLG becomes transparent[83]. Electro-absorption modulation in SLG has been achieved by $E_F$ modulation[71,72]. $E_F$ modulation also causes phase modulation because $\alpha$ and $n$ depend on $E_F$ (REF.[80]). When interband transitions are inhibited, absorption can occur only as a result of intraband transitions. These are primarily a consequence of long-range scattering induced by, for example, impurities, trap states and screening. A convenient way of describing the overall effect of intraband transitions is the scattering time $\tau$ (BOX 3). The longer the $\tau$, the lower the intraband absorption, that is, the more transparent SLG becomes in the $E_F$ range where interband transitions are excluded because of Pauli blocking. In this case, an $E_F$ modulation results in variations in $n$, thus enabling phase modulation[70,77,86].

*Romagnoli, M., Sorianello, V., Midrio, M. et al. Graphene-based integrated photonics for next-generation datacom and telecom. Nat Rev Mater **3,** 392–414 (2018).*
*https://doi.org/10.1038/s41578-018-0040-9*

# Appendix III

**Box 1 | Basic concepts of optical modulation**

The aim of a communication system is to transfer a message from one point to another[286]. Whether the message brings news to the receiver depends on the unpredictability of the message[286]. There is no point in transmitting a message if the receiver already knows its content. In digital communication systems messages are sent by modulating a source into sequences of bits[89]. The amplitude or phase of a light source can be used to encode the electrical signal into light that propagates along the optical channel. The most common method is binary encoding[287] by amplitude modulation, which is achieved by inducing ones (i.e. 'light on') and zeros (i.e. 'light off') by absorption or interference modulation[288]. The first case is known as electro-absorption modulation[61], and the second as Mach–Zehnder interferometer (MZI) modulation[61]. Phase modulation is an alternative used in complex modulation formats to achieve high-spectral-density[289] communication channels and maximize the ratio of data rate to spectral bandwidth.

In integrated photonics, the amplitude and phase can be modulated by acting on the electro-optical material that constitutes the waveguide[290] or, in the case of single-layer graphene (SLG), the material placed on top of the waveguide core[70–72,77,291]. The communication link is terminated with a receiver containing a photodetector. This system can discriminate an encoded signal, for example a binary signal, against the channel noise, and transfer the optical signal into a signal that can be processed by the electronics. The communication link is typically an optical fibre, and its performance is, among other factors, limited by the accumulated chromatic dispersion of the optical fibre (ps $nm^{-1}$ $km^{-1}$ multiplied by the length of the link, which determines the inter-symbol interference) and the power penalty[292] (the ratio of the average power required for a given value of extinction ratio to the power required for the ideal case of infinite extinction ratio). The extinction ratio is the ratio of the signal power representing the logical bits '1' and '0' and is commonly expressed in dB. The average power is the mean of the power of the '1' and '0' bits. For example, if the power for the '1'-bit is 1 mW and that of the '0'-bit is 0.5 mW, the extinction ratio is $10\log_{10}(2) \sim 3$ dB, and the average power is 0.75 mW. A low extinction ratio indicates that a fraction of the power is un-modulated, which leads to a reduction in the receiver signal.

The term datacom describes communication within data centres, comprising links of short lengths (~2 km) according to the Ethernet Alliance. The term telecom is used for longer links[85], from tens of kilometres to transoceanic distances. In datacom, link lengths are shorter, hence, smaller extinction ratios are tolerable in some cases, because the priority is to reduce size[293], insertion loss and power consumption[293]. In telecoms, the penalty contributions arise from chromatic dispersion, channel losses, nonlinearities and accumulated amplified spontaneous emission noise of erbium-doped optical amplifiers[85]. Although chromatic dispersion can be managed by a combination of appropriate signal coding and digital post-processing at the receiver[294] and losses can be compensated by optical amplifiers, nonlinearities and noise remain crucial impairment factors[85].

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