lecture: *Optical Modulators in Silicon Photonic Circuits*

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Oct 2009

Outline

I-Introduction :

- Optical modulation
- Figure of merits

II-Mechanisms for Optical Modulation in group IV materials (Si, Ge)

- Electroabsorption
- Electrorefraction
- Free carrier concentration variation

III-Waveguide integrated silicon optical modulator using free carrier concentration variations

- Waveguide integrated optical modulator considerations
- Silicon optical modulators using free carrier concentration variations:
  - Carrier injection in PIN diode
  - Carrier shifts in Bipolar Mode Field Effect Transistor
  - Carriers accumulation in Metal Oxyde Semiconductor capacitors
  - Carrier depletion in PN/PIN diode

Introduction

Optical telecommunications

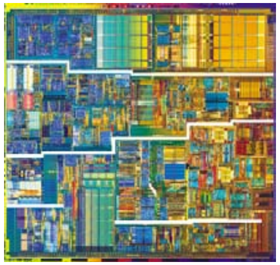
Higher integration density

Reduced component costs

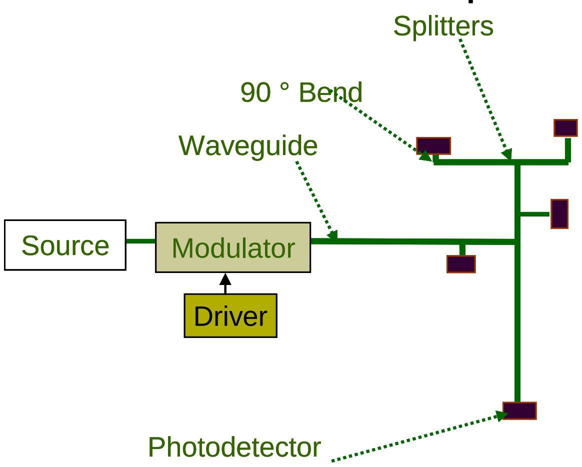
Optical interconnects

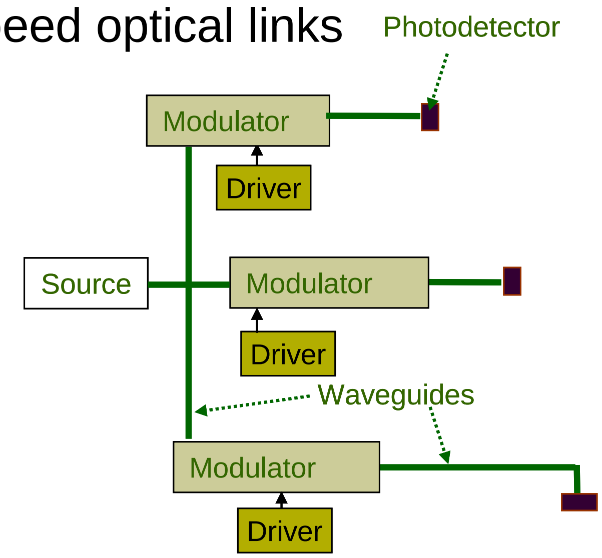
Clock signal distribution

High data rate links



Example of high speed optical links





Optical modulation

Direct modulation of the laser beam

- Simple ☺
- Cost-effective ☺
- Compact ☺
- Chirp: output frequency shifts with drive signal 😐
  - Carrier induced (Transient chirp)
  - Temperature variation due to carrier modulation (slow chirp)
- Limited extinction ratio 😐
  - Laser is not turn off at 0-bits
- Impact on "distance . bit-rate" product 😐

External modulation

- Additional component 😐
- Additional loss 😐
- Higher speed ☺
- Large extinction ratio ☺
- Low chirp ☺
  - Push pull configuration
- Low modulation distortion ☺

High performance optical transmission systems are based on external modulation

External optical modulator

III-V modulator on Si

- Bonding technology 😐
- Limitation of the number of modulator on the silicon chip 😐
- Cost 😐
- Well known ☺
- Good performances ☺
- Mature device ☺

Silicon-based modulator

- Less mature device 😐
  - Development is required
- Physical effect for optical modulation: 😐
  - more limited in silicon than in III-V material
  - Less flexibility on material alloys
- Compatible with CMOS technology ☺
- Low cost ☺
  - for high production volume

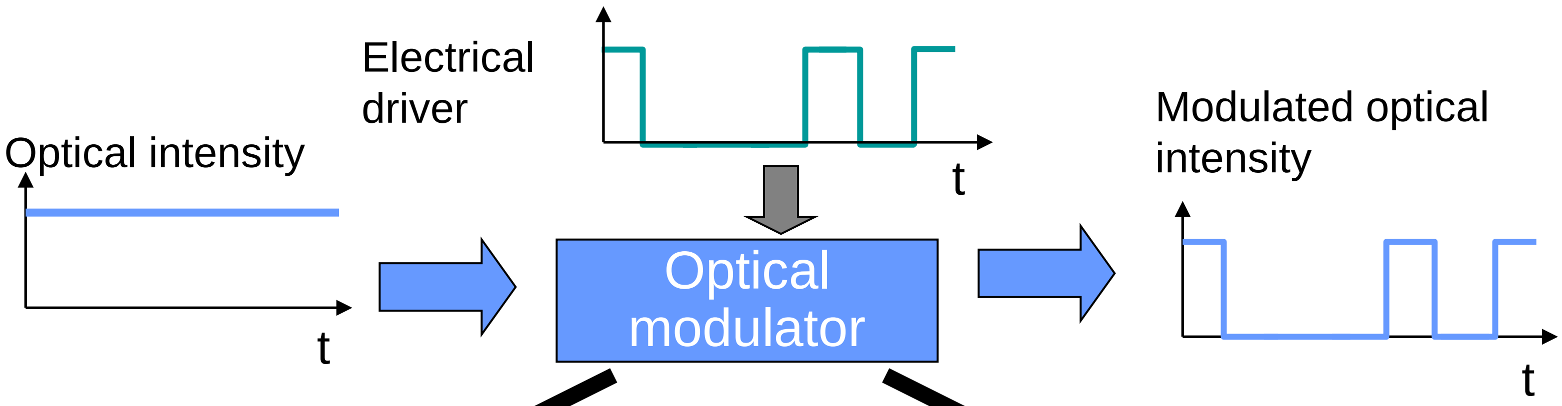
External optical modulator

- Silicon based modulator: key element to develop high speed optical links in the telecom wavelength range

Main challenges for optical modulators:

- Compatibility with silicon technology
- Low bias voltage
- High bandwidth
  - Frequency operation > 10 GHz
  - High data operation from 10 Gbit/s to 40 Gbit/s
- Integration in submicron SOI waveguide
  - Low insertion loss
  - Large extinction ratio

Optical modulation



Electroabsorption

Absorption coefficient variation under an electric field

↓

Intensity modulation

Electrorefraction

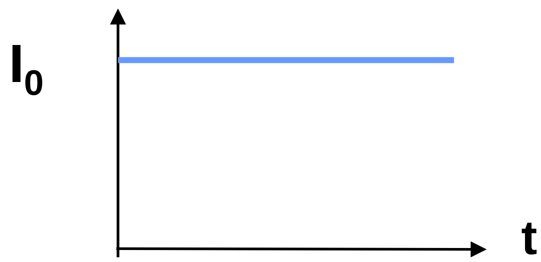
Refractive index variation under an electric field

Phase modulation

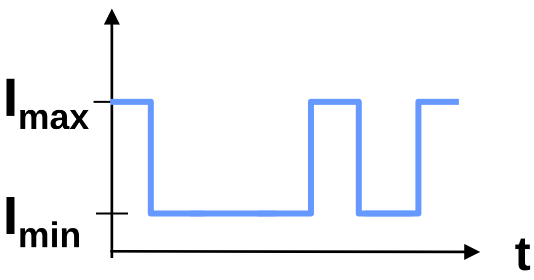
↓ *interferometer*

Intensity modulation

Figure of merits

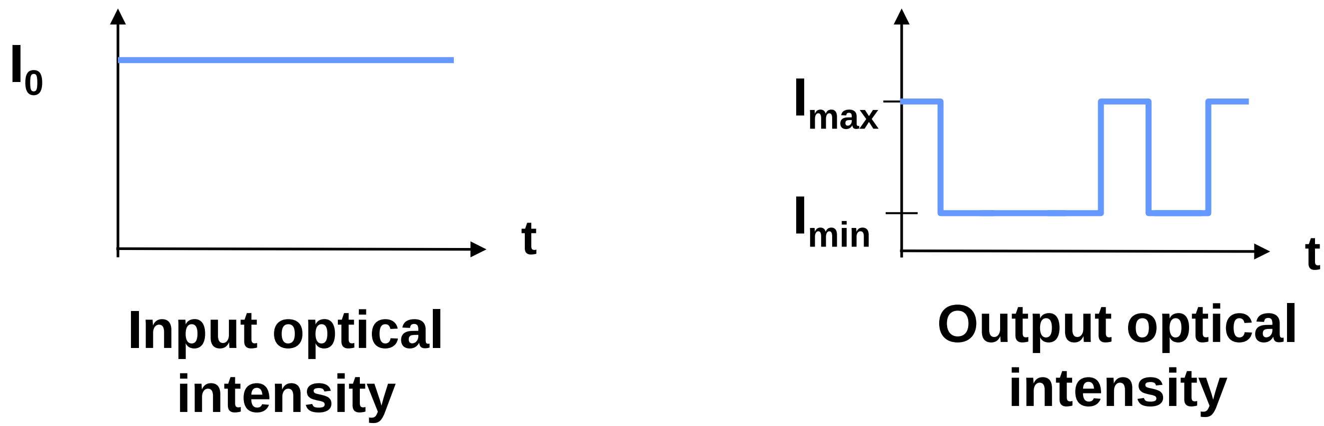


Input optical intensity



Output optical intensity

- Basic criterion:
  - «Distinction» of the minimum (I_{min}) and the maximum (I_{max}) intensity levels
  - Loss



- Distinction between I_{min} et I_{max}
  - MD : Modulation Depth - %

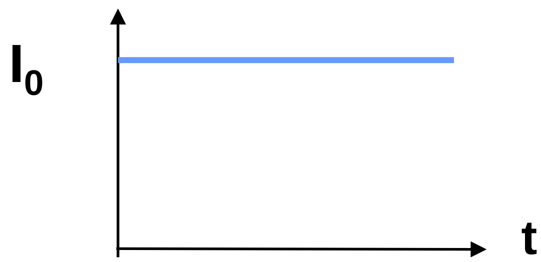
$$MD = \frac{I_{max} - I_{min}}{I_{max}}$$

  - Extinction ratio (ER) - dB

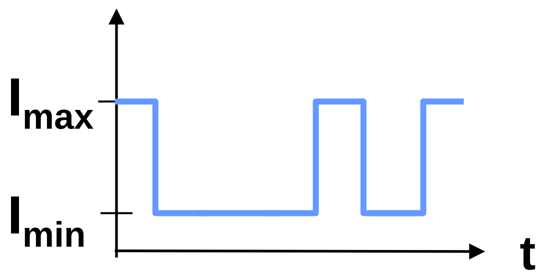
$$ER = 10 \log \left(I_{max} / I_{min} \right)$$

Example:

If I_{max}=0.1mW and I_{min}=0.01mW - MD=90% et ER=10 dB



Input optical intensity



Output optical intensity

- Insertion loss
  - Loss at « ON » state

$$P = 10\log\left(\frac{I_0}{I_{max}}\right)$$

Example:

If I_0=1mW and I_{max}=0.1mW then P = 10dB

Modulator speed

What are the limitations of the modulator speed?

- Intrinsic speed
  - Physical phenomenon limitation
- RC time constant
  - Electrical circuit limitation
- RF signal propagation
  - impedance adaptation
  - Matching of electrical and optical velocities

Modulator speed

- ***Intrinsic speed:*** Time constant of the physical phenomenon responsible of the interaction between the semiconductor and the EM wave. The intrinsic speed depends on the physical effect used:

  - ***Electro-absorption :***
    - The cut-off wavelength (at the absorption edge) is shifted by applying an external voltage to the semiconductor: Intrinsically high speed

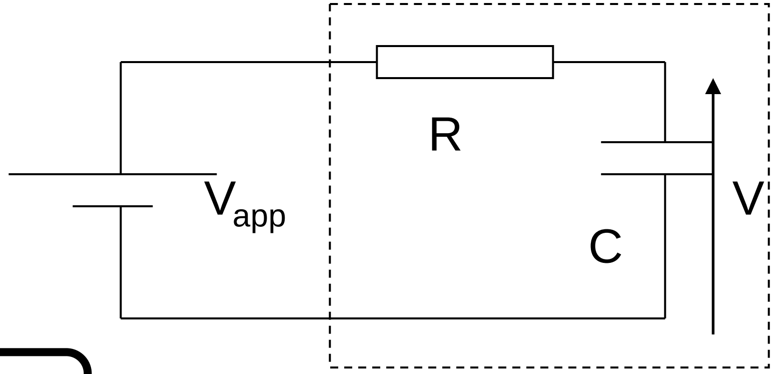
    (f >>GHz).

  - ***Electro-refraction:*** depends on the index variation origin
    - Thermal variation of the refractive index : very slow
    - Free carrier concentration variation : time constant from ps (carrier depletion) to ms (carrier recombination)

Bandwidth of the electrical circuit

The equivalent electrical scheme for MOS capacitor and pin diode under reverse bias voltage is a capacitor

Modulator electrical scheme



$$f_c = \frac{1}{2\pi.RC}$$ ↗ when R and/or C ↘

$$V = \frac{V_{appl}}{1 + j2\pi RCf} = \frac{V_{appl}}{1 + j\frac{f}{f_C}}$$

- RC time constant should be minimized
  - Resistance R
    - Increase of the doped regions of contacts
    - Decrease of the distance between contacts and active region
  - Capacitance C
    - Directly given by the geometry and the modulator optimization process

Modulator speed

RF electrical signal propagation

- RF signal at f> GHz is a wave propagating on an electrical waveguide.
  - Coplanar electrodes are mainly used. They have to be defined according to the optical modulator geometry and the required cut-off frequency

- Copropagating electrical and optical waves:
  - Matching of electrical and optical wave velocities

- Impedance adaptation is required to avoid electrical signal reflection
  - 50 ohms is the impedance of the most RF equipments

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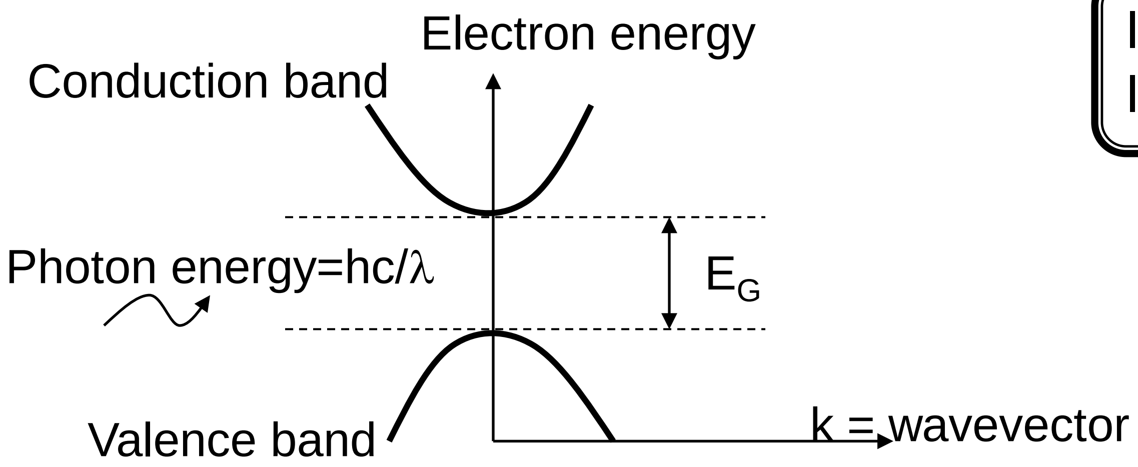
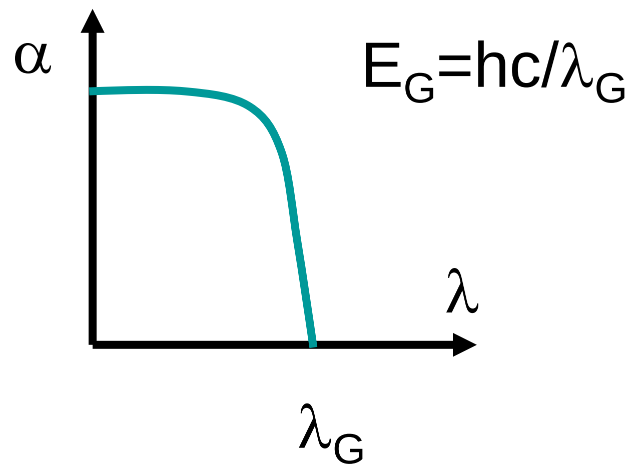
Absorption in direct bandgap SC

- Interaction between semiconductor (SC) and optical wave
- By applying an electrical command, the material should be absorbant or transparent.
- Photon absorption in SC :
  - Energy conservation
  - Wavevector conservation



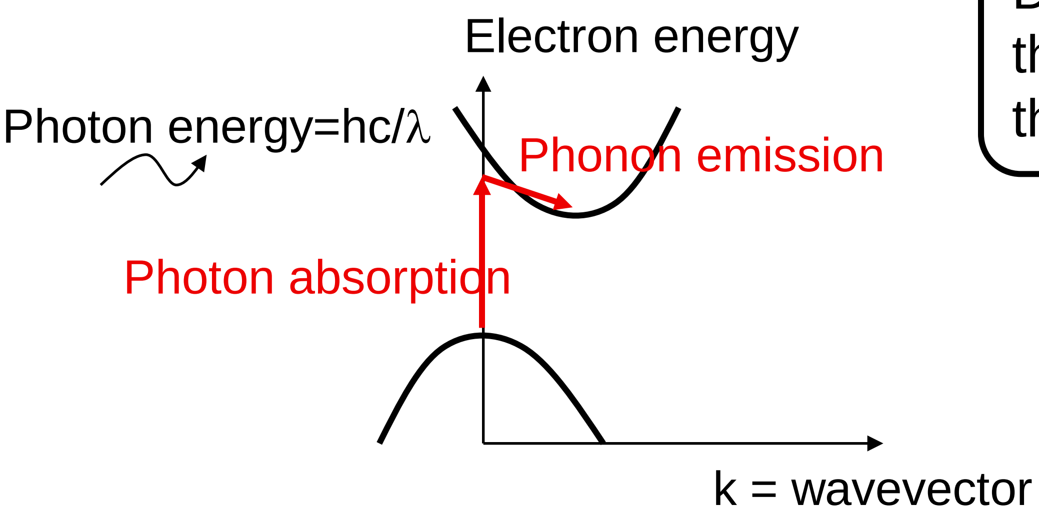
Direct bandgap semiconductor

If $hc/\lambda < E_G$ ⇨ Transparent
If $hc/\lambda > E_G$ ⇨ absorbant



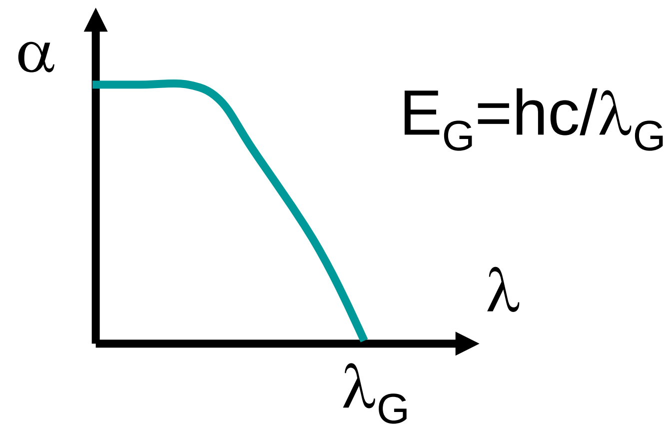
Absorption in indirect bandgap SC

- A two-step phenomenon is required in indirect bandgap semiconductor (SC)
  - Wavevector is conserved via a phonon interaction *(phonon is a quantum of lattice vibration)*



indirect bandgap semiconductor

Due to this phonon mechanism, the absorption probability is lower than in the previous case

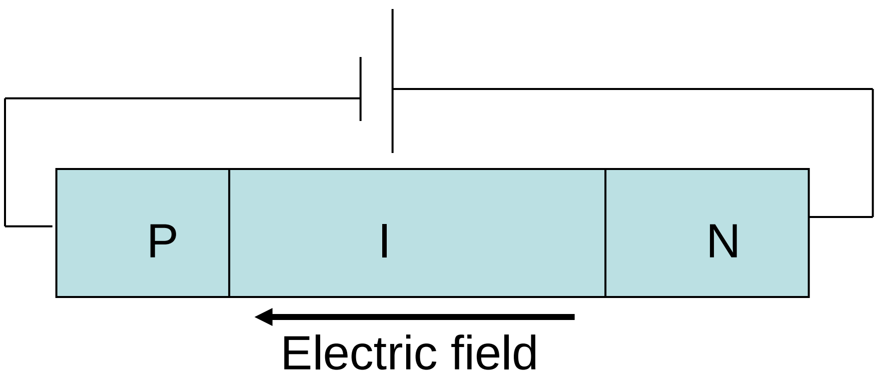


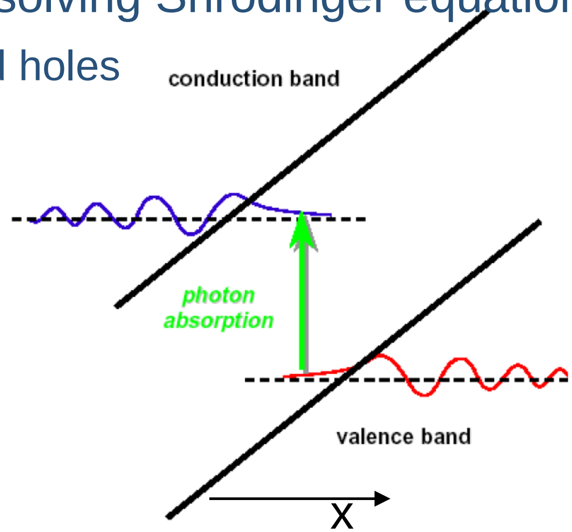
- III-V semiconductors (GaAs, InGaAs et InGaAsP,…): direct gap
- Group IV semiconductors (Si, Ge,…): indirect gap

The absorption band edge is less abrupt than for direct band gap SC

Franz –Keldysh effect

- Homogeneous semiconductor under electrical bias
- Example: pin diode under reverse bias voltage
- The absorption phenomenon is described by solving Shrödinger equations
  - Determination of wavefunction of electrons and holes





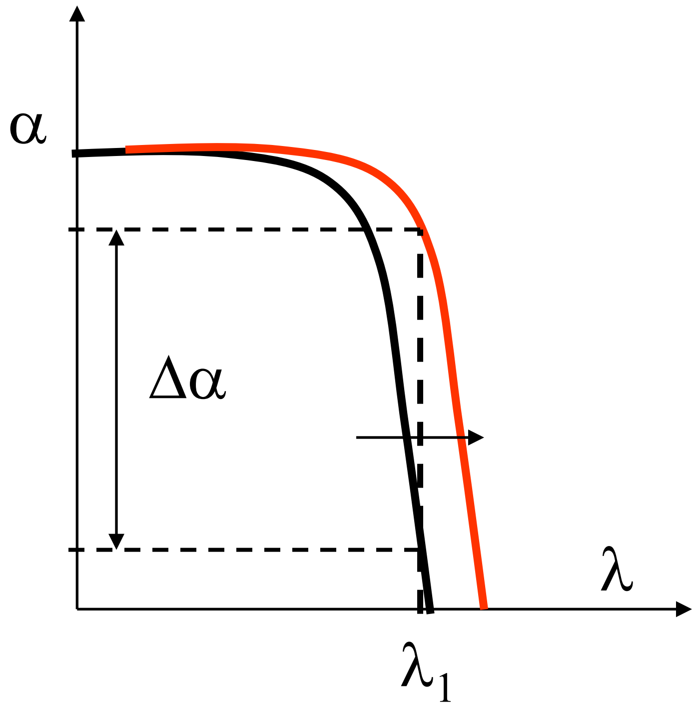
Band edges are tilted due do the electrical field

- Electron and hole wavefunctions extends in the bandgap:
  - Overlap between electron and hole wavefunctions allows absorption of photon with an energy lower than bandgap energy.

Franz-Keldysh effect: photon-assisted tunnelling absorption effect

Franz –Keldysh effect

- Optical modulator based on Franz-Keldysh effect:
  - Red-shift of the absorption band-edge



- Direct bandgap SC
  - Absorption coefficient variation
    - Abrupt absorption band edge
- Indirect bandgap SC
  - Absorption coefficient variation is reduced

Electroabsorption in group IV materials

Bandgap	Bulk-Si	Bulk-Ge
Direct	3.3 eV 0.37µm	0.8 eV 1.55 µm
Indirect	1.13 eV 1.1µm	0.66 eV 1.88µm

- Silicon is transparent at λ > 1.1 µm, and is an indirect bandgap material => Electroabsorption is not possible at telecommunication wavelengths
- Germanium direct bandgap energy is at telecommunication wavelengths. As the direct bandgap energy is not very different from the indirect bandgap energy, germanium absorption is not so different from a direct bandgap material

Franz-Keldysh effect

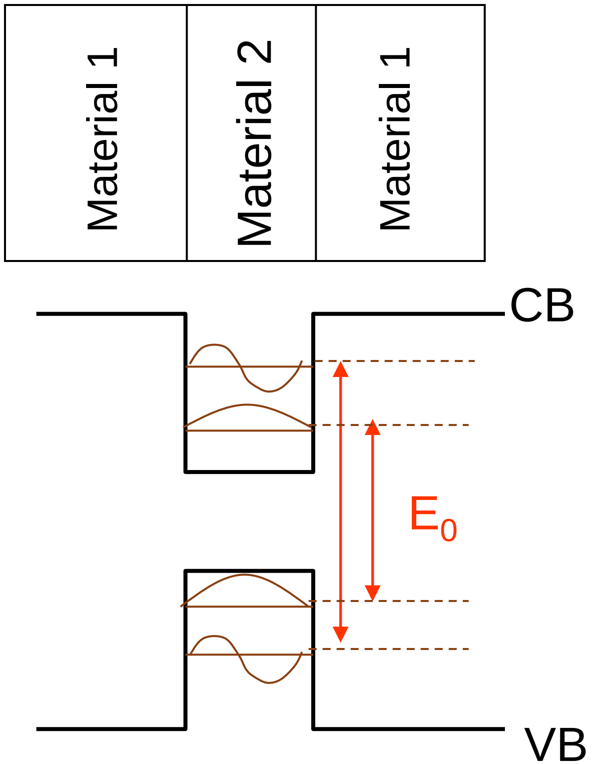
- SiGe modulator using Franz-Keldysh effect has been demonstrated:
  - Design of material composition and strain of $Ge_{1-x}Si_x$ to achieve modulation at 1.55µm
  - Integrated devices using amorphous Si waveguides
  - Bandwidth = 1.2 GHz

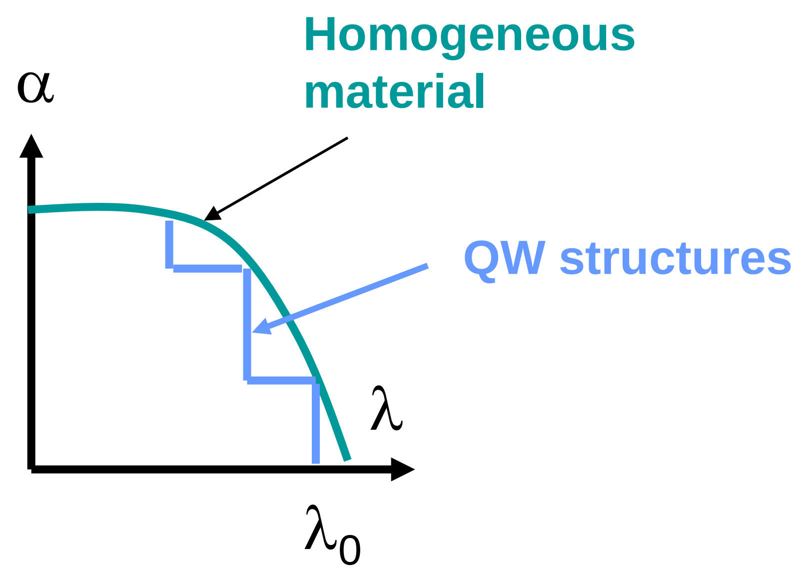
Liu et al., Opt. Express 15, 623 (2007)
Liu et al., Nature Photonics 2, 433 - 437 (2008)

Absorption in quantum well (QW) structures ?

Ex : GaAlAs / GaAs/GaAlAs

- Heterostructures formed by a thin layer of a narrower-gap semiconductor between thicker layers of a wider-gap material lead to the formation of potential wells for electrons and holes.
  - Possible transition between discrete energy level





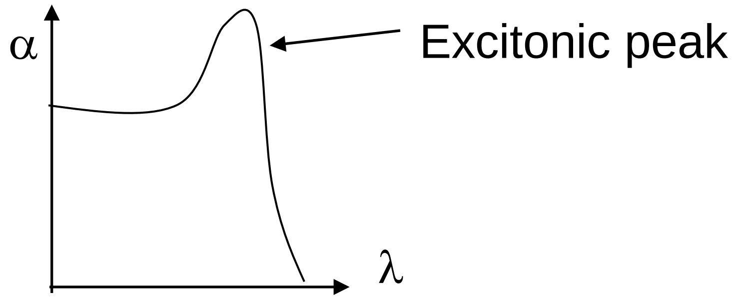
$E_0 = hc/\lambda_0$

- Absorption edge in QW structures is more abrupt than in homogeneous material
- E_0 depends on the quantum well thickness
  - Adjustment of the wavelength is possible

Electroabsorption in QW structures

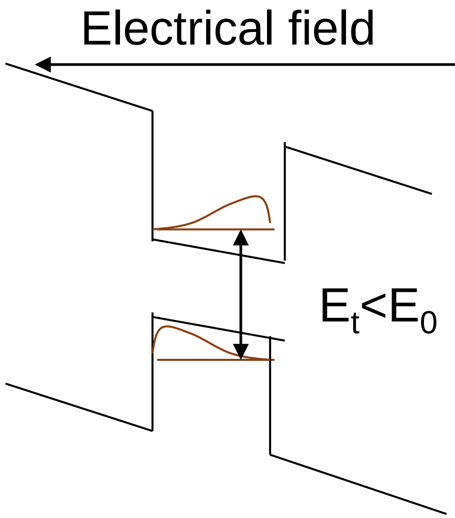
- Excitonic peaks ?
  - When a photon is absorbed: an electron is excited in the conduction band, leaving a hole in the valence band. Hole and electron are attracted by the Coulomb force. The exciton results from the binding of the electron with its hole. As a result, the exciton has slightly less energy than the unbound electron and hole.

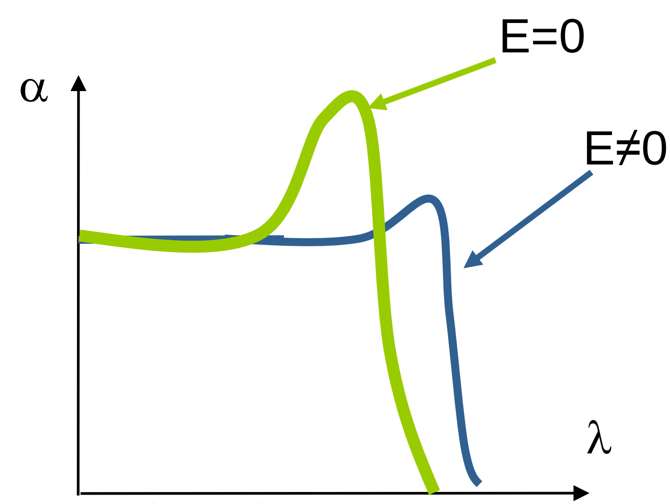
⇨ **Apparition of peaks in absorption**



Quantum Confined Stark effect (QCSE)

- How does the absorption coefficient change when an electrical field is applied on a QW structure ?
  - Shift of the energy levels inside the well : redshift of the absorption coefficient
  - Decrease of the excitonic peak, because of hole and electron wavefunction overlap decrease.





Quantum confined Stark effect (QCSE)

Quantum Confined Stark effect (QCSE)

- Direct bandgap SC (III-V materials)
  - QCSE is more efficient than Franz Keldysh effect (a larger absorption coefficient is generally obtained.
  - Well thickness is modified to tune the absorption edge wavelength
  - Intrinsically high speed process
- Integration of QCSE modulator on silicon ?
- QCSE in group IV materials ?

Quantum Confined Stark effect (QCSE)

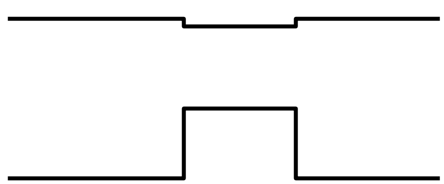
- Integration of III-V QCSE modulator on silicon:
  - Hybrid silicon evanescent electroabsorption modulator
  - AlGaInAs quantum wells
  - Extinction ratio over 10dB, modulation bandwidth of 10 GHz. Open eye at 10Gb/s

Kuo et al., Opt. Express 16, 9936 (2008)

Quantum Confined Stark effect (QCSE)

- QCSE in group IV material:
  - 4.2% of lattice mismatch between germanium and silicon => growth of $Si_{1-x}Ge_x$ in Si substrate : critical thickness, depending on x = germanium fraction

- Growth of $Si_{1-x}Ge_x$ in Si substrate



➢ Type I heterostructure with a bandgap energy offset mainly in the valence band with a conduction band offset lower than 10 meV

➢ Weak electron confinement ⇨ low excitonic phenomenon

QCSE in SiGe/Si structures ?

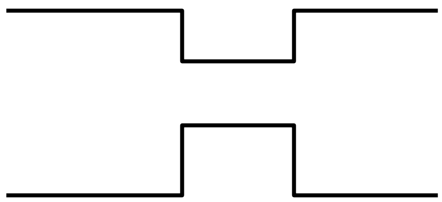
- Modulator based on absorption band edge shift in SiGe/Si heterostructure:
  - Limited performances:
    - Extinction ratio: 1.55 dB
    - Insertion loss: 28.5 dB for a 100 µm long device

Qasaimeh et al IEEE JQE, 33 (9), (1997).

Quantum Confined Stark Effect

QCSE in SiGe/Ge structures ?

- Growth of $Si_{1-x}Ge_x$/Ge on relaxed $Si_{1-x}Ge_x$ buffer



$Si_{1-x}Ge_x$ Ge Si

Type I alignment with a strong conduction band and valence band energy offset

Kuo and al, Stanford, Nature (2005)

Kuo et al. IEEE JSTQE 12, 1503 (2006)

Roth et al., Electronics Lett. 44, 49 (2008)

Demonstration of quantum confinement at the direct gap, and strong excitonic absorption peaks in the spectra.

Demonstration of QCSE with strength comparable to that in III-V materials.

Electroabsorption silicon based modulators

- **Homogeneous GeSi: Franz-Keldysh effect:**
  - 10-dB extinction ratio at 1.540 nm
  - Operating spectrum range of about 1.539–1.553 µm
  - 3-dB bandwidth of 1.2 GHz

- **Integration of III-V on silicon**
  - Hybrid silicon evanescent modulator
  - Extinction ratio over 10dB, modulation bandwidth of 10 GHz. Open eye at 10 Gb/s

- **$Si/Si_{1-x}Ge_x$ quantum well:** Quantum confined Stark effect
  - weak effect: low electron confinement in the well
  - Limited performances

- **$Si_{1-x}Ge_x/Ge$ quantum well** : Quantum confined Stark effect
  - 3 dB modulation possible with 1 V swing
  - Fundamental limit to speed ~ 1 ps

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Electrorefraction

- Electrorefraction = variation of the refractive index with and electrical field.

- Semiconductor optical properties are modified with the application of an electrical field :
  - field –dependent permittivity

$$P = \varepsilon_0 \left(\chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \ldots \right)$$

P=Polarisation

$\chi^{(i)}$ = i-order component of the susceptibility (tensor)

$$D = \varepsilon_0 . E + P = \varepsilon_0 . \varepsilon_r . E$$

Electric displacement field

$$\Rightarrow \varepsilon_R = 1 + \chi^{(1)} + \chi^{(2)} E + \chi^{(3)} E^2 + \ldots$$

Relative permittivity

Electrorefraction

Refractive index $n = \sqrt{\varepsilon_R} = \sqrt{1 + \chi^{(1)} + \chi^{(2)}E + \chi^{(3)}E^2 + \ldots}$

$$\Rightarrow \quad n = n_0 + \frac{\chi^{(2)}E}{2n_0} + \frac{\chi^{(3)}E^2}{2n_0} + \ldots$$

The refractive index depends on the applied electric field

$$n = n_0 - \frac{n_0^3 r E}{2} - \frac{n_0^3 g E^2}{2} - \ldots$$

r : linear electro-optic coefficient $r = -\frac{\chi^{(2)}}{n_0^4}$

⇒ Pockels effect

g : quadratic electro-optic coefficient $g = -\frac{\chi^{(3)}}{n_0^4}$

⇒ Kerr effect

- Pockels effect:
  - $LiNbO_3$, III-V semi-conductors (GaAs), polymer, …
  - Modulation speed: f > 70 GHz
  - No Pockels effect in silicon (centrosymmetric crystal)

- Kerr effect:
  - In silicon : low refractive index change at telecommunication wavelengths
    - $\Delta n = 2\ 10^{-5}$ for $E = 5\ 10^{5}$ V/cm

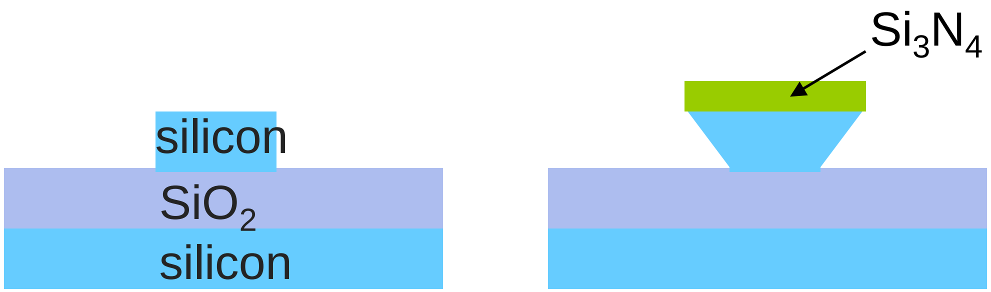
Soref et Bennett IEEE JQE QE-23 (1), (1987).

Electrorefraction

Is it possible to obtain a linear electro-optic effect in silicon or germanium ?

- **Strained silicon**
  - The crystal symmetry can be broken by the deposition of a straining layer (Si_3N_4) on top of a silicon waveguide.

Jacobsen et al, Nature 441, 199 (2006)



Apparition of Pockels effect

$$\chi^{(2)} \approx 15\, pm/V$$

$$\Delta n = \frac{\chi^{(2)} E}{2 n_0}$$

for $E = 5.10^5$ V/cm, $\Delta n \sim 10^{-6}$

SiGe superlattice

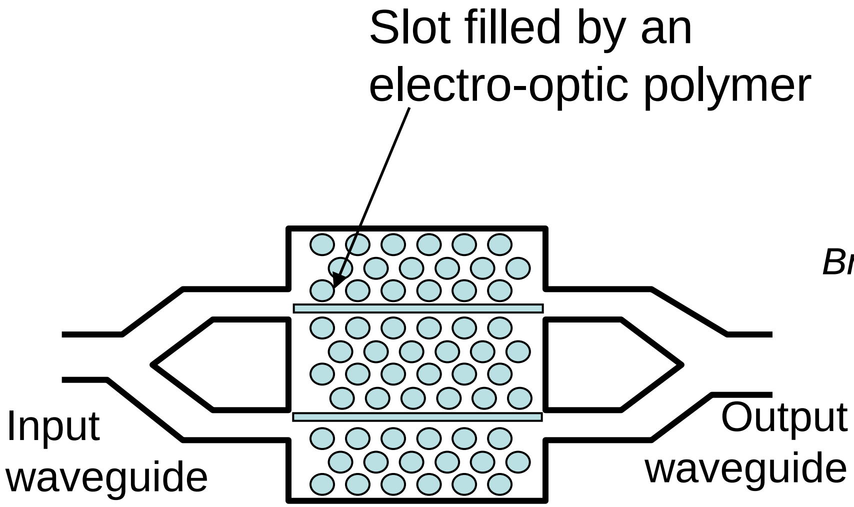
- The intrinsic inversion symetry can be broken in SiGe superlattices
- Superlattice of 34 periods based on a trilayer heterostructure: $Si/Si_{0.75}Ge_{0.25}/Si_{0.5}Ge_{0.5}$
- Theoretical demonstration of a linear electro-optic coefficient: r = $5.8.10^{-10}$ cm/V

Yu and al, PRB 73, 235328 (2006)

$$\Delta n = \frac{r n_0^3 E}{2}$$

for E = 5.10^{5} V/cm, $\Delta n=10^{-4}$

Integration of an electrooptic material in Si photonic crystal waveguide



Brosi et al Opt. Express 16, 4177 (2008)

- A modulation bandwidth of 78 GHz and a length of about 80 µm at a drive voltage amplitude of 1 V is predicted

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Refractive index variation in silicon

Large refractive index variation in bulk silicon can also be obtained by:

- <u>Thermal variations</u>
  - thermo-optic coefficient in silicon = 2.10^{-4} K^{-1} at 1.55µm

  → $\Delta n = 2\times10^{-3}$ if $\Delta T = 10$ K

  - Effect very slow (time constant ~ms) : cannot be used for high speed modulation

BUT it can be a parasistic effect for high speed optical modulators.

- <u>Free carrier concentration variations</u>
  - Largely used for optical modulation (most efficient way to achieve phase modulation in silicon)

Free-carrier concentration variation

Free carrier concentration variations in silicon

are responsible for optical properties variations
(intraband transition : free carrier absortion +…)

↓

Refractive index and absorption coefficient variations

Free-carrier concentration variation

- Free carrier concentration variations in silicon

At λ=1,3 µm

$$\Delta n = -6.2\times10^{-22}\Delta N - 6\times10^{-18}\Delta P^{0,8}$$

$$\Delta\alpha = 6\times10^{-18}\Delta N + 4\times10^{-18}\Delta P$$

ΔN = e^- density variation (cm^{-3})

ΔP = h^+ density variation (cm^{-3})

At λ=1,55 µm

$$\Delta n = -8.8\times10^{-22}\Delta N - 8.5\times10^{-18}\Delta P^{0,8}$$

$$\Delta\alpha = 8.5\times10^{-18}\Delta N + 6\times10^{-18}\Delta P$$

Example: for $\Delta P=10^{18}$ cm^{-3}

Δn = 1.5 10^{-3} at λ=1.3µm

Δn = 2.1 10^{-3} at λ=1.55µm

Soref et al IEEE JQE QE-23 (1), (1987).

Free-carrier concentration variation

How is it possible to obtain free carrier concentration variation in silicon?

Carrier injection in PN/PIN diode (forward bias)

Carrier plasma shift in bipolar mode field-effect transistor (BMFET).

Carrier accumulation in MOS capacitor

Carrier depletion in PN/PIN diodes (reverse bias)

Free-carrier concentration variation

- Optical modulator based on free-carrier concentration variation ?
  - The available absorption coefficient variation is not sufficient to be used in an absorption modulator
  - Most of silicon modulators use refractive index variation by refraction index variation

Phase modulation

Interferometer

Intensity modulation

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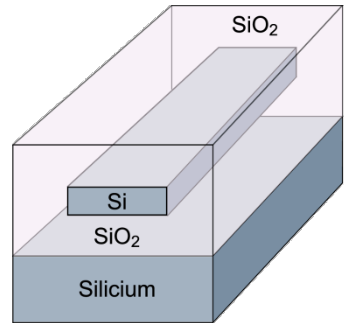
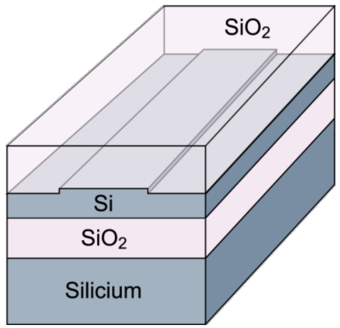
Waveguide integrated optical modulator

Silicon optical waveguides:

- Silicon on insulator substrate
- Rib or strip waveguide

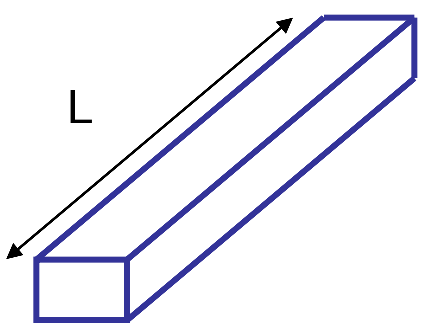




Phase propagation in an optical waveguide:

(E_1, φ_1)

Amplitude and phase after propagation in the waveguide



(E_0, φ_0)

Amplitude and phase at the waveguide input

$$\varphi_1 = \varphi_0 + \frac{2\pi}{\lambda} n_{eff} L$$

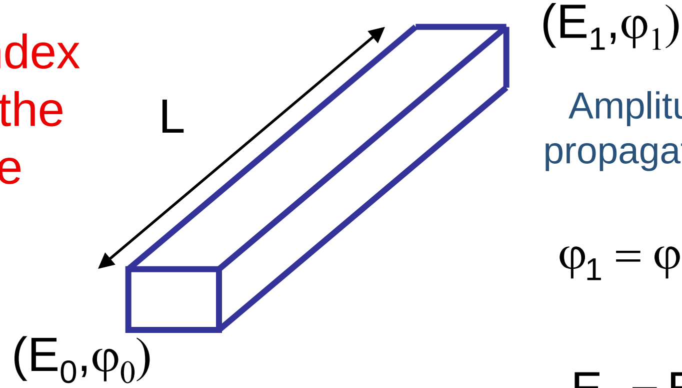
$$E_1 = E_0 e^{\left(-\alpha/_2 L\right)}$$

(α is intensity absorption coefficient)

Waveguide integrated optical modulator

Phase modulation:

Refractive index variation in the waveguide



Amplitude and phase after propagation in the waveguide

$$\varphi_1 = \varphi_0 + \frac{2\pi}{\lambda}\left(n_{eff} + \Delta n_{eff}\right)L$$

$$E_1 = E_0 e^{\left(-\alpha/2 L\right)}$$

Amplitude and phase at the waveguide input

Δneff depends on:

- The refractive index variation due to free carrier concentration variation
- The overlap between the optical mode and the refractive index variation region

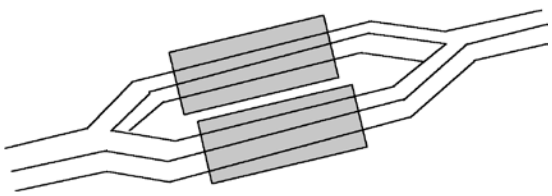
$$\Delta\varphi = \frac{2\pi}{\lambda}\Delta n_{eff} L$$

$$\Delta\varphi = \pi \Leftrightarrow L = L_\pi = \frac{\lambda}{2\Delta n_{eff}}$$

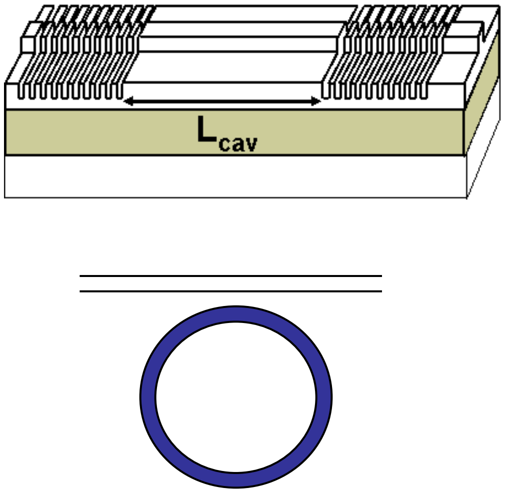
Waveguide integrated optical modulator

To convert phase modulation into intensity modulation:
waveguide integrated interferometric structure

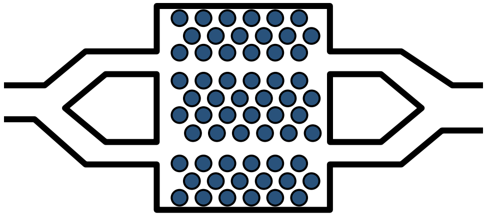
Mach Zehnder



Resonators



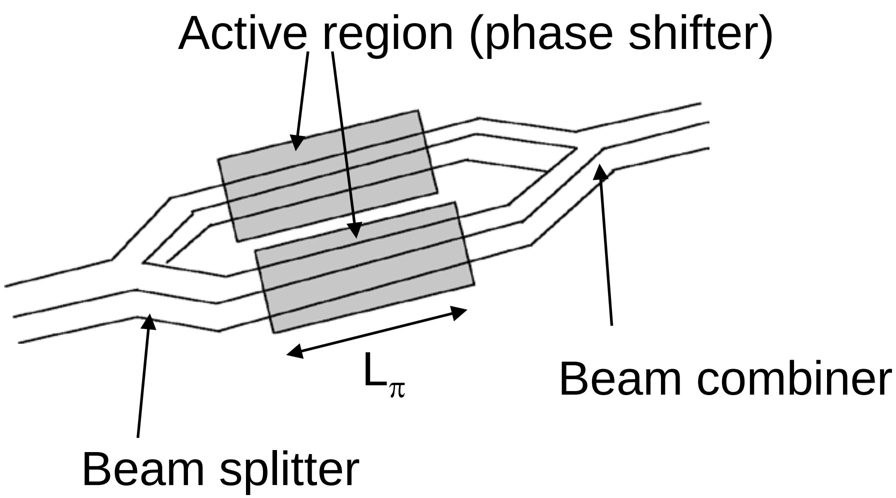
Photonic crystal



Waveguide integrated optical modulator

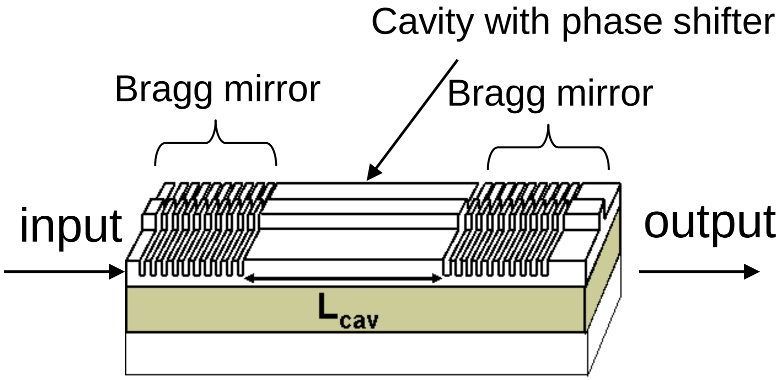
Mach Zehnder

- The incident beam is splitted in two beams propagating in both waveguides
- At the ouptut combiner, interferences occur:
  - Constructive interferences if beams are in phase
  - Destructive interferences if beams are in phase opposition
- To go from constructive to destructive interferences, π phase shift is required

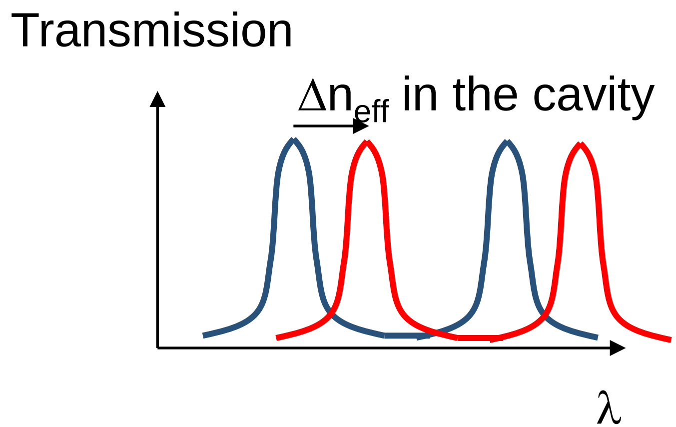


Even for single arm drive modulator, the phase shifter is integrated in both arms, to have the same loss in both waveguide (totally destructive interference is possible only with same amplitude beams)

Resonators



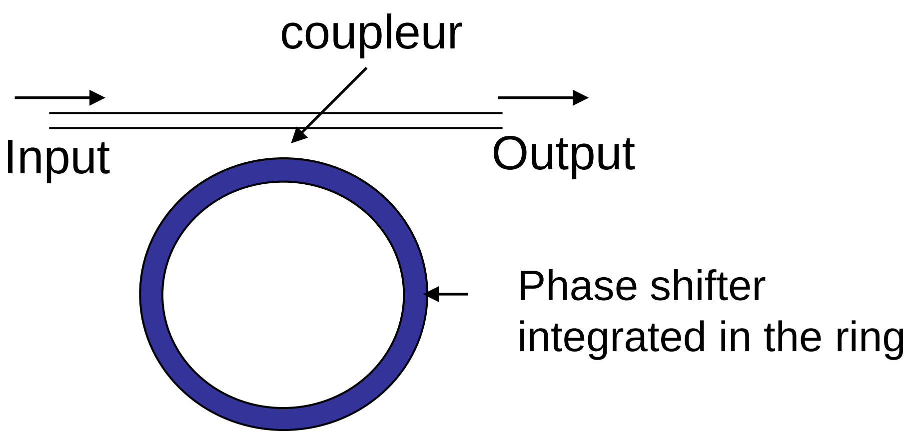
Fabry-Perot cavity



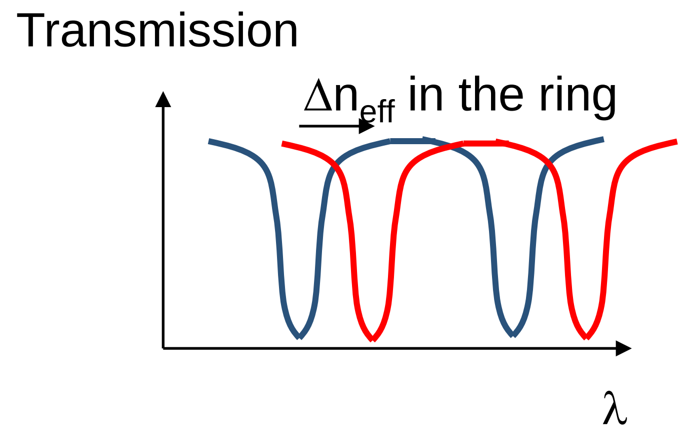
- Interferences between light successively reflected by both mirrors.
- Bragg mirror are used for waveguide integrated mirrors

- When the optical path is n the wavelength, with n integer, the transmission is maximum.
- If a phase variation is made in the cavity, the ubove condiction leads to a shift of the transmission spectrum $\Rightarrow$ transmission variation (at a given wavelength)

- Resonators



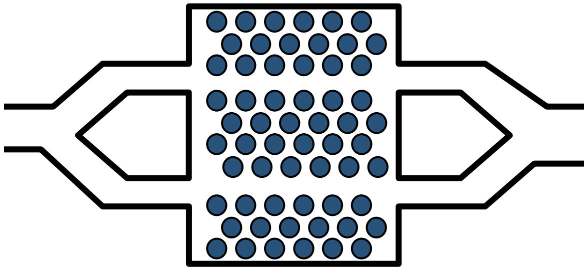
Ring resonator



- Part of the incident beam is coupled into the ring. After propagation along the ring, light is partially coupled in the straight waveguide back ⇒ Interferences

Waveguide integrated optical modulator

- Photonic crystals

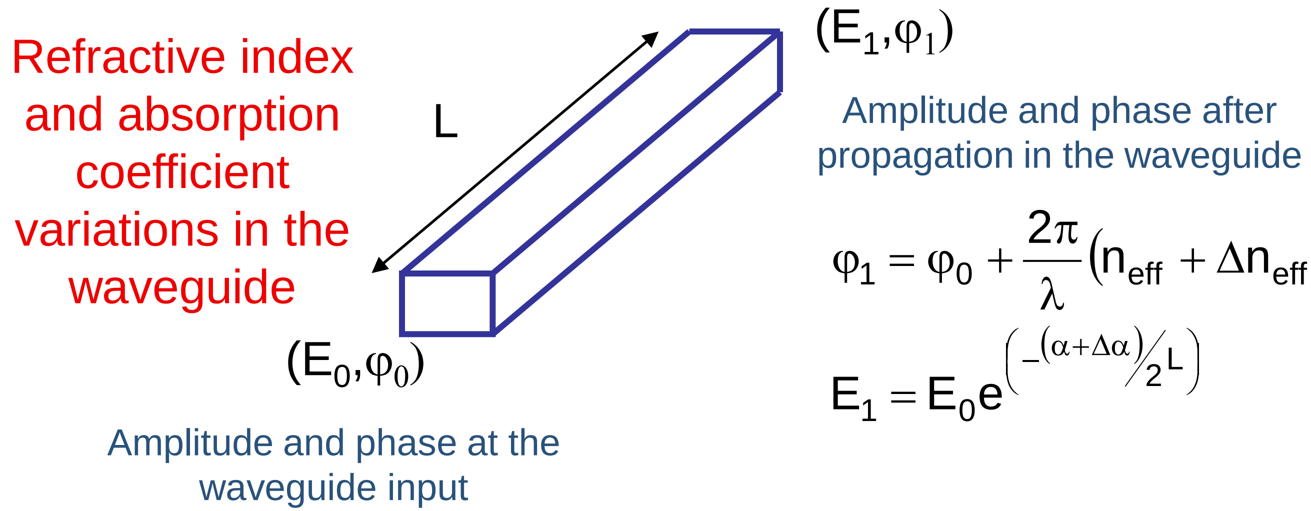


$$v_g = \frac{d\omega}{dk}$$

- Photonic crystal can be used to tailored dispersion properties (Photonic band gap, geant and anormal dispersion, etc…)
- For optical modulator, *slow wave in photonic crystals* can be used to reduce the phase shifter length, for example in Mach Zehnder interferometer

Waveguide integrated optical modulator

Refractive index variation goes along with absorption coefficient variation:



$$\varphi_1 = \varphi_0 + \frac{2\pi}{\lambda}\left(n_{eff} + \Delta n_{eff}\right)L$$

$$E_1 = E_0 e^{\left(-\frac{(\alpha+\Delta\alpha)}{2}L\right)}$$

This can be a parasitic effect, for example:

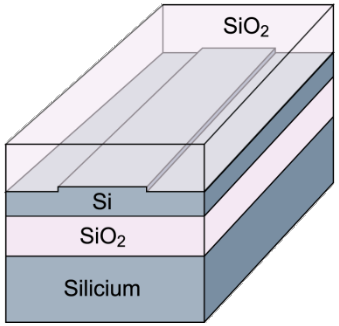
• when using Mach Zehdner interferometer, if the output field amplitudes are not the same, interference cannot be entirelly destructive, and Imin $\neq 0$ at the modulator output)

•In resonators absorption increase is responsible for mimimum transmission increase

Waveguide integrated optical modulator

- Free carrier concentration variation in a silicon waveguide:
  - The electronic structure has to be integrated in an optical waveguide

Rib waveguides are required (in strip waveguide it is not possible to have the electrical contacts)



  - Doped silicon and metal are responsible for large optical loss

Careful design of the electronic structure is required, to achieve simultaneously:
• large refractive index variation,
• large overlap of the active region with the guided mode,
• low optical loss

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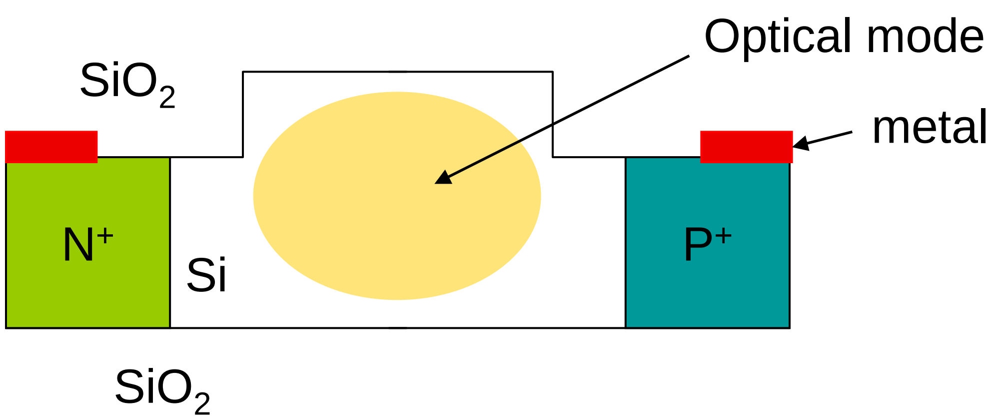
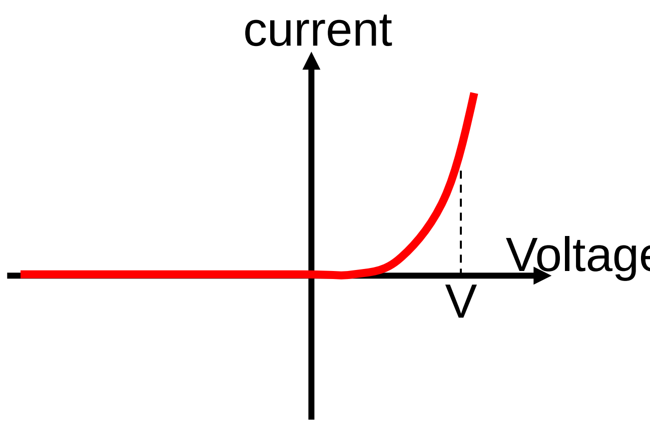
Optical modulator based on carrier injection in pin diode (direct bias)

- Electron and hole injection in a waveguide
- Effective index variation Δn_{eff}~ a few 10^{-3}



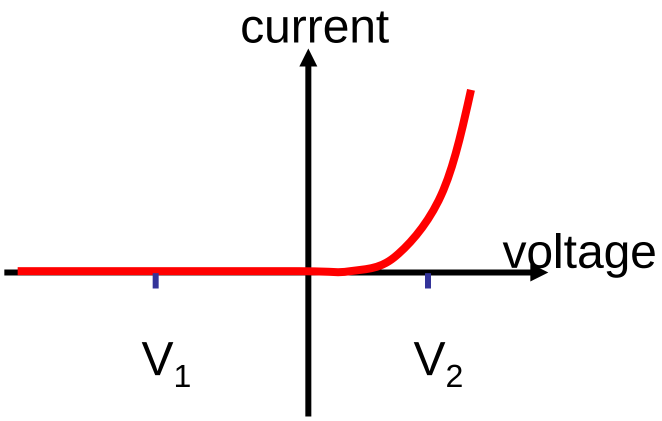


- When bias goes from V to 0, free carriers in the intrinsic part of the diode have to recombine.
- The modulator speed is limited due to carrier recombination time
  - Commutation time: few 10 ns

  ⇨Cut-off frequency: few 100 MHz

Optical modulator based on carrier injection in pin diode (direct bias)

- To increase the speed:
  - Direct <u>and</u> reverse biasing



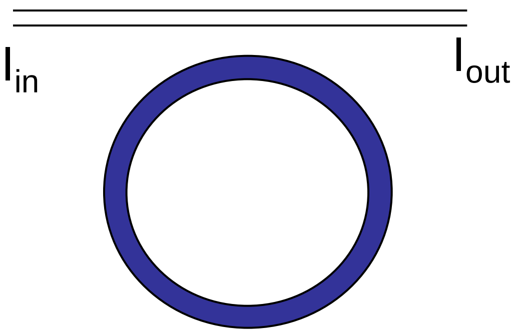
Theoretically:

- Switching time = 1.3 ns for V_1=-1 and V_2=0.87 V
- $\Delta n_{eff} \sim 10^{-3}$

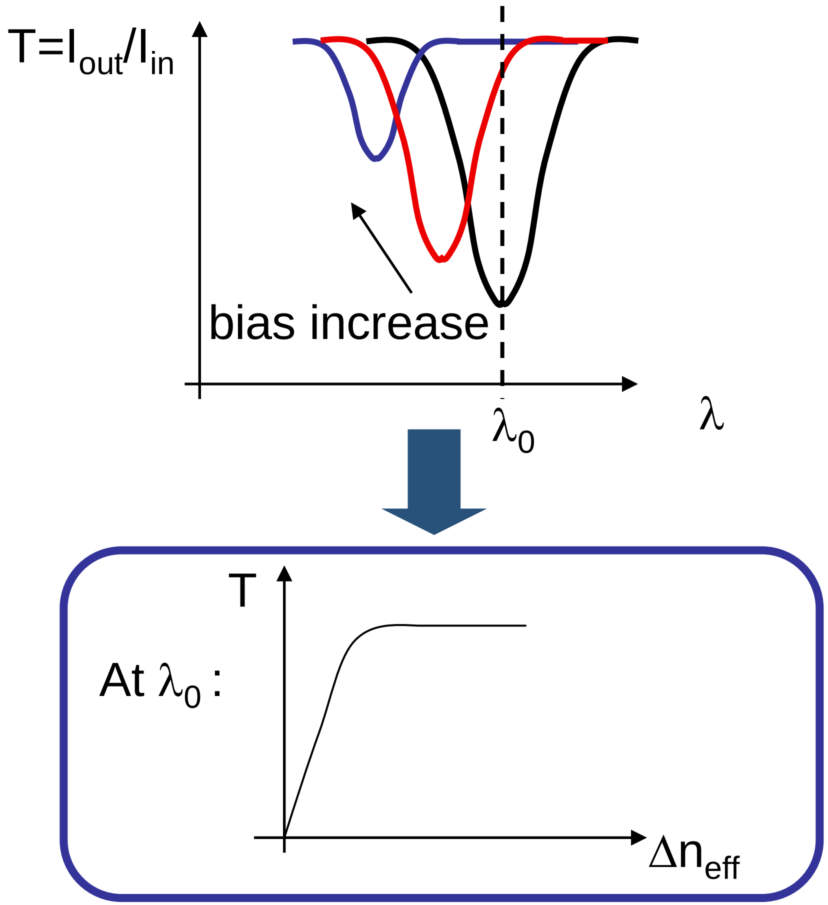
Barrios et al JLT 21(10) 2003

The optical response time can also be reduced thanks
<u>to a nonlinear transfer function of the interferometer</u>

For example:



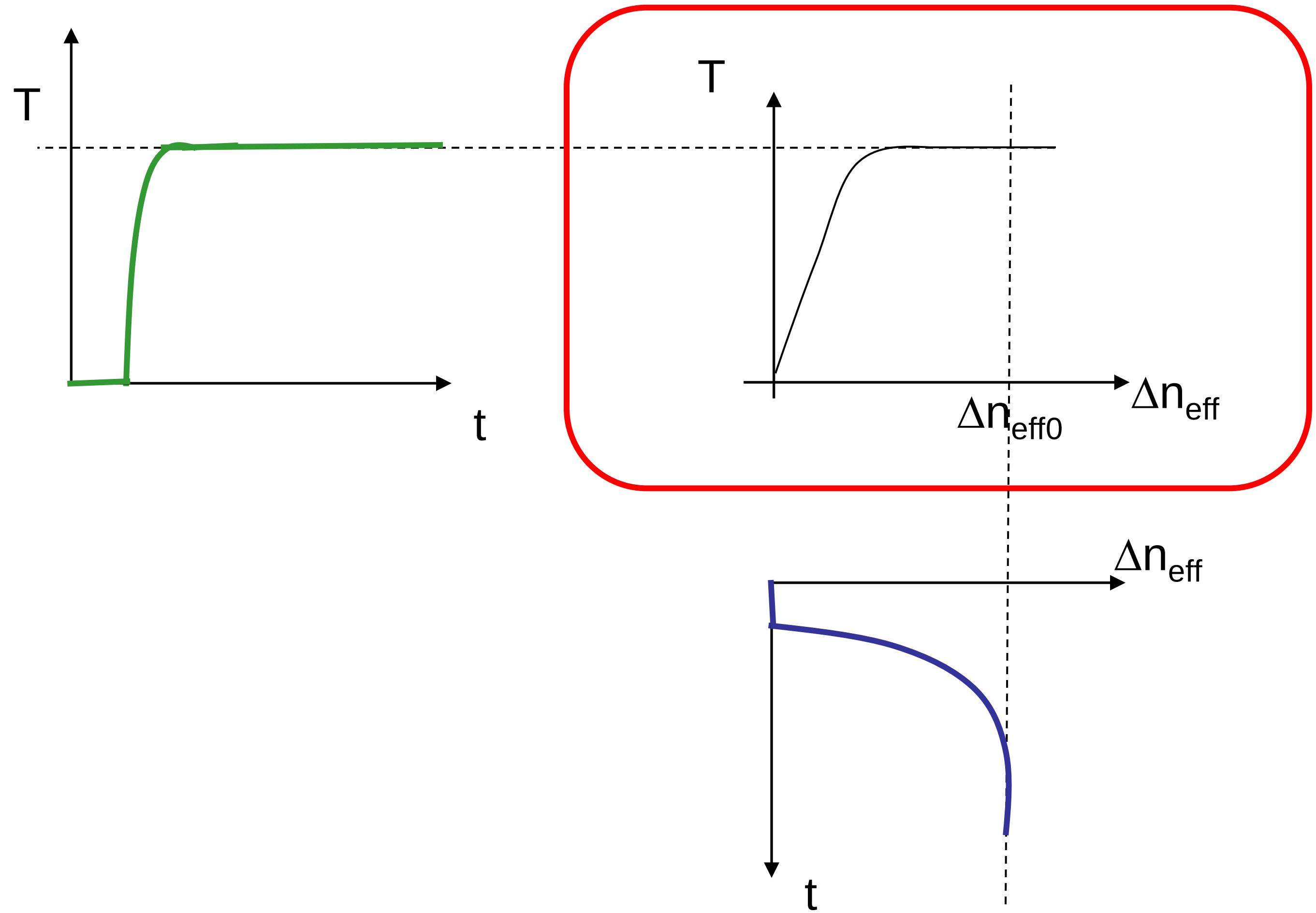
Direct biased PIN diode integrated in a microring resonator



Xu and al, Nature 2005

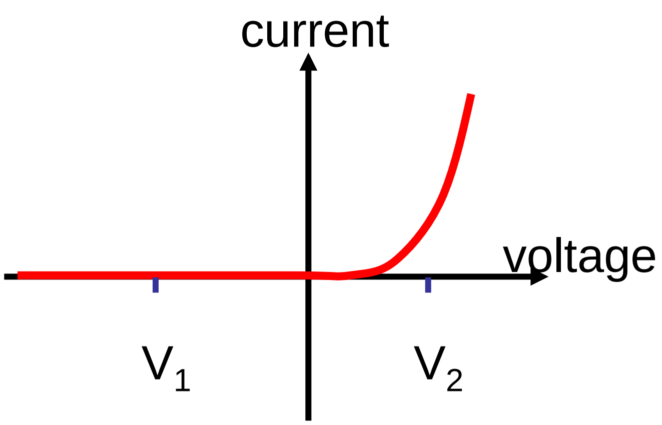
Integrated optical modulator: carrier injection

Principle of the optical response time reduction thanks
to a nonlinear transfer function of the interferometer



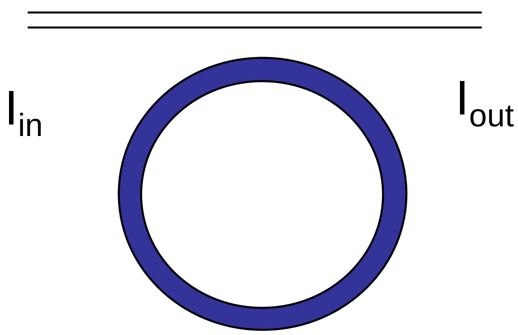
Integrated optical modulator: carrier injection

Experimentally:



Direct <u>and</u> reverse biasing

+



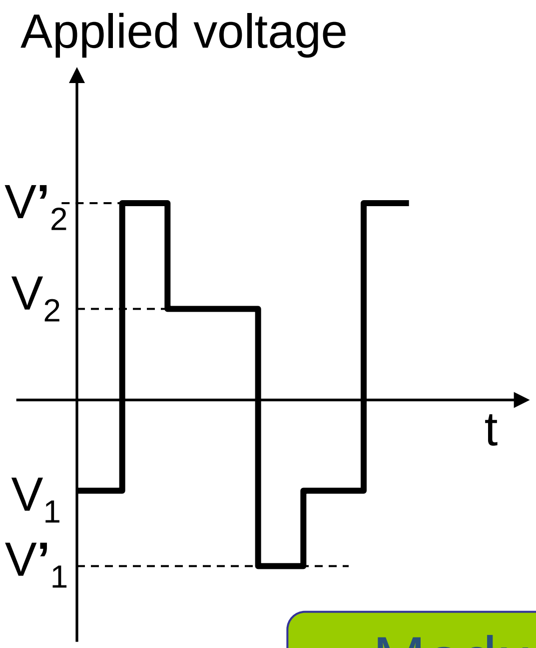
ring resonator

Modulation at 1.5 Gbit/s

Xu and al, Nature 2005

Integrated optical modulator: carrier injection

To go further: prehemphasis of the driving signal: pulses are added to the NRZ signal



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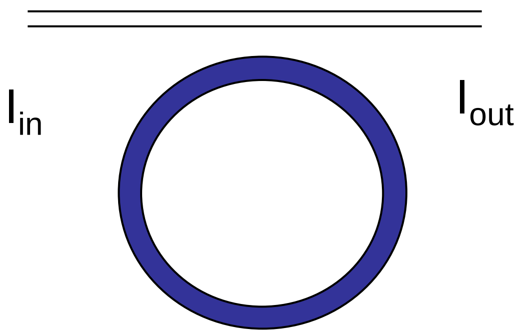
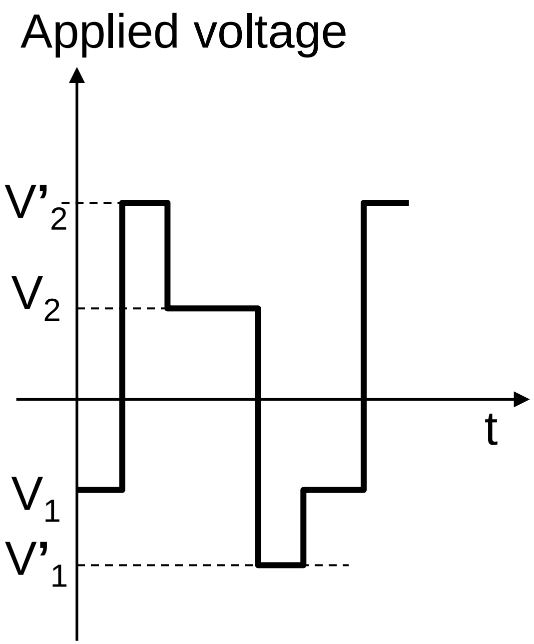


Modulation at 18 Gbit/s

Integrated optical modulator: carrier injection

Carrier injection in PIN diode using prehemphasis of the driving signal and Mach Zehnder interferometer:



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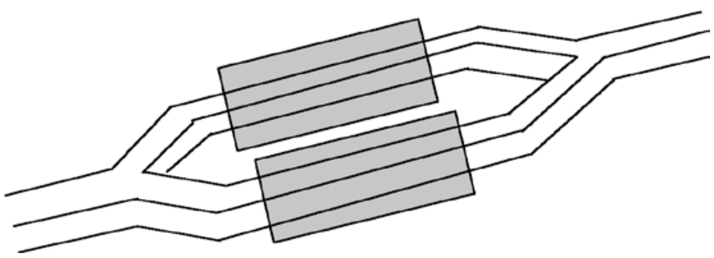

Mach Zehnder

Open eye diagram at 10 Gbit/s

Green et al. Opt. Express 15, 17106 (2007)

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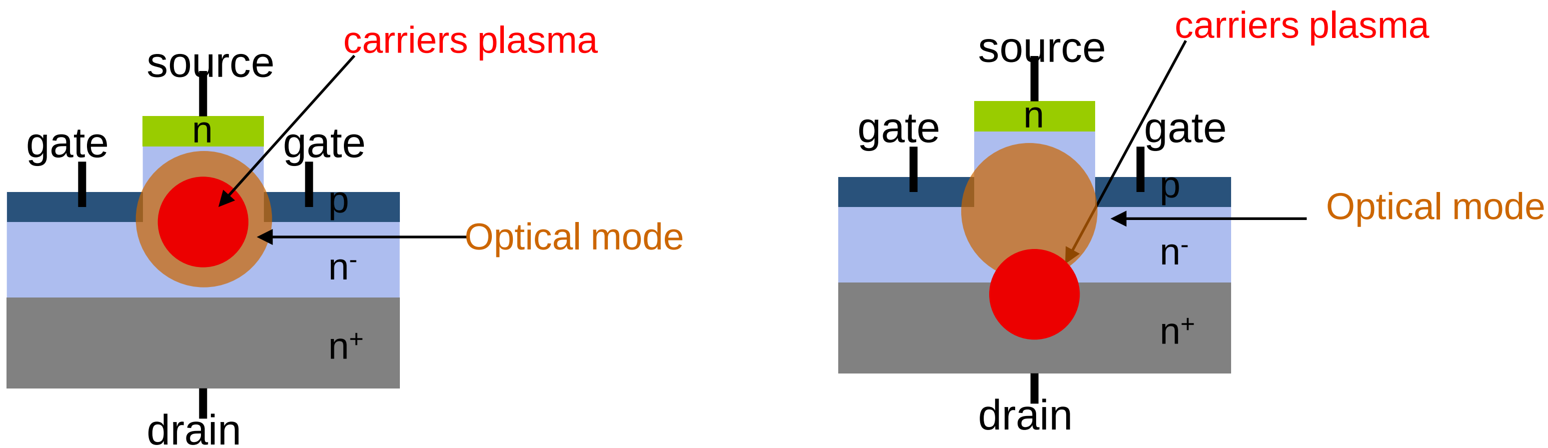
Integrated optical modulator :BMFET

BMFET (Bipolar Mode Field Effect Transistor)

- 3 electrodes: source, drain gate
- Electron and hole plasma continually injected
- Modulation by plasma shift



Sciuto et al IEEE JLT, 21 (1), (2003).

Theoretical evaluation: switching time of a few nanosecondes
$\Rightarrow$ operating frequency of a few hundred MHz.

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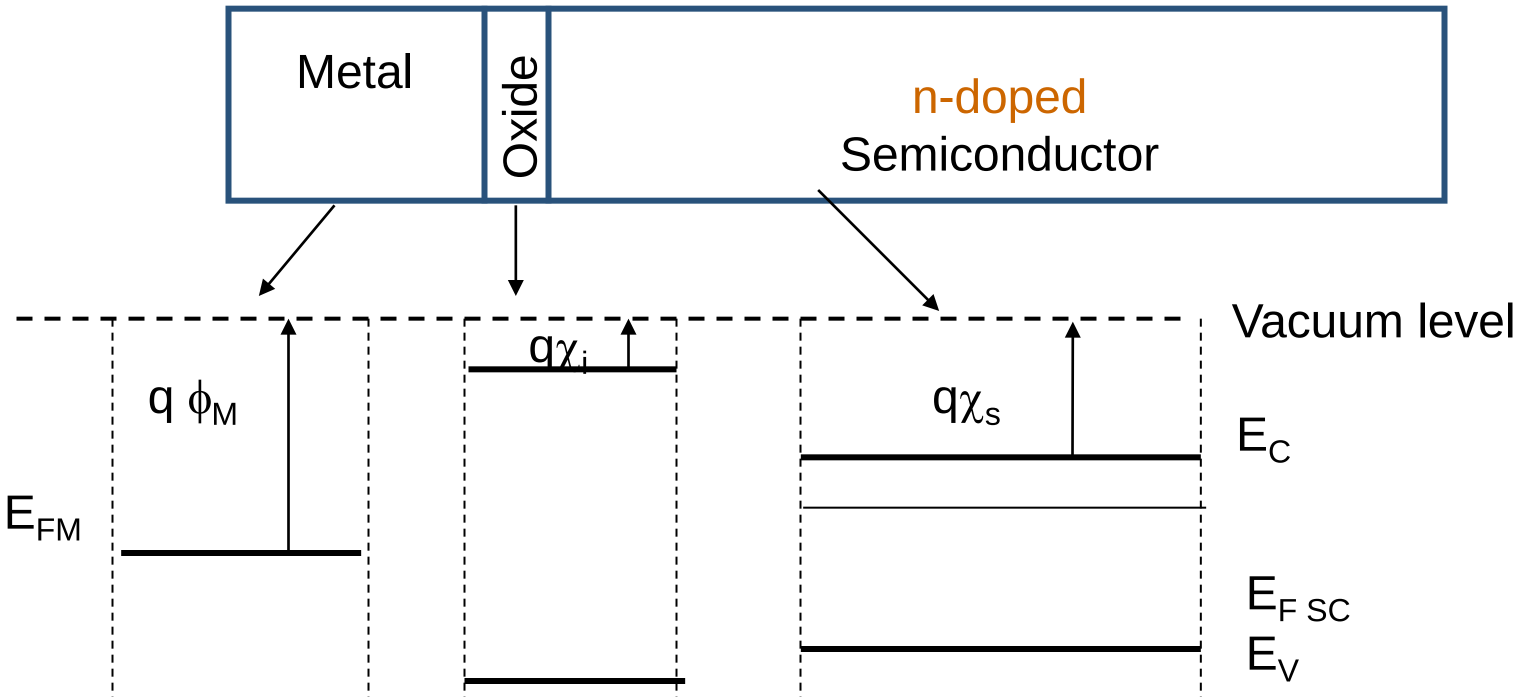
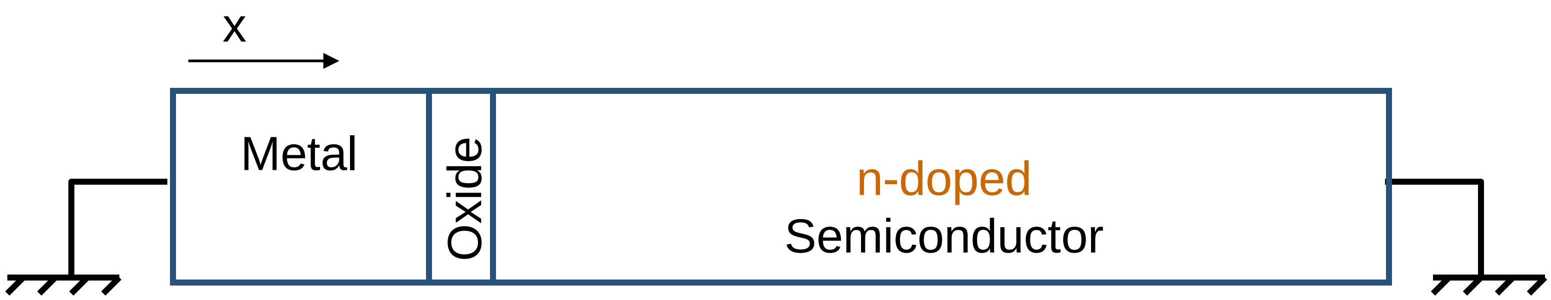
Metal Oxyde Semiconductor (MOS) capacitor:

- gate electrode (metal or polysilicon)
- silicon oxide dielectric insulator
- doped semiconductor (n in the following)

Metal workfunction: ϕ_M
Insulator electron affinity: χ_i
Silicon electron affinity: χ_s



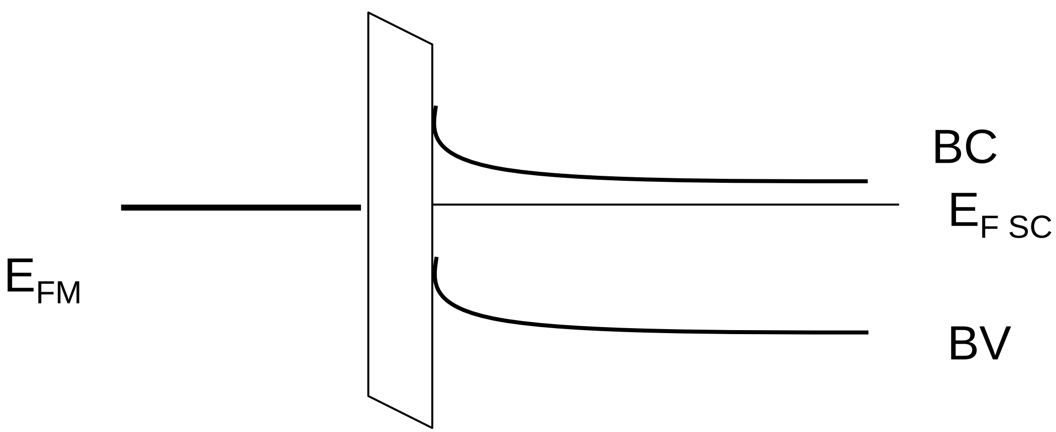
Potential band diagram of the different parts without contact

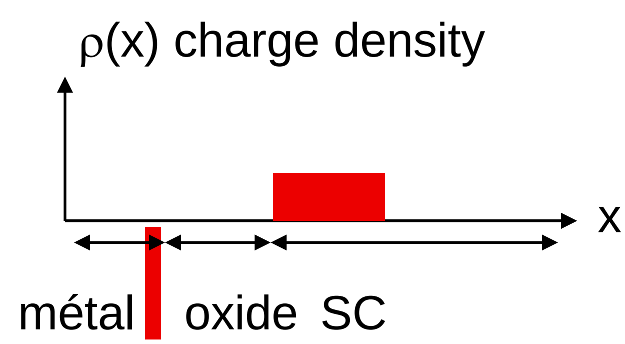


Around the oxyde layer:

- ionized donors in semiconductor
- electrons in metal

Depletion

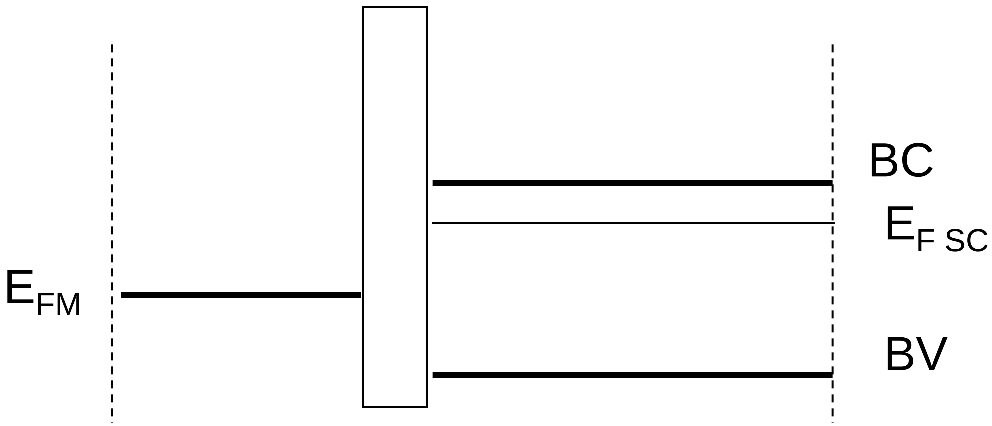




Integrated optical modulator: MOS capacitor

Flat Band regime : $V_g=V_{FB}>0$
No charges around the oxide

Flat Band



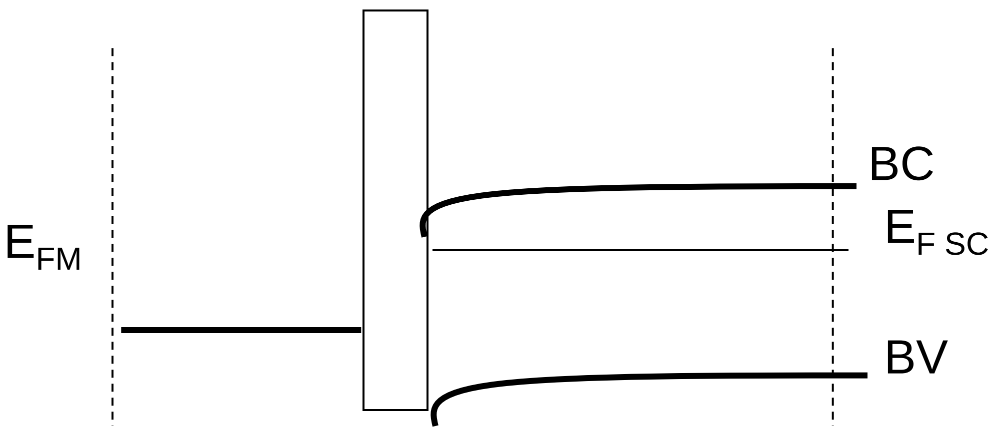
Integrated optical modulator: MOS capacitor

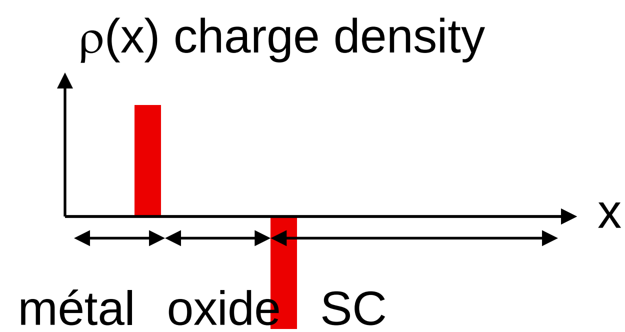
$V_g > V_{FB}$:

Around the oxyde layer:

- Electron accumulation in semiconductor
- Hole accumulation in metal

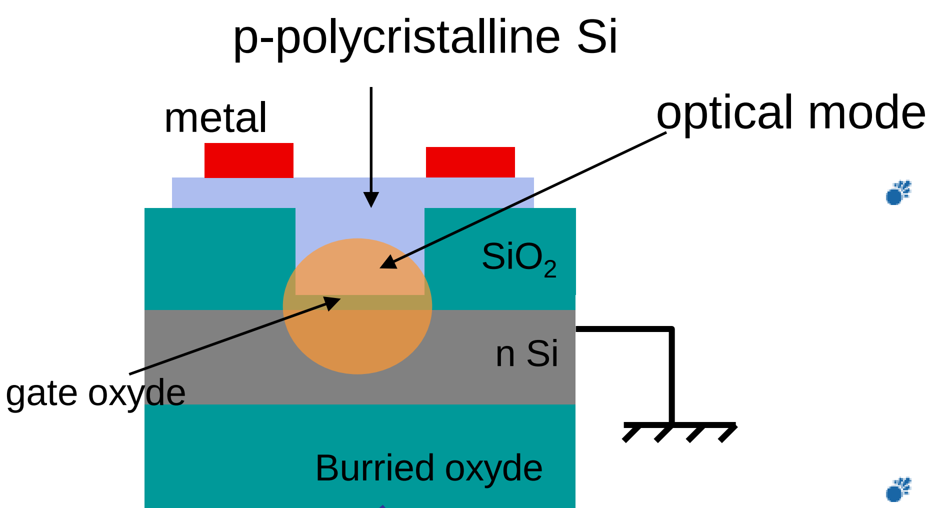
Accumulation



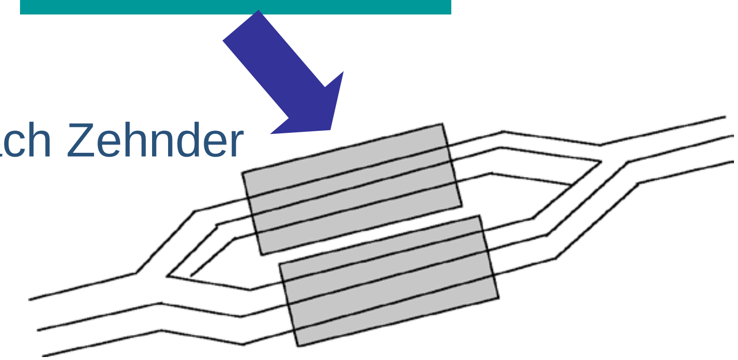


Integrated optical modulator: MOS capacitor

Silicon modulator using MOS capacitor in accumulation: first modulator with GHZ bandwidth



+ Mach Zehnder



Liu et al, Nature, 427, 615-618 (2004).

- L_π decreases when the drive voltage V increase: to compare phase shifter efficiency: product V L_π
  - $V_\pi L_\pi$= 7.7 V   cm (Δn_{eff}=4 10^{-5} for Vd=4V)
- Small signal modulation :
  - -3dB bandwidth >1GHz
- PRBS modulation :
  - data transmission at 1 Gbit/s

Silicon modulator using MOS capacitor in accumulation improvments

- Improvment of the RC time constant and loss tradeoff:
  - Gate : polysilicon has been replaced by monocrystalline Si
  - Waveguide: geometry optimization
- Modulator biasing:
  - 3.45 mm long phase shifter (C=26, 4pF) has been divided in eleven 315 µm-long sections.
  - Low impedance driver using HBT technology (70 GHz)

Experimental results:

- $V_\pi L_\pi$=3.3V.cm
- Loss = 10dB
- Data transmission:
  - 6 Gbit/s, with extinction ratio = 4.5 dB
  - 10 Gbit/s, with extinction ratio = 3.8 dB

Liao et al, Optics express, 13 (8) (2005)

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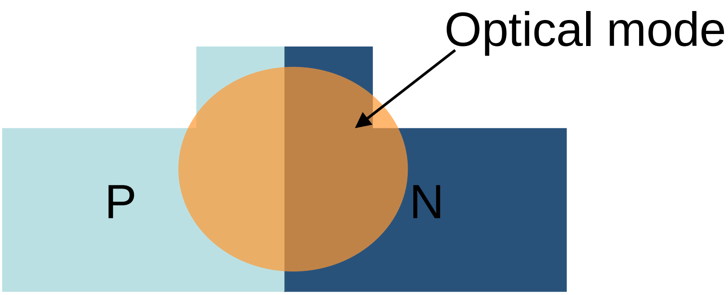
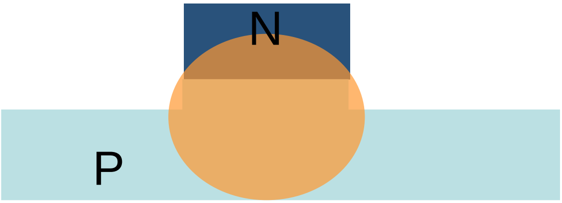
Integrated optical modulator: carrier depletion

Carrier depletion in PN diode

In reverse biased pn diode, the space charge region region is widened, leading to electron and hole concentration variation in the junction region



Vertical junction



Horizontal junction

- Theoretical performances: birefringence free device
  - *Gardes et al Opt. Express 13, 8845 (2005)*
  - $V_\pi L_\pi$=2.5 V cm
  - rise and fall times: 7 ps (drive voltage =-5 volts)
  - excess loss: 2 dB for TE and TM polarizations

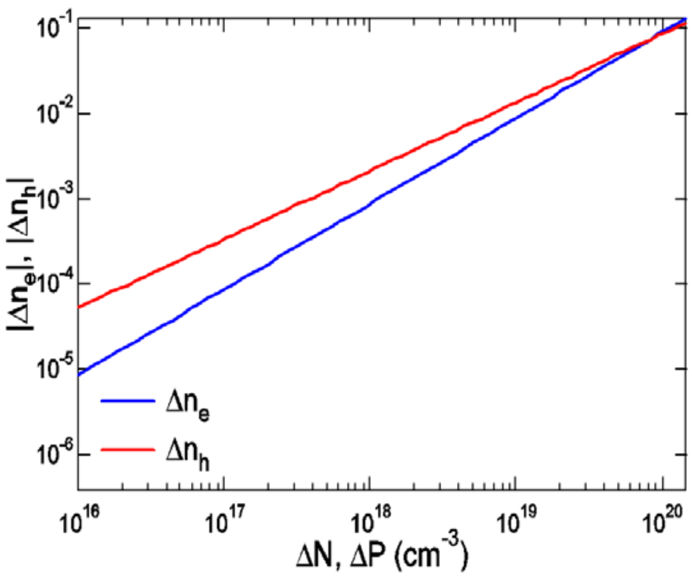
Integrated optical modulator: carrier depletion

Demonstrations of high speed modulation using carrier depletion in PN diode

- Vertical PN junction in Mach Zehnder interferometer with integrated driver:
  - *T. Pinguet et al, Group IV Photonics (2007)*
  - Extinction Ratio > 6dB at 10 Gbit/s
  - Insertion loss: 3dB
- Horizontal PN junction in Mach Zehnder interferometer with integrated load
  - *Liu et al Opt. Express 15, 660 (2007)*
  - *Liu et al., Semicond. Sci. Technol. 23, 064001 (2008)*
  - Static performances: modulation depth: >20 dB, insertion loss ~7 dB
  - Dynamic performances: -3 dB bandwidth: > 30 GHz
  - Data transmission: 40 Gbit/s with ~1dB Extinction Ratio
- Vertical PN junction in a ring resonator
  - *F. Gardes et al, Optics express (2009)*
  - -3 dB bandwidth = 19 GHz

Carrier depletion in PIN diode:

- When a PIN diode is reverse biased, the electrical field increase in the intrinsic region.
- If carriers are located in the intrinsic region at equilibrium, they will be depleted with reverse bias.



Which carriers should we use?

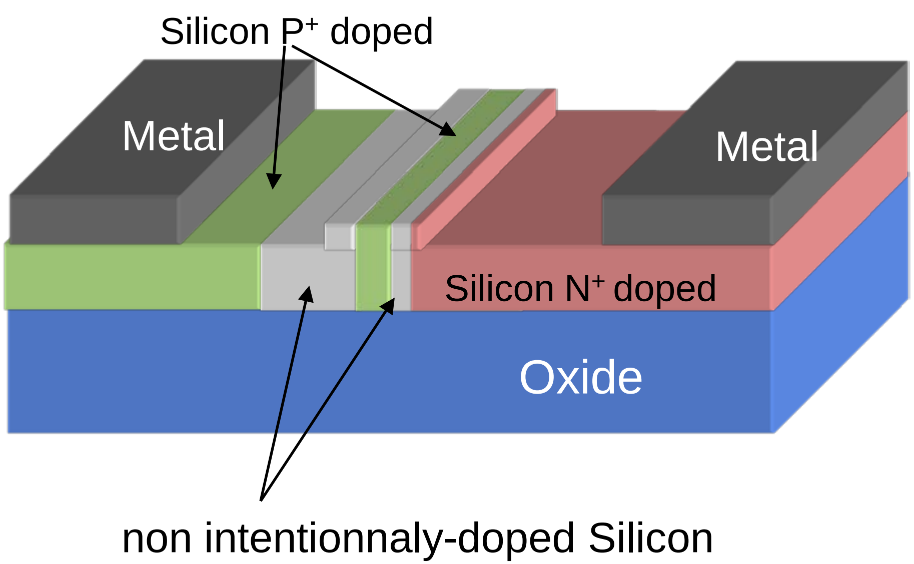
λ=1.55 µm

$$\Delta n = -8.8 \times 10^{-22} \Delta N - 8.5 \times 10^{-18} \Delta P^{0,8}$$

Free holes are more efficient than free electrons for refractive index variation for $\Delta N, \Delta P < 10^{20}\ cm^{-3}$

Soref et al IEEE JQE QE-23 (1), (1987).

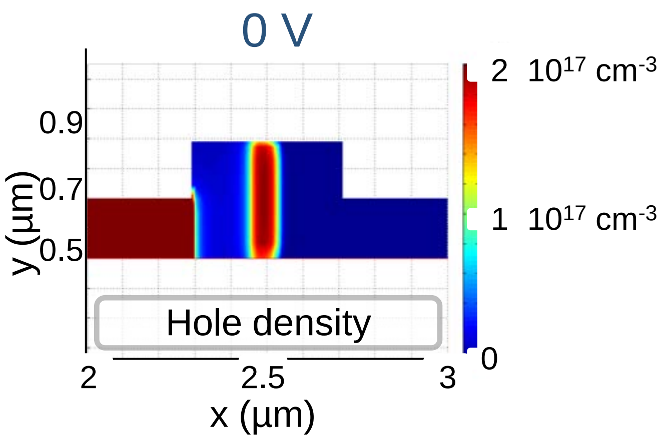
Carrier depletion in lateral PIN diode

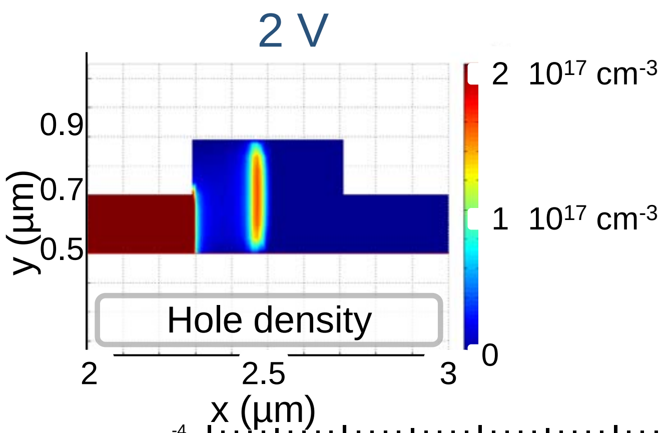


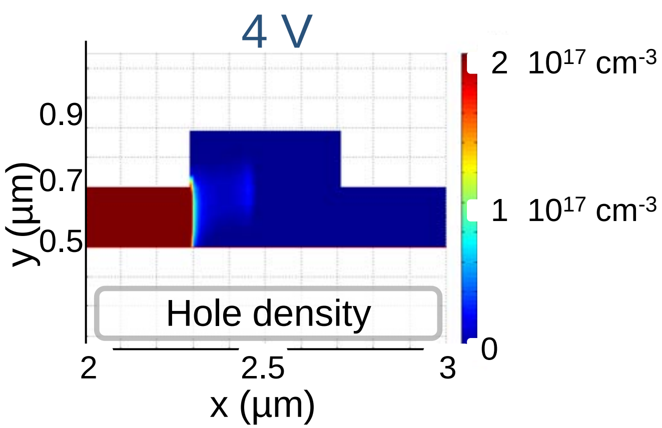
- P doped slit in the rib waveguide
  - Large modulation efficiency (overlap with guided mode)
  - Low optical loss (the waveguide is not entirely doped)
- Reduced capacitance (~ 0.2-0.3 fF/µm)
  - Reduction of RC time constants
  - Reduction of electrical power

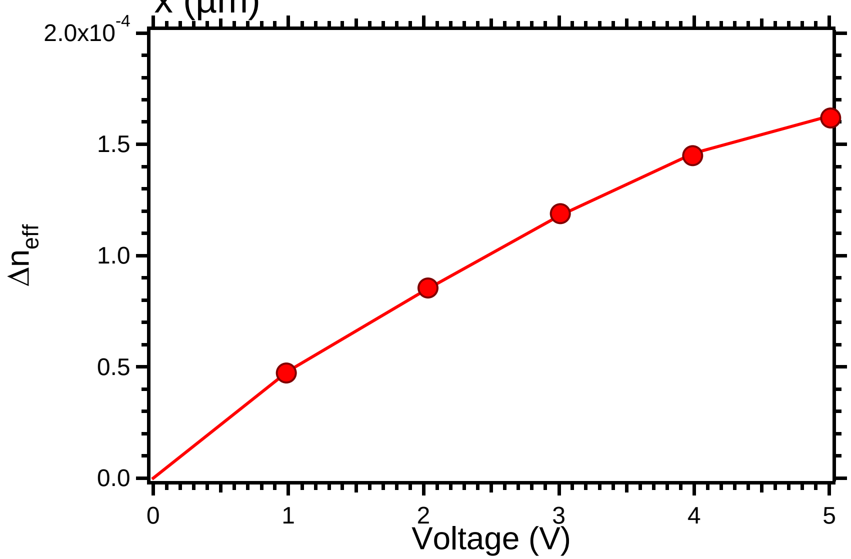
Integrated optical modulator: carrier depletion

Operating principle: electrical and optical simulations (reverse biased)





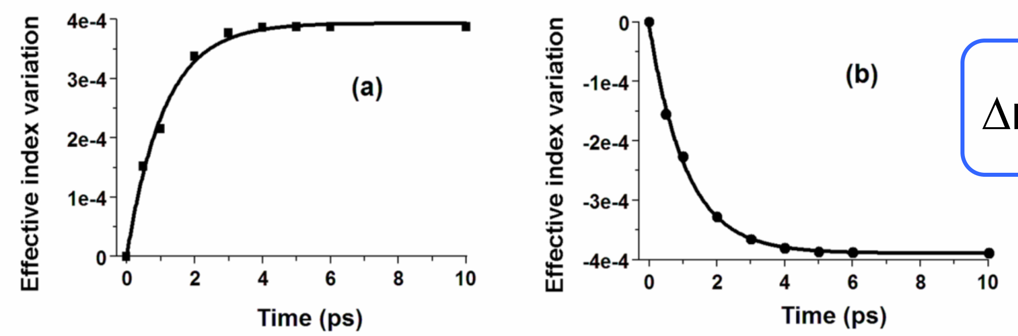




Integrated optical modulator: carrier depletion

Theoretical evaluation of device speed

- Intrinsic speed



$$\Delta n_{eff} = A+B\exp(-t/\tau) \qquad \tau=1.1\ \text{ps}$$

maximum bandwidth:

$1/2\pi\tau$ = 145 GHz

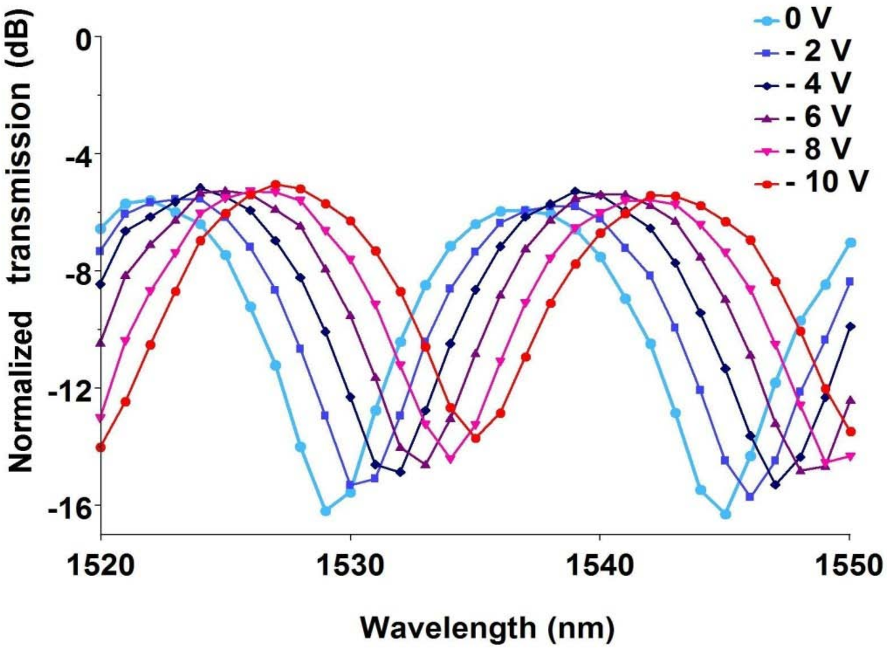
- RC time constant
  - Compromise between modulation efficiency, optical loss and RC time constant to be found for each waveguide design

- RF signal propagation along the few mms long phase shifter length

Integrated optical modulator: carrier depletion

Experimental demonstration

- Carrier depletion in PIN diode with p-doped slit in the intrinsic region
- Assymetric Mach Zehnder interferometer
- Phase shifter length = 4 mm



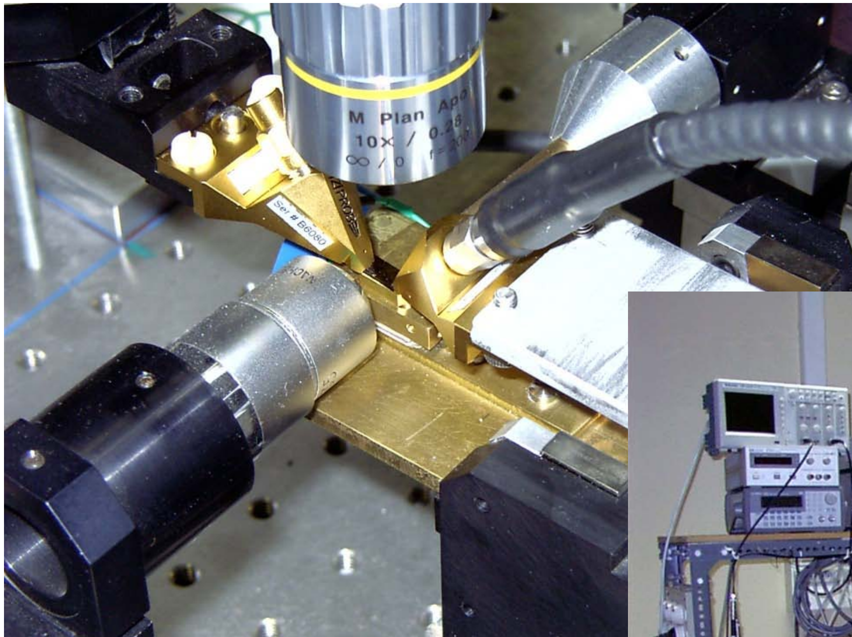
DC experimental results:

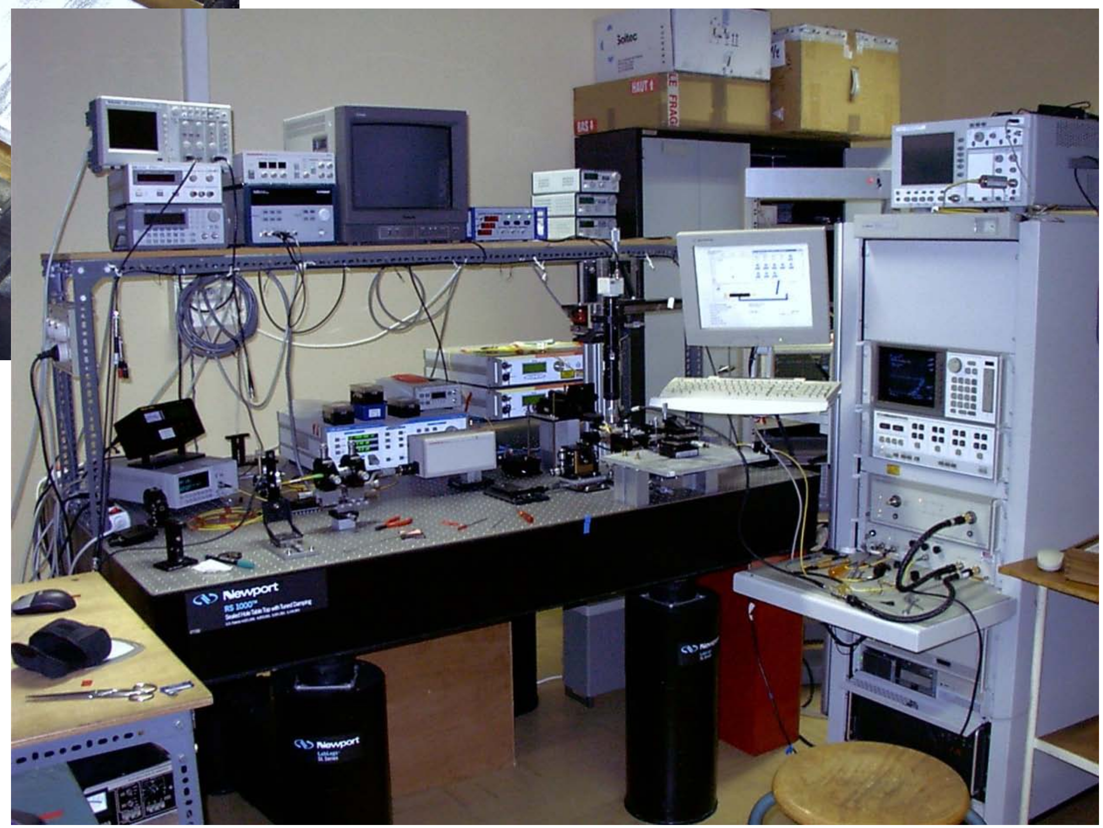
- ❑ Insertion loss = 5 dB
- ❑ Contrast ratio up to 14 dB
- ❑ $V_\pi L_\pi$ = 5 V.cm

D. Marris-Morini et al, Optics express, 16, 2008

Integrated optical modulator: carrier depletion

RF experimental benches

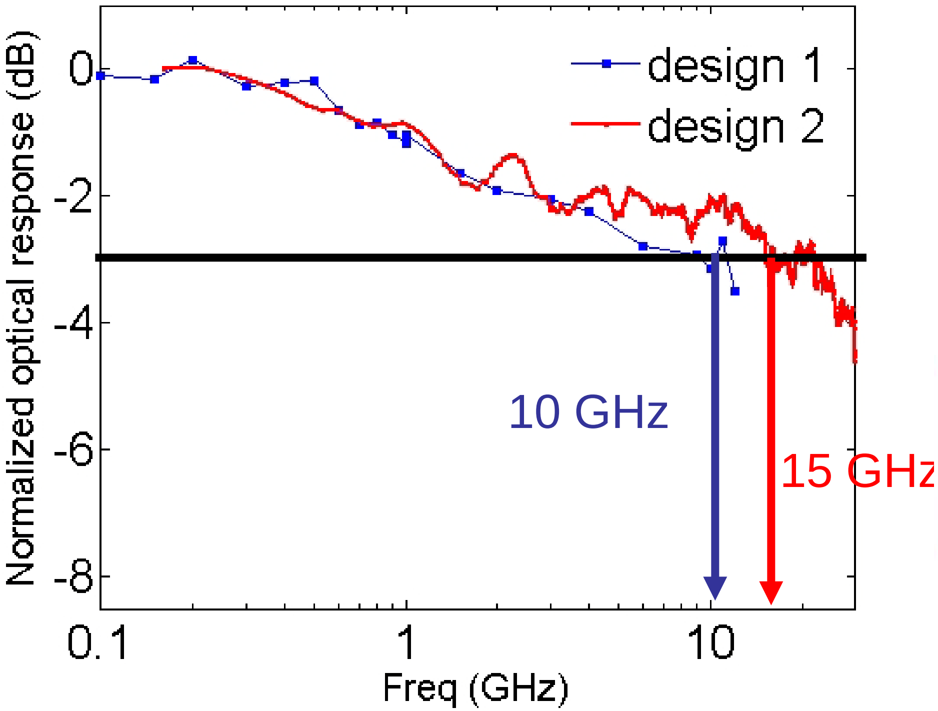


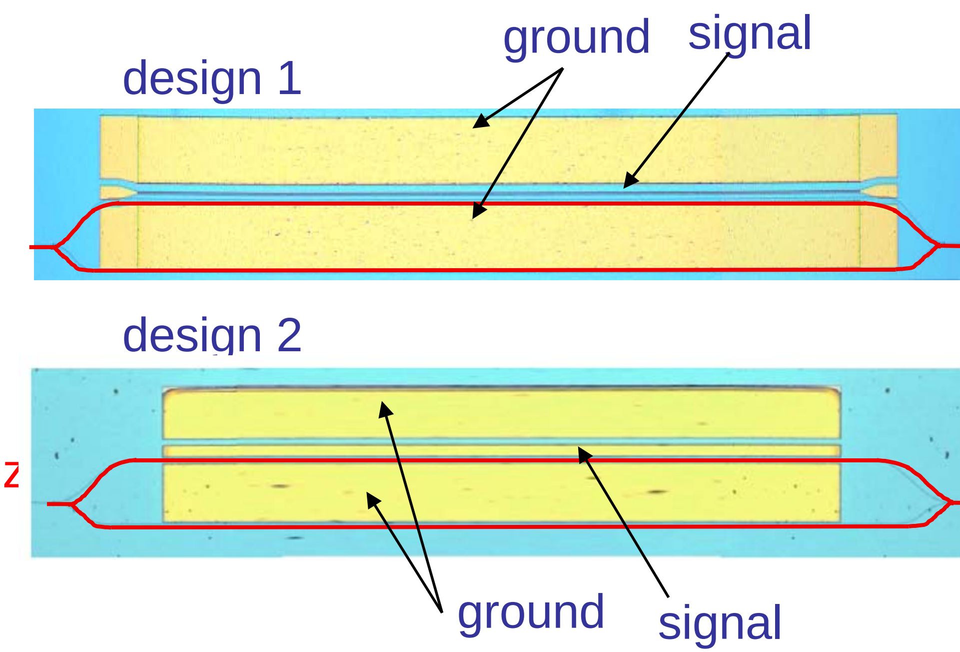


Integrated optical modulator: carrier depletion

Experimental demonstration: small-signal optical response

Two design for coplanar waveguide electrodes have been compared





D. Marris-Morini et al, Group IV photonics 2008

Conclusion

- Intensive research have been made in silicon photonics in the last years.
- Silicon based optical modulator is one of the fundamental building blocs for high performance data transmission systems.
- Optical modulation in/on silicon-based device has been proposed and demonstrated using a large number of physical effect:
    - Electroabsorption using Franz-Keldysh and Quantun Confined Stark effects in SiGe and SiGe/Ge structures
    - Electro-refraction in strained silicon and SiGe supperlattice
    - Integration of III-V or polymer on silicon
    - Free carrier concentration variations in silicon using carrier injection, accumulation, depletion, …

Conclusion

- Numerous experimental demonstrations of optical modulator integrated in/on silicon waveguides have been made until the 1st demonstration of GHz modulation 5 years ago.
- Impressive progress in silicon modulators let's hope that silicon based 10 and 40 Gbit/s data transmission systems will be available in the next years, for various applications (telecommunications, optical interconnect on microelectronics chips, core to core communications in microprocessors, etc…)

Acknowledgements

IEF (Orsay, France)

- Suzanne LAVAL
- Eric CASSAN
- Xavier LE ROUX
- Paul CROZAT
- Daniel PASCAL
- Sylvain MAINE
- Anatole LUPU
- David BOUVILLE
- Samson EDMOND
- Mathieu HALBWAX

CEA - LETI (Grenoble, France)

- Jean Marc FEDELI

French RMNT project (CAURICO)

http://pages.ief.u-psud.fr/caurico/

Basic Technological Research

European Community's Seventh Framework Program (FP7)

“pHotonics ELectronics functional Integration on CMOS”

European Community's Sixth Framework Program (FP6)

Clean rooms

IEF/MINERVE

CEA/LETI Grenoble, France