Si Photonics

Lecture 11 : Si Modulators

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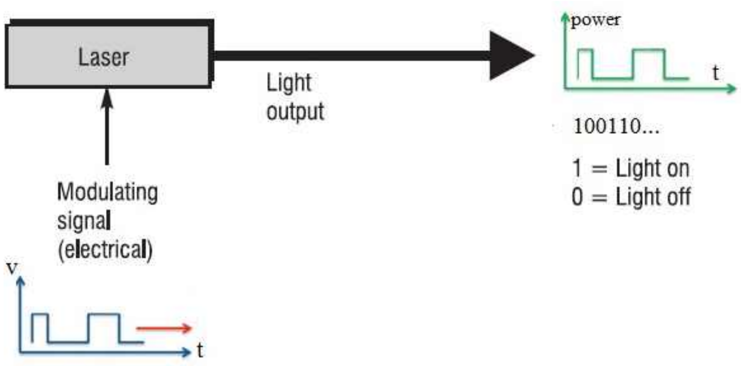
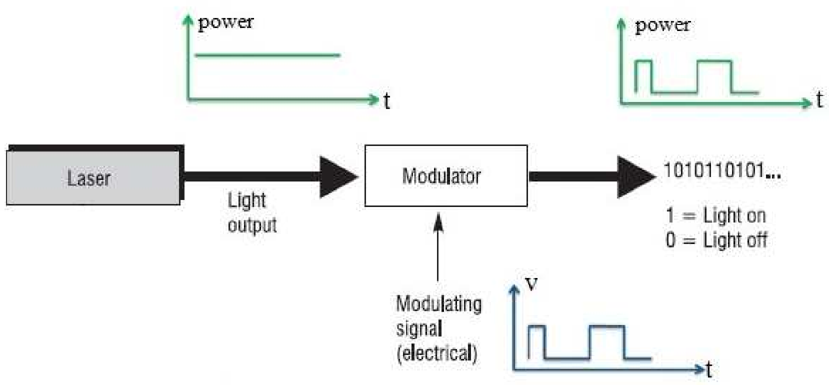
Lecture 11: Si Waveguide Devices

How to generate light signals with (digital) information?

Direct Modulation



External Modulation



- Simple
- For high-speed modulation, semiconductor laser suffers from frequency chirp

(Change in lasing frequency ➔ Suffers from fiber dispersion in long-distance optical comm.)

- No Si laser

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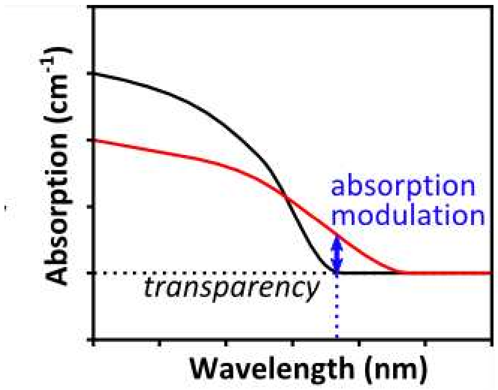
External modulation

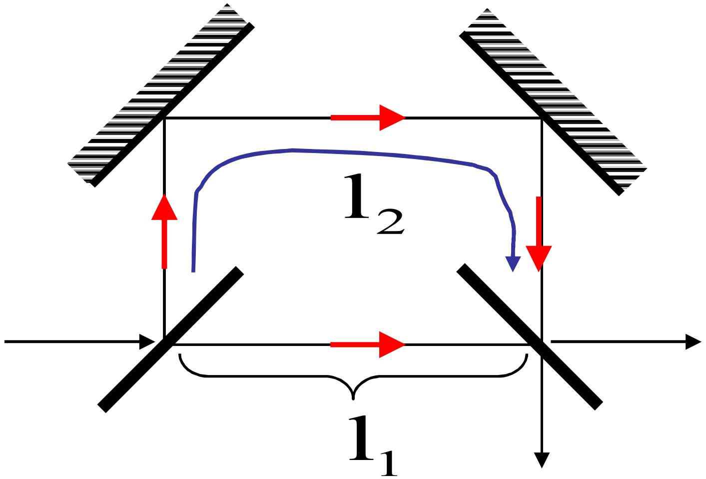
I. Refractive index modulation

II. Bandgap (absorption) modulation



In Si photonics, Type I is often used

Mach-Zehnder Interferometer



$$I_{out,\,bottom} = \frac{I_{in}}{2}\left[1+\cos\left(kl_1 - kl_2\right)\right]$$

What happens when (kl_1-kl_2) changes?

Output intensity changes

Intensity modulation

➔ MZ Modulator (MZM)

MZM with waveguides?

Modulation with voltage signals?

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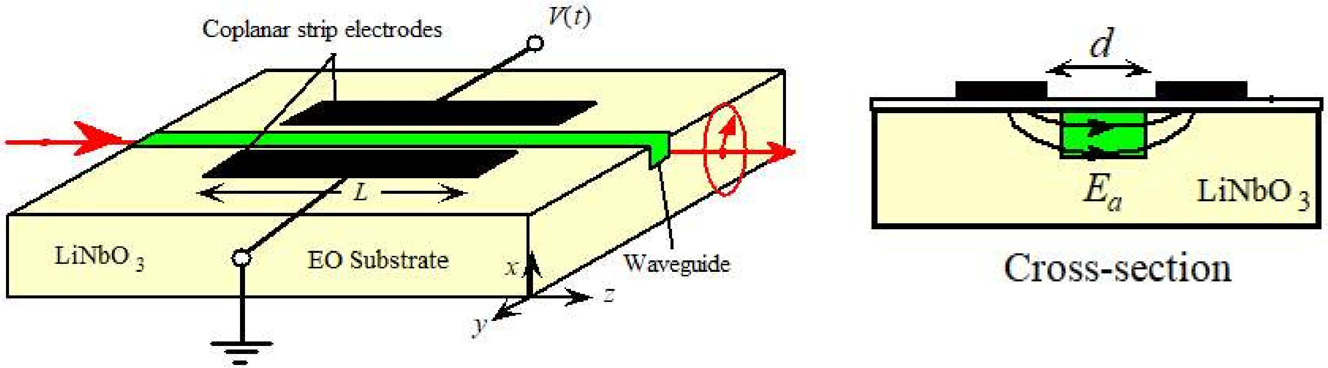
$LiNbO_3$ (Lithium Niobate) waveguide

Waveguides are formed by metal (Ti) doping



Very small loss for the wavelength of interest

Refractive index of $LiNbO_3$ can be changed by E-field (Large linear electro-optic effect or Pockels effect)

➔ Voltage controlled phase shift or delay line

EO effect is very fast (Speed is limited by electrodes)

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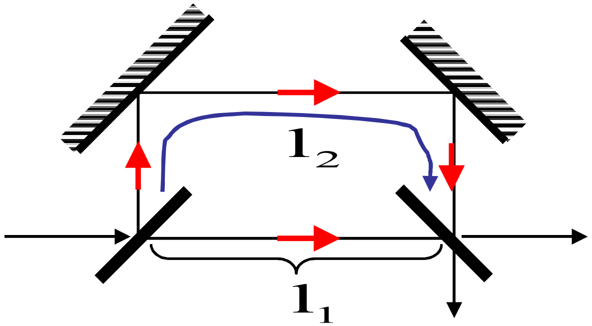
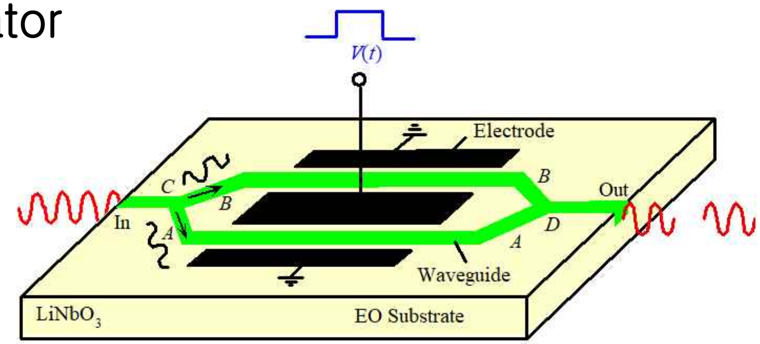
$LiNbO_3$ (Lithium Niobate) MZ Modulator





$$I_{out} = \frac{I_{in}}{2}\left[1+\cos\left(kl_1 - kl_2\right)\right] ==> \frac{I_{in}}{2}\left[1+\cos\left(\left(\beta_1-\beta_2\right)L\right)\right] \qquad \beta_1 = n_{eff,1}k_o \qquad \beta_2 = n_{eff,2}k_o$$

With V(t), $n_{eff,1} = n_{eff,0} + \Delta n_{eff}(V(t))$ $\quad n_{eff,2} = n_{eff,0} - \Delta n_{eff}(V(t))$

$$\beta_1 - \beta_2 = 2\Delta n_{eff}(V(t))k_o$$

$$I_{out} = \frac{I_{in}}{2}\left[1+\cos\left(2\Delta n_{eff}(V(t))k_0 L\right)\right]$$

➔ Widely used in high-performance optical communication systems

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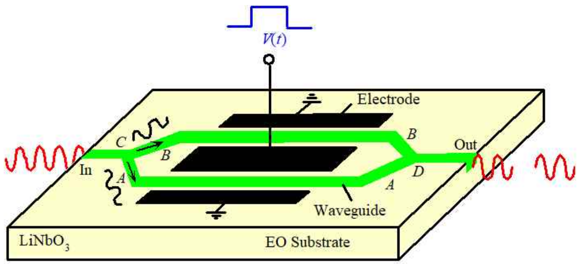


$$I_{out} = \frac{I_{in}}{2}\left[1 + \cos\left(2\Delta n_{eff}(V(t))k_0 L\right)\right]$$

How to realize Si MZM?

Change Si waveguide effective index with *V(t)*

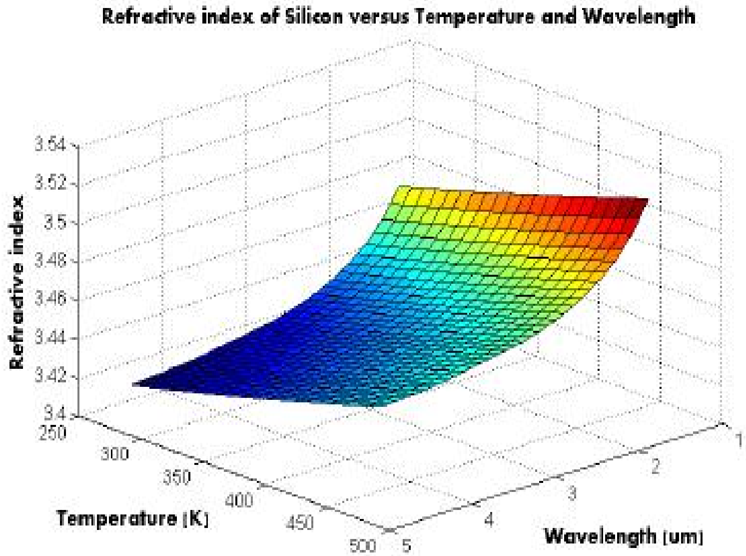
But Si does not have any linear E-O effect

Si refractive index changes with temperature

For 1500nm at RT, $dn/dT = 1.87 \times 10^{-4}\ K^{-1}$

Efficient but slow

➔ Used for slow switching devices



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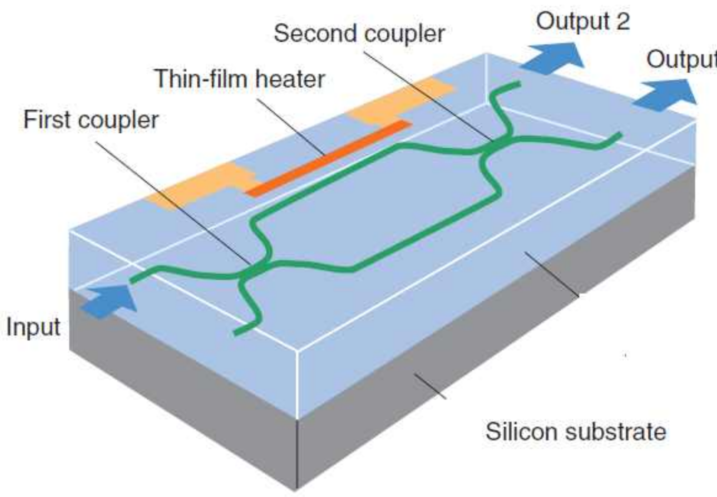
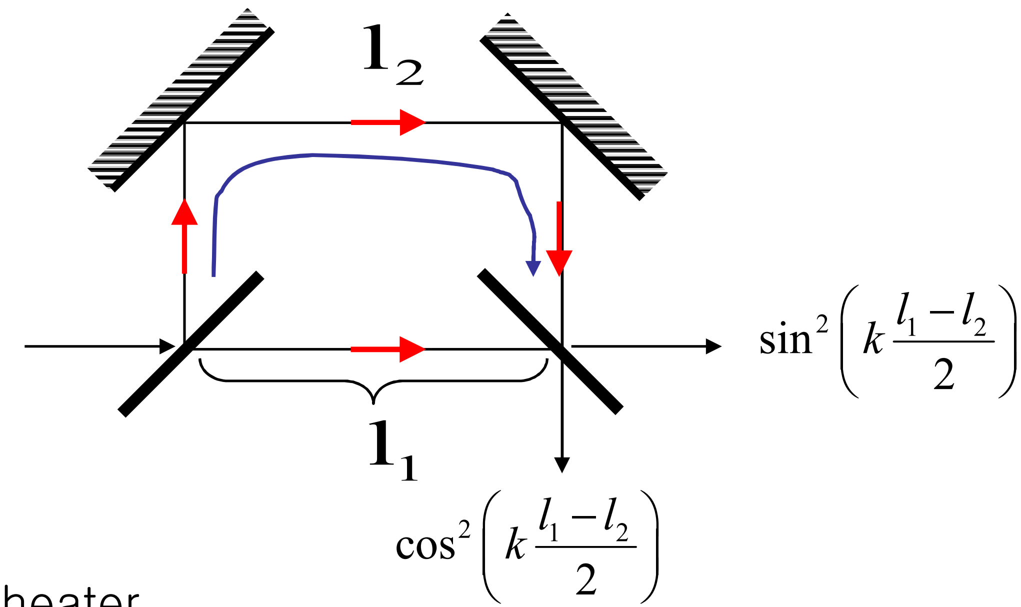
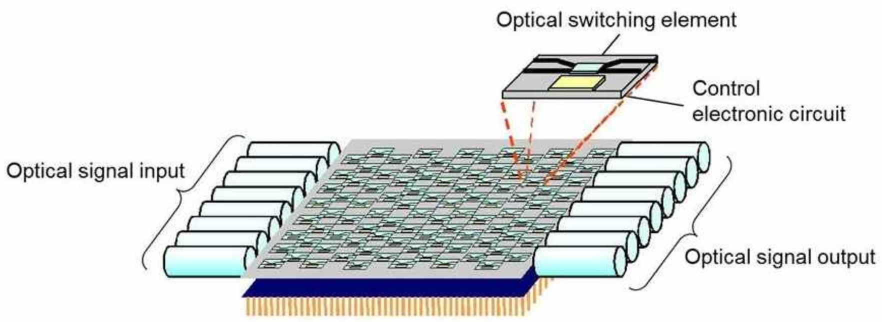
Si MZI Switch





Temperature change with a built-in heater



Optical switching

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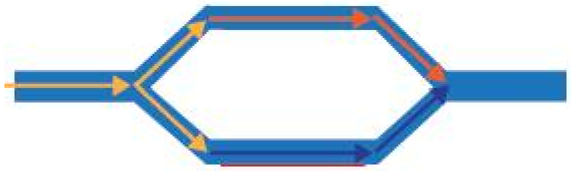
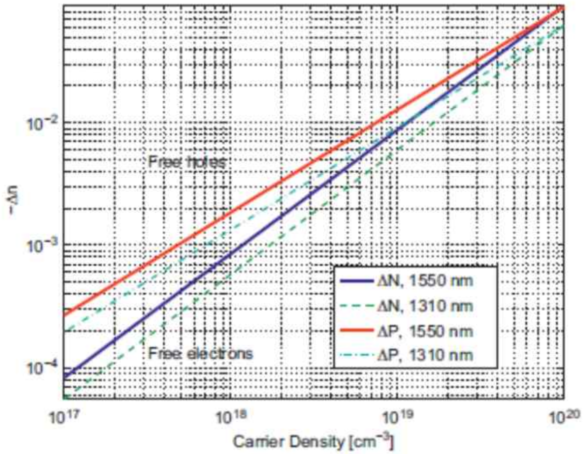
Si MZM



$$\frac{I_{in}}{2}\left[1+\cos\left(n_{eff,1}-n_{eff,2})k_0 L\right)\right]$$

How to change Si refractive index with voltage fast?

Change amount of carriers (N and P) inside Si waveguides



Plasma dispersion effect

$$\Delta n\ (\text{at } 1550\,\text{nm}) = -8.8\times10^{-22}\Delta N - 8.5\times10^{-18}\Delta P^{0.8}$$
$$\Delta n\ (\text{at } 1310\,\text{nm}) = -6.2\times10^{-22}\Delta N - 6\times10^{-18}\Delta P^{0.8}.$$

(Soref and Benett)

More carriers ➔ Smaller refractive index

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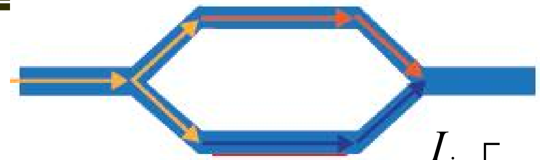
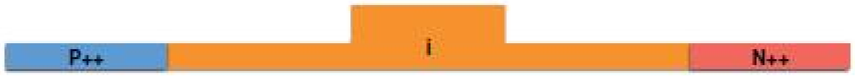
How to change N, P?

Forward-biased PIN Junction



$$\frac{I_{in}}{2}\left[1+\cos\left(n_{eff,1}-n_{eff,2}\right)k_0 L\right]$$



More carriers

Smaller refractive index

➔ Smaller effective index

Very efficient

But not fast enough due to carrier life time (~ 1 nsec)

Injected carriers induce loss

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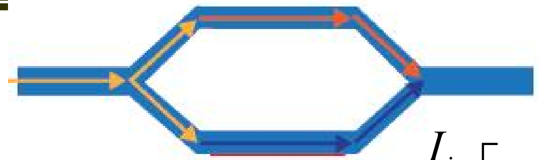
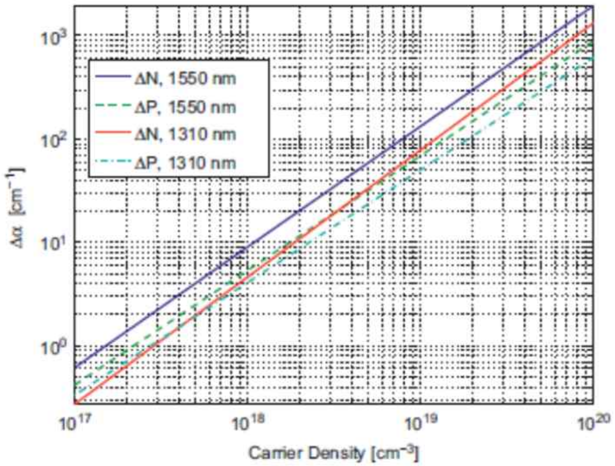
How to change N, P?

Forward-biased PIN Junction



$$\frac{I_{in}}{2}\left[1+\cos\left(n_{eff,1}-n_{eff,2}\right)k_0 L\right)\right]$$



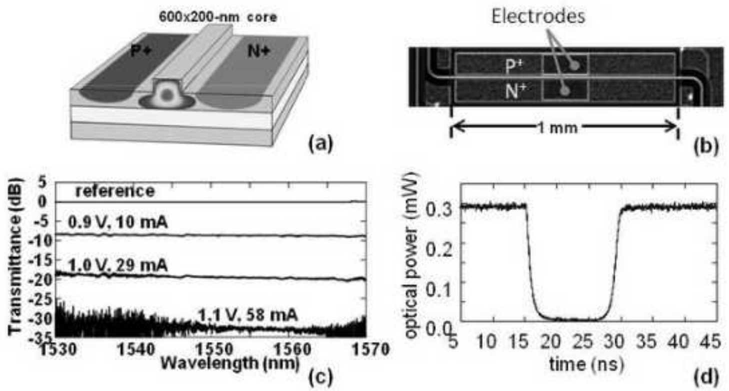
$$\Delta\alpha \text{ (at 1550 nm)} = 8.5\times10^{-18}\Delta N + 6\times10^{-18}\Delta P \ [\text{cm}^{-1}]$$

$$\Delta\alpha \text{ (at 1310 nm)} = 6\times10^{-18}\Delta N + 4\times10^{-18}\Delta P \ [\text{cm}^{-1}],$$

Refractive index change ←→ Loss change

(Kramers-Kronig relationship)

➔ Variable Optical Attenuator



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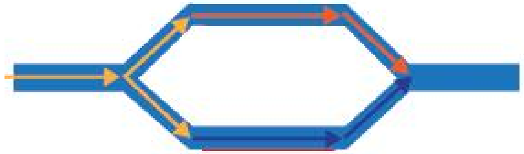
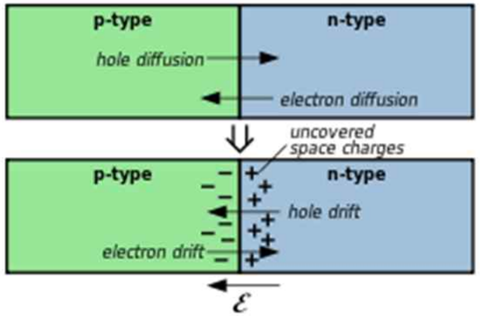
How to change N, P very fast?

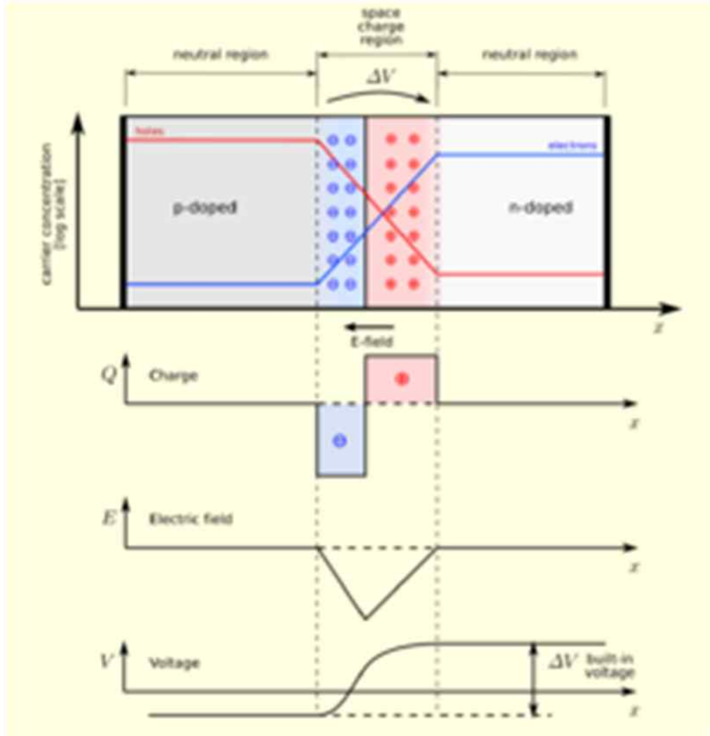


$$\frac{I_{in}}{2}\left[1+\cos\left(\left(n_{eff,1}-n_{eff,2}\right)k_0 L\right)\right]$$

Reversed-Biased PN Junction



Formation of depletion region
Between P and N regions



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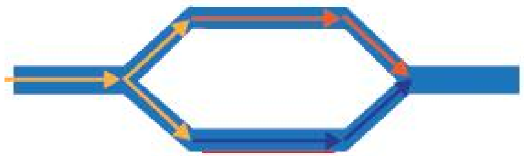
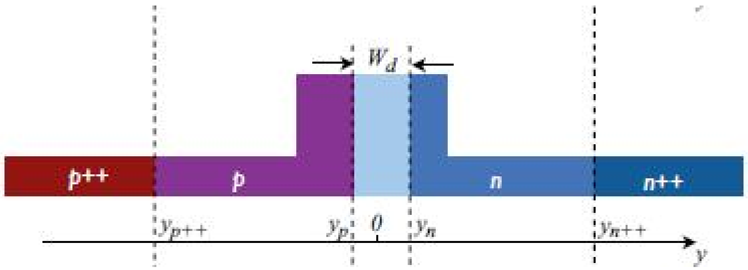
How to change N, P very fast?



$$\frac{I_{in}}{2}\left[1+\cos\left(n_{eff,1}-n_{eff,2}\right)k_0 L\right)\right]$$

Reverse-biased PN Junction

Assuming uniform abrupt junction



$$W_d = \sqrt{\frac{2\epsilon_0\epsilon_s(N_A+N_D)(V_{bi}-V)}{qN_AN_D}}$$

With larger reverse bias, larger W_d

Less plasma dispersion effect because less carriers interact with guided light

Larger refractive index

➔ Larger effective index

Not as efficient as thermal, PIN phase shifter

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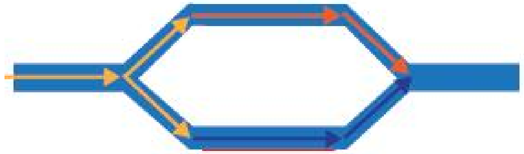
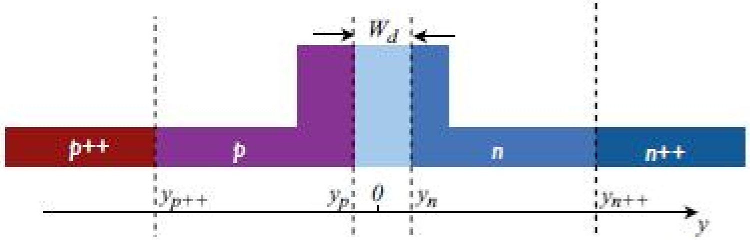
How to change N, P very fast?



$$\frac{I_{in}}{2}\left[1+\cos\left(n_{eff,1}-n_{eff,2}\right)k_0 L\right]$$

Reverse-biased PN Junction



$$W_d=\sqrt{\frac{2\epsilon_0\epsilon_s(N_A+N_D)(V_{bi}-V)}{qN_AN_D}}$$

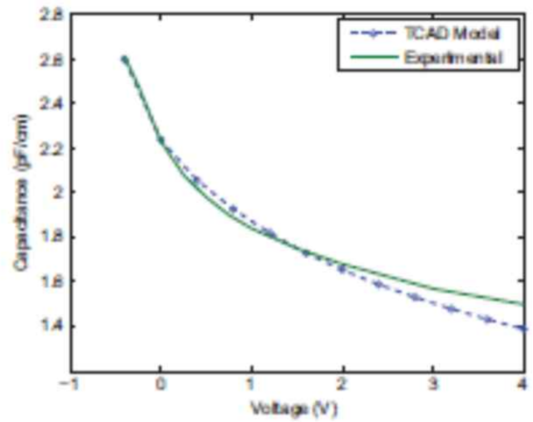
Frequency response:

Dominated by RC time constant

R: Series resistance

C: Junction capacitance = Area x ε_{si} / W_d

$$\sim\sqrt{\frac{q\epsilon_0\epsilon_s}{2(1/N_D+1/N_A)(V_{bi}-V)}}$$



➔ Most popular method for high-speed Si phase shifter

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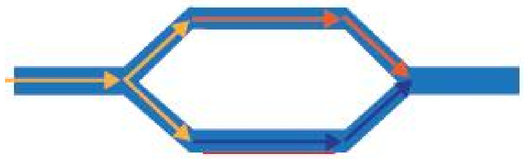
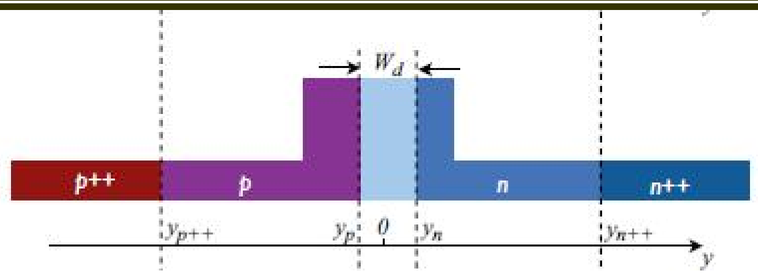
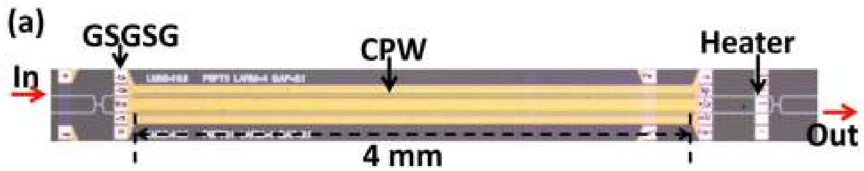
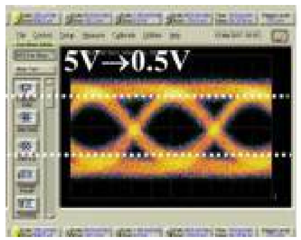


$$\frac{I_{in}}{2}\left[1+\cos\left(n_{eff,1}-n_{eff,2}\right)k_0 L\right]$$







25 Gbps operation

(Optics Letters, Vol. 24, No. 3, p. 403, 2018)

Built-in heater required ➔ Compensating phase shift due to process variation

Very long ➔ Requires transmission line electrodes with impedance termination

Smaller Si modulator?

Lecture 11: Si Waveguide Devices

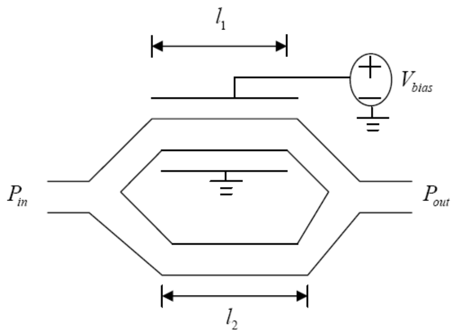
Homework #1

Consider a Mach-Zehnder interferometer shown below. The effective index that 1.5 μm light experiences while traveling inside the interferometer is 3.5 when no bias voltage is applied. Due to manufacturing problems, $l_1 = 100\mu m$ and $l_2 = 100.1\mu m$ are not the same.

(a) What is the output power when the input power is $1mW$ at 1.5 μm and no bias is applied? Assume P_{out} has $\cos^2$ dependence on P_{in}.

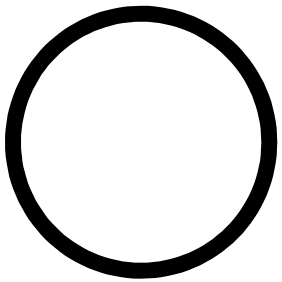
We want to use the interferometer as an optical on/off switch by applying voltage to the upper arm as shown. The effective index of the upper arm increases 0.001 per 1 volt applied.

(b) What is the voltage with the smallest absolute value that needs to be applied to make the switch on?



Lecture 11: Si Waveguide Devices

Consider a ring waveguide



Assuming there is light circulating inside the ring

Resonance condition:

$$e^{-j\beta(2\pi r)} = 1$$

$$n_{eff} \frac{2\pi}{\lambda} 2\pi r = 2m\pi \qquad L = m\frac{\lambda}{n_{eff}}$$

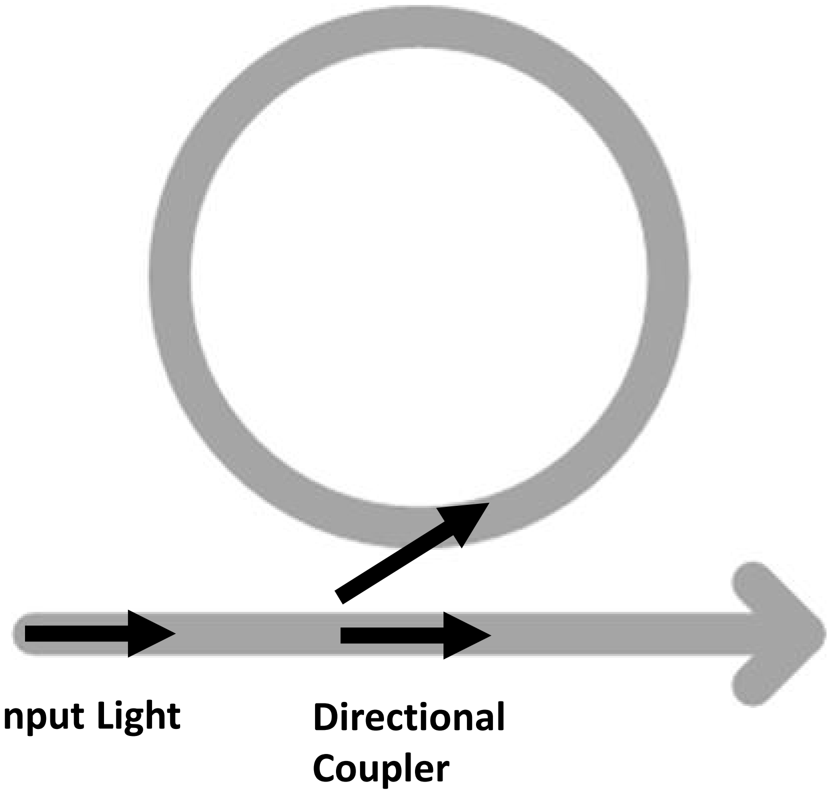
What can we do with this?

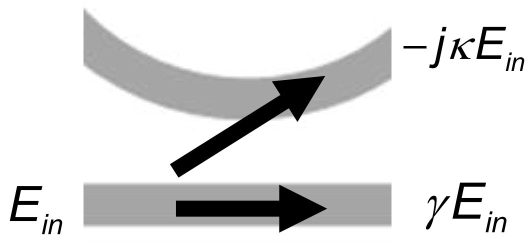
Effectively F-P resonator

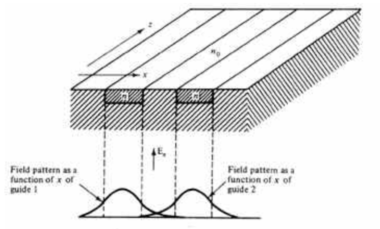
How to couple light in and out?

Lecture 11: Si Waveguide Devices

- Ring Interferometer (Top View)







With only one input

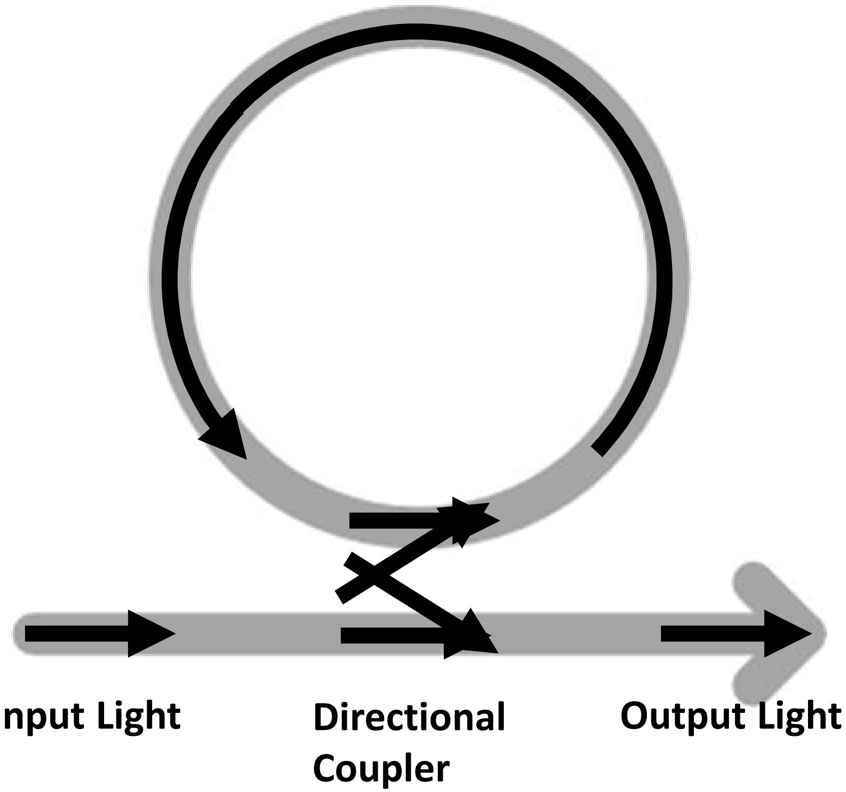
$$\begin{bmatrix} a_1(z) \\ a_2(z) \end{bmatrix} \sim \begin{bmatrix} -j\sin(\kappa' z) \\ \cos(\kappa' z) \end{bmatrix}$$

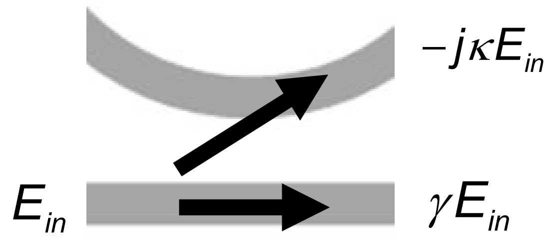
$$\gamma = \cos(\kappa' d) \qquad \kappa = \sin(\kappa' d)$$

$$(\gamma^2 + \kappa^2 = 1)$$

Lecture 11: Si Waveguide Devices

- Ring Interferometer (Top View)





$(\gamma^2 + \kappa^2 = 1)$

α: amount after one circulation

L: ring circumference

$$E_{out} = E_{in}\gamma + E_{in}(-j\kappa)(\alpha e^{-jn_{eff}k_0L})(-j\kappa)$$
$$+E_{in}(-j\kappa)(\alpha e^{-jn_{eff}k_0L})\gamma(\alpha e^{-jn_{eff}k_0L})(-j\kappa)$$
$$\cdots$$

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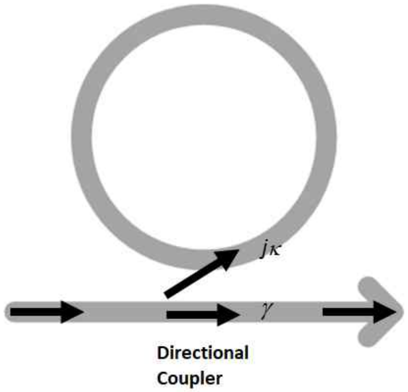
Ring Interferometer



$$E_{out} = E_{in}\gamma + E_{in}(-j\kappa)(\alpha e^{-jn_{eff}k_0L})(-j\kappa)$$
$$+E_{in}(-j\kappa)(\alpha e^{-jn_{eff}k_0L})\gamma(\alpha e^{-jn_{eff}k_0L})(-j\kappa)$$
$$\cdots$$

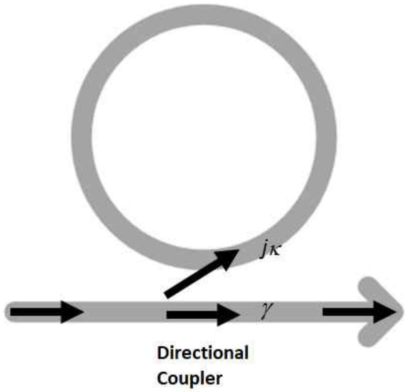
$$(\beta = n_{eff}k_0)$$

$$\frac{E_{out}}{E_{in}} = \gamma - \kappa^2\alpha e^{-j\beta L} - \kappa^2\alpha^2\gamma e^{-j2\beta L} - \kappa^2\alpha^3\gamma^2 e^{-j3\beta L} - \cdots$$

$$= \gamma - \kappa^2\sum_{n=1}^{\infty}\alpha^n\gamma^{n-1}e^{-jn\beta L} = \gamma - \frac{\kappa^2\alpha e^{-j\beta L}}{1-\alpha\gamma e^{-j\beta L}} = \frac{\gamma - \alpha e^{-j\beta L}}{1-\alpha\gamma e^{-j\beta L}}$$

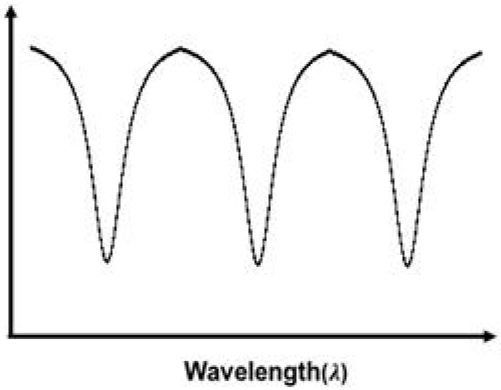
Lecture 11: Si Waveguide Devices

Ring Interferometer



$$E_{out} = E_{in}\gamma \quad + E_{in}(-j\kappa)(\alpha e^{-j\beta L})(-j\kappa)$$
$$+E_{in}(-j\kappa)(\alpha e^{-j\beta L})\gamma(\alpha e^{-j\beta L})(-j\kappa) + \ldots$$

$$\frac{E_{out}}{E_{in}} = \frac{\gamma - \alpha e^{-j\beta L}}{1 - \alpha\gamma e^{-j\beta L}} \qquad T = \left|\frac{E_{out}}{E_{in}}\right|^2 = \frac{\alpha^2 + \gamma^2 - 2\alpha\gamma\cos(\beta L)}{1 + (\alpha\gamma)^2 - 2\alpha\gamma\cos(\beta L)}$$



It can be shown min. transmission occurs when $\beta L = 2m\pi$ (Resonance condition)

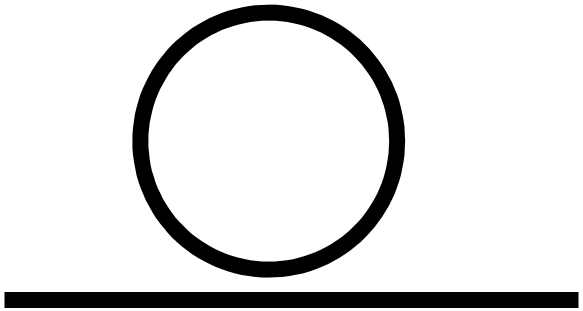
$$n_{eff}\frac{2\pi}{\lambda}L = 2m\pi \qquad L = m\frac{\lambda}{n_{eff}} \qquad T = \left|\frac{E_{out}}{E_{in}}\right|^2 = \frac{(\alpha-\gamma)^2}{(1-\alpha\gamma)^2}$$

T=0 if $\gamma=\alpha$; critical coupling

$\gamma<\alpha$; over coupling

$\gamma>\alpha$; under coupling

Lecture 11: Si Waveguide Devices



What good is this?

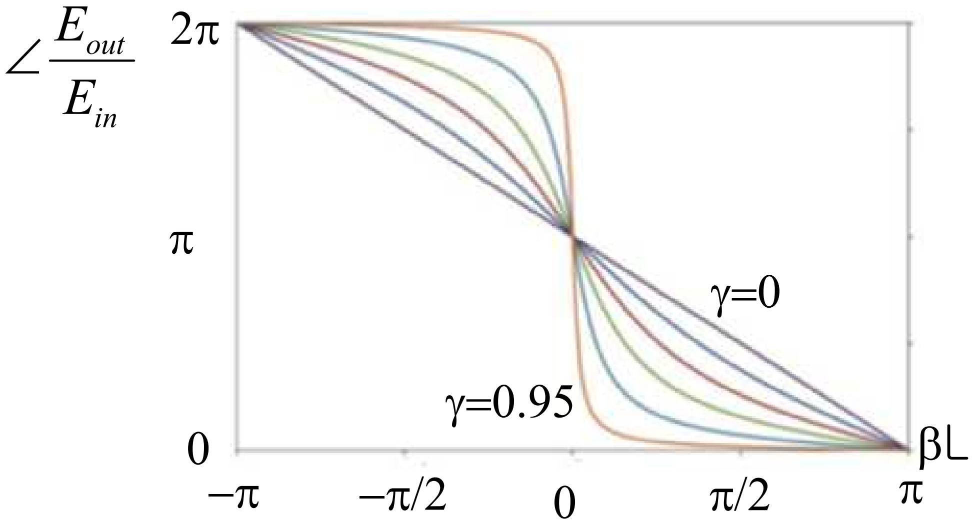
If α=1, $\frac{E_{out}}{E_{in}} = \frac{\gamma - e^{-j\beta L}}{1-\gamma e^{-j\beta L}}$ $T = \frac{\alpha^2 + \gamma^2 - 2\alpha\gamma\cos(\beta L)}{1+(\alpha\gamma)^2 - 2\alpha\gamma\cos(\beta L)}$

$= 1$

Phase-domain filter

➔ Optical All-Pass Filter

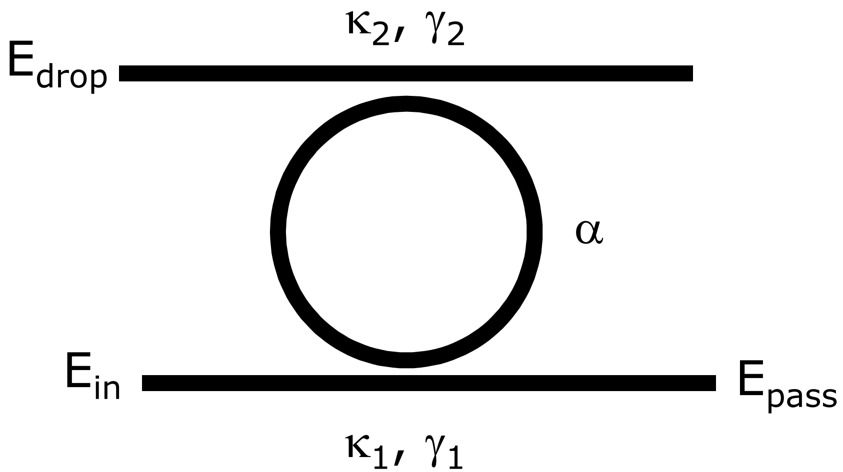
Optical Delay Line



Lecture 11: Si Waveguide Devices

Homework #2

Consider a ring interferometer consisting of two directional couplers, top and bottom, shown below.



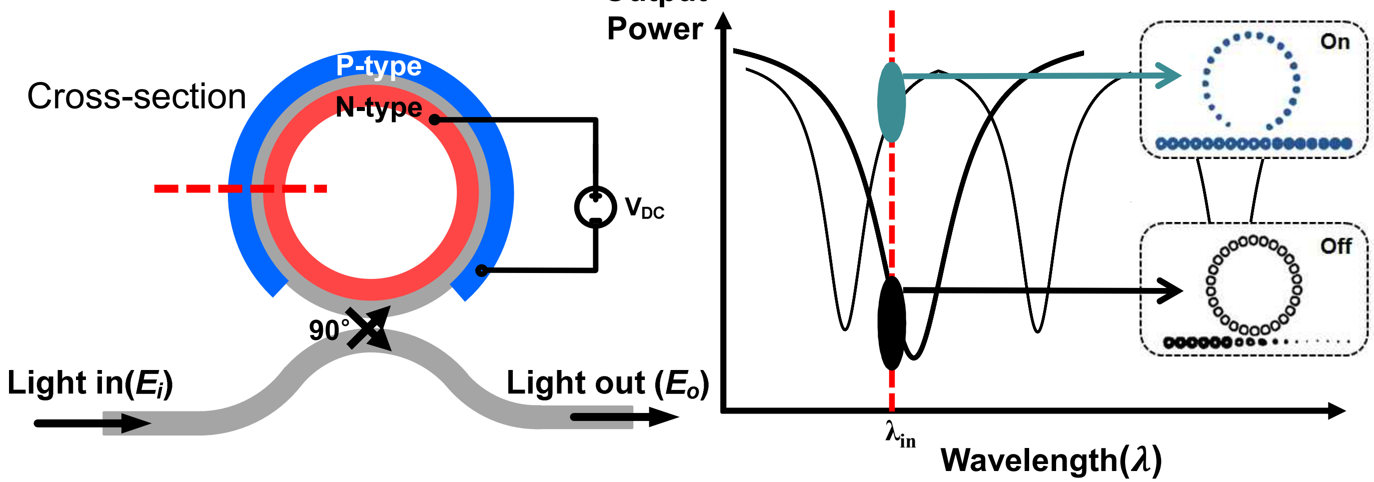
(a) Determine the expression for E_{pass}/E_{in}

(b) What is the FSR in terms of wavelength for this interferometer?

(c) What is the FSR of this interferometer if n_{eff} changes with the wavelength , or $dn_{eff}/d\lambda$ is not zero?

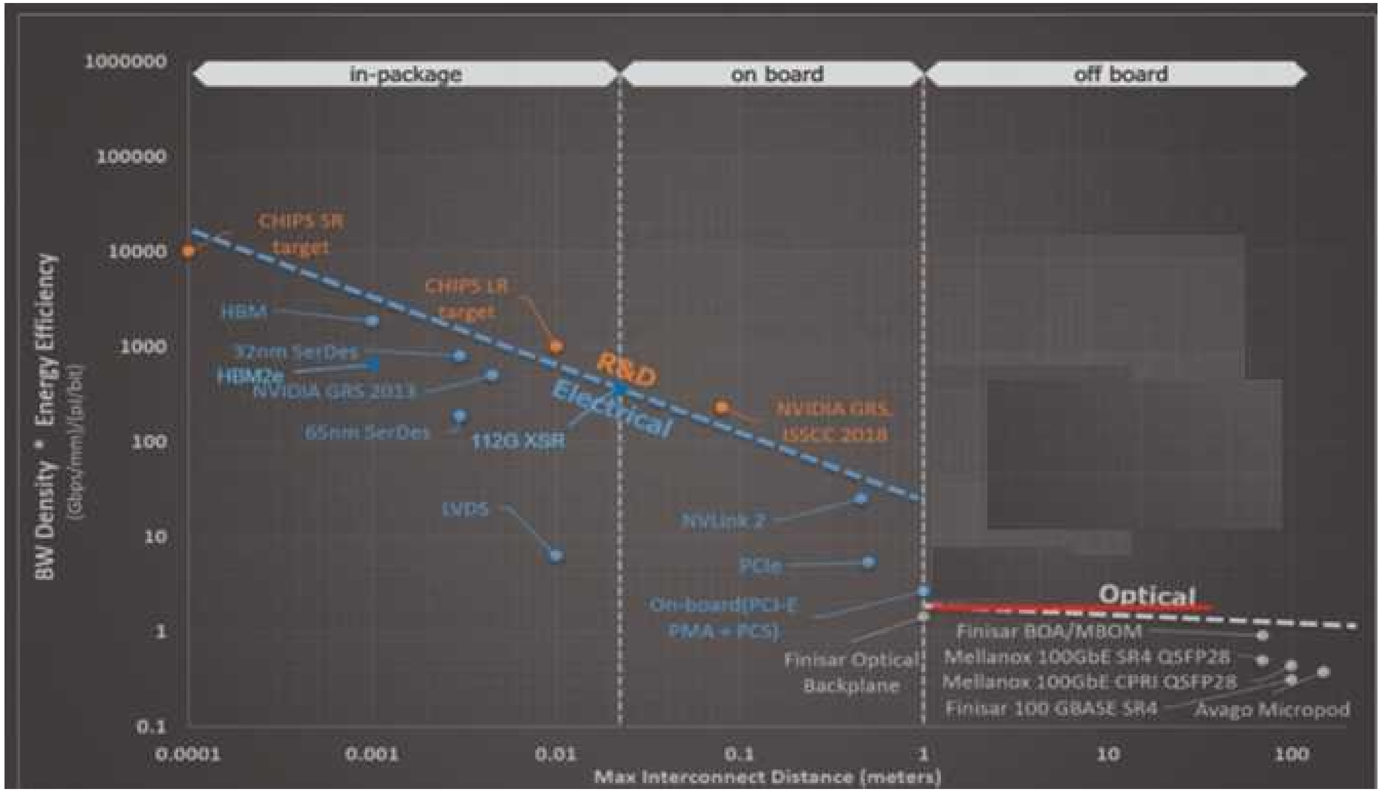
Si intensity modulator based on ring interferometer?

$$L = m\frac{\lambda}{n_{eff}}$$



Lecture 11: Si Waveguide Devices

Interconnect Figure of Merit



(Darpa)

Si photonics is expected to close the gap and improve overall performance