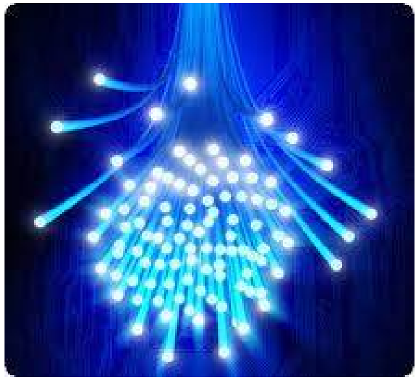
Opto-Electronics and Photonics

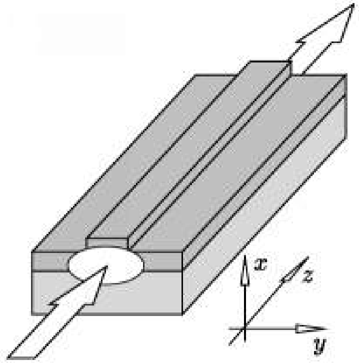
Lecture 18 : Planar Waveguide Devices

Woo-Young Choi

Dept. of Electrical and Electronic Engineering
Yonsei University

Lecture 18: Planar Waveguide Devices

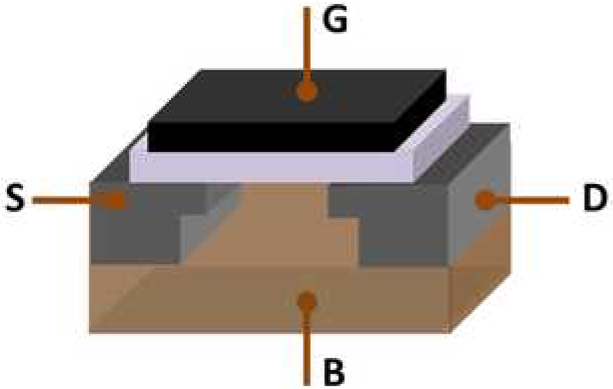




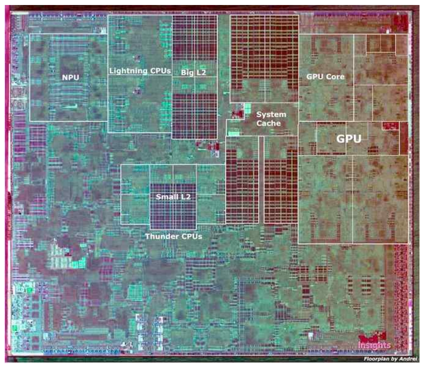
Planar waveguide

➔ Device

➔ Photonic Integrated Circuit



Transistor



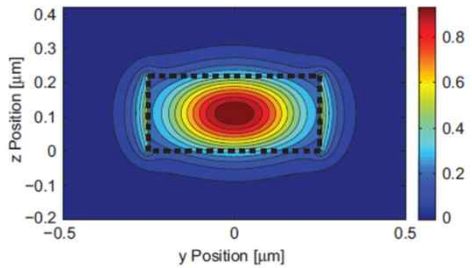
Integrated Circuit

Lecture 18: Planar Waveguide Devices

3-Dimensional waveguide

Detailed analysis complicated

➔ Numerical solution easily available



Intensity profile for the fundamental TE mode

In general, TE_{mn} TM_{mn} modes

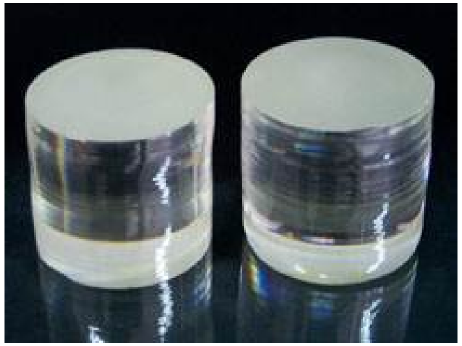
Materials requirements for planar dielectric waveguides

- Precise control of dimension and refractive index
- Low loss at desired λ
- Mass production possible
- Electrical control of refractive index (Electro-optic effect)
- Integration

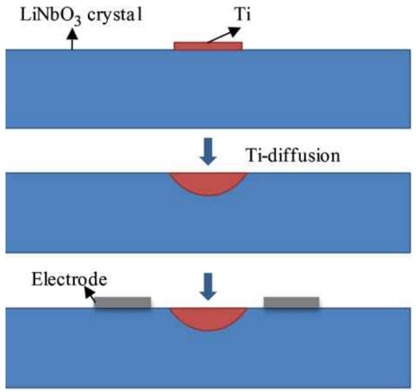
Lecture 18: Planar Waveguide Devices

Materials used for waveguides

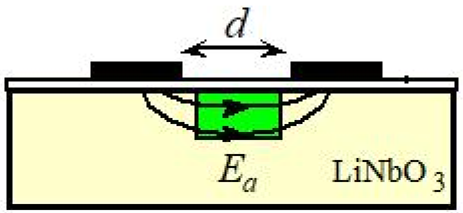
- Ceramics : $LiNbO_3$ (Lithium Niobate) with Ti doping for core



Transparent to 1.55μm light



Efficient refractive index modulation by E-field
(Large electro-optic effect)

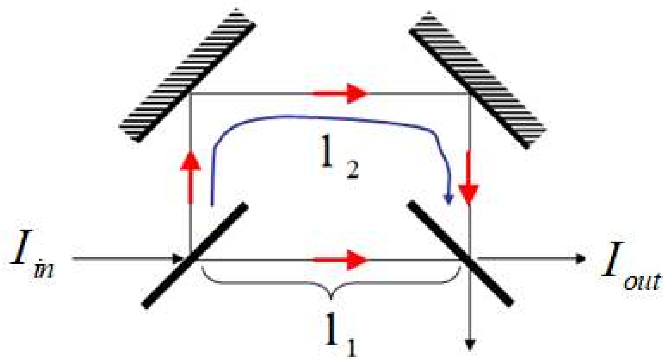


$$\triangle n_{eff} \sim E$$

➔ Phase modulation of incident light

➔ Mach-Zehnder Modulator

Mach-Zehnder Interferometer (Lecture 12)

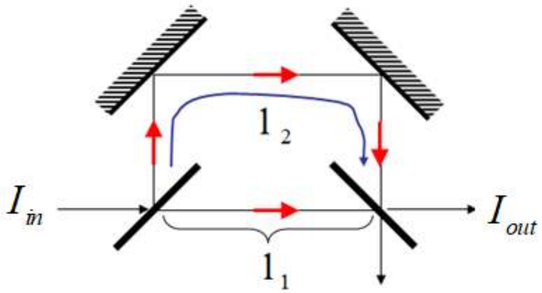


$$\frac{I_{out}}{I_{in}} = \cos^2\left(\frac{kl_1 - kl_2}{2}\right)$$

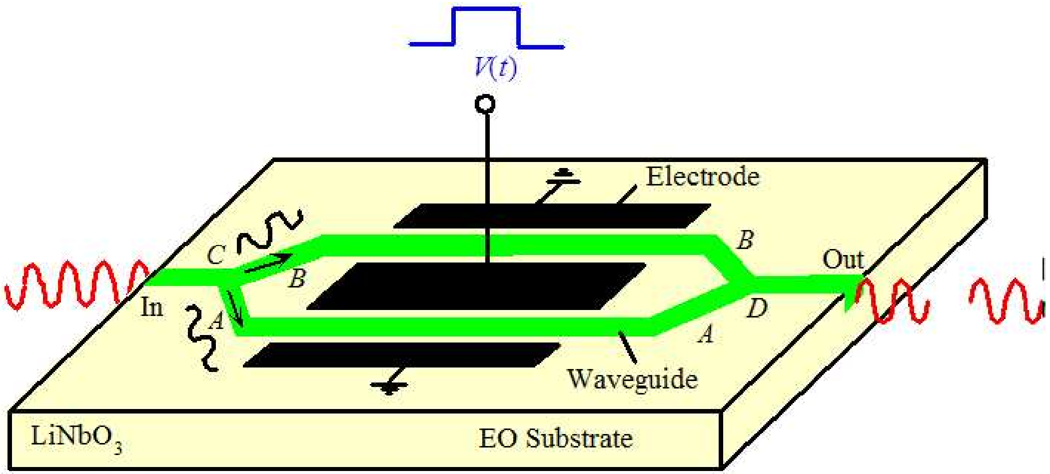
If (kl_1-kl_2) can be changed with voltage, I_{out} can be modulated

➔ Optical intensity modulator

Lecture 18: Planar Waveguide Devices



$$\frac{I_{out}}{I_{in}} = \cos^2\left(\frac{kl_1 - kl_2}{2}\right)$$



Upper arm: $n_{eff} + \Delta n_{eff}(V)$ Lower arm: $n_{eff} - \Delta n(V)$

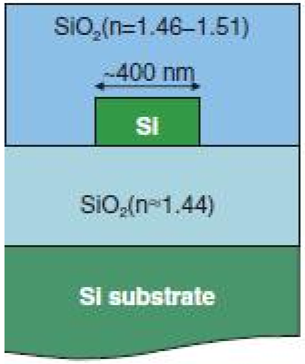
$$\frac{I_{out}}{I_{in}} = \cos^2\left(\frac{kl_1 - kl_2}{2}\right) \rightarrow \cos^2\left(\frac{(n_{eff} + \Delta n_{eff})k_0 l - (n_{eff} - \Delta n_{eff})k_0 l}{2}\right) = \cos^2\left(\Delta n_{eff} k_0 l\right)$$

Mach-Zehnder Modulator (MZM) => A key device for high-speed optical comm.

But not good for mass production, integration

Lecture 18: Planar Waveguide Devices

SoI (Si on Insulator)   Si (core)/ SiO_2 (cladding)

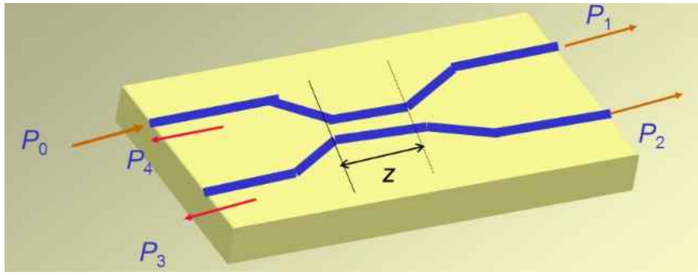


- Si is transparent to 1.55μm light ➔ Good planar waveguides
- Not efficient E-O effect
- Si fabrication technology very mature ➔ Advanced technique for Si intensity modulators

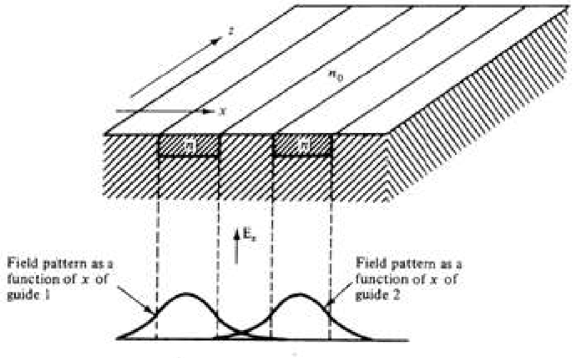
➔ Si Photonic Integrated Circuits

Lecture 18: Planar Waveguide Devices

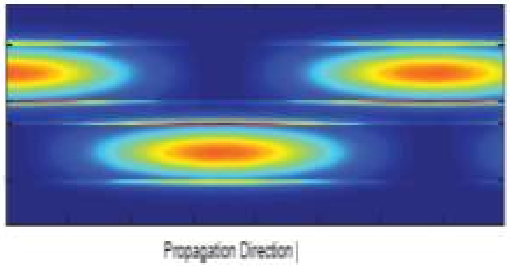
- Directional Coupler



Two waveguides placed very close to each other



Energy transfer between two waveguides



$$P_1 = P_0 \cos^2(az)$$

$$P_2 = P_0 \sin^2(az)$$

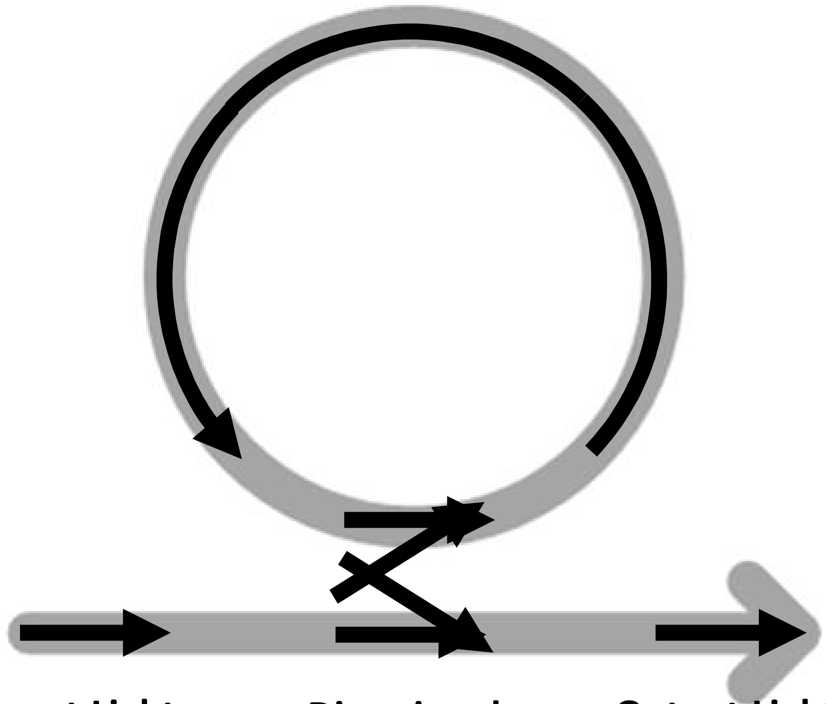
az = $\pi/2$ ➔ Spatial switch

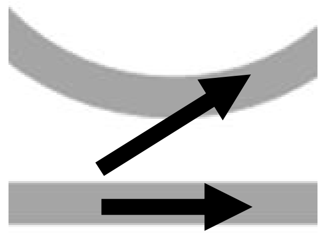
az = $\pi/4$ ➔ Power divider (Beam Splitter)

Amount of coupling can be changed by carrier injection or temperature

Lecture 18: Planar Waveguide Devices

- Ring Resonator (Top View)





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

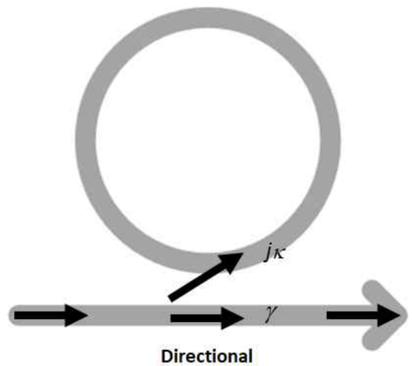
α: amount after one circulation

L: ring circumference

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

Lecture 18: Planar Waveguide Devices

- Ring Resonator (Top View)

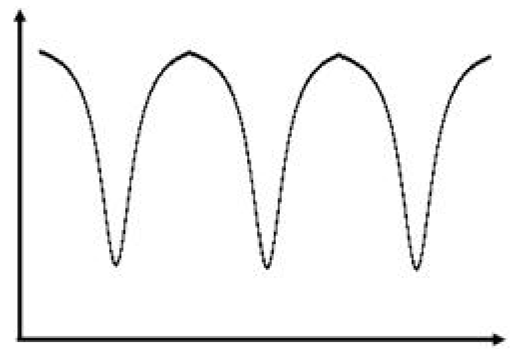


$$(\theta = n_{eff} k_0 L)$$

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

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

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

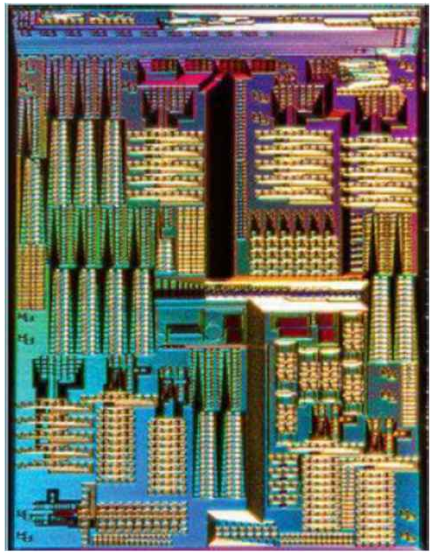


Interferometer ←

It can be shown min. transmission occurs when $\theta = 2m\pi$ ==> $L = m\frac{\lambda_{res}}{n_{eff}}$

Lecture 18: Planar Waveguide Devices

Si Photonic Integrated Circuits



Si PIC's used in High-Performance Data Centers

Lecture 18: Planar Waveguide Devices

Homework (Due 11/15)

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?