Lect. 16: Planar Waveguide Devices

Issues for practical waveguides

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

Materials used for waveguides

- Silica with Ge doping ➔ Optical fiber
- Dielectric materials: $LiNbO_3$ (Lithium Niobate)
- Semiconductor-based: Si/SiO_2

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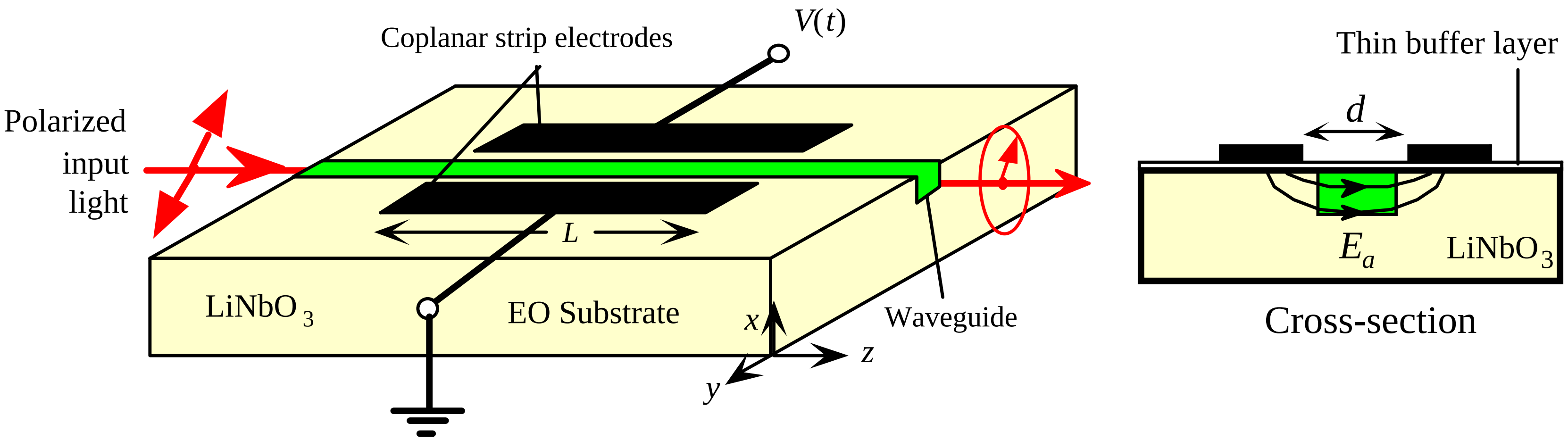
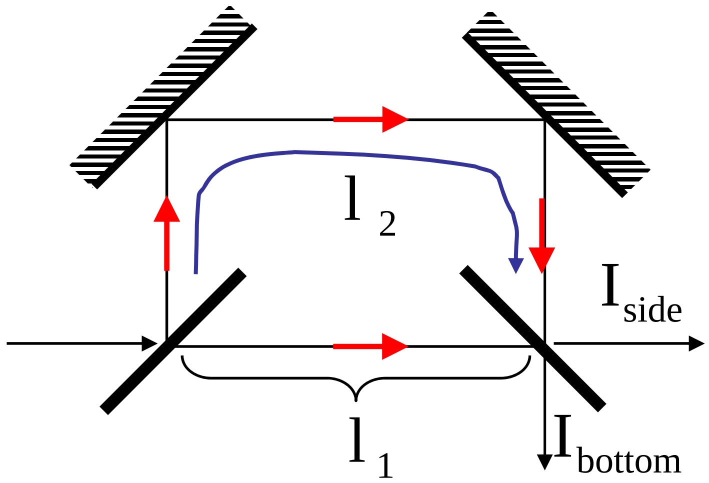
$LiNbO_3$ waveguide



- Waveguide Core formation by Ti doping
- Core refractive index modulation by V(t): E-field enhances refractive index

➔ Phase modulation of incident light

Mach-Zehnder Interferometer:



$$E_{out,\,side} = \frac{1}{2}\left(e^{-jkl_2} - e^{-j2kl_1}\right) = \frac{1}{2}e^{-jk\frac{l_2+l_1}{2}}\left(\mathrm{e}^{-jk\frac{l_2-l_1}{2}} - \mathrm{e}^{jk\frac{l_2-l_1}{2}}\right)$$

$$I_{out,\,side} = \sin^2\left(k\frac{l_1-l_2}{2}\right)$$

$$E_{out,\,bottom} = \frac{j}{2}\left(e^{-jkl_1} + e^{-jkl_2}\right) = \frac{j}{2}e^{-jk\frac{l_1+l_2}{2}}\left(e^{-jk\frac{l_1-l_2}{2}} + e^{jk\frac{l_1-l_2}{2}}\right)$$

$$I_{out,\,bottom} = \cos^2\left(k\frac{l_1-l_2}{2}\right)$$

Realize M-Z interferometer with wave devices

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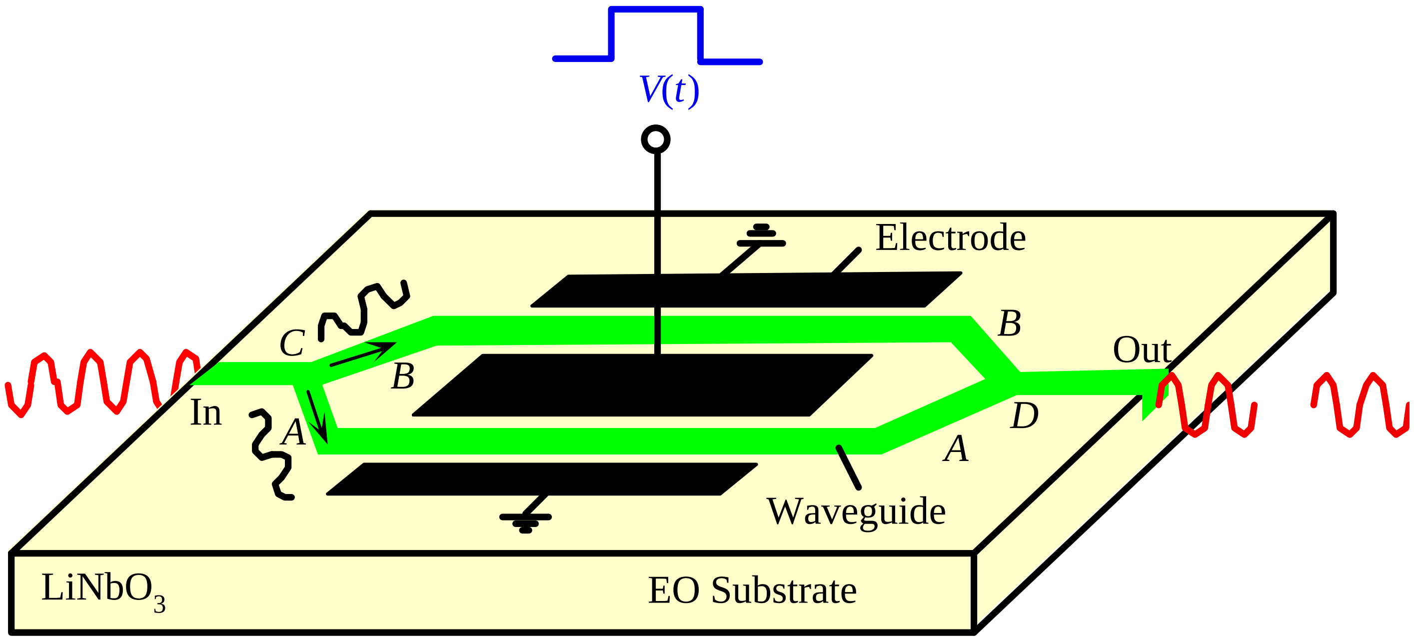
Mach-Zehnder Modulator (MZM)



With voltage applied, light travelling in two different arms experiences different amount of phase shift

LiNbO3 MZM is the standard optical modulator for long distance optical communication

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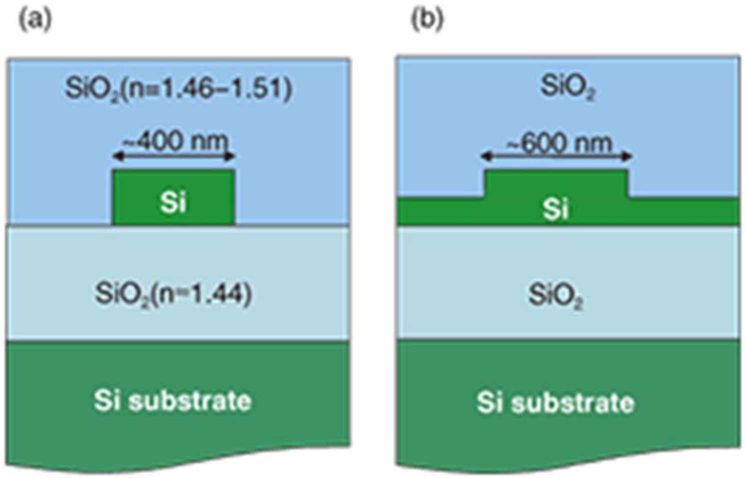
Waveguides based on Si technology (Si Photonics)



- Si is transparent to 1.5μm light
- Si fabrication technology is very mature
- Si photonics provides possibility of integrating photonics and electronics on Si wafer

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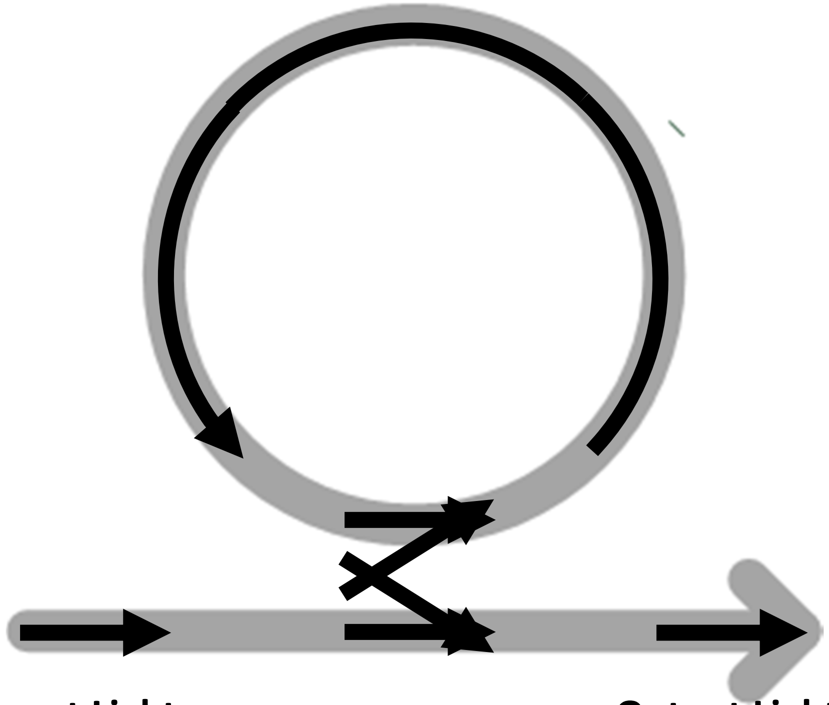
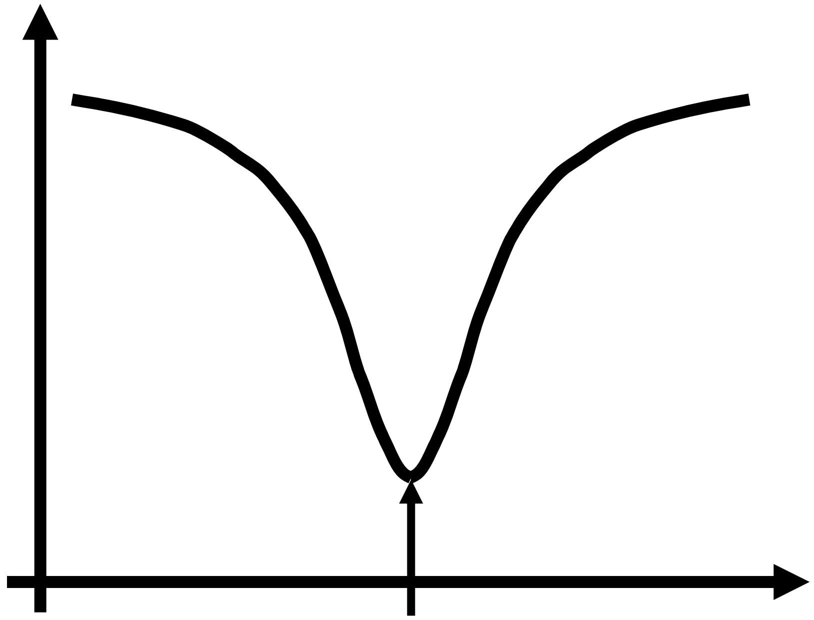
- Ring Resonator





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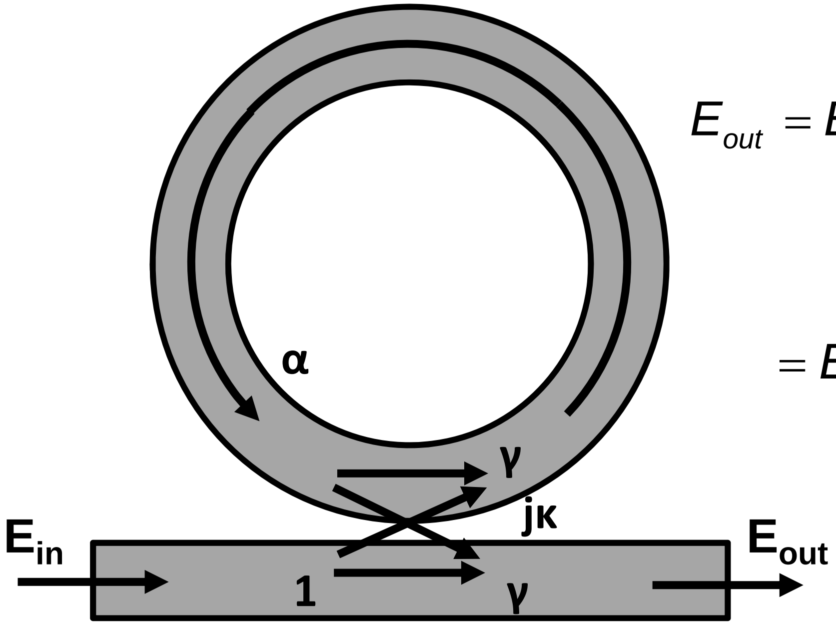

$$E_{out} = E_{in}\left(\gamma - \kappa^2 \alpha e^{-j\theta} - \kappa^2\alpha^2\gamma e^{-j2\theta} - \kappa^2\alpha^3\gamma^2 e^{-j3\theta} - \cdots\right)$$

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

$$= E_{in}\left[\gamma - \kappa^2 \sum_{n=1}^{\infty} \alpha^n \gamma^{n-1} e^{-jn\theta}\right]$$

- Through coefficient: γ (ratio for through light)
- Coupling coefficient: κ (field ratio of coupled light at the coupler)
- Loss coefficient: α (field ratio after one round-trip)

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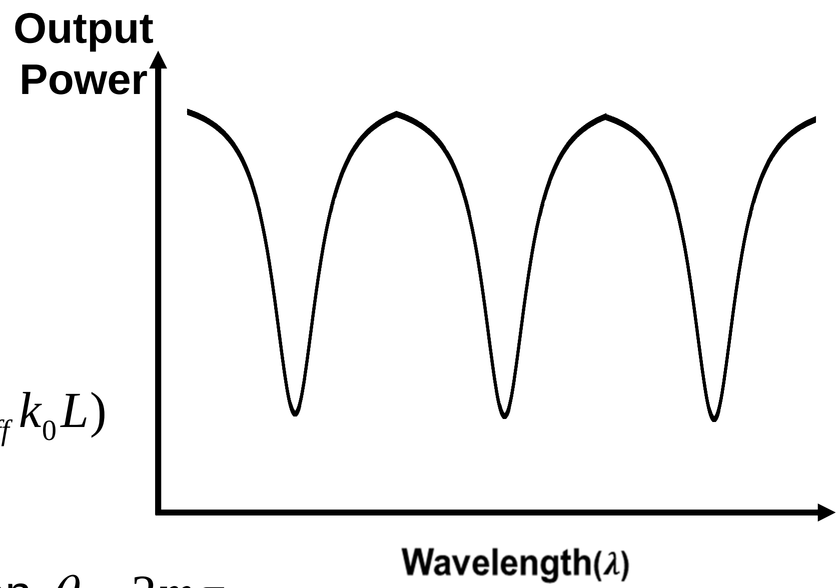
$$\frac{E_{out}}{E_{in}} = \left[\gamma - \kappa^2 \sum_{n=1}^{\infty} \alpha^n \gamma^{n-1} e^{-jn\theta}\right]$$

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

$$\frac{P_{out}}{P_{in}} = \left|\frac{E_{out}}{E_{in}}\right|^2 = \frac{\gamma^2 + \alpha^2 - 2\gamma\alpha\cos(\theta)}{1+(\gamma\alpha)^2 - 2\gamma\alpha\cos(\theta)} \quad (\theta = n_{eff} k_0 L)$$

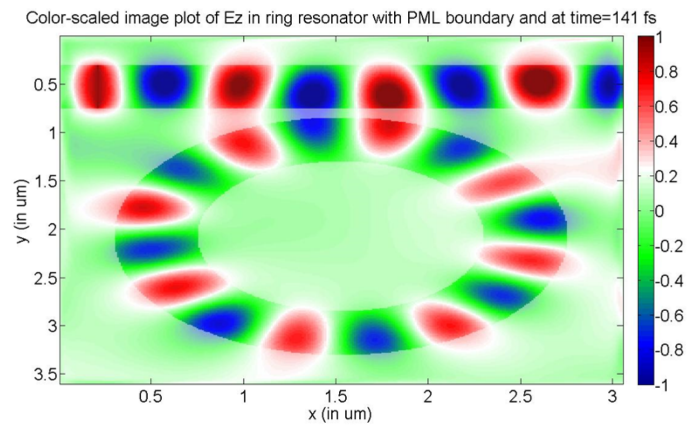


It can be shown min. transmission occurs when $\theta = 2m\pi$

$$\frac{P_{out}}{P_{in}} = \frac{(\gamma-\alpha)^2}{(1+\gamma\alpha)^2}$$

Resonance condition: $m\lambda_{res} = n_{eff} L$

➔ Wavelength-domain filter



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Homework:
(See the figure next page. Assume P_{out} has $\cos^2$ dependence on P_{in})

Consider a Mach-Zehnder interferometer shown below. The refractive index that $1.5\,\mu m$ 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)(10) What is the output power when the input power is $1mW$ at $1.5\,\mu m$ and no bias is applied?

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

(b)(10) What is the voltage with the smallest absolute value that needs to be applied to make the switch on?

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Homework: