EE 232 Lightwave Devices
Lecture 9: Integrated Photonic Components (2)

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Reading: Chuang, Chap 8, 13.3.1-13.3.3

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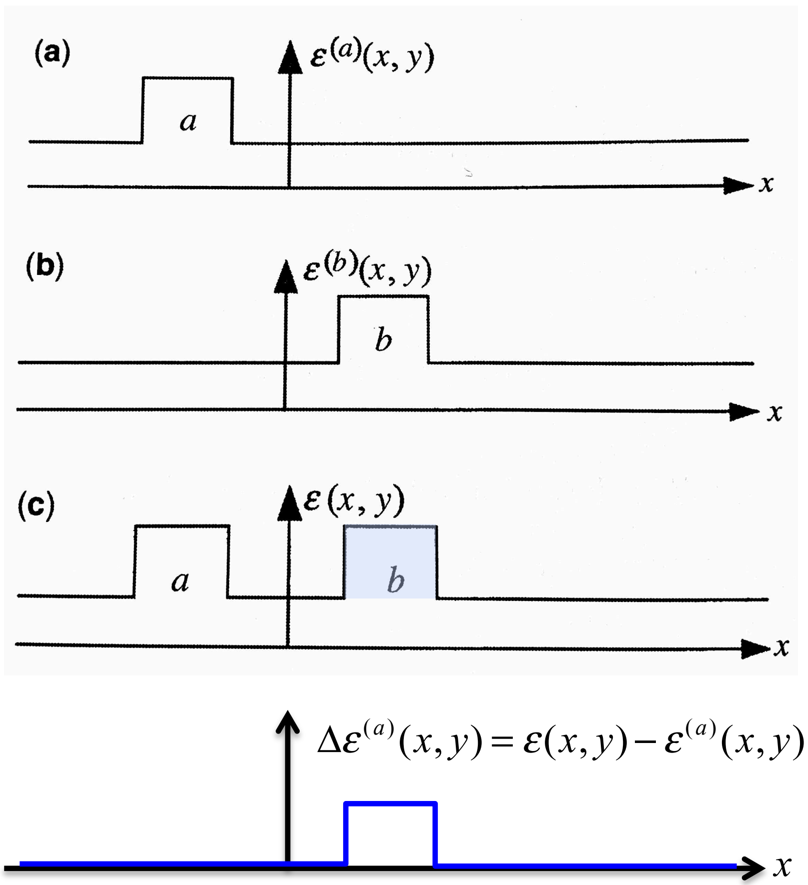
Coupling Coefficient

$$K_{ab} = \frac{\omega}{4}\iint \Delta\varepsilon^{(a)}\left[\mathbf{E}_t^{(a)}\cdot\mathbf{E}_t^{(b)} - \mathbf{E}_z^{(a)}\cdot\mathbf{E}_z^{(b)}\right]dxdy$$

$$\Delta\varepsilon^{(a)}(x,y) = \varepsilon(x,y) - \varepsilon^{(a)}(x,y)$$



Note: the field is normalized to have unity power flow

$$-\frac{1}{2}\int\int E_y H_x^* \, dx\, dy = \frac{\beta}{2\omega\mu}\int\int\left|E_y\right|^2 dxdy = 1$$

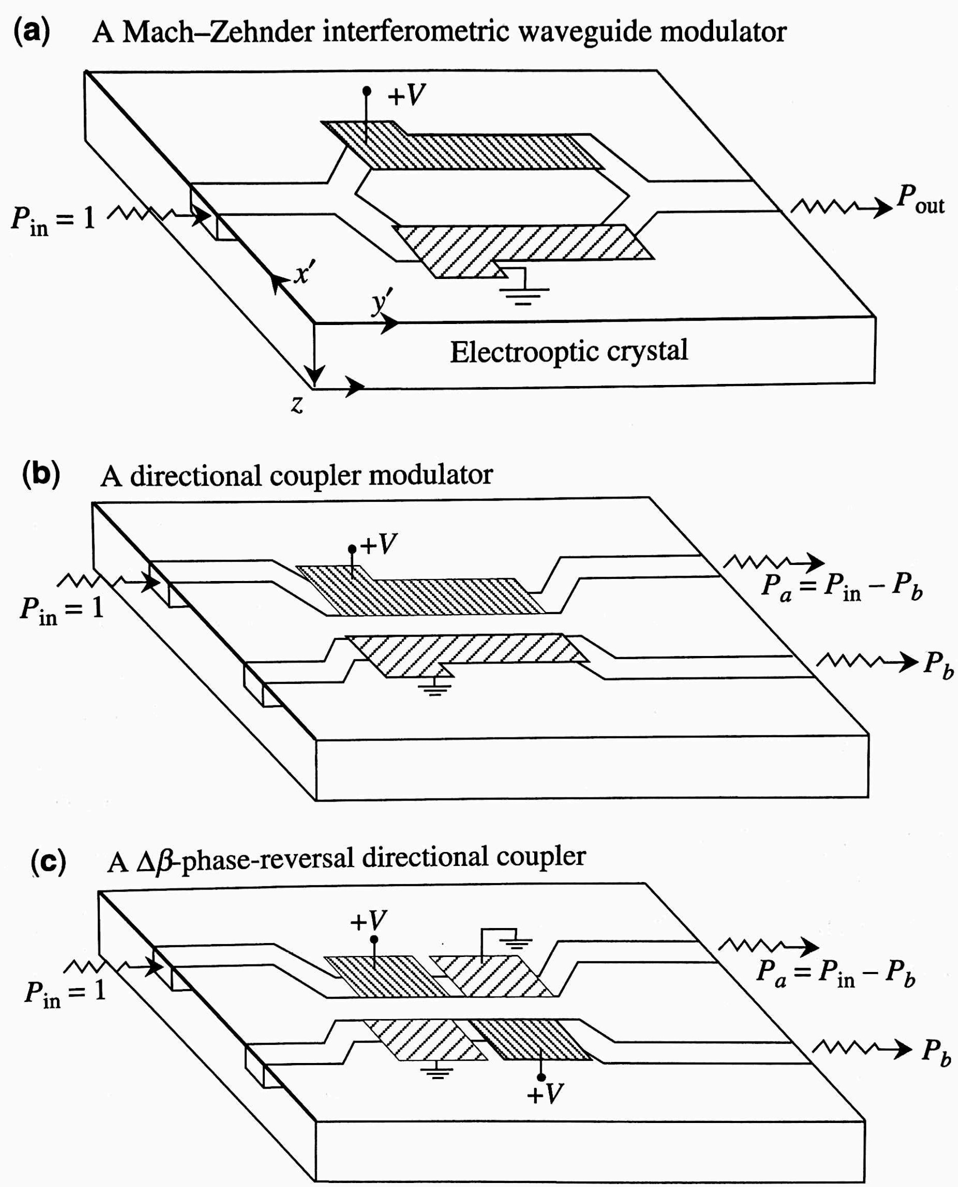
$$\int\int\left|E_y\right|^2 dx\, dy = \frac{2\omega\mu}{\beta}$$

$$\text{Unit : } [\omega\varepsilon][\frac{\omega\mu}{\beta}] = [\frac{\omega^2\mu\varepsilon}{\beta}]$$

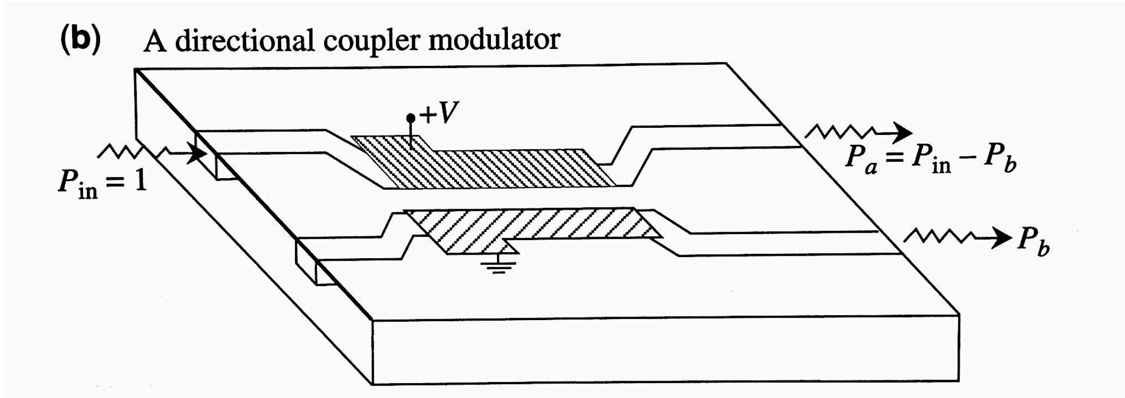
$$= [\frac{\omega^2 n^2}{c^2\beta}] = [\frac{\beta^2}{\beta}] = [\beta]$$

For detail, see p.332 of Chuang and the reference there.

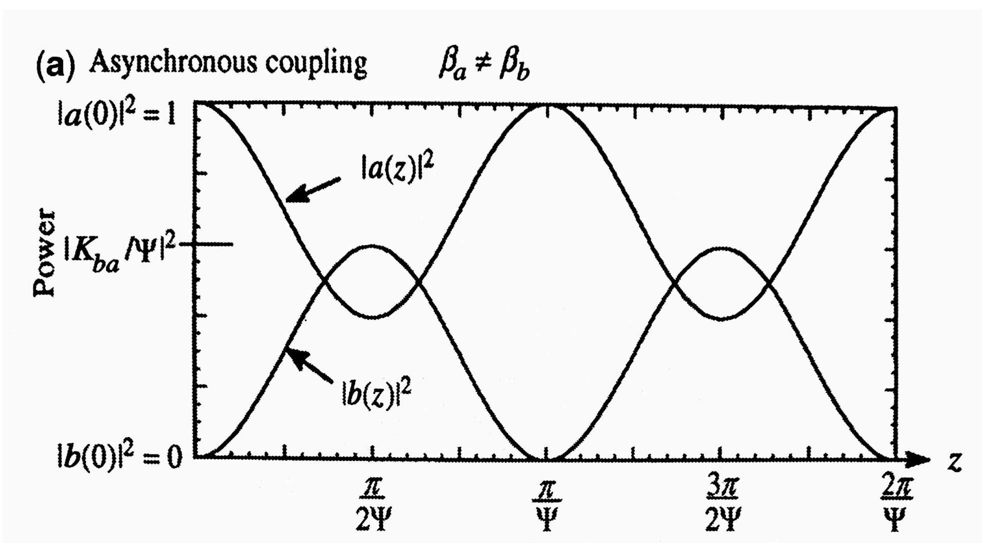
Electro-Optic Switches (Modulators)



Directional Coupler Switch



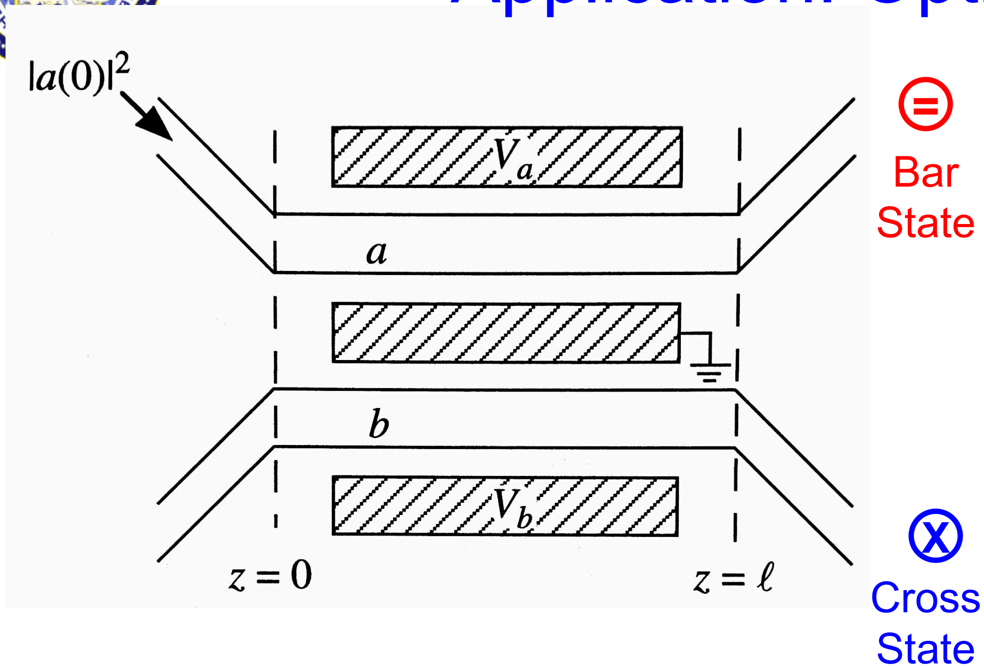
$$P_b = |b(z)|^2 = \frac{|K_{ab}|^2}{\left(\frac{\Delta\beta}{2}\right)^2 + |K_{ab}|^2} \sin^2\left(\sqrt{\left(\frac{\Delta\beta}{2}\right)^2 + |K_{ab}|^2} \cdot z\right)$$

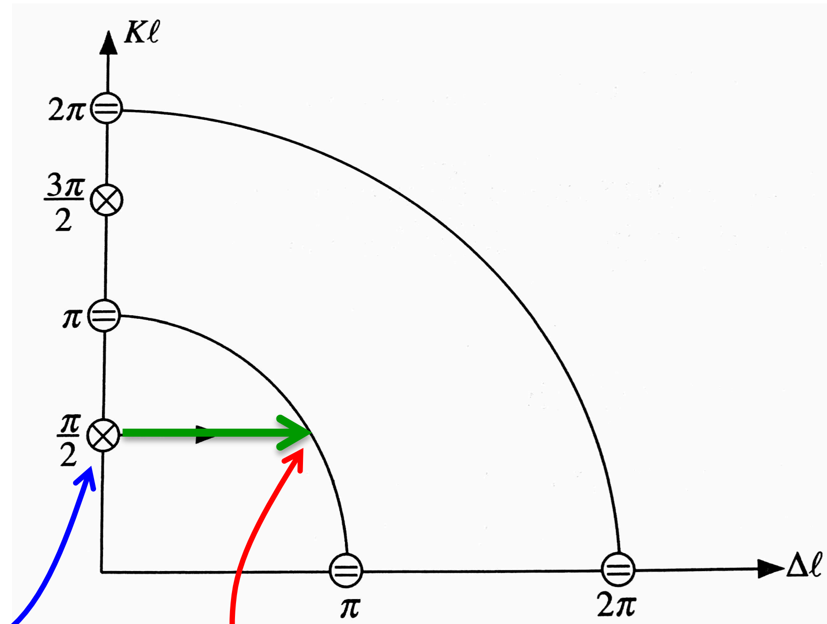


$\Delta\beta$ can be changed by

- Electro-optic effect (in nonlinear $\chi^{(2)}$ media)
- Thermo-optic effect
- Carrier injection (in semiconductor)

Application: Optical Switches





Switch from Cross to Bar state:

Select length such that $K_{ab} l = \frac{\pi}{2}$ (Cross State)

$\Delta = \beta_a - \beta_b$ is tunable by electro-optic, or thermo-optic effect

Bar State: $\sqrt{\left(\frac{\Delta\beta}{2}\right)^2 + \left|K_{ab}\right|^2} \cdot l = \pi$

$\Rightarrow \Delta\beta \cdot l = \sqrt{3}\pi$

Issue with Directional Switch

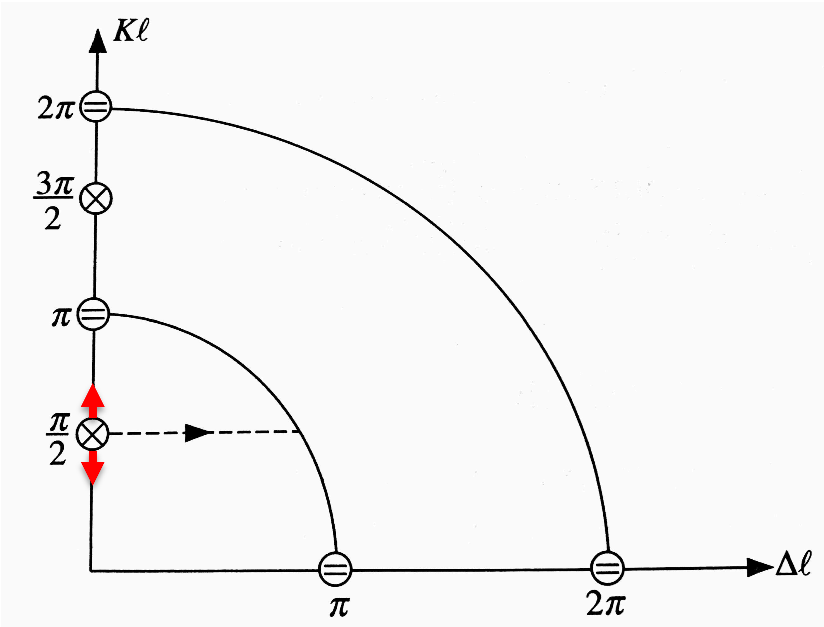
If the coupler length of fabricated device deviate from the designed value: $K_{ab} l \neq \frac{\pi}{2}$

The Cross port output is no longer zero:

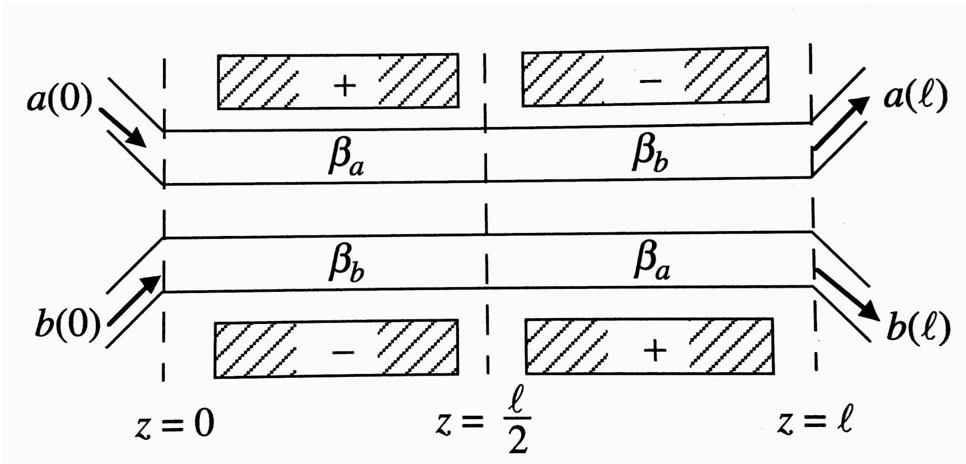
$$P_b = |b(z)|^2 = \sin^2\left(K_{ab} \cdot l\right) \neq 0$$

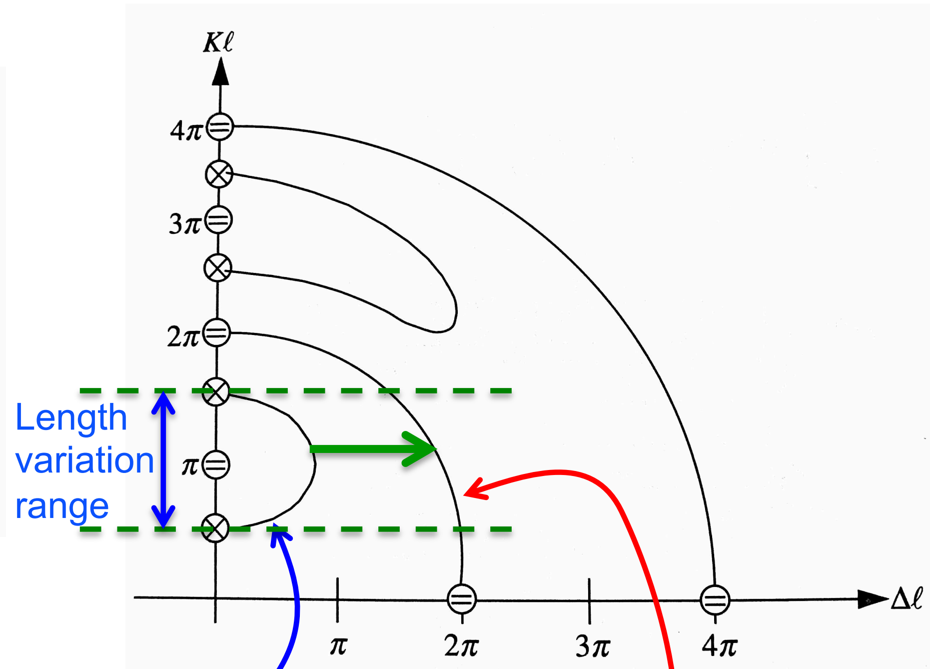
$\Rightarrow$ Nonzero crosstalk,

cannot be corrected by electrical bias



Improved Switch: Alternating $\Delta\beta$ Coupler





$$a(l) = \left[\cos^2\frac{ql}{2} + \frac{\Delta^2 - K^2}{q^2}\sin^2\frac{ql}{2}\right]e^{i\phi l}$$

$$b(l) = i\frac{2K}{q}\sin\frac{ql}{2}\left[\cos\frac{ql}{2} + i\frac{\Delta}{q}\sin\frac{ql}{2}\right]e^{i\phi l}$$

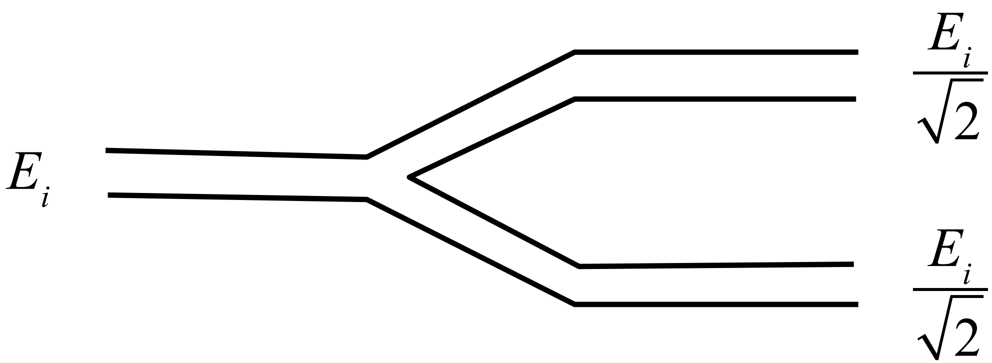
Cross State: $a(l) = 0 \quad \Rightarrow \quad \cot^2\frac{ql}{2} = \frac{K^2 - \Delta^2}{K^2 + \Delta^2}$ Note: $q = \sqrt{K^2 + \Delta^2}$

Bar State: $b(l) = 0 \quad \Rightarrow \quad \begin{cases} \sin\frac{ql}{2} = 0 \quad \text{or} \\ \cos^2\frac{ql}{2} + \frac{\Delta^2}{q^2}\sin^2\frac{ql}{2} = 0 \end{cases}$

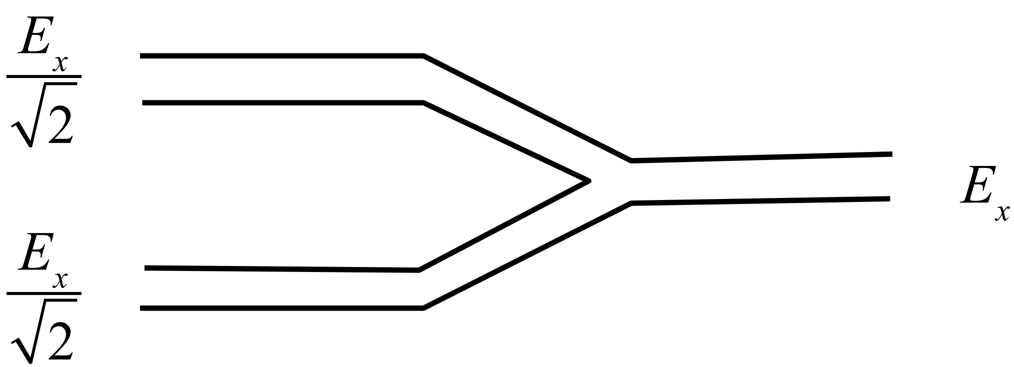
Both Cross and Bar states can be adjusted by changing $\Delta\beta$

Y-Branch

Splitter



Combiner

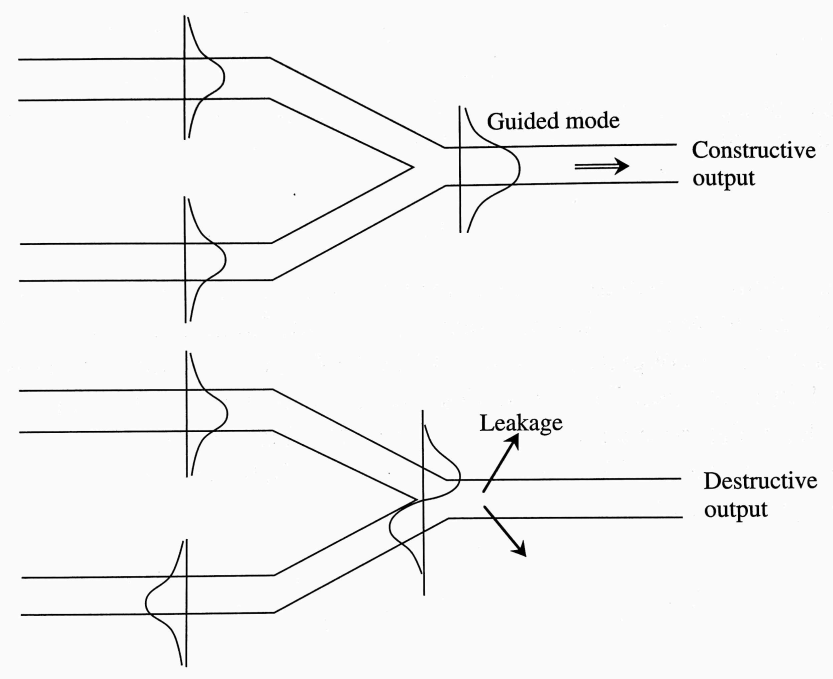


Y-Branch Combiner

In-phase modes

$\frac{E_x}{\sqrt{2}}$

$\frac{E_x}{\sqrt{2}}$



E_x

Out-of-phase modes

$\frac{E_x}{\sqrt{2}}$

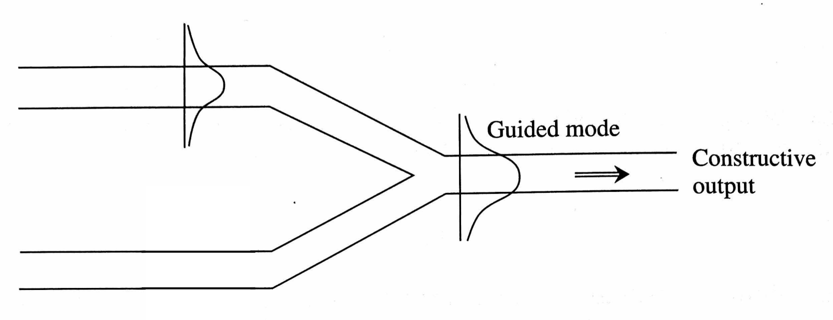
$-\frac{E_x}{\sqrt{2}}$

0

Superposition

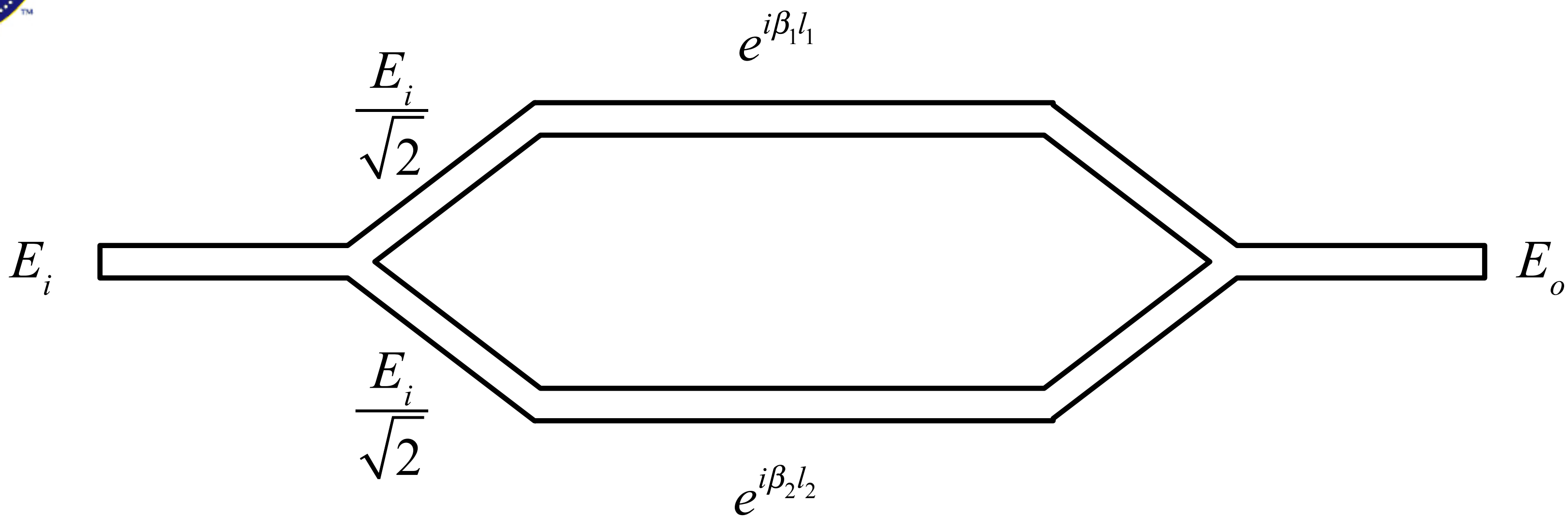
$2\frac{E_x}{\sqrt{2}}$

0



E_x

Mach-Zehnder Interferometer



$$E_o = \frac{1}{\sqrt{2}}\left(\frac{1}{\sqrt{2}} E_i e^{i\beta_1 l_1}\right) + \frac{1}{\sqrt{2}}\left(\frac{1}{\sqrt{2}} E_i e^{i\beta_2 l_2}\right) = \frac{1}{2} E_i e^{i\frac{\beta_1 l_1 + \beta_2 l_2}{2}}\left(e^{i\frac{\beta_1 l_1 - \beta_2 l_2}{2}} + e^{-i\frac{\beta_1 l_1 - \beta_2 l_2}{2}}\right)$$

$$= E_i e^{i\frac{\beta_1 l_1 + \beta_2 l_2}{2}} \cos\left(\frac{\beta_1 l_1 - \beta_2 l_2}{2}\right)$$

$$\left|E_o\right|^2 = \left|E_i\right|^2 \cos^2\left(\frac{\beta_1 l_1 - \beta_2 l_2}{2}\right)$$

Response of MZI

For $l_1 = l_2$

$$\left|E_o\right|^2 = \left|E_i\right|^2 \cos^2\left(\frac{\Delta\beta \cdot l}{2}\right)$$