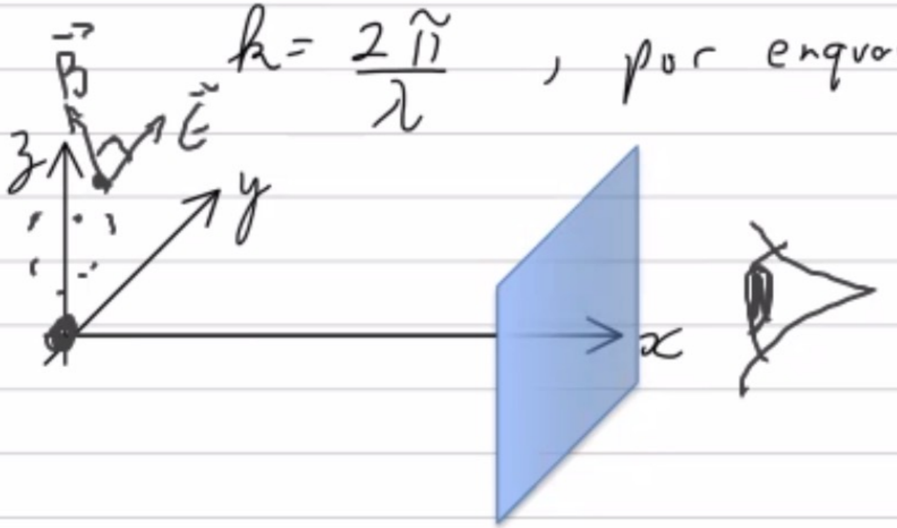
Eletromagnetismo Ótica e Ondas eletromagnéticas

- TEORIA Eletromagnética justifica as LEIS da Ótica.
- Lei de Malus
- Lei de Snell Descartes
- Lei de Brewster
- Todas contidas e derivadas a partir das equações de Maxwell...

Solução básica: Onda plana

- Para uma direção, temos o <u>vetor de onda</u> $\vec{k}$

$$k = \frac{2\pi}{\lambda} \quad , \text{ por enquanto } \vec{k} = k \cdot \hat{x}$$



(usando $\hat{x}, \hat{y}, \hat{z}$ em lugar de $\hat{i}, \hat{j}, \hat{k}$)

- Onda transversa: Como no caso da corda, temos um <u>plano</u> transverso

↳ descrição por 2 componentes

$$\vec{E} = E_y \, \hat{y} + E_z \, \hat{z} \quad , \text{ com } E_y = E_y(x,t)$$

$$E_z = E_z(x,t)$$

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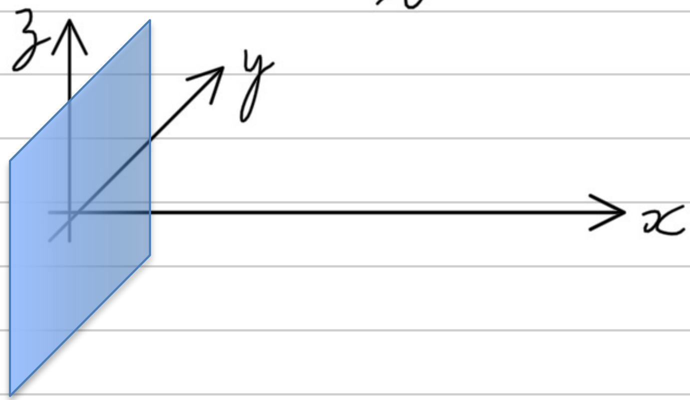

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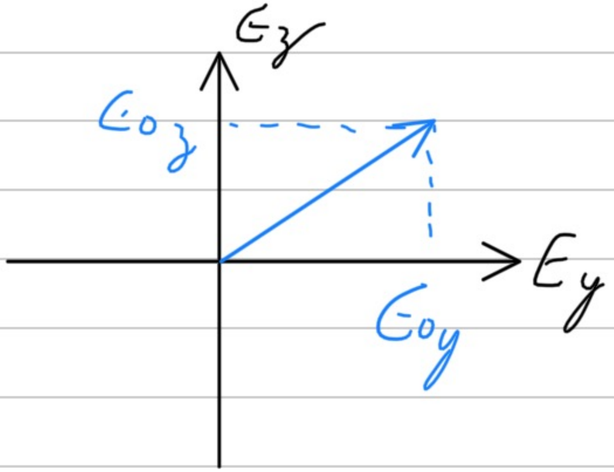
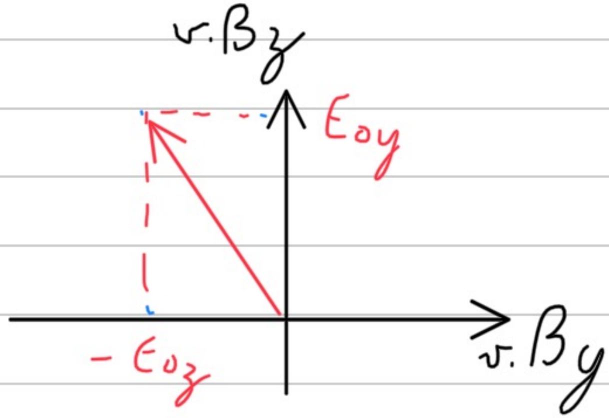
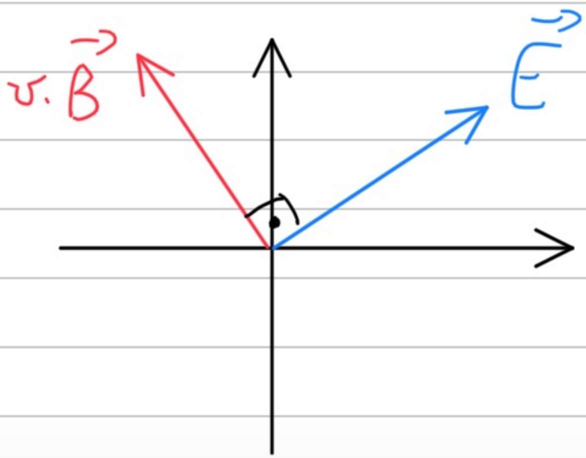
Solução harmônica: $E_y(x,t) = E_{0y} \cos(kx - \omega t + \varphi_y)$

$$E_z(x,t) = E_{0z} \cos(kx - \omega t + \varphi_z)$$

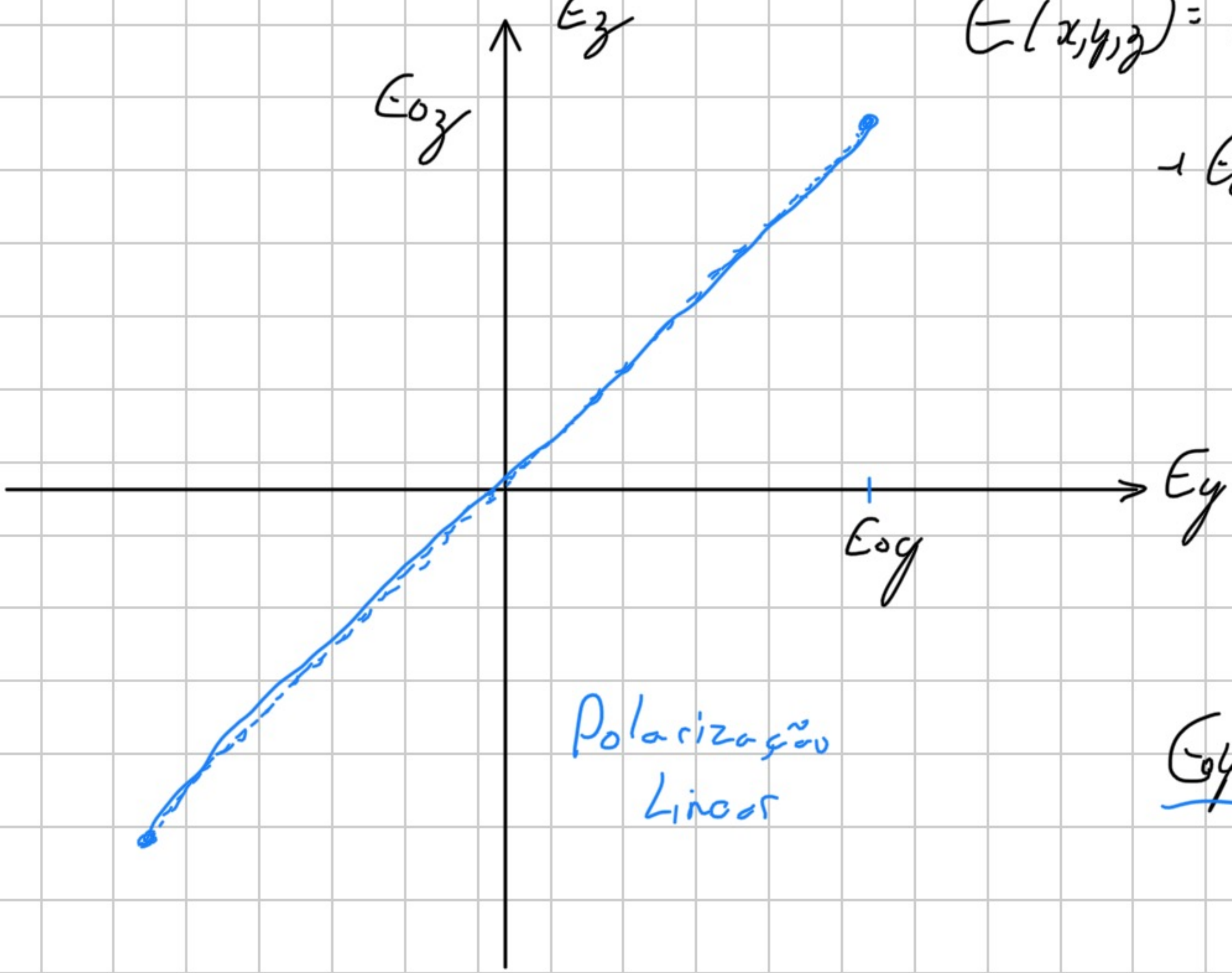
Plano transverso → visto do eixo x







Polarização



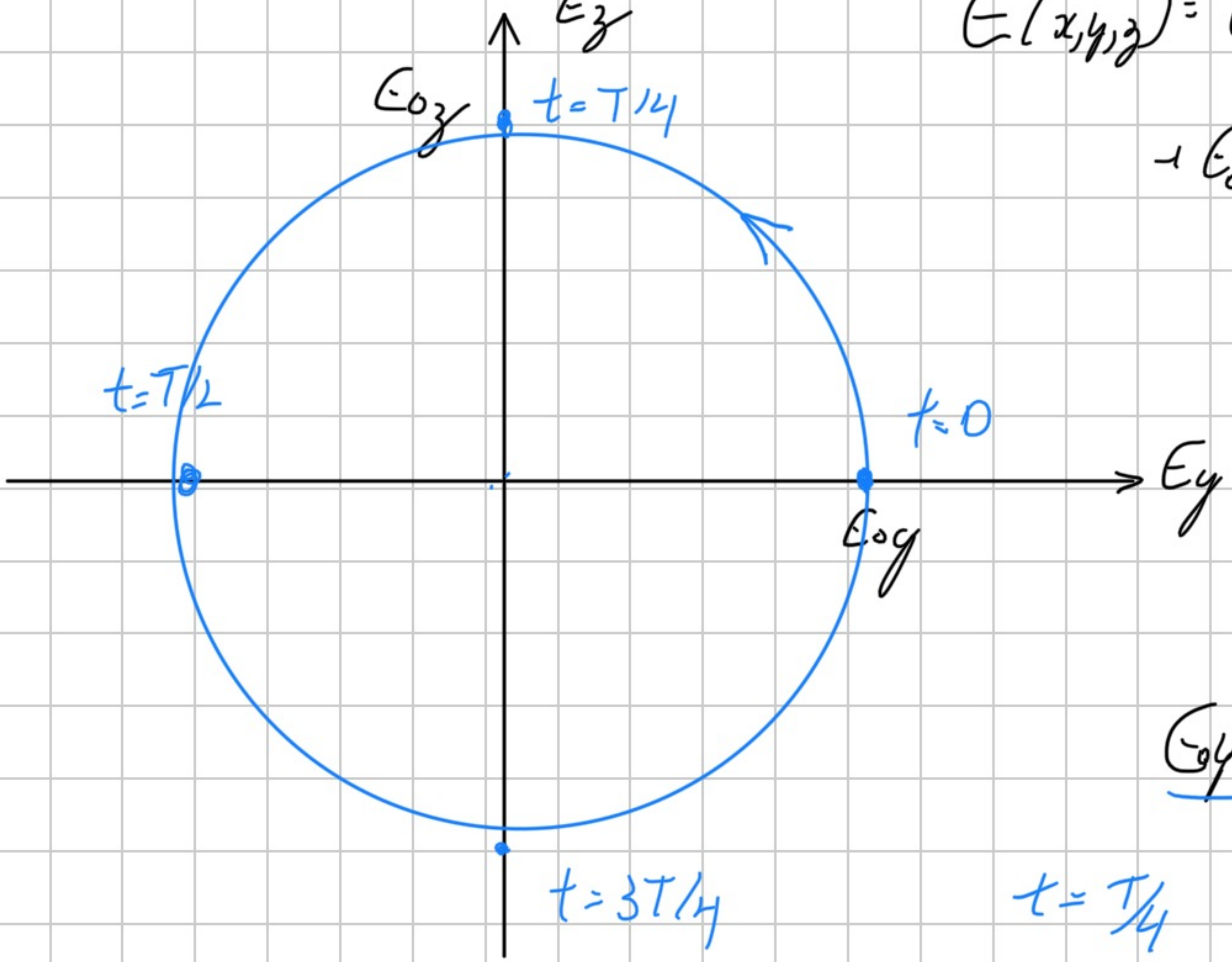
$$\vec{E}(x,y,z) = E_{0y}\cos(kx - \omega t + \varphi_y)\,\hat{y} + E_{0z}\cos(kx - \omega t + \varphi_z)\,\hat{z}$$

$$\varphi_y = \varphi_z = 0$$

$x = 0$

$$E_{0y} = E_{0z}$$

$$\vec{E}(x,y,z) = E_{0y} \cos(kx - \omega t + \varphi_y)\,\hat{y} + E_{0z} \cos(kx - \omega t + \varphi_z)\,\hat{z}$$



$\varphi_y = 0$

$\varphi_z = \pi/2$

$x = 0$

$\underline{E_{0y} = E_{0z}}$

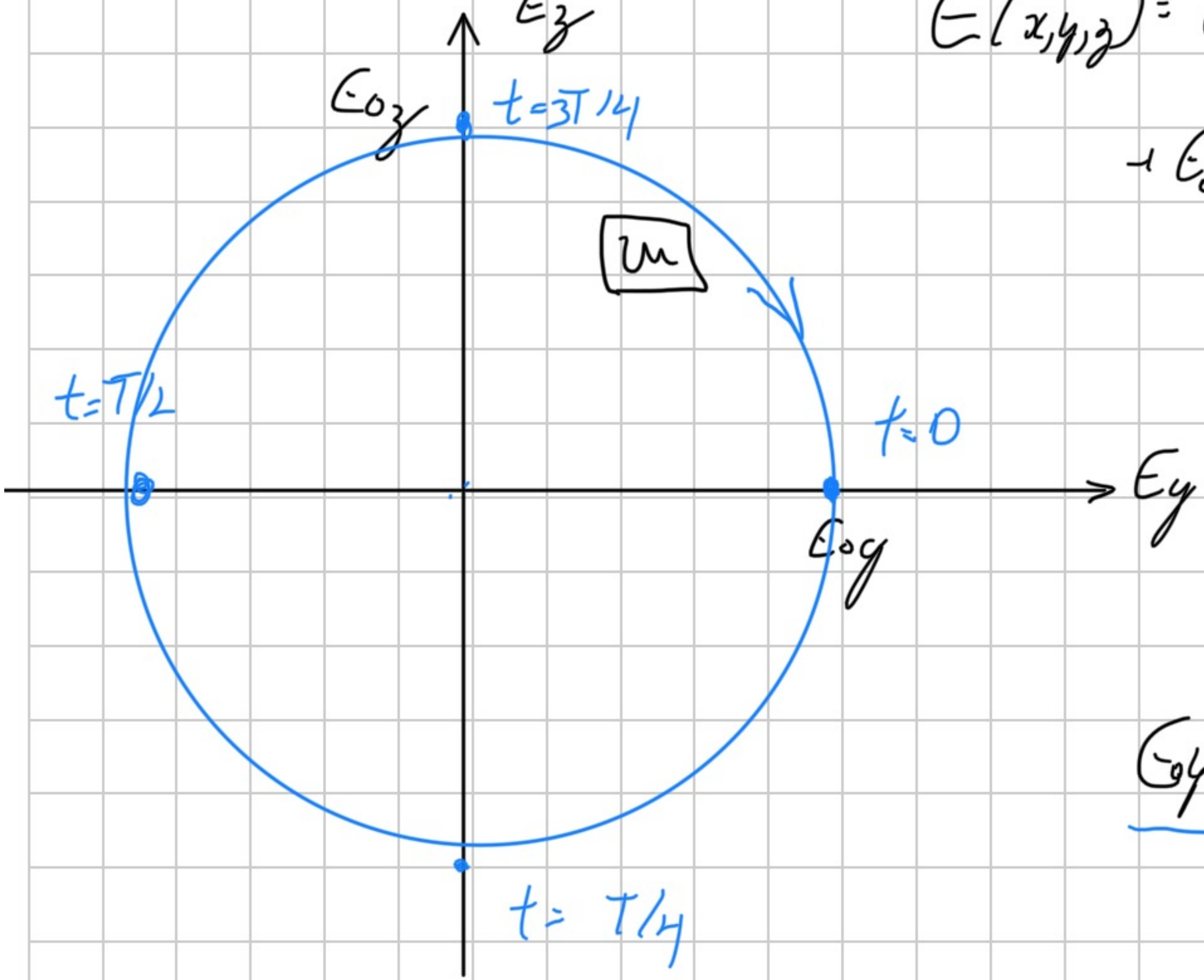
$t = T/4 \quad \omega t = \pi/2 \quad \varphi_y - \omega t = -\pi/2$

$\varphi_z - \omega t = 0$

Polarização circular destra

$t = T/2 \quad \omega t = \pi$

$\varphi_y - \pi = -\pi \quad , \quad \varphi_z - \pi = -\pi/2$



$$\vec{E}(x,y,z) = E_{0y}\cos(kx - wt + \varphi_y)\,\hat{y} + E_{0z}\cos(kx - wt + \varphi_z)\,\hat{z}$$

$\varphi_y = 0$

$\varphi_z = -\pi/2$

$x = 0$

$E_{0y} = E_{0z}$

Polarização circular sinistra

Intensidade: $I = \langle S \rangle = \frac{\langle \vec{E} \times \vec{B} \rangle}{\mu} = c^2 \epsilon \langle \vec{E} \times \vec{B} \rangle =$

$$= \frac{c\,\epsilon \langle E^2 \rangle}{2}$$

$$|\vec{E} \times \vec{B}| = \frac{E^2}{c}$$

$$\vec{B} = \frac{E}{c}$$

$$E^2 = \vec{E} \cdot \vec{E} = E_y^2 + E_z^2$$

$$\vec{E} = E_y \hat{y} + E_z \hat{z} \quad , \quad E^2 = E_y^2 \underbrace{\hat{y} \cdot \hat{y}}_{1} + E_z^2 \underbrace{\hat{z} \cdot \hat{z}}_{1}$$

$$+ E_y E_z (\underbrace{\hat{y} \cdot \hat{z}}_{0} + \underbrace{\hat{z} \cdot \hat{y}}_{0})$$

Polarização
- Linear
- Circular
- Elíptica

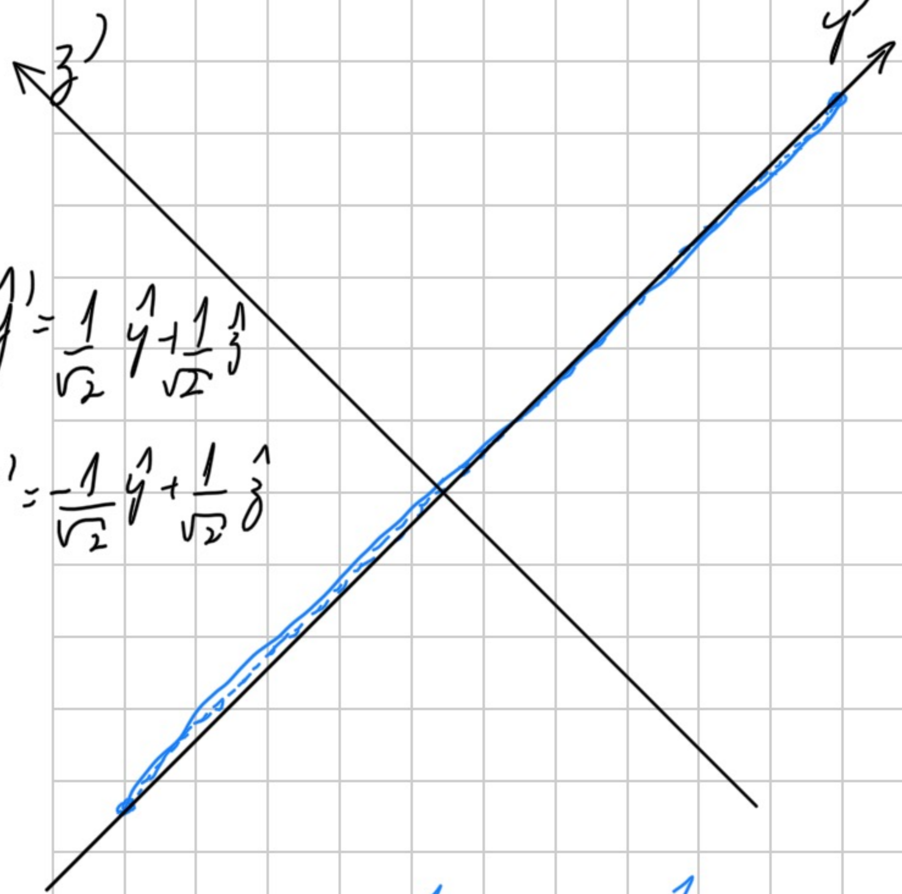
$$\left.\begin{matrix} \\ \\ \end{matrix}\right\} \quad \begin{matrix} E_{0y}, \varphi_y \\ E_{0z}, \varphi_z \end{matrix}$$

Polarização

- Linear
- Circular
- Elíptica

$\left.\right\}$ E_{0y}, φ_y

E_{0z}, φ_z



$$\vec{E}(x,y,z) = E_{0y}\cos(kx-\omega t+\varphi_y)\,\hat{y} + E_{0z}\cos(kx-\omega t+\varphi_z)\,\hat{z}$$

$$\hat{y}' = \frac{1}{\sqrt{2}}\hat{y} + \frac{1}{\sqrt{2}}\hat{z}$$

$$\hat{z}' = -\frac{1}{\sqrt{2}}\hat{y} + \frac{1}{\sqrt{2}}\hat{z}$$

$$\vec{E}(x,y',z',t) = \sqrt{2}\,E_{0y}\cos(kx-\omega t+\varphi_y)\,\hat{y}'$$

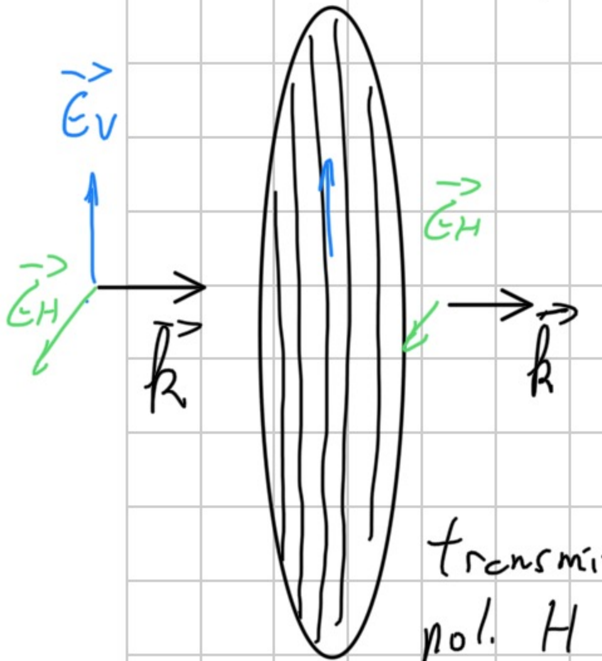
$\varphi_y = \varphi_z$, $E_{0y} = E_{0z}$

$$\hat{y}'\cdot\hat{z}' = -\frac{1}{\sqrt{2}}\cdot\frac{1}{\sqrt{2}}\,\underbrace{\hat{y}\cdot\hat{y}}_{1} + \frac{1}{\sqrt{2}}\cdot\frac{1}{\sqrt{2}}\,\underbrace{\hat{z}\cdot\hat{z}}_{=1} = 0$$

Lei de Malus

Polarizador → transmite uma polarização linear

reflete ou absorve a polarização

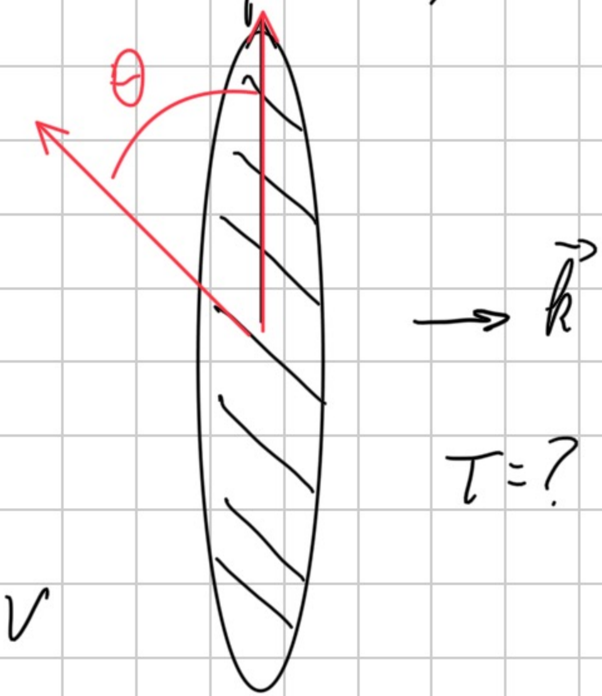


transmite pol. H / absorve V

$<100\%$ | $\sim 0\%$

$T_H >> T_V$

$T = \frac{P_{saída}}{P_{entrada}}$

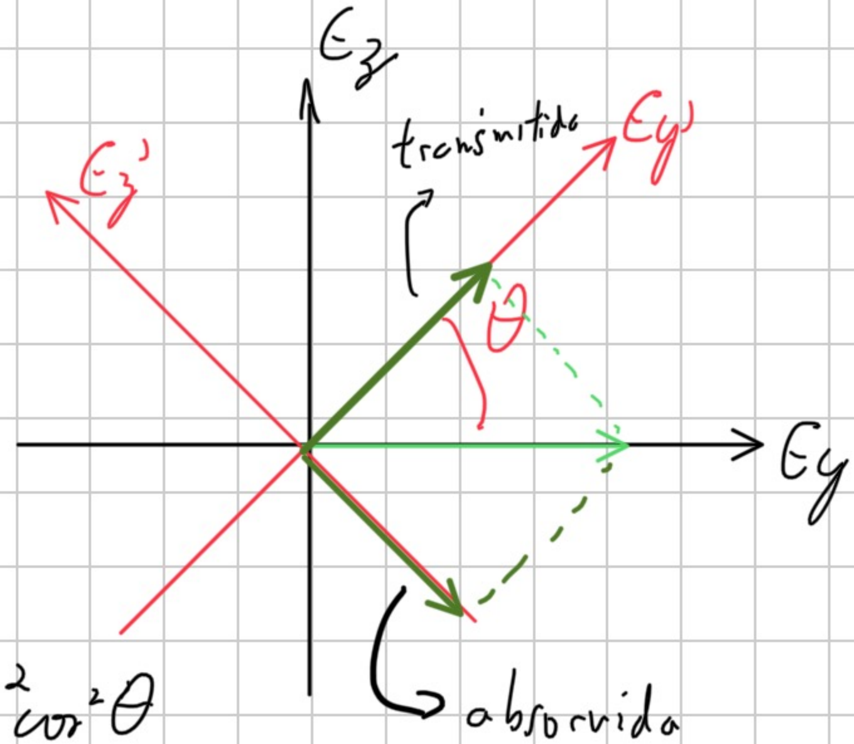


$T = ?$

$\vec{E}_H = E_y \cos(kx - \omega t + \varphi)\hat{y}$

$$T = \frac{P_{saída}}{P_{entrada}}$$

$E_y' = E_y \cdot \cos\theta$



$$I_{saída} \propto |E_y'|^2 = |E_y|^2 \cos^2\theta$$

$$\frac{I_{saída}}{I_{entr.}} = \cos^2\theta \rightsquigarrow \underline{\text{Lei de Malus}}$$

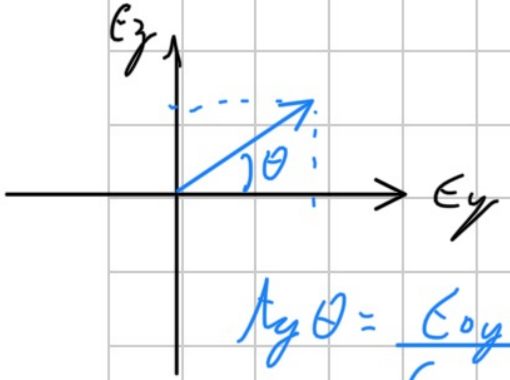
Manipulando a polarização

$\vec{E} = E_y(x,t)\,\hat{y} + E_z(x,t)\,\hat{z} \rightarrow \qquad \vec{\mathcal{E}} = \mathcal{E}_{0y}\, e^{i(kx-\omega t)}\,\hat{y} + \mathcal{E}_{0z}\, e^{i(kx-\omega t)}\,\hat{z}$

$E_y(x,t) = E_{0y}\cos(kx-\omega t+\varphi_y) \qquad = \underbrace{\left(\mathcal{E}_{0y}\,\hat{y} + \mathcal{E}_{0z}\,\hat{z}\right)} e^{i(kx-\omega t)}$

$$\vec{\mathcal{E}}_0 = \left(\mathcal{E}_{0y}\,\hat{y} + \mathcal{E}_{0z}\,\hat{z}\right)$$

Lin. Pol. $\vec{\mathcal{E}}_0 = E_{0y}\, e^{i\varphi}\,\hat{y} + E_{0z}\, e^{i\varphi}\,\hat{z} = \left(E_{0y}\,\hat{y} + E_{0z}\,\hat{z}\right)e^{i\varphi}$

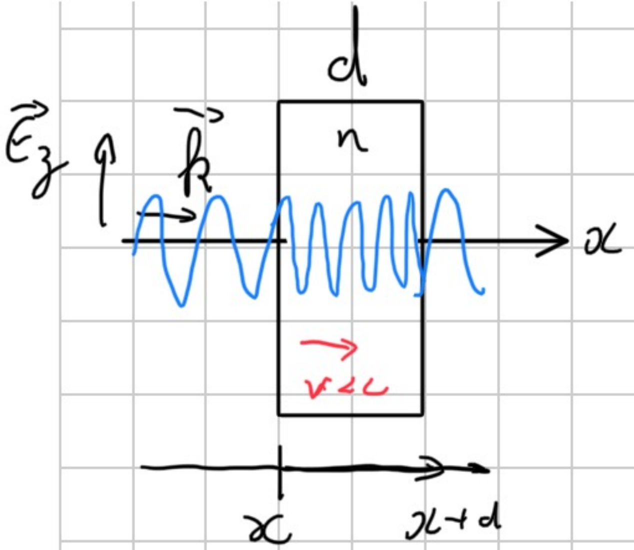


$\tan\theta = \dfrac{E_{0y}}{E_{0z}}$

$v_y \neq v_z \qquad v_y = \dfrac{c}{n_y} = \dfrac{1}{\mu\epsilon_y}$

birrefringentes

$\vec{D} = \epsilon\vec{E}$ X $\vec{D} = \begin{bmatrix} \epsilon_x & 0 & 0 \\ 0 & \epsilon_y & 0 \\ 0 & 0 & \epsilon_z \end{bmatrix} \begin{bmatrix} E_x \\ E_y \\ E_y \end{bmatrix} = \overleftrightarrow{\epsilon}\cdot\vec{E}$



$$\vec{E}(x,t) = E_z \cdot \hat{z}\, e^{i(kx-\omega t)}$$

$$\downarrow$$

$$\vec{E}(x+d,t) = E_z\, \hat{z}\, e^{i(kx-\omega t)} \cdot e^{i(k'd)}$$

$$k = \frac{\omega}{v} = \frac{\omega}{c} \cdot n \qquad k'd = \frac{2\pi}{c \cdot T} \cdot nd = 2\pi \cdot \underbrace{\frac{nd}{\lambda}}_{\text{fase adicional}}$$

Entrada

$$\vec{E}_0 = E_{0y}\, e^{i\varphi}\, \hat{y} + E_{0z}\, e^{i\varphi}\, \hat{z} = \left(E_{0y}\, \hat{y} + E_{0z}\, \hat{z}\right) e^{i\varphi}$$

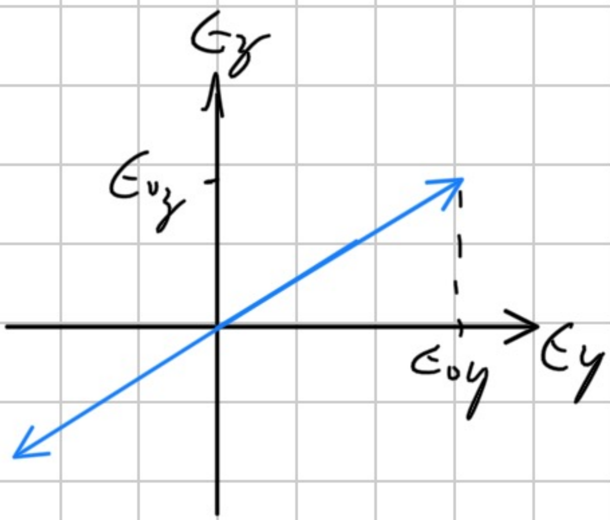
Saída

$$\vec{E}_0' = E_{0y}\, e^{i\varphi} \cdot e^{i\varphi_y}\, \hat{y} + E_{0z}\, e^{i\varphi}\, e^{i\varphi_z}\, \hat{z}$$

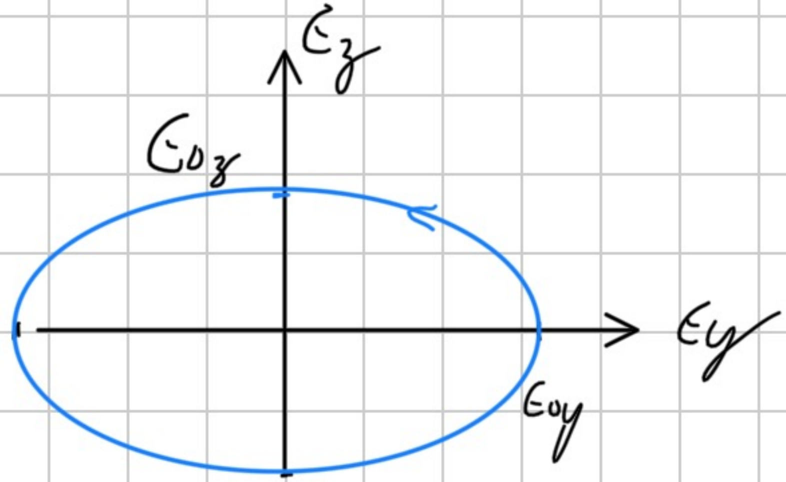
Se $\varphi_z - \varphi_y = 2\pi (n_z - n_y) \dfrac{d}{\lambda} = \dfrac{\pi}{2}$ $\quad e^{i\pi/2} = \cos \pi/2 + i \operatorname{sen} \pi/2 = 0 + i = i$

$E_{0y} = E_{0z} \Rightarrow$ linear $\rightarrow$ circular $\begin{cases} \text{sinistra} \\ \text{destra} \end{cases}$

Lâmina de 1/4 de onda: $2\pi (n_z - n_y) \dfrac{d}{\lambda} = \dfrac{\pi}{2} \Rightarrow (n_z - n_y) d = \dfrac{\lambda}{4}$



$\Rightarrow$



Se $\varphi_z - \varphi_y = 2\pi (n_z - n_y) \frac{d}{\lambda} = \pi$

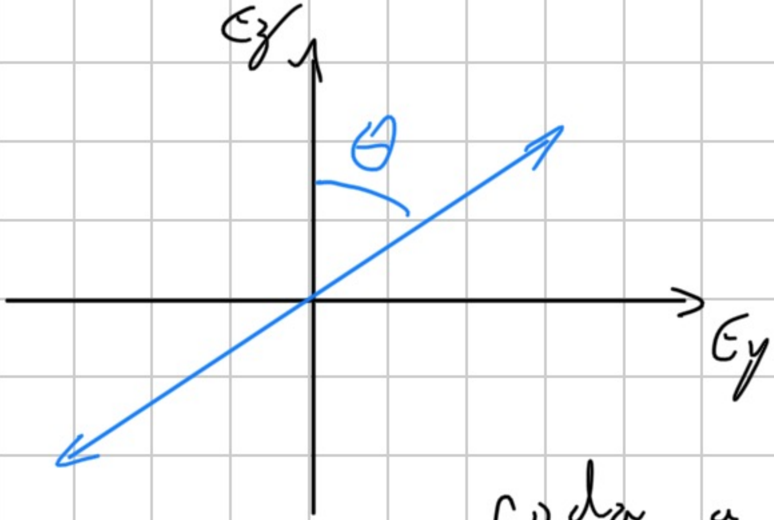
$e^{i\pi} = \cos\pi + i \sin\pi$

$\downarrow \qquad \downarrow$

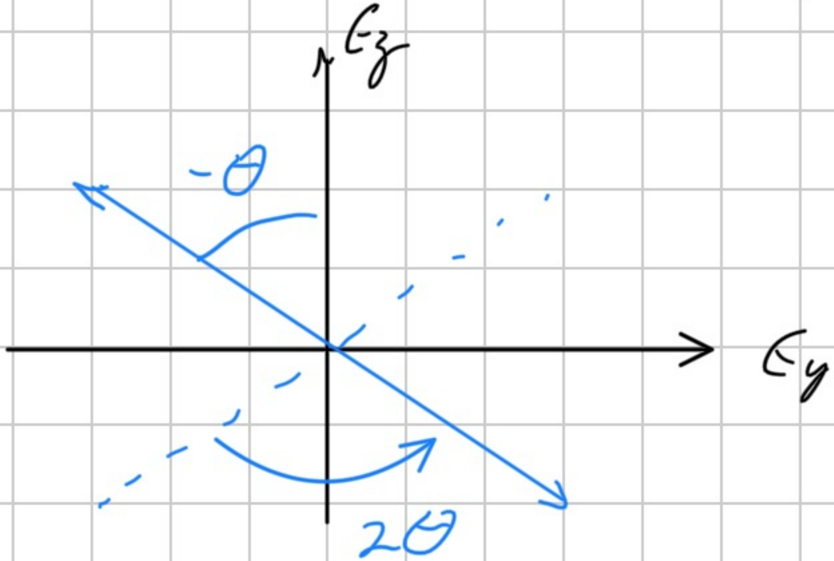
$= -1 \qquad 0$

$\vec{E_0} = (E_y \hat{y} - E_z \hat{z}) e^{i(\varphi - \varphi_y)}$

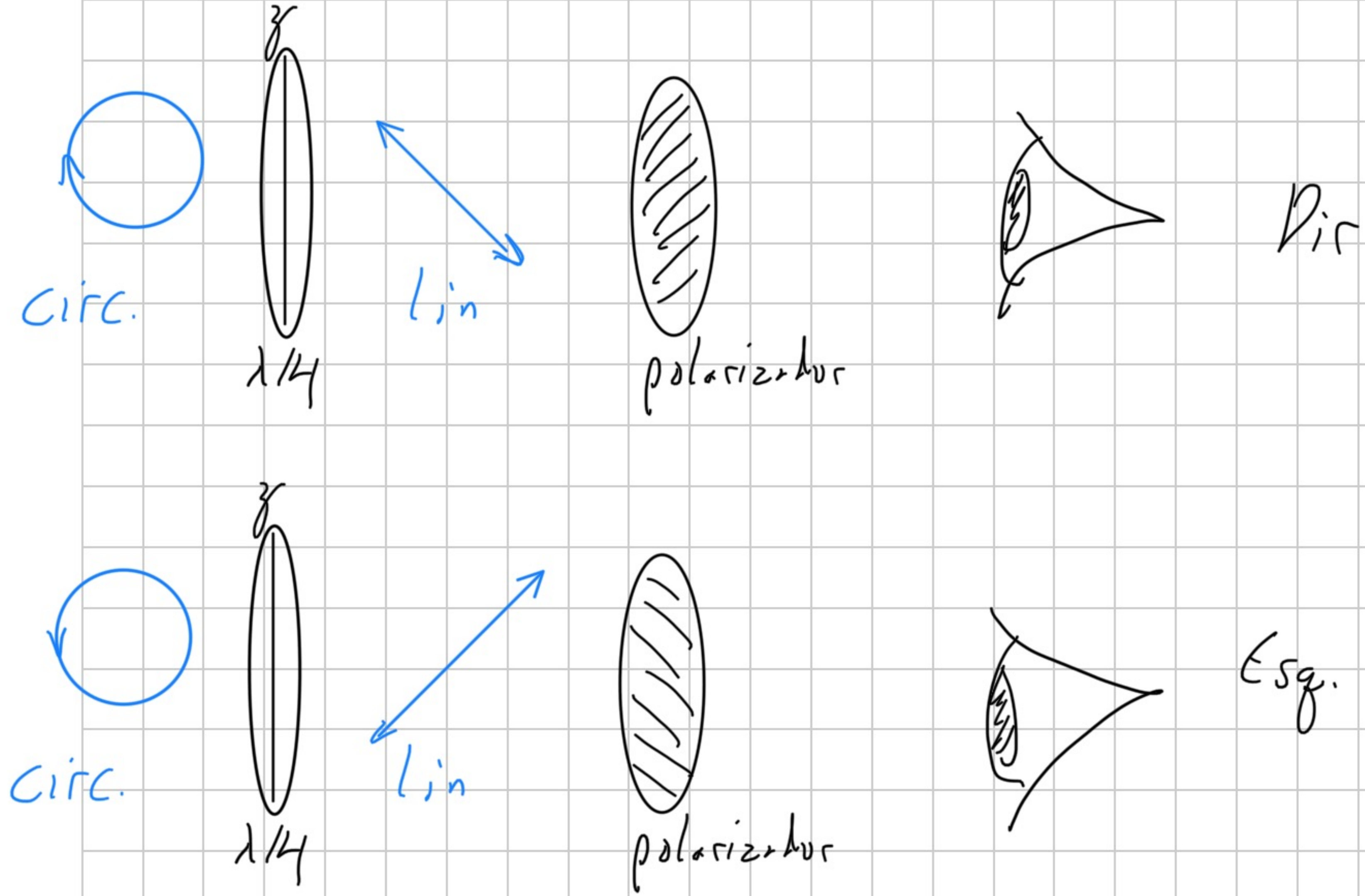
$(n_z - n_y) d = \lambda/2$



roda a polarização



Óculos 3-D



Para saber mais:

→ Física 4 – H. M. Nussenzveig, Cap. 5

→ Óptica/Optics – Eugene Hecht, Cap. 8 (versão em português pela Calouste-Gulbenkian