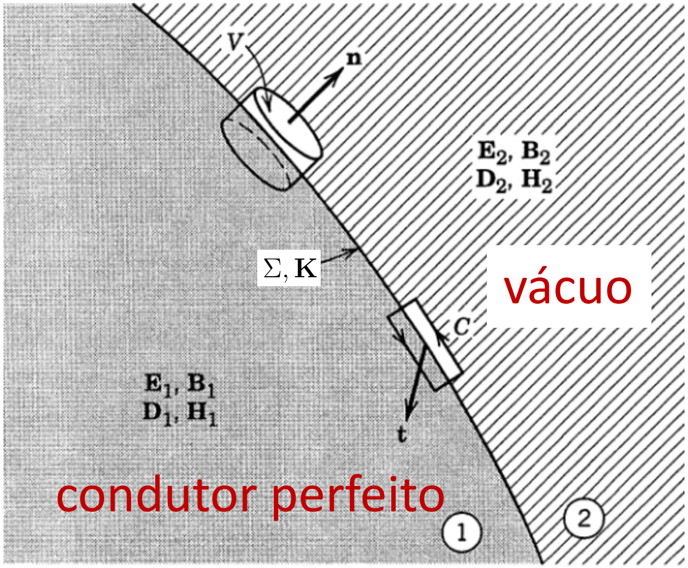
FI 008 – Eletrodinâmica I

1º Semestre de 2020
28/04/2020
Aula 13

Aula passada



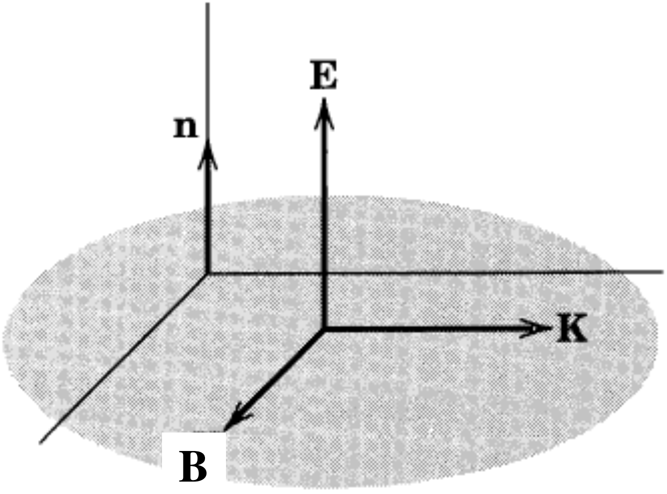
$$
\begin{aligned}
\hat{\mathbf{n}} \cdot \mathbf{B}_2 &= \hat{\mathbf{n}} \cdot \mathbf{B}_1 \\
\hat{\mathbf{n}} \times \mathbf{E}_2 &= \hat{\mathbf{n}} \times \mathbf{E}_1 \\
\hat{\mathbf{n}} \cdot \mathbf{E}_2 - \hat{\mathbf{n}} \cdot \mathbf{E}_1 &= \frac{\Sigma}{\epsilon_0} \\
\hat{\mathbf{n}} \times \mathbf{B}_2 - \hat{\mathbf{n}} \times \mathbf{B}_1 &= \mu_0 \mathbf{K}
\end{aligned}
$$

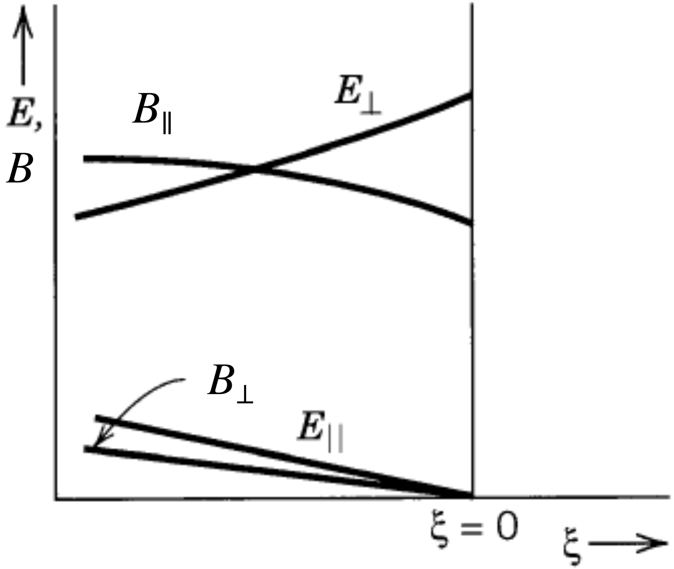
$$\mathbf{E}_1 = \mathbf{E}_c = 0; \ \mathbf{B}_1 = \mathbf{B}_c = 0$$

$$
\boxed{
\begin{aligned}
\hat{\mathbf{n}} \cdot \mathbf{B}_V &= 0 \\
\hat{\mathbf{n}} \times \mathbf{E}_V &= 0 \\
\hat{\mathbf{n}} \cdot \mathbf{E}_V &= \frac{\Sigma}{\epsilon_0} \\
\hat{\mathbf{n}} \times \mathbf{B}_V &= \mu_0 \mathbf{K}
\end{aligned}
}
$$

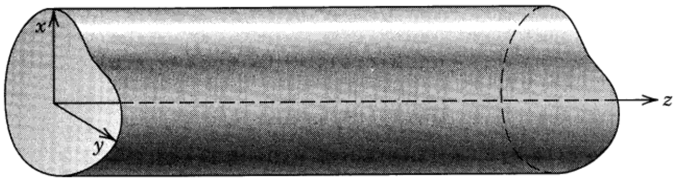
Aula passada

$$\hat{\mathbf{n}} \cdot \mathbf{B}_V = 0$$
$$\hat{\mathbf{n}} \times \mathbf{E}_V = 0$$
$$\hat{\mathbf{n}} \cdot \mathbf{E}_V = \frac{\Sigma}{\epsilon_0}$$
$$\hat{\mathbf{n}} \times \mathbf{B}_V = \mu_0 \mathbf{K}$$





Aula passada



$$\mathbf{E}(\mathbf{x},t) = \mathbf{E}(x,y)\,e^{i(\pm kz-\omega t)}$$

$$\mathbf{B}(\mathbf{x},t) = \mathbf{B}(x,y)\,e^{i(\pm kz-\omega t)}$$

$$\boldsymbol{\nabla}_t = \hat{\mathbf{x}}\frac{\partial}{\partial x} + \hat{\mathbf{y}}\frac{\partial}{\partial y}$$

$$\mathbf{E} = \mathbf{E}_t + E_z\hat{\mathbf{z}}$$

$$\mathbf{B} = \mathbf{B}_t + B_z\hat{\mathbf{z}}$$

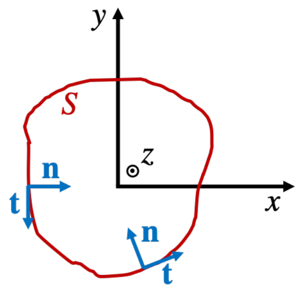
Modo TM ($B_z = 0$)

$$\left(\nabla_t^2 + \gamma^2\right) E_z = 0$$

$$E_z\big|_S = 0$$

$$\gamma^2 \mathbf{E}_t = \pm ik\boldsymbol{\nabla}_t E_z$$

$$\mathbf{B}_t = \pm\frac{\omega}{c^2 k}\hat{\mathbf{z}}\times\mathbf{E}_t$$



$$\boxed{\gamma^2 = \frac{\omega^2}{c^2} - k^2}$$

Modo TE ($E_z = 0$)

$$\left(\nabla_t^2 + \gamma^2\right) B_z = 0$$

$$\hat{\mathbf{n}}\cdot\boldsymbol{\nabla}_t B_z\big|_S = 0$$

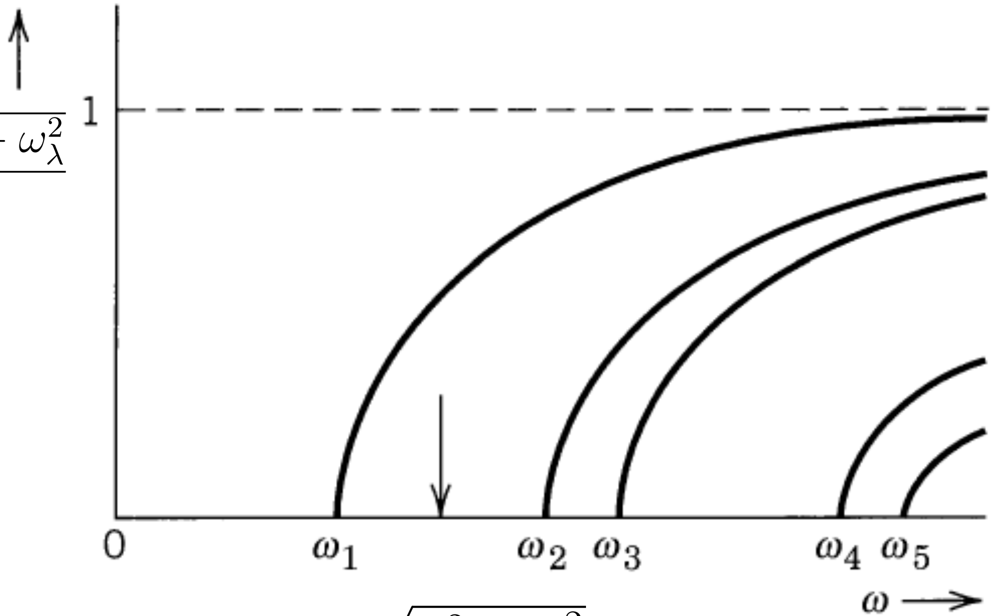
$$\gamma^2 \mathbf{B}_t = \pm ik\boldsymbol{\nabla}_t B_z$$

$$\mathbf{E}_t = \mp\frac{\omega}{k}\hat{\mathbf{z}}\times\mathbf{B}_t$$

Aula passada

Só há propagação se a frequência for maior que a frequência de corte.

$$\frac{ck_\lambda}{\omega} = \frac{\sqrt{\omega^2 - \omega_\lambda^2}}{\omega}$$



$$\boxed{\omega_\lambda = c\gamma_\lambda}$$

Velocidades de fase e de grupo:

$$v_p = \frac{\omega}{k} = \frac{\sqrt{\omega^2 - \omega_\lambda^2}}{\omega} c > c$$

$$v_g = \frac{d\omega}{dk} = \frac{\omega}{\sqrt{\omega^2 - \omega_\lambda^2}} c < c$$

Aula passada

Guia retangular:

Campo elétrico **E**: linhas contínuas
Campo magnético **B**: linhas tracejadas

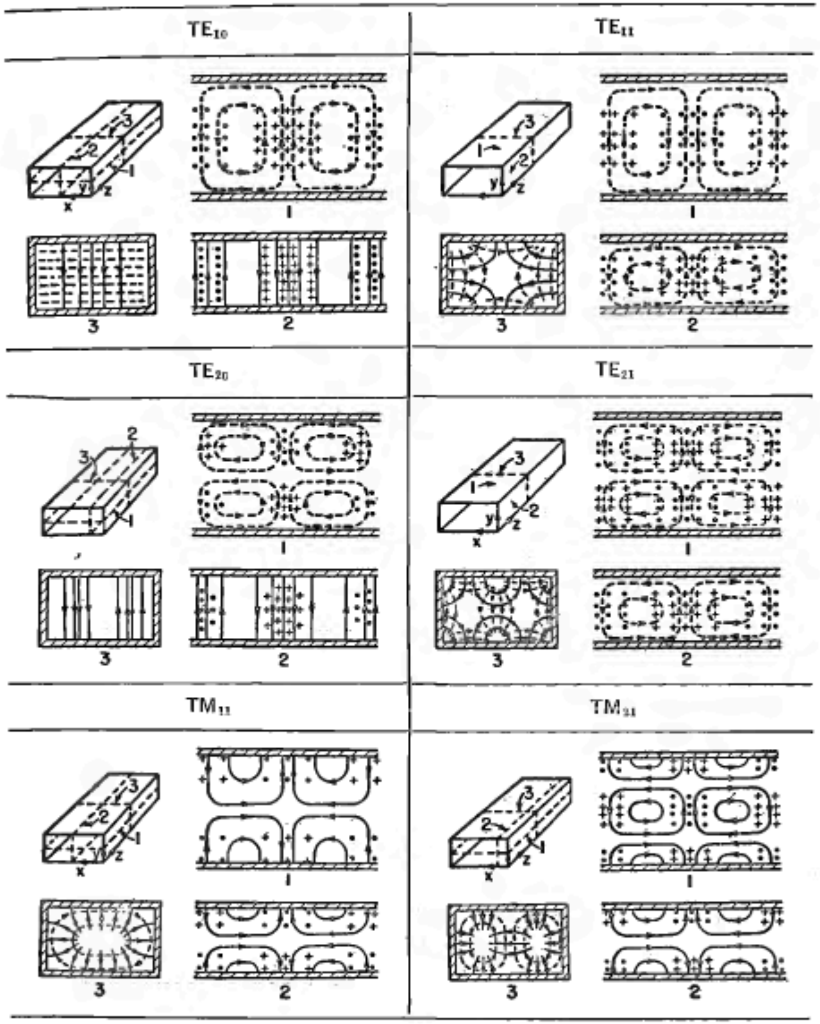
Modo $TE_{1,0}$

$$B_z = B_0 \cos\left(\frac{\pi x}{a}\right) e^{i(k_{1,0}z - \omega t)}$$

$$B_x = -i\left(\frac{k_{1,0}a}{\pi}\right) B_0 \sin\left(\frac{\pi x}{a}\right) e^{i(k_{1,0}z - \omega t)}$$

$$E_y = icB_0 \sin\left(\frac{\pi x}{a}\right) e^{i(k_{1,0}z - \omega t)}$$

$$\boxed{\omega_{1,0} = \frac{\pi}{a}c}$$



Aula passada

P = potência propagada através da seção reta do guia.

$$P_{TM} = \pm \frac{\omega\sqrt{\omega^2 - \omega_\lambda^2}}{2\mu_0 c \omega_\lambda^2} \int_{S.R.} |E_z|^2 \, da,$$

$$P_{TE} = \pm \frac{c\omega\sqrt{\omega^2 - \omega_\lambda^2}}{2\mu_0 \omega_\lambda^2} \int_{S.R.} |B_z|^2 \, da.$$

dU/dz = energia dos campos por unidade de comprimento do guia.

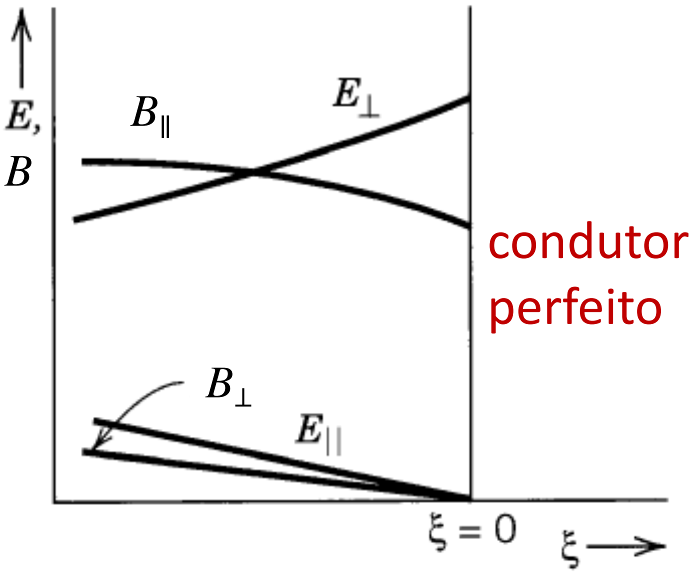
$$\frac{dU_{TM}}{dz} = \frac{\varepsilon_0}{2} \frac{\omega^2}{\omega_\lambda^2} \int_{S.R.} |E_z|^2 \, da,$$

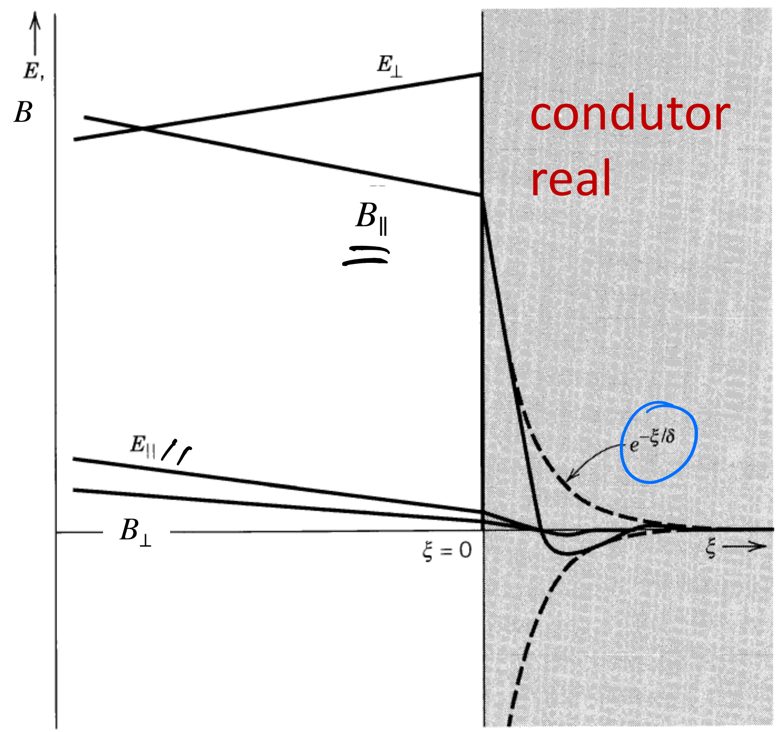
$$\frac{dU_{TE}}{dz} = \frac{1}{2\mu_0} \frac{\omega^2}{\omega_\lambda^2} \int_{S.R.} |B_z|^2 \, da.$$

$$\boxed{\frac{P}{dU/dz} = \pm \frac{\sqrt{\omega^2 - \omega_\lambda^2}}{\omega} c = v_g}$$

Atenuação em guias de ondas

Condutor perfeito x Condutor real





δ = SKIN DEPTH
= COMPRIMENTO PELICULAR

Atenuação da potência propagada

$e^{ik_\lambda z}$ $\quad k_\lambda \to k_\lambda + \Delta k_\lambda + i\beta_\lambda \Rightarrow e^{i(k_\lambda + \Delta k_\lambda)z}\, e^{-\beta_\lambda z}$

→ VAI ATENUAR OS CAMPOS

→ POTÊNCIA PROPAGADA $\quad P \to P(z) = P_0\, e^{-2\beta_\lambda z}$

β_λ → DESCREVE A ATENUAÇÃO

$$\frac{dP}{dz} = -2\beta_\lambda P(z) \Rightarrow \boxed{\beta_\lambda = \frac{-dP/dz}{2P_0}}$$

P_0 = POTÊNCIA NÃO ATENUADA

$-\frac{dP}{dz}$ = EFEITO DA ATENUAÇÃO

Comportamento dos campos dentro de um condutor real

$$\nabla \cdot \mathbf{D} = \rho_F$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathrm{B}}{\partial t}$$

$$\nabla \cdot \mathrm{B} = 0$$

$$\nabla \times \mathbf{H} = \mathbf{J}_F + \frac{\partial \mathrm{D}}{\partial t}$$

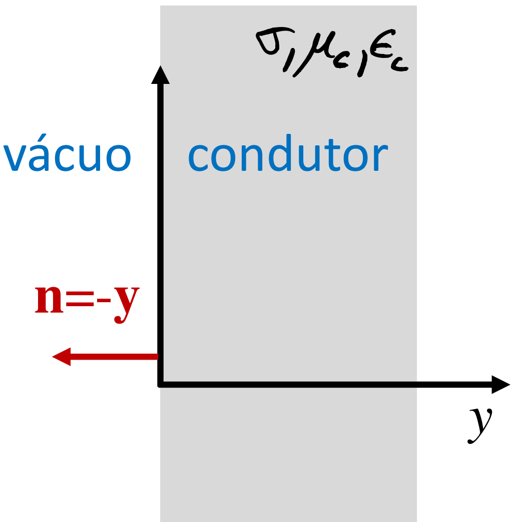
ρ_F, $\vec{J}_F$ SÃO DENSIDADES DE CARGA E CORRENTE LIVRES DENTRO DO CONDUTOR

MEIOS LINEARES: $\vec{D} = \epsilon_c \vec{E}$

$\vec{H} = \frac{1}{\mu_c} \vec{B}$

$$\vec{H}_{v\parallel} = \vec{H}_{c\parallel} \Rightarrow \frac{\vec{B}_{v\parallel}}{\mu_0} = \frac{\vec{B}_{c\parallel}}{\mu_c}$$

NOTE QUE NÃO HÁ $\vec{K}_F$ PORQUE ESTAMOS "RESOLVENDO" A CORRENTE NA ESCALA δ



$$\bar{\nabla} \times \bar{E}_c = -\frac{\partial \vec{B}_c}{\partial t} = i\omega \vec{B}_c = i\omega\mu_c \vec{H}_c$$

$$\bar{\nabla} \times \vec{H}_c = \vec{J}_F + \frac{\partial \vec{D}_c}{\partial t} = \sigma \vec{E}_c - i\omega\epsilon_c \vec{E}_c$$

$$= \underbrace{(\sigma - i\omega\epsilon_c)}_{\bar{\sigma}} \vec{E}_c \equiv \bar{\sigma} \vec{E}_c$$

VARIAÇÃO NA DIREÇÃO $y \sim \delta$

" " " $x, z \sim \frac{1}{k_\lambda} \gg \delta$

$\frac{1}{k_\lambda} \sim 1$ cm (MICRO-ONDAS)

$\delta \sim 10^{-4}$ cm

$$\Rightarrow \vec{\nabla} \cong \hat{y}\frac{\partial}{\partial y} = -\hat{n}\frac{\partial}{\partial y}$$

$$\bar{H}_c = \frac{1}{i\omega\mu_c} \bar{\nabla} \times \bar{E}_c = \frac{i}{\omega\mu_c} \hat{n} \times \frac{\partial \bar{E}_c}{\partial y} \quad (1)$$

$$\bar{E}_c = \frac{1}{\bar{\sigma}} \bar{\nabla} \times \bar{H}_c = -\frac{1}{\bar{\sigma}} \hat{n} \times \frac{\partial \bar{H}_c}{\partial y} \quad (2)$$

$$\hat{n} \cdot \bar{H}_c = 0$$

$$\hat{n} \cdot \bar{E}_c = 0$$

$$\Rightarrow \hat{n} \cdot \frac{\partial \bar{H}_c}{\partial y} = \hat{n} \cdot \frac{\partial \bar{E}_c}{\partial y} = 0$$

$$\hat{n}\times(1) \Rightarrow \hat{n}\times\bar{H}_c = \frac{i}{\omega\mu_c}\hat{n}\times\left[\hat{n}\times\frac{\partial\bar{E}_c}{\partial y}\right] = -\frac{i}{\omega\mu_c}\frac{\partial\bar{E}_c}{\partial y} \quad (3)$$

$$\frac{\partial}{\partial y}(2) \Rightarrow \frac{\partial\bar{E}_c}{\partial y} = \frac{1}{\bar{\sigma}}\hat{n}\times\frac{\partial^2\bar{H}_c}{\partial y^2} \Rightarrow \hat{n}\times\frac{\partial^2\bar{H}_c}{\partial y^2} = -\bar{\sigma}(i\omega\mu_c)(\hat{n}\times\bar{H}_c)$$

$$\Rightarrow \frac{\partial^2}{\partial y^2}(\hat{n}\times\bar{H}_c) = -i\underbrace{\omega\mu_c\bar{\sigma}}(\hat{n}\times\bar{H}_c) \quad (4)$$

$$\mu_c\omega\bar{\sigma} = \underbrace{\mu_c\omega\sigma}_{\frac{2}{\delta^2}} - i\underbrace{\mu_c\epsilon_c\omega^2}_{n^2\frac{\omega^2}{c^2}\cong n^2k_r^2}$$

$$n^2\frac{\omega^2}{c^2} \cong n^2 k_r^2 \longrightarrow k_r \sim cm^{-1}$$

$$\delta = \left(\frac{2}{\mu_c\omega\sigma}\right)^{1/2} \cong \frac{6{,}5\ cm}{\sqrt{\nu(Hz)}}$$ PARA O COBRE

SE $\nu \sim 10^9\ Hz \Rightarrow \boxed{\delta \sim 10^{-4}\ cm}$

$$\frac{1}{\delta^2} \sim 10^8\ cm^{-2} \gg n^2\frac{\omega^2}{c^2} \sim cm^{-1} \Rightarrow \mu_c\omega\bar{\sigma} \cong \mu_c\omega\sigma$$

$$\bar{\sigma} \cong \sigma$$

$$\frac{\partial^2}{\partial y^2}(\hat{m}\times\bar{H}_c) = -i\,\omega\mu_c\sigma\,(\hat{m}\times\bar{H}_c) = -\frac{2i}{\delta^2}(\hat{m}\times\bar{H}_c)$$

$$\hookrightarrow \frac{d^2 f}{dy^2} = K^2 f \Rightarrow f(y) = e^{\pm K y}$$

$$\Rightarrow \hat{m}\times H_c(y) = e^{\pm\sqrt{\frac{-2i}{\delta^2}}\,y}\,(\hat{m}\times\bar{H}_c(0))$$

$$\sqrt{\frac{-2i}{\delta^2}} = \frac{\sqrt{2}}{\delta}\sqrt{e^{-i\frac{\pi}{2}}} = \frac{\sqrt{2}}{\delta}\,e^{-i\frac{\pi}{4}} = \frac{\sqrt{2}}{\delta}\,\frac{1}{\sqrt{2}}(1-i) = \frac{(1-i)}{\delta}$$

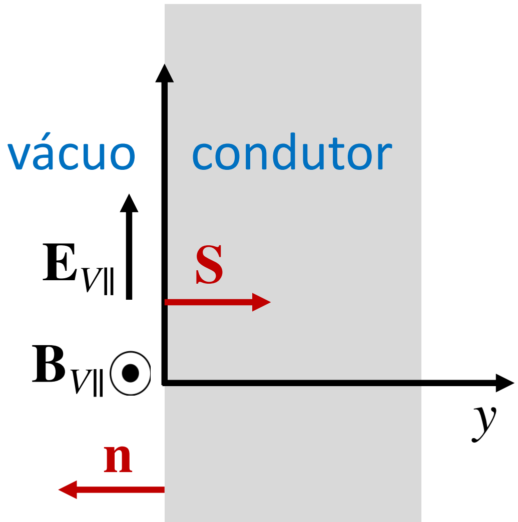
$$\bar{H}_c(y) = \bar{H}_c(0)\,e^{-(1-i)\,y/\delta} = \bar{H}_{c\parallel}\,e^{iy/\delta}\,e^{-y/\delta}$$

$$\text{DA (2)}: \quad \bar{E}_c = -\frac{1}{\sigma}\,\hat{m}\times\frac{\partial\bar{H}_c}{\partial y} \Rightarrow \boxed{\bar{E}_c(y) = \frac{(1-i)}{\sigma\delta}(\hat{m}\times\bar{H}_{c\parallel})\,e^{iy/\delta}\,e^{-y/\delta}}$$

$$\Rightarrow \text{Como } \bar{H}_{c\parallel} = \bar{H}_{v\parallel} \Rightarrow \bar{E}_c(y) = \frac{(1-i)}{\sigma\delta}(\hat{m}\times\bar{H}_{v\parallel})\,e^{iy/\delta}\,e^{-y/\delta}$$

$$\boxed{\bar{E}_c(y) = \frac{(1-i)}{\mu_0\sigma\delta}(\hat{m}\times\bar{B}_{v\parallel})\,e^{iy/\delta}\,e^{-y/\delta}}$$

Cálculo das perdas



$$\vec{E}_{c\|} = \vec{E}_{V\|}$$

$$\mathbf{E}_c\,(y=0) \;=\; \frac{1}{\mu_0\sigma\delta}\,(1-i)\,\hat{\mathbf{n}}\times\mathbf{B}_{c\|}\,(y=0)$$

$$\Rightarrow \mathbf{E}_{V\|}\big|_S \;=\; \frac{1}{\mu_0\sigma\delta}\,(1-i)\,\hat{\mathbf{n}}\times\mathbf{B}_{V\|}\big|_S$$

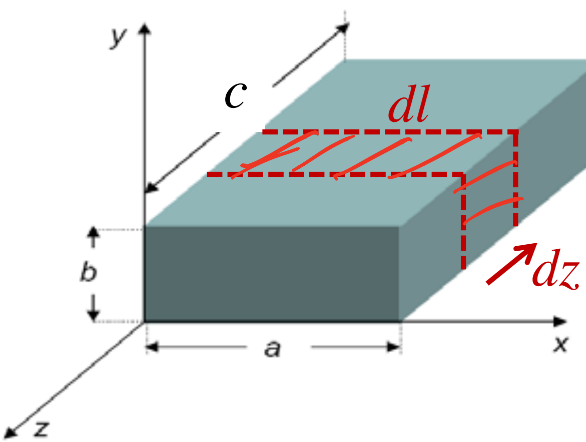
$$\langle \vec{S}_{Loss} \rangle = \frac{1}{2\mu_0}\,\mathrm{Re}\left[\vec{E}_{V\|}\times\vec{B}^{*}_{V\|}\right]$$

$$= \frac{1}{2\mu_0^2}\,\frac{1}{\sigma\delta}\,\mathrm{Re}\Big[(1-i)\underbrace{(\hat{n}\times\vec{B}_{V\|})\times\vec{B}^{*}_{V}}_{-|\vec{B}_{V\|}|^2\,\hat{n}}\Big]$$

$$\langle \vec{S}_{Loss} \rangle = -\frac{1}{2\mu_0^2\sigma\delta}\,|\vec{B}_{V\|}|^2\,\hat{n}$$

$$\frac{dP_{Loss}}{da} = -\langle \vec{S}_{Loss} \rangle\cdot\hat{n} = \frac{1}{2\mu_0^2\sigma\delta}\,|\vec{B}_{V\|}|^2$$

da ↳ ÁREA DA INTERFACE ENTRE VÁCUO E CONDUTOR



$$P_{LOSS} = \int \frac{dP_{LOSS}}{da}\, d\ell\, dz$$

$$\frac{dP_{LOSS}}{dz} = \int_{S.R.} \frac{dP_{LOSS}}{da}\, d\ell = -\frac{dP(z)}{dz}$$

$$\Rightarrow -\frac{dP(z)}{dz} = -\int_{S.R.} \frac{dP_{LOSS}}{da}\, d\ell$$

$$\Rightarrow \boxed{-\frac{dP(z)}{dz} = \frac{1}{2\mu_0^2 \sigma \delta} \oint_{S.R.} |\vec{B}_{\parallel}|^2\, d\ell}$$

$$\beta_\lambda = \frac{-dP/dz}{2P_0}$$

↳ POTÊNCIA DO GUIA IDEAL (EM TEORIA DE PERTURBAÇÃO)

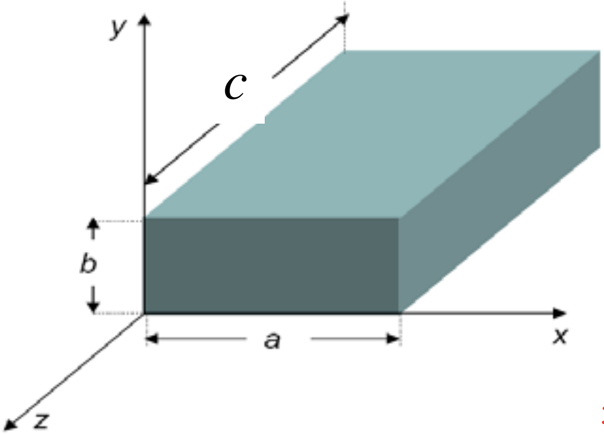
Atenuação em guias de ondas

$$\beta_\lambda = \frac{c}{2\mu_0\sigma\delta_\lambda}\,\frac{\omega\left(\frac{\omega}{\omega_\lambda}\right)^{1/2}}{\omega_\lambda^2\sqrt{\omega^2-\omega_\lambda^2}}\,\frac{\oint\left|\frac{\partial E_z}{\partial n}\right|^2 dl}{\int_{S.R.}\left|E_z\right|^2 da}\;(\text{modos TM})$$

$$\beta_\lambda = \frac{1}{2\mu_0 c\sigma\delta_\lambda}\left[\left(\frac{\omega}{\omega_\lambda}\right)\left(\frac{\omega^2}{\omega_\lambda^2}-1\right)\right]^{-1/2}\frac{\oint\left[\frac{c^2}{\omega_\lambda^4}\left(\omega^2-\omega_\lambda^2\right)\left|\hat{\boldsymbol{n}}\times\boldsymbol{\nabla}_t B_z\right|^2+\left|B_z\right|^2\right]dl}{\int_{S.R.}\left|B_z\right|^2 da}\;(\text{modos TE})$$

$$\delta_\lambda = \sqrt{\frac{2}{\mu_c\sigma\omega_\lambda}}$$

Cavidades ressonantes



PODEMOS ANALISAR CAVIDADES RESSONANTES QUE SÃO GUIAS DE ONDAS FECHADOS POR "TAMPAS" CONDUTORAS EM

$z=0$ e $z=d$

$e^{\pm ikz} \rightarrow A\cos kz + B\sin kz$

IMPOR CONDIÇÕES DE CONTORNO NAS TAMPAS:

$$E_{\parallel}\big|_S = 0 \Rightarrow \vec{E}_t\big|_{z=0,d} = 0$$

$$B_{\perp}\big|_S = 0 \Rightarrow B_z\big|_{z=0,d} = 0$$

Modos TM

$B_z = 0$

$$\vec{E}_t = \pm \frac{ik}{\gamma^2} \vec{\nabla}_t E_z = \frac{1}{\gamma^2} \vec{\nabla}_t \left(\frac{\partial E_z}{\partial z} \right)$$

SE $E_z = A \cos kz + B \sin kz$

$$\frac{1}{k} \frac{\partial E_z}{\partial z} = -A \sin kz + B \cos kz$$

IMPONDO AGORA $\vec{E}_t \big|_{z=0,d} = 0$

$\Rightarrow \vec{E}_t \big|_{z=0} \propto \boxed{B = 0}$

$\vec{E}_t \big|_{z=d} \propto \sin kd = 0$

$k = p \frac{\pi}{d} \quad (p = 0, 1, 2, \ldots)$

$E_z \propto \cos\left(p \frac{\pi}{d} z \right)$

Modos TM em cavidades

$$E_z(\mathbf{x},t) = E_z(x,y)\cos\left(\frac{p\pi z}{d}\right)e^{-i\omega t} \quad (p=0,1,2,3,\ldots)$$

$$\mathbf{E}_t(\mathbf{x},t) = -\frac{p\pi}{d\gamma^2}\sin\left(\frac{p\pi z}{d}\right)\boldsymbol{\nabla}_t E_z(x,y)\,e^{-i\omega t}$$

$$\mathbf{B}_t(\mathbf{x},t) = \frac{i\omega}{\gamma^2 c^2}\cos\left(\frac{p\pi z}{d}\right)\hat{\mathbf{z}}\times\boldsymbol{\nabla}_t E_z(x,y)\,e^{-i\omega t}$$

$$\omega_{\lambda,p} = c\left[\gamma_\lambda^2 + \left(\frac{p\pi}{d}\right)^2\right]^{1/2}$$

$$\gamma_\lambda^2 = \frac{\omega^2}{c^2} - k^2 = \frac{\omega^2}{c^2} - \left(\frac{p\pi}{d}\right)^2 \Rightarrow \omega_{\lambda,p} = c\left[\gamma_\lambda^2 + \left(\frac{p\pi}{d}\right)^2\right]^{1/2}$$

Modos TE

$B_z\big|_{z=0,d} = 0$ $\quad$ $B_z = B_z(x,y)\,[A\cos kz + B\sin kz]$

$\rightarrow A = 0$ $\quad$ $\sin kd = 0 \Rightarrow k = \frac{p\pi}{d}$ $\quad (p = 1, 2, 3, \ldots)$

$\vec{E}_t\big|_{z=0,d} = 0$ $\quad$ $\vec{E}_t = -i\frac{\omega}{\gamma^2}\sin\left(\frac{p\pi z}{d}\right)\hat{z}\times\vec{\nabla}_t B_z(x,y)$

$\vec{E}_t$ É AUTOMATICAMENTE NULO EM $z = 0, d$

Modos TE em cavidades

$$B_z(\mathbf{x},t) \;=\; B_z(x,y)\sin\left(\frac{p\pi z}{d}\right)e^{-i\omega t} \quad (p=1,2,3,\ldots)$$

$$\mathbf{B}_t(\mathbf{x},t) \;=\; \frac{p\pi}{d\gamma^2}\cos\left(\frac{p\pi z}{d}\right)\boldsymbol{\nabla}_t B_z(x,y)\,e^{-i\omega t}$$

$$\mathbf{E}_t(\mathbf{x},t) \;=\; -\frac{i\omega}{\gamma^2}\sin\left(\frac{p\pi z}{d}\right)\hat{\mathbf{z}}\times\boldsymbol{\nabla}_t B_z(x,y)\,e^{-i\omega t}$$

$$\omega_{\lambda,p} = c\left[\gamma_\lambda^2 + \left(\frac{p\pi}{d}\right)^2\right]^{1/2}$$

Modos em cavidades ressonantes

Modos TM:

$$E_z(\mathbf{x},t) = E_z(x,y)\cos\left(\frac{p\pi z}{d}\right)e^{-i\omega t} \quad (p=0,1,2,3,\ldots)$$

$$\mathbf{E}_t(\mathbf{x},t) = -\frac{p\pi}{d\gamma^2}\sin\left(\frac{p\pi z}{d}\right)\boldsymbol{\nabla}_t E_z(x,y)\,e^{-i\omega t}$$

$$\mathbf{B}_t(\mathbf{x},t) = \frac{i\omega}{\gamma^2 c^2}\cos\left(\frac{p\pi z}{d}\right)\hat{\mathbf{z}}\times\boldsymbol{\nabla}_t E_z(x,y)\,e^{-i\omega t}$$

Modos TE:

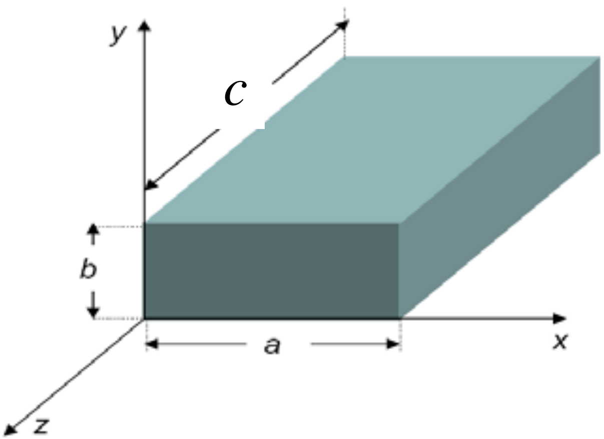
$$B_z(\mathbf{x},t) = B_z(x,y)\sin\left(\frac{p\pi z}{d}\right)e^{-i\omega t} \quad (p=1,2,3,\ldots)$$

$$\mathbf{B}_t(\mathbf{x},t) = \frac{p\pi}{d\gamma^2}\cos\left(\frac{p\pi z}{d}\right)\boldsymbol{\nabla}_t B_z(x,y)\,e^{-i\omega t}$$

$$\mathbf{E}_t(\mathbf{x},t) = -\frac{i\omega}{\gamma^2}\sin\left(\frac{p\pi z}{d}\right)\hat{\mathbf{z}}\times\boldsymbol{\nabla}_t B_z(x,y)\,e^{-i\omega t}$$

$$\omega_{\lambda,p} = c\left[\gamma_\lambda^2 + \left(\frac{p\pi}{d}\right)^2\right]^{1/2}$$

Cavidades retangulares



$$\omega_{m,n,p} = \pi c \left[\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{d}\right)^2 \right]^{1/2}$$

$$\gamma_{m,n} = \left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2$$

MODOS TM: $m = 1, 2, 3, \ldots$; $n = 1, 2, 3, \ldots$; $p = 0, 1, 2, \ldots$ $\Rightarrow$ MODO DE MENOR FREQUÊNCIA

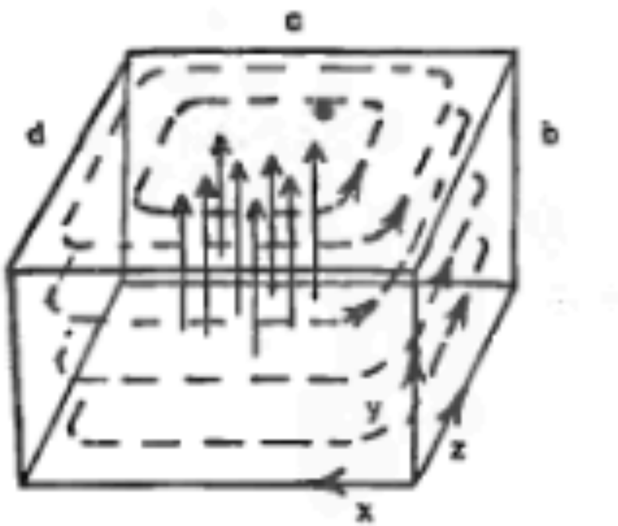
$$\omega_{110} = \pi c \left(\frac{1}{a^2} + \frac{1}{b^2} \right)^{1/2}$$

MODOS TE: $m = 0, 1, 3 \ldots$; $n = 0, 1, 2, \ldots$; $m + n > 0$; $p = 1, 2, 3, \ldots$ $\Rightarrow$ MENOR FREQUÊNCIA:

ω_{011} OU ω_{101}

SE $(a > b) \Rightarrow \omega_{1,0,1} = \pi c \left(\frac{1}{a^2} + \frac{1}{d^2} \right)^{1/2}$

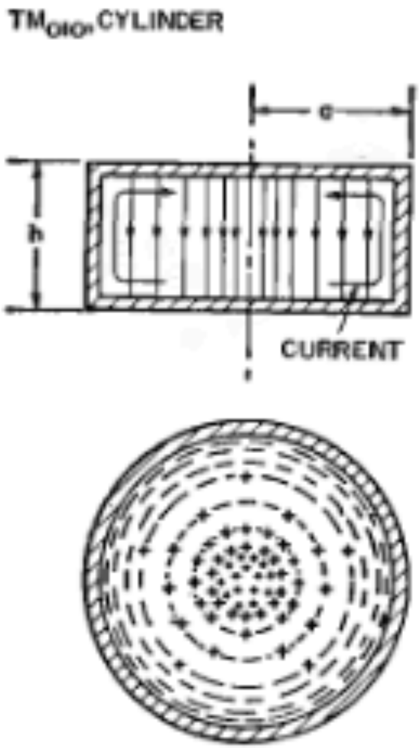
Cavidades retangulares



Campo elétrico **E**: linhas contínuas
Campo magnético **B**: linhas tracejadas

Cavidades cilíndricas

Campo elétrico **E**: linhas contínuas
Campo magnético **B**: linhas tracejadas



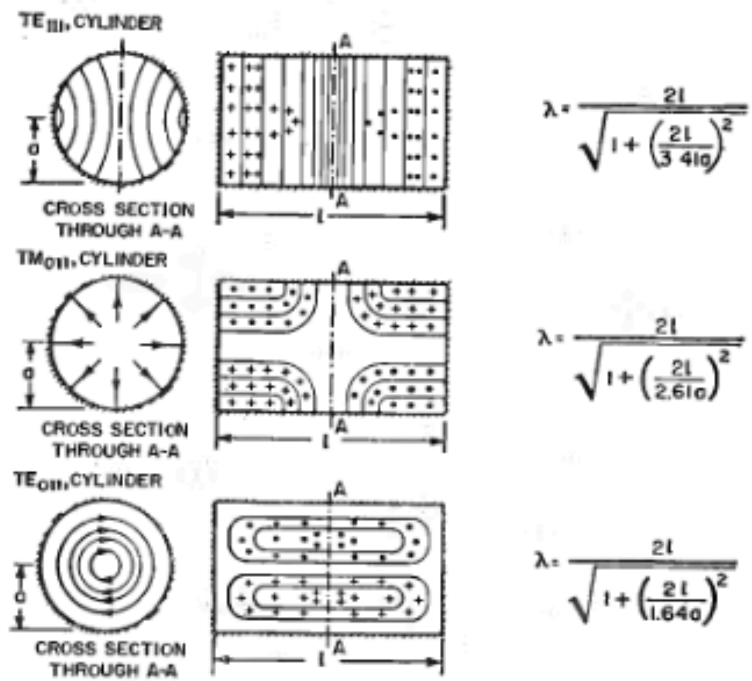


FIG. 5b-6. Field configurations for several selected modes. λ is the resonant wavelength.

Cavidade esférica

Campo elétrico **E**: linhas contínuas
Campo magnético **B**: linhas tracejadas

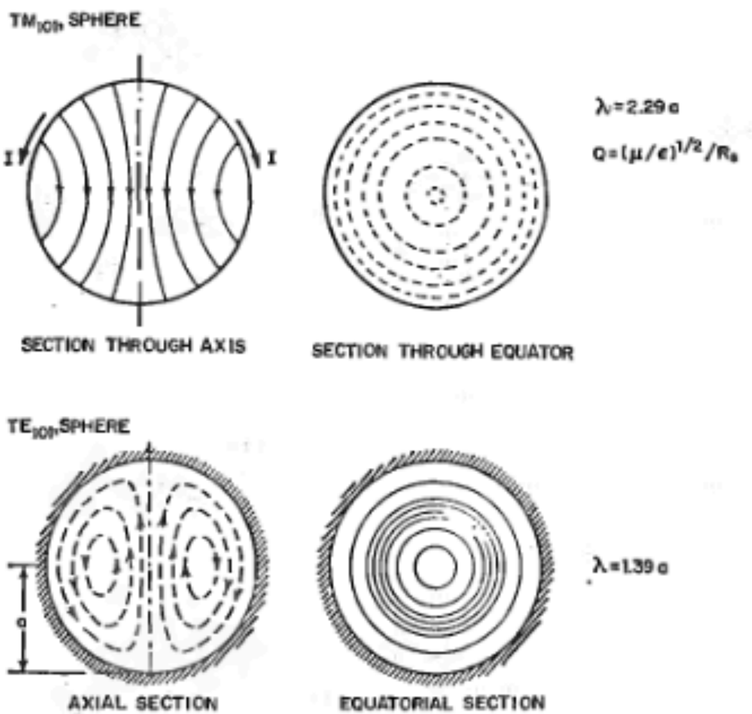


Fig. 5b-6 (*Continued*)