Lecture 7: Wave Guidance

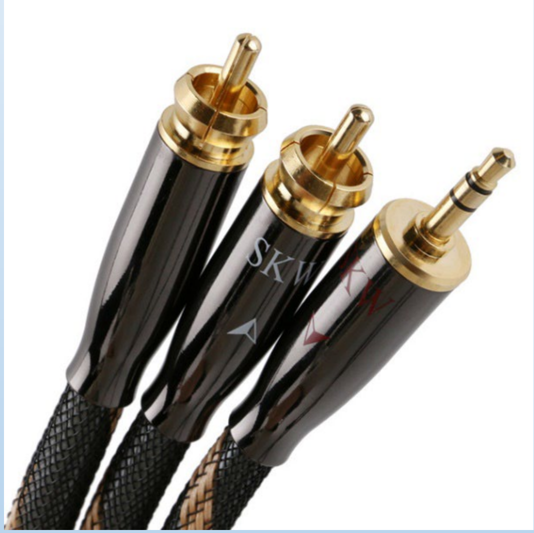
Outline

- Guidance by Conducting Parallel Plates
- Rectangular Waveguide
- TEM Mode and Coaxial Cable
- Generic Form of Guided Waves
- Slab Dielectric Waveguide

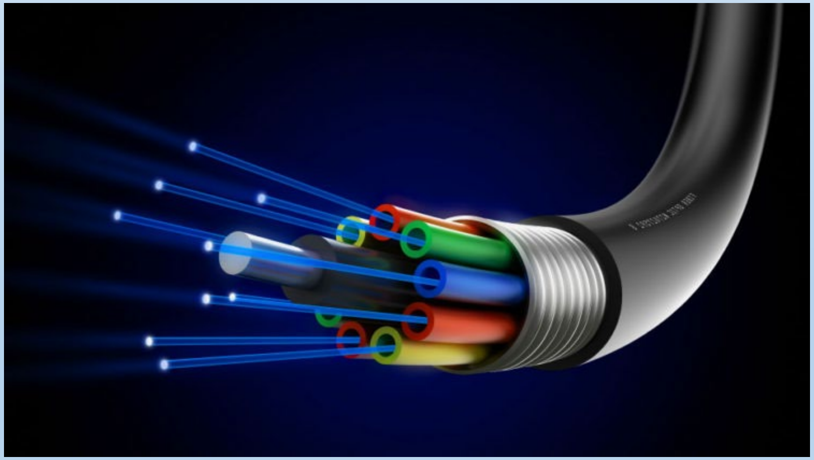
Wave Guidance Devices

Microwave Waveguides

Digital Audio Coaxial cable



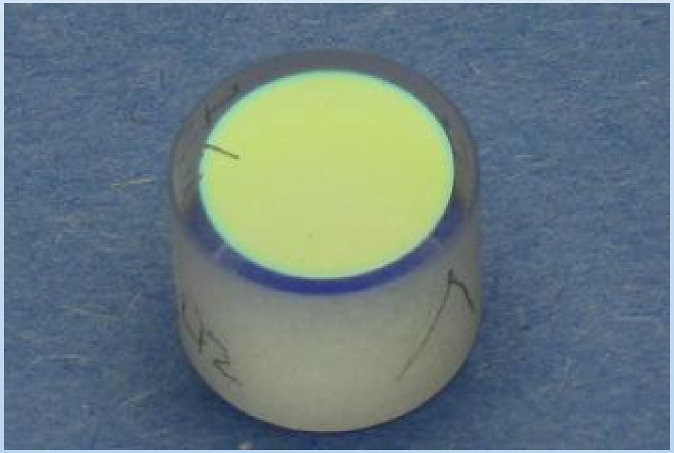
Optical fiber



Reflection by Mirrors

METAL REFLECTION

MULTILAYER REFLECTION

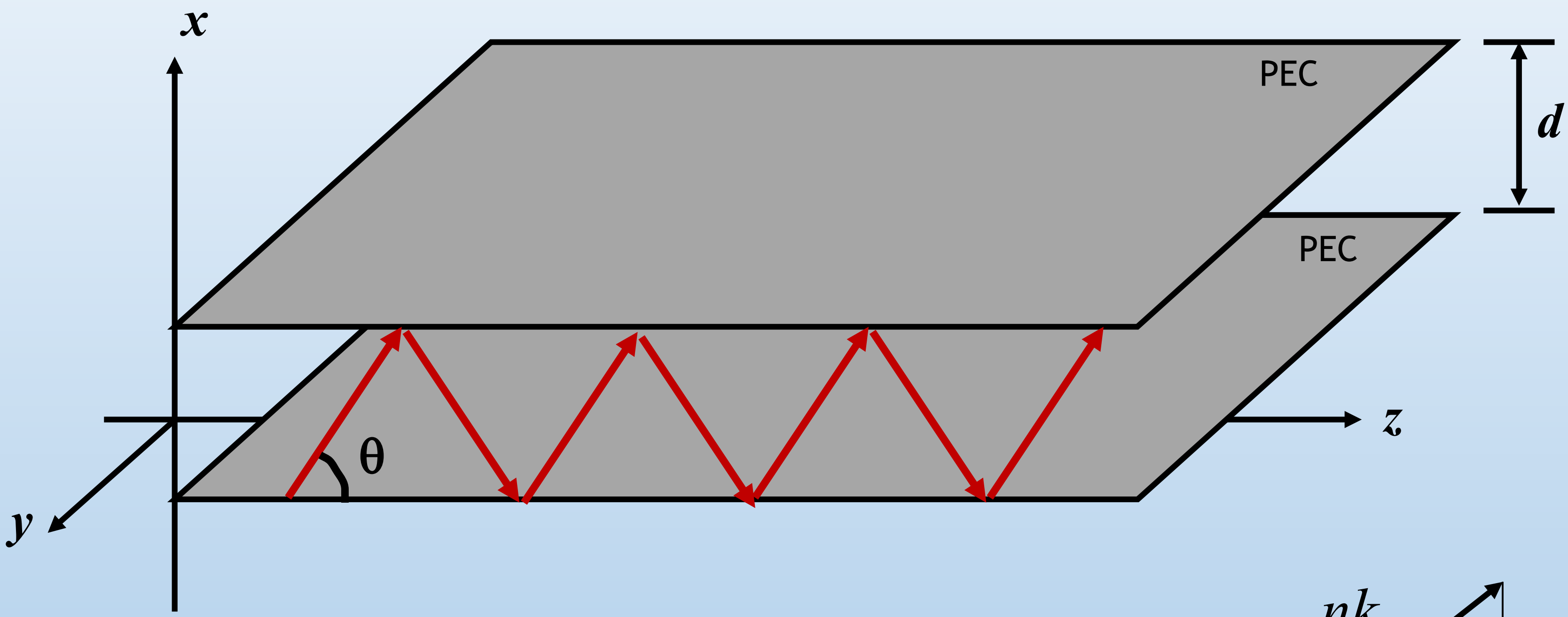


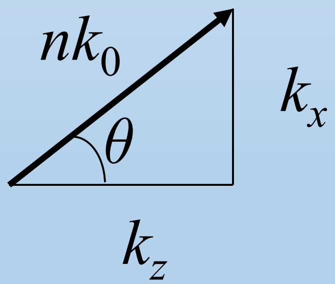
http://en.wikipedia.org/wiki/File:Dielectric_laser_mirror_from_a_dye_laser.JPG

TOTAL INTERNAL REFLECTION

Guidance by Conducting Parallel Plates

We can transport light along the z-direction by bouncing it between two PECs





..the ray moves along both y- and z-axes..

$$E = \left(A_1 e^{-jk_x x} + A_2 e^{jk_x x}\right) e^{-jk_z z}$$

...where

$$k_x = nk_0 \sin\theta \qquad k_z = nk_0 \cos\theta$$

$$\nabla \times \vec{E} = -\mathrm{j}\omega\mu\vec{H}$$

$$\begin{cases} \dfrac{\partial}{\partial y}E_z - \dfrac{\partial}{\partial z}E_y = -j\omega\mu H_x \\ \dfrac{\partial}{\partial z}E_x - \dfrac{\partial}{\partial x}E_z = -j\omega\mu H_y \\ \dfrac{\partial}{\partial x}E_y - \dfrac{\partial}{\partial y}E_x = -j\omega\mu H_z \end{cases}$$

$$\nabla \times \vec{H} = \mathrm{j}\omega\varepsilon\vec{E}$$

$$\begin{cases} \dfrac{\partial}{\partial y}H_z - \dfrac{\partial}{\partial z}H_y = j\omega\varepsilon E_x \\ \dfrac{\partial}{\partial z}H_x - \dfrac{\partial}{\partial x}H_z = j\omega\varepsilon E_y \\ \dfrac{\partial}{\partial x}H_y - \dfrac{\partial}{\partial y}H_x = j\omega\varepsilon E_z \end{cases}$$

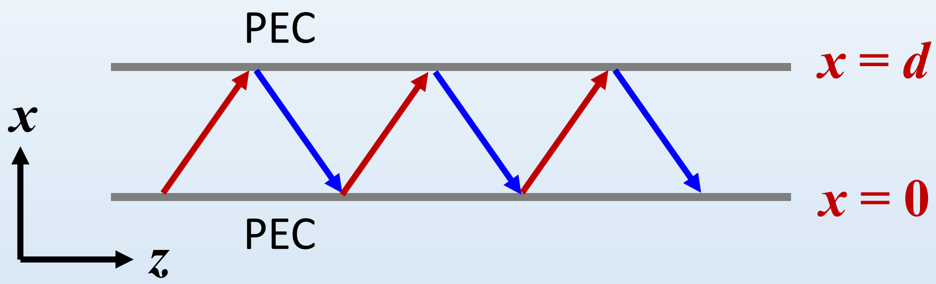
$$\begin{cases} \dfrac{\partial}{\partial z}E_y = j\omega\mu H_x \\ \dfrac{\partial}{\partial x}E_y = -j\omega\mu H_z \\ \dfrac{\partial}{\partial z}H_x + \dfrac{\partial}{\partial x}H_z = j\omega\varepsilon E_y \end{cases}$$

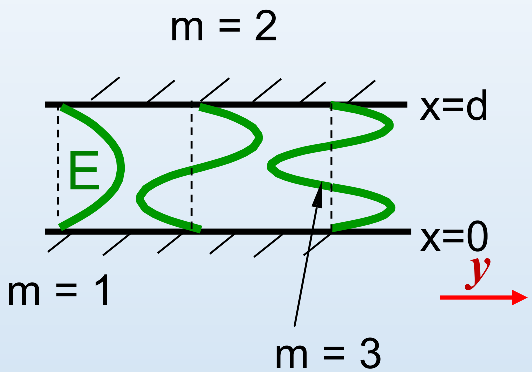
$\boxed{E_y、H_x、H_z}$ **TE模**

$$\begin{cases} \dfrac{\partial}{\partial z}H_y = -j\omega\varepsilon E_x \\ \dfrac{\partial}{\partial x}H_y = j\omega\varepsilon E_z \\ \dfrac{\partial}{\partial z}E_x + \dfrac{\partial}{\partial x}E_z = -j\omega\mu H_y \end{cases}$$

$\boxed{H_y、E_x、E_z}$ **TM模**

TE Waveguide Modes





$$\vec{E} = \hat{y}\left(A_1 e^{-jk_x x} + A_2 e^{jk_x x}\right)e^{-jk_z z}$$

$$m\lambda_x / 2 = d$$

Boundary Conditions: $E_y\left(0, z\right) = E_y\left(d, z\right) = 0$

$$\Rightarrow \begin{cases} A_1 = -A_2 \\ \sin\left(k_x d\right) = 0 \end{cases}$$

$$\boxed{k_x d = m\pi}$$

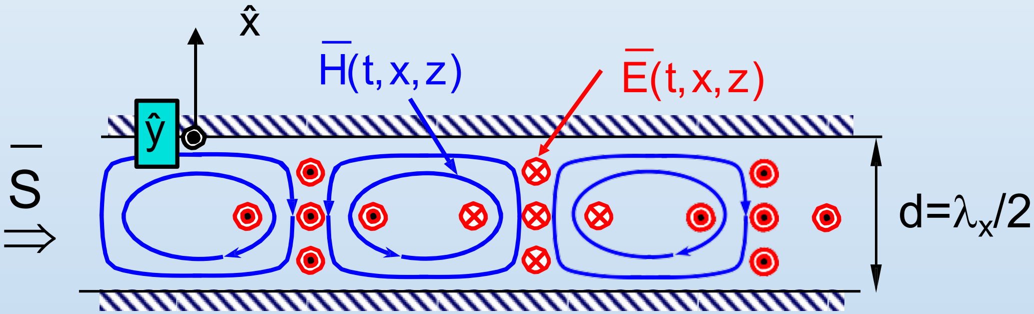
(Guidance Condition)

$$\boxed{\begin{aligned} E_y(x,z) &= E_0 \sin(k_x x)\, e^{-jk_z z} \\ H_x(x,z) &= -\frac{k_z}{\omega\mu} E_0 \sin(k_x x)\, e^{-jk_z z} \\ H_z(x,z) &= -\frac{k_x}{j\omega\mu} E_0 \cos(k_x x)\, e^{-jk_z z} \end{aligned}}$$

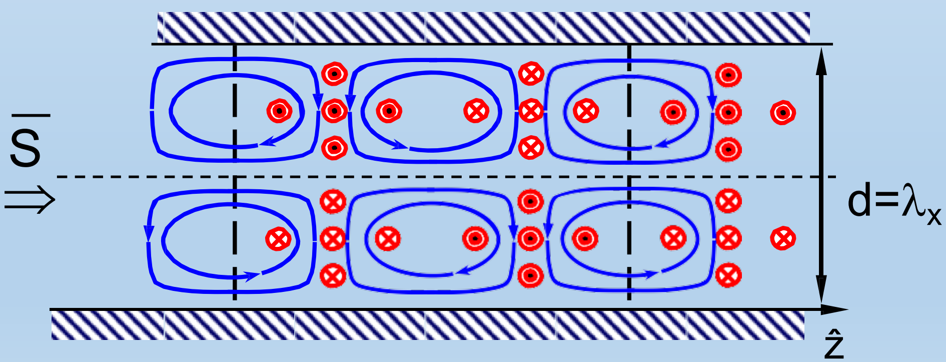
TE Mode Patterns

TE modes: $E_y(x,z) = E_0 \sin(k_x x) e^{-jk_z z}$

TE_1 mode:



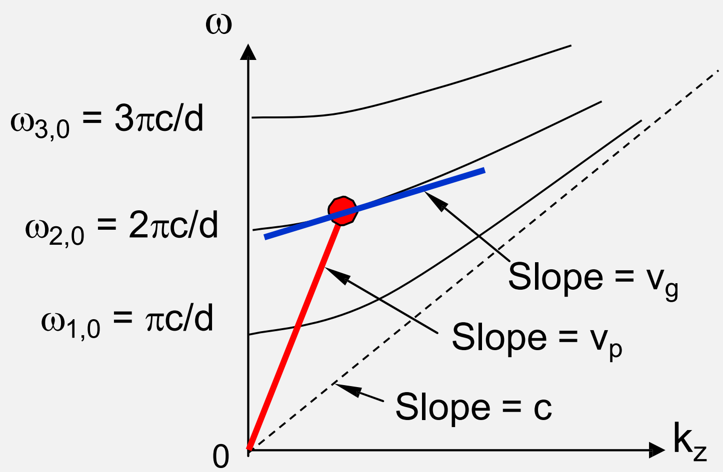
TE_2 mode:



$k_x d = m\pi$ ⇨ $m\lambda_x/2 = d$

$$k_z = \sqrt{\left(\frac{\omega}{c}\right)^2 - \left(\frac{m\pi}{d}\right)^2}$$

(Dispersion Relation)



$$v_{phase} = \omega/k_z$$

$$v_{group} = d\omega/dk_z$$

$$\nabla \times \vec{E} = -\mathrm{j}\omega\mu\vec{H}$$

$$\begin{cases} \dfrac{\partial}{\partial y}E_z - \dfrac{\partial}{\partial z}E_y = -j\omega\mu H_x \\ \dfrac{\partial}{\partial z}E_x - \dfrac{\partial}{\partial x}E_z = -j\omega\mu H_y \\ \dfrac{\partial}{\partial x}E_y - \dfrac{\partial}{\partial y}E_x = -j\omega\mu H_z \end{cases}$$

$$\nabla \times \vec{H} = \mathrm{j}\omega\varepsilon\vec{E}$$

$$\begin{cases} \dfrac{\partial}{\partial y}H_z - \dfrac{\partial}{\partial z}H_y = j\omega\varepsilon E_x \\ \dfrac{\partial}{\partial z}H_x - \dfrac{\partial}{\partial x}H_z = j\omega\varepsilon E_y \\ \dfrac{\partial}{\partial x}H_y - \dfrac{\partial}{\partial y}H_x = j\omega\varepsilon E_z \end{cases}$$

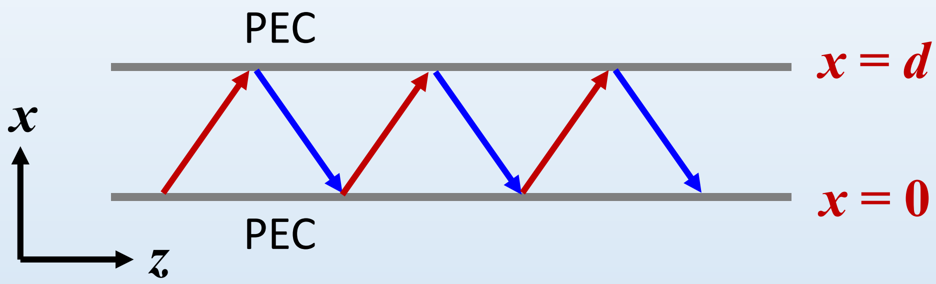
$$\begin{cases} \dfrac{\partial}{\partial z}E_y = j\omega\mu H_x \\ \dfrac{\partial}{\partial x}E_y = -j\omega\mu H_z \\ \dfrac{\partial}{\partial z}H_x + \dfrac{\partial}{\partial x}H_z = j\omega\varepsilon E_y \end{cases}$$

$\boxed{\boldsymbol{E_y}、\boldsymbol{H_x}、\boldsymbol{H_z}}$ **TE模**

$$\begin{cases} \dfrac{\partial}{\partial z}H_y = -j\omega\varepsilon E_x \\ \dfrac{\partial}{\partial x}H_y = j\omega\varepsilon E_z \\ \dfrac{\partial}{\partial z}E_x + \dfrac{\partial}{\partial x}E_z = -j\omega\mu H_y \end{cases}$$

$\boxed{\boldsymbol{H_y}、\boldsymbol{E_x}、\boldsymbol{E_z}}$ **TM模**

TM Waveguide Modes



$$\nabla \times \vec{H} = j\omega\varepsilon\vec{E}$$

$$\nabla \times \vec{E} = -j\omega\mu\vec{H}$$

$$\vec{H} = \hat{y}\left(A_1 e^{-jk_x x} + A_2 e^{jk_x x}\right)e^{-jk_z z}$$

Boundary Conditions: $E_z(0,z) = E_z(d,z) = 0$

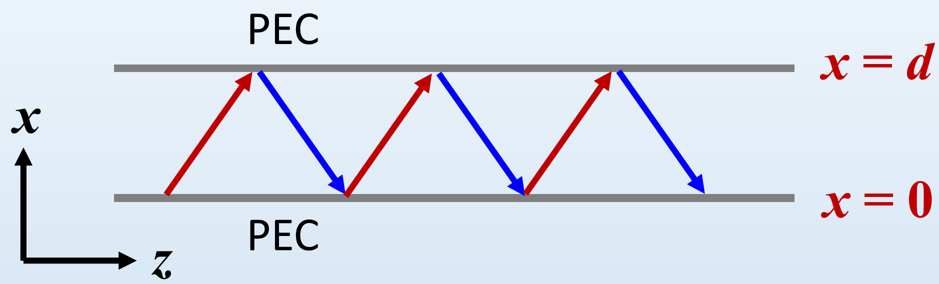
$$\begin{cases} A_1 = A_2 \\ \sin(k_x d) = 0 \end{cases}$$

$$\boxed{k_x d = m\pi}$$

(Guidance Condition)

$$\boxed{\begin{aligned} H_y(x,z) &= H_0 \cos(k_x x) e^{-jk_z z} \\ E_x(x,z) &= \frac{k_z}{\omega\varepsilon} H_0 \cos(k_x x) e^{-jk_z z} \\ E_z(x,z) &= -\frac{k_x}{j\omega\varepsilon} H_0 \sin(k_x x) e^{-jk_z z} \end{aligned}}$$

Cutoff Frequency



$$k_x d = m\pi \quad \Rightarrow \quad k_z = \sqrt{\left(\frac{\omega}{c}\right)^2 - \left(\frac{m\pi}{d}\right)^2} \quad \textbf{(Dispersion Relation)}$$

$$\boxed{\omega = \frac{m\pi c}{d}}$$

- **Cutoff Frequencies of the TE_m and TM_m modes (m>0)**
- **No cutoff frequency and TM_0 (TEM mode)**
- **TE_0 mode does not exist.**

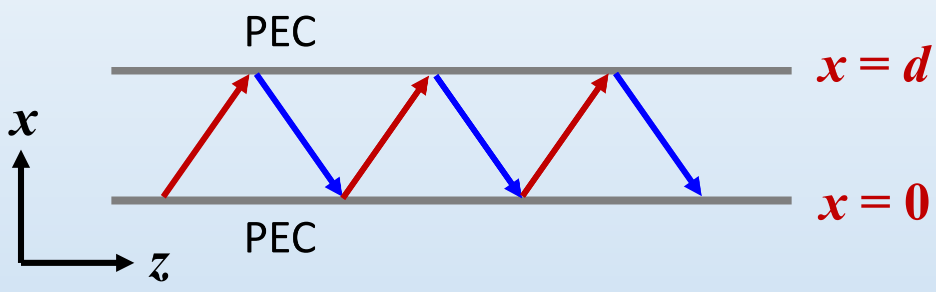
TEM mode:

$$\vec{H} = \hat{y} H_0 \exp(-jkz)$$

$$\vec{E} = \hat{x} E_0 \exp(-jkz)$$

Rectangular Waveguide

(a) Parallel-plate waveguide (Two PEC boundaries)



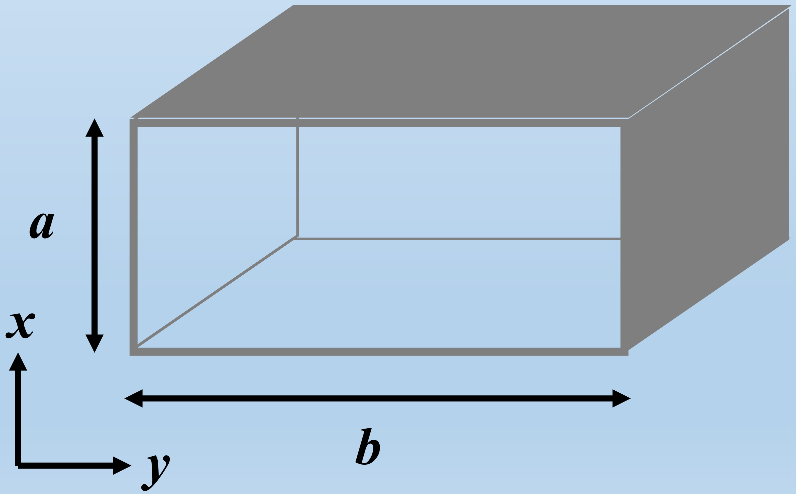
TE mode:

$$H_z(x,z) = H_0 \cos(k_x x) e^{-jk_z z}$$

TM mode:

$$E_z(x,z) = E_0 \sin(k_x x) e^{-jk_z z}$$

(a) Rectangular waveguide (Four PEC boundaries)



TE mode:

$$H_z(x,y,z) = H_0 \cos(k_x x)\cos(k_y y) e^{-jk_z z}$$

TM mode:

$$E_z(x,y,z) = E_0 \sin(k_x x)\sin(k_y y) e^{-jk_z z}$$

Transverse Components

$$\nabla \times \vec{E} = -j\omega\mu\vec{H} \qquad \nabla \times \vec{H} = j\omega\varepsilon\vec{E} \qquad \nabla \to \hat{x}\frac{\partial}{\partial x} + \hat{y}\frac{\partial}{\partial y} - \hat{z}jk_z$$

$$\frac{\partial}{\partial y}E_z + jk_zE_y = -j\omega\mu H_x \qquad \frac{\partial}{\partial y}H_z + jk_zH_y = j\omega\varepsilon E_x$$

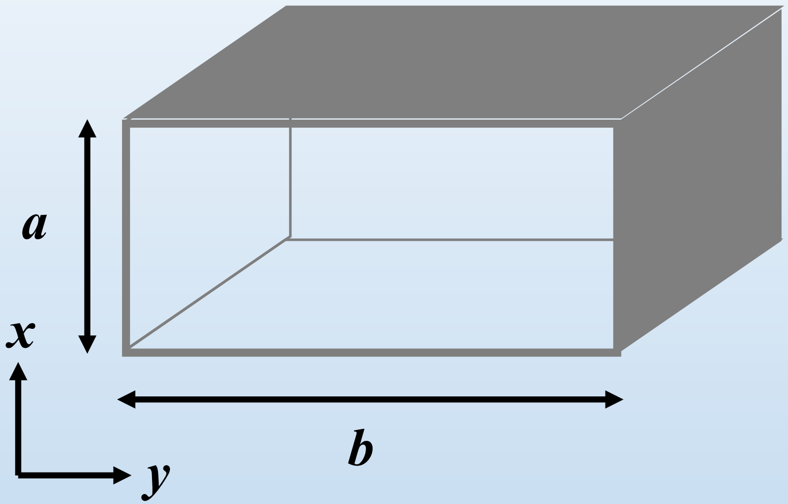
$$-\frac{\partial}{\partial x}E_z - jk_zE_x = -j\omega\mu H_y \qquad -\frac{\partial}{\partial x}H_z - jk_zH_x = j\omega\varepsilon E_y$$

$$\frac{\partial}{\partial x}E_y - \frac{\partial}{\partial y}E_x = -j\omega\mu H_z \qquad \frac{\partial}{\partial x}H_y - \frac{\partial}{\partial y}H_x = j\omega\varepsilon E_z$$

$$H_x = \frac{1}{k^2 - k_z^2}\left(j\omega\varepsilon\frac{\partial}{\partial y}E_z - jk_z\frac{\partial}{\partial x}H_z\right) \qquad E_x = \frac{-1}{k^2 - k_z^2}\left(jk_z\frac{\partial}{\partial x}E_z + j\omega\mu\frac{\partial}{\partial y}H_z\right)$$

$$H_y = \frac{-1}{k^2 - k_z^2}\left(j\omega\varepsilon\frac{\partial}{\partial x}E_z + jk_z\frac{\partial}{\partial y}H_z\right) \qquad E_y = \frac{-1}{k^2 - k_z^2}\left(jk_z\frac{\partial}{\partial y}E_z - j\omega\mu\frac{\partial}{\partial x}H_z\right)$$

Rectangular Waveguide - TE_{mn} Mode



$$H_z = \cos(k_x x)\cos(k_y y)e^{-jk_z z}$$

$$H_x = \frac{jk_x k_z}{\omega^2\mu\varepsilon - k_z^2}\sin(k_x x)\cos(k_y y)e^{-jk_z z}$$

$$H_y = \frac{jk_y k_z}{\omega^2\mu\varepsilon - k_z^2}\cos(k_x x)\sin(k_y y)e^{-jk_z z}$$

$$E_x = \frac{j\omega\mu k_y}{\omega^2\mu\varepsilon - k_z^2}\cos(k_x x)\sin(k_y y)e^{-jk_z z}$$

$$E_y = \frac{-j\omega\mu k_x}{\omega^2\mu\varepsilon - k_z^2}\sin(k_x x)\cos(k_y y)e^{-jk_z z}$$

Boundary Conditions:

(1) Ex = 0 at y = 0 and b

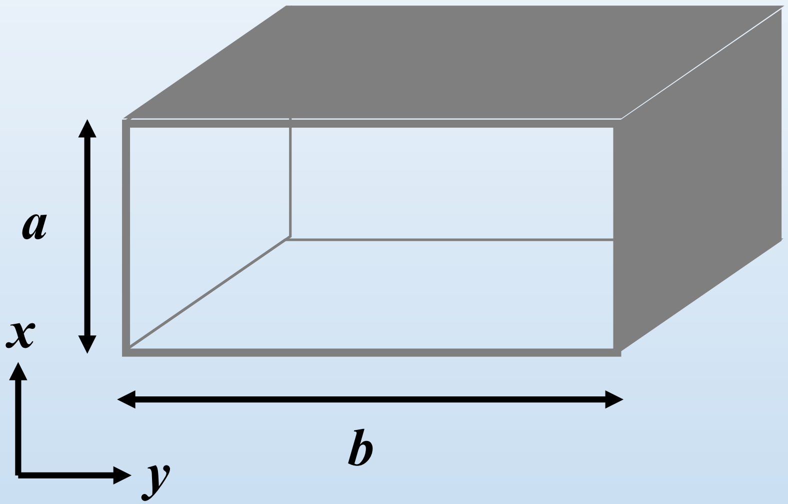
(2) Ey = 0 at x = 0 and a

$$\boxed{\begin{aligned} k_x a &= m\pi \\ k_y b &= n\pi \end{aligned}}$$

(Guidance Condition)

$$\boxed{k_z = \sqrt{\left(\frac{\omega}{c}\right)^2 - \left(\frac{m\pi}{a}\right)^2 - \left(\frac{n\pi}{b}\right)^2}}$$

Rectangular Waveguide - TM_{mn} Mode



$$E_z(x,y,z) = \sin(k_x x)\sin(k_y y)e^{-jk_z z}$$

$$E_x = \frac{-jk_x k_z}{\omega^2 \mu\varepsilon - k_z^2}\cos(k_x x)\sin(k_y y)e^{-jk_z z}$$

$$E_y = \frac{-jk_y k_z}{\omega^2 \mu\varepsilon - k_z^2}\sin(k_x x)\cos(k_y y)e^{-jk_z z}$$

$$H_x = \frac{j\omega\varepsilon k_y}{\omega^2 \mu\varepsilon - k_z^2}\sin(k_x x)\cos(k_y y)e^{-jk_z z}$$

$$H_y = \frac{-j\omega\varepsilon k_x}{\omega^2 \mu\varepsilon - k_z^2}\cos(k_x x)\sin(k_y y)e^{-jk_z z}$$

Boundary Conditions:

(1) Ex = 0 at y = 0 and b

(2) Ey = 0 at x = 0 and a

$$\boxed{\begin{aligned} k_x a &= m\pi \\ k_y b &= n\pi \end{aligned}}$$

(Guidance Condition)

$$\boxed{k_z = \sqrt{\left(\frac{\omega}{c}\right)^2 - \left(\frac{m\pi}{a}\right)^2 - \left(\frac{n\pi}{b}\right)^2}}$$

Cut-off characteristics

$$k_c = \sqrt{k_x^2 + k_y^2} = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$$

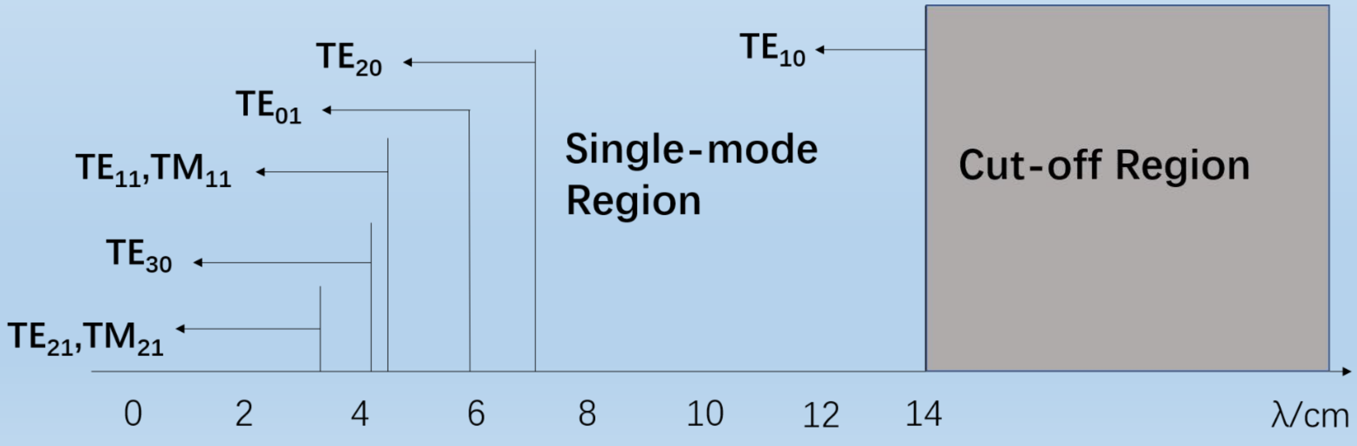
Cut-off frequency

$$f_c = \frac{1}{2\sqrt{\varepsilon\mu}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$

Cut-off wavelength

$$\lambda_c = \frac{2\pi}{k_c} = \frac{2}{\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}}$$

For a=7cm, b=3cm



TE_{10} Waveguide Mode

$$\boxed{\begin{aligned} k_x a &= m\pi \\ k_y b &= n\pi \end{aligned}}$$

TE_{10} Mode m=1, n=0

$$H_z = \cos(k_x x)\cos(k_y y)e^{-jk_z z} \longrightarrow H_z = cos\left(\frac{\pi}{a}x\right)e^{-jk_z z}$$

$$H_x = \frac{jk_x k_z}{\omega^2\mu\varepsilon - k_z^2}\sin(k_x x)\cos(k_y y)e^{-jk_z z} \longrightarrow H_x = \frac{jk_z}{k_c^2}\frac{\pi}{a} sin\left(\frac{\pi}{a}x\right)e^{-jk_z z}$$

$$H_y = \frac{jk_y k_z}{\omega^2\mu\varepsilon - k_z^2}\cos(k_x x)\sin(k_y y)e^{-jk_z z} \longrightarrow H_y = 0$$

$$E_x = \frac{j\omega\mu k_y}{\omega^2\mu\varepsilon - k_z^2}\cos(k_x x)\sin(k_y y)e^{-jk_z z} \longrightarrow E_x = 0$$

$$E_y = \frac{-j\omega\mu k_x}{\omega^2\mu\varepsilon - k_z^2}\sin(k_x x)\cos(k_y y)e^{-jk_z z} \longrightarrow E_y = \frac{-j\omega\mu}{k_c^2}\frac{\pi}{a} sin\left(\frac{\pi}{a}x\right)e^{-jk_z z}$$

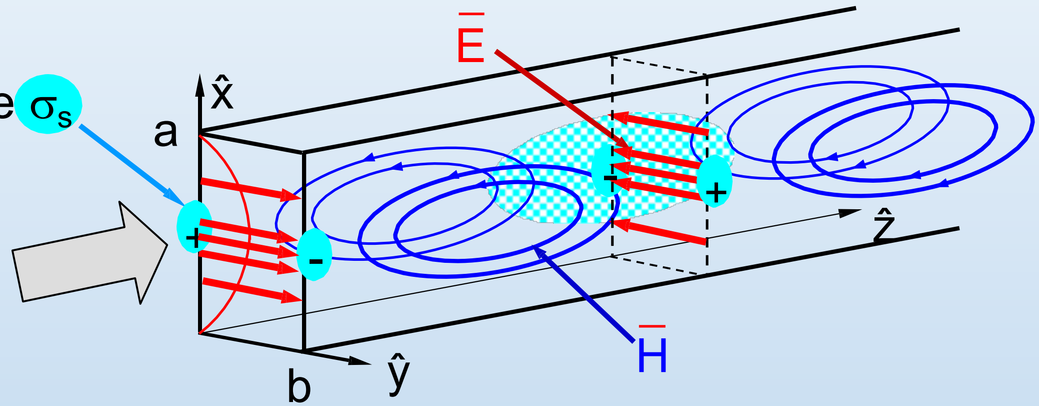
TE_{10} Waveguide Mode

Add Sidewalls to TE_1 Parallel Plate Waveguide $\Rightarrow$ TE_{10}:

Surface charge σ_s

$\sigma_s = \hat{n} \cdot \varepsilon \bar{E}$

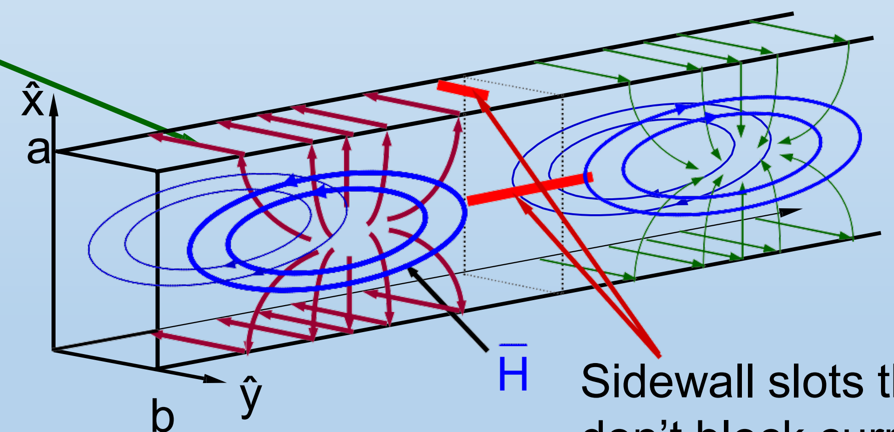
Power flow



Surface current $\bar{J}_s$

$\bar{J}_s = \hat{n} \times \bar{H}$

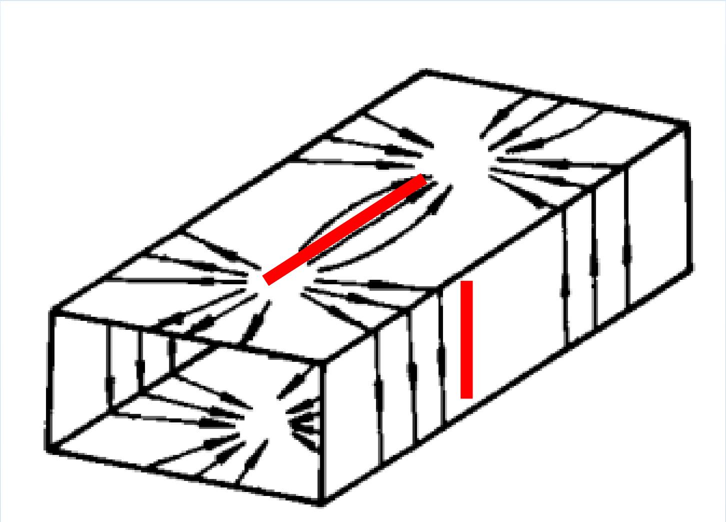
Antennas can be coupled through holes or slots; slots at angles can radiate

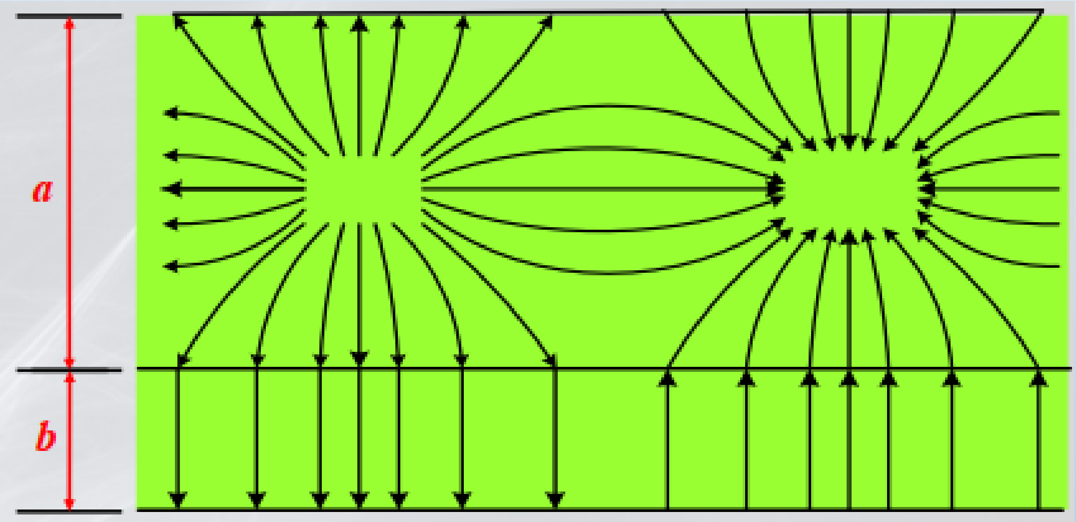


Sidewall slots that don't block current

TE_{10} Waveguide Mode

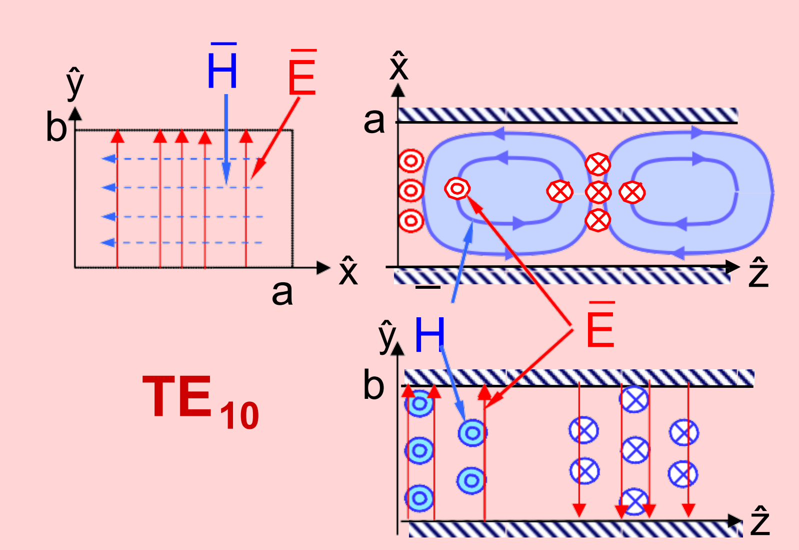
TE_{10} Mode: surface current distribution

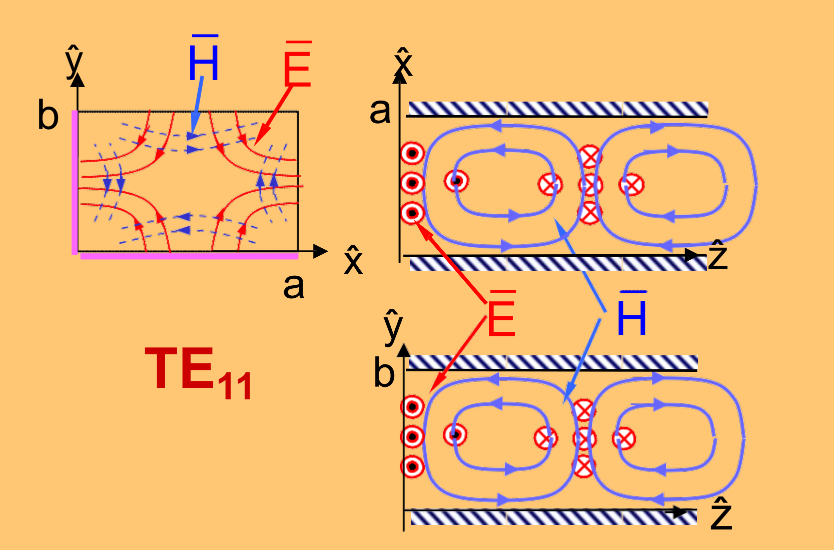


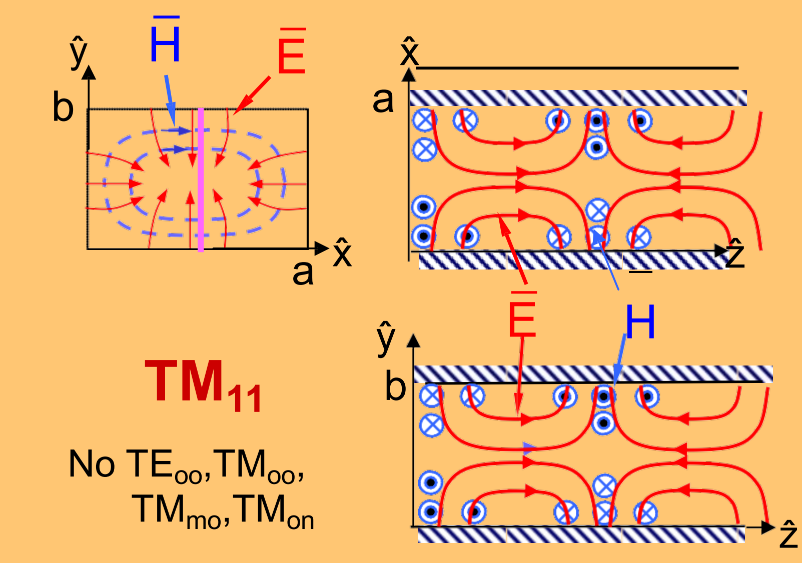


Sidewall slots that
don't block current

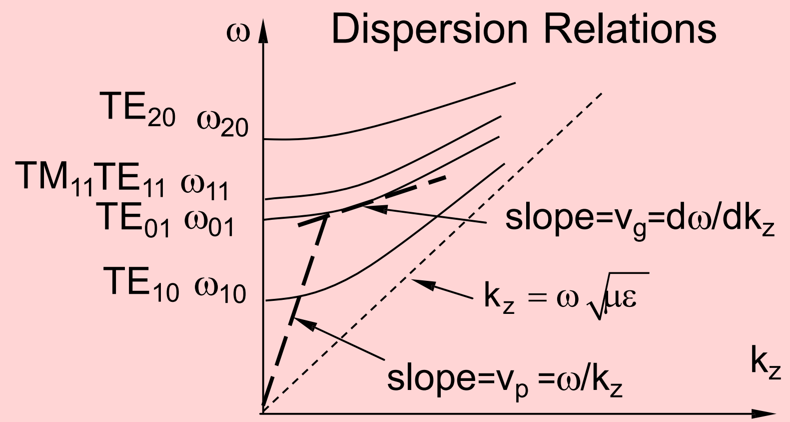
Rectangular Waveguide Modes







$$k_z = \sqrt{\left(\frac{\omega}{c}\right)^2 - \left(\frac{m\pi}{a}\right)^2 - \left(\frac{n\pi}{b}\right)^2} \quad TE(M)_{mn} : a > b$$



Example

For regular metal rectangular waveguides BJ-100(a=22.86 mm, b=10.16mm), the waveguide is filled with a uniform medium ε_r=2.1.

(a). Find the cutoff frequencies of the top 5 modes with longer Cut-off wavelengths.

(b). If the operating frequency is 9GHz， 11GHz, what modes might exist in waveguides?

Solution

$$\lambda_c = \frac{2\pi}{k_c} = \frac{2}{\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}} \qquad f_c = \frac{\mathrm{v}}{\lambda_c} = \frac{\mathrm{c}}{\sqrt{\varepsilon_r}\lambda_c}$$

(a) For TE_{10} mode , $\lambda_c = 2a = 4.57cm$ $\quad f_c = 4.53GHz$

For TE_{20} mode , $\lambda_c = a = 2.29cm$ $\quad f_c = 9.06GHz$

For TE_{01} mode , $\lambda_c = 2b = 2.03cm$ $\quad f_c = 10.19GHz$

For TE_{11} & TM_{11} mode , $\lambda_c = \frac{2ab}{\sqrt{a^2 + b^2}} = 1.86cm$ $\quad f_c = 11.15GHz$

(b). If the operating frequency is 9GHz， 11GHz, what modes might exist in waveguides?

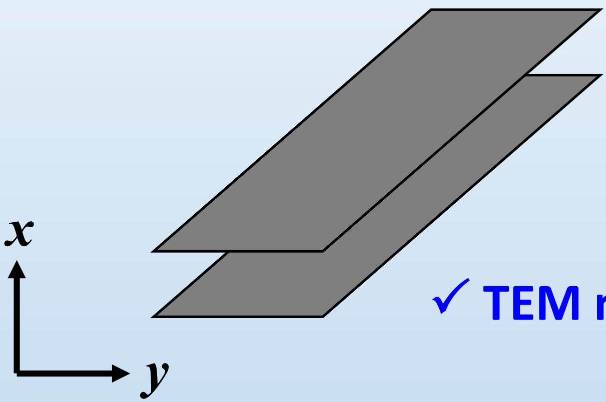
Transmission condition： $f > f_c$，

For 9GHz, only TE_{10} mode

For 11GHz, three modes can exist in waveguides :TE_{10} TE_{20} TE_{01}

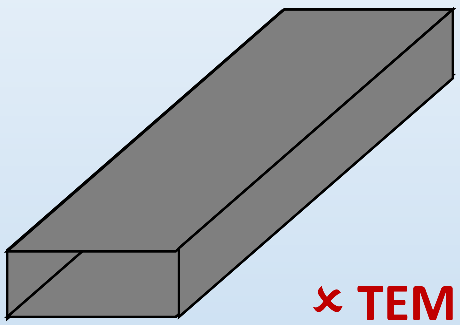
TEM Mode Analysis

Parallel Metallic Plates



✓ TEM mode

Rectangular Metallic Waveguide



✗ TEM mode

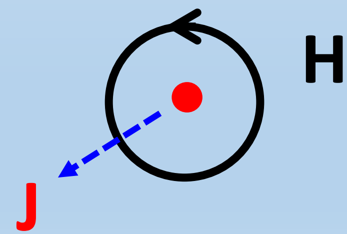
What's the reason?

TEM mode requires $E_z = 0$ and $H_z = 0$

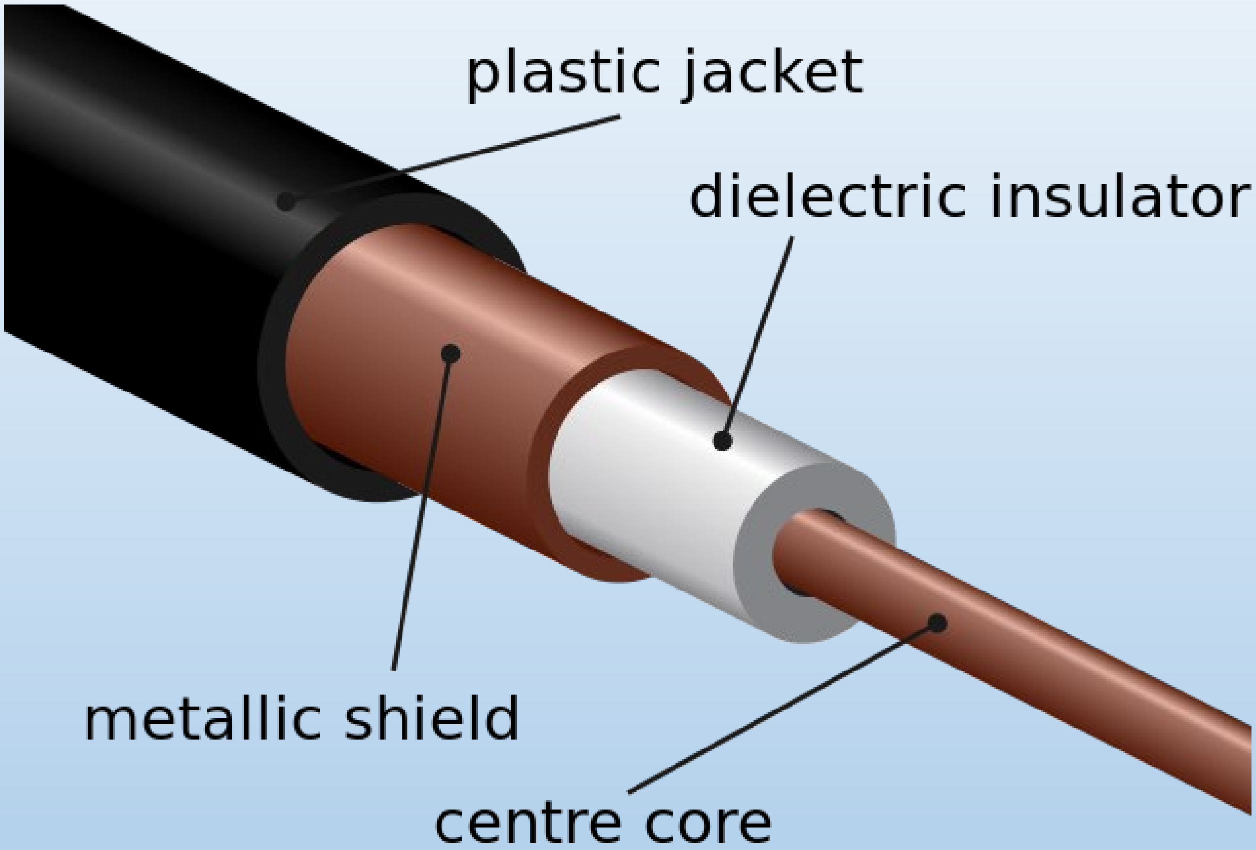
Single-conductor waveguides cannot support TEM waves.

Because:

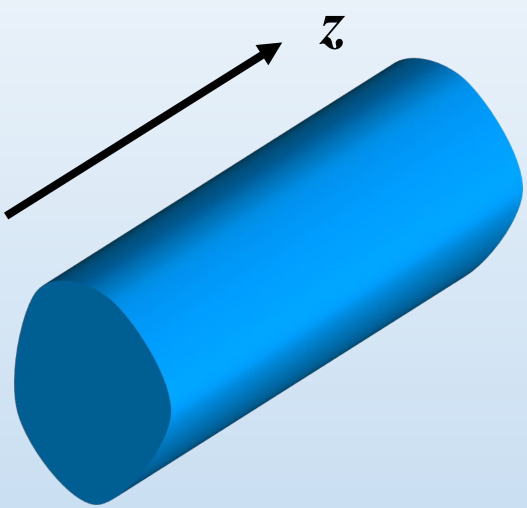
- **H forms a loop**
- **Absence of magnetic charges**
- **There must be a longitudinal electric current/field**



Coaxial Cable



Generic Form of Guided Waves



$$\vec{E}(x,y,z) = \vec{E}_0(x,y)\exp(-jkz)$$
$$\vec{H}(x,y,z) = \vec{H}_0(x,y)\exp(-jkz)$$

$$\vec{E}_0(x,y), \vec{H}_0(x,y)$$

$$\vec{E}_0(x,y) = \hat{x}E_{0x}(x,y) + \hat{y}E_{0y}(x,y) + \hat{z}E_{0z}(x,y)$$

$$\vec{H}_0(x,y) = \hat{x}H_{0x}(x,y) + \hat{y}H_{0y}(x,y) + \hat{z}H_{0z}(x,y)$$

$$\nabla^2 \vec{E} + k^2 \vec{E} = 0$$

$$\nabla^2 \vec{H} + k^2 \vec{H} = 0$$

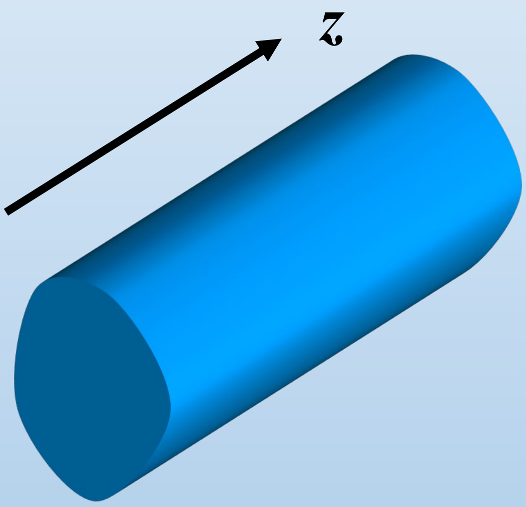
(Helmholtz wave equation)

$$\nabla \to \hat{x}\frac{\partial}{\partial x} + \hat{y}\frac{\partial}{\partial y} - \hat{z} j k_z$$

$$\nabla^2 \to \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} - k_z^2$$

Uncoupled Equations for E_{0z} and H_{0z}

$$\begin{cases} \left(\dfrac{\partial^2}{\partial x^2} + \dfrac{\partial^2}{\partial y^2} + k^2 - k_z^2\right) E_{0z}(x,y) = 0 \\ \left(\dfrac{\partial^2}{\partial x^2} + \dfrac{\partial^2}{\partial y^2} + k^2 - k_z^2\right) H_{0z}(x,y) = 0 \end{cases}$$



TE mode: $E_{0z} = 0$

TM mode: $H_{0z} = 0$

TEM mode: $E_{0z} = 0$ and $H_{0z} = 0$

Transverse Components

$$\nabla \times \vec{E} = -j\omega\mu\vec{H} \qquad \nabla \times \vec{H} = j\omega\varepsilon\vec{E} \qquad \nabla \rightarrow \hat{x}\frac{\partial}{\partial x} + \hat{y}\frac{\partial}{\partial y} - \hat{z}jk_z$$

$$\frac{\partial}{\partial y}E_z + jk_zE_y = -j\omega\mu H_x \qquad \frac{\partial}{\partial y}H_z + jk_zH_y = j\omega\varepsilon E_x$$

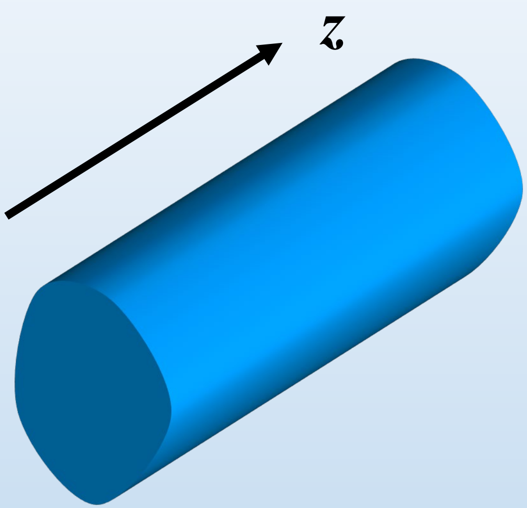
$$-\frac{\partial}{\partial x}E_z - jk_zE_x = -j\omega\mu H_y \qquad -\frac{\partial}{\partial x}H_z - jk_zH_x = j\omega\varepsilon E_y$$

$$\frac{\partial}{\partial x}E_y - \frac{\partial}{\partial y}E_x = -j\omega\mu H_z \qquad \frac{\partial}{\partial x}H_y - \frac{\partial}{\partial y}H_x = j\omega\varepsilon E_z$$

$$H_x = \frac{1}{k^2 - k_z^2}\left(j\omega\varepsilon\frac{\partial}{\partial y}E_z - jk_z\frac{\partial}{\partial x}H_z\right) \qquad E_x = \frac{-1}{k^2 - k_z^2}\left(jk_z\frac{\partial}{\partial x}E_z + j\omega\mu\frac{\partial}{\partial y}H_z\right)$$

$$H_y = \frac{-1}{k^2 - k_z^2}\left(j\omega\varepsilon\frac{\partial}{\partial x}E_z + jk_z\frac{\partial}{\partial y}H_z\right) \qquad E_y = \frac{-1}{k^2 - k_z^2}\left(jk_z\frac{\partial}{\partial y}E_z - j\omega\mu\frac{\partial}{\partial x}H_z\right)$$

General Method for Waveguide Problems



(1) Solve for E_{0z} and H_{0z} with boundary conditions

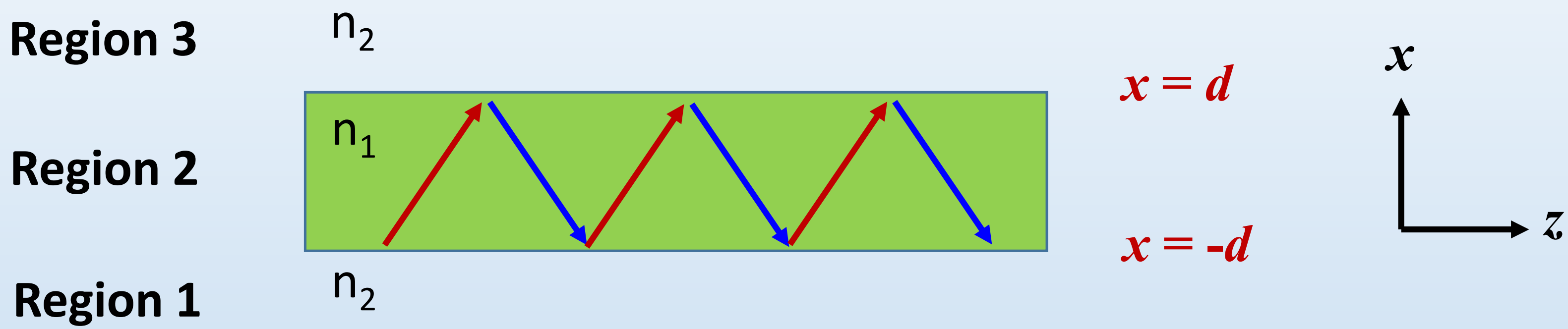
$$\begin{cases} \left(\dfrac{\partial^2}{\partial x^2}+\dfrac{\partial^2}{\partial y^2}+k^2-k_z^2\right)E_{0z}(x,y)=0 \\ \left(\dfrac{\partial^2}{\partial x^2}+\dfrac{\partial^2}{\partial y^2}+k^2-k_z^2\right)H_{0z}(x,y)=0 \end{cases}$$

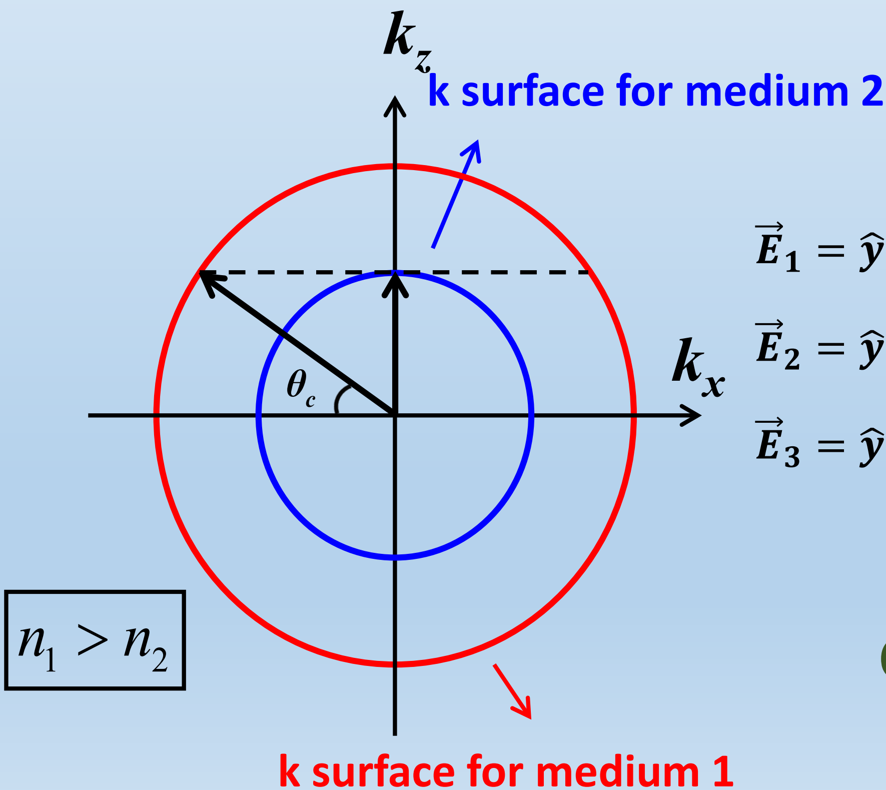
(2) Calculate the transverse components

$$H_x=\frac{1}{k^2-k_z^2}\left(j\omega\varepsilon\frac{\partial}{\partial y}E_z-jk_z\frac{\partial}{\partial x}H_z\right) \qquad E_x=\frac{-1}{k^2-k_z^2}\left(jk_z\frac{\partial}{\partial x}E_z+j\omega\mu\frac{\partial}{\partial y}H_z\right)$$

$$H_y=\frac{-1}{k^2-k_z^2}\left(j\omega\varepsilon\frac{\partial}{\partial x}E_z+jk_z\frac{\partial}{\partial y}H_z\right) \qquad E_y=\frac{-1}{k^2-k_z^2}\left(jk_z\frac{\partial}{\partial y}E_z-j\omega\mu\frac{\partial}{\partial x}H_z\right)$$

Slab Dielectric Waveguide





$$\vec{E}_1 = \hat{y}E_1 \exp(\alpha x - jk_z z)\,, x < -d$$

$$\vec{E}_2 = \hat{y}(A\sin(k_x x) + B\cos(k_x x))\,\exp(-jk_z z)\,, -d < x < d$$

$$\vec{E}_3 = \hat{y}E_3 \exp(-\alpha x - jk_z z)\,, x > d$$

Critical angle: $\theta_c = \sin^{-1}\dfrac{n_2}{n_1}$

Slab Dielectric Waveguide – TE mode

Dispersion Relation

$$k_x^2 + k_z^2 = n_1^2 k_0^2$$
$$-\alpha^2 + k_z^2 = n_2^2 k_0^2$$

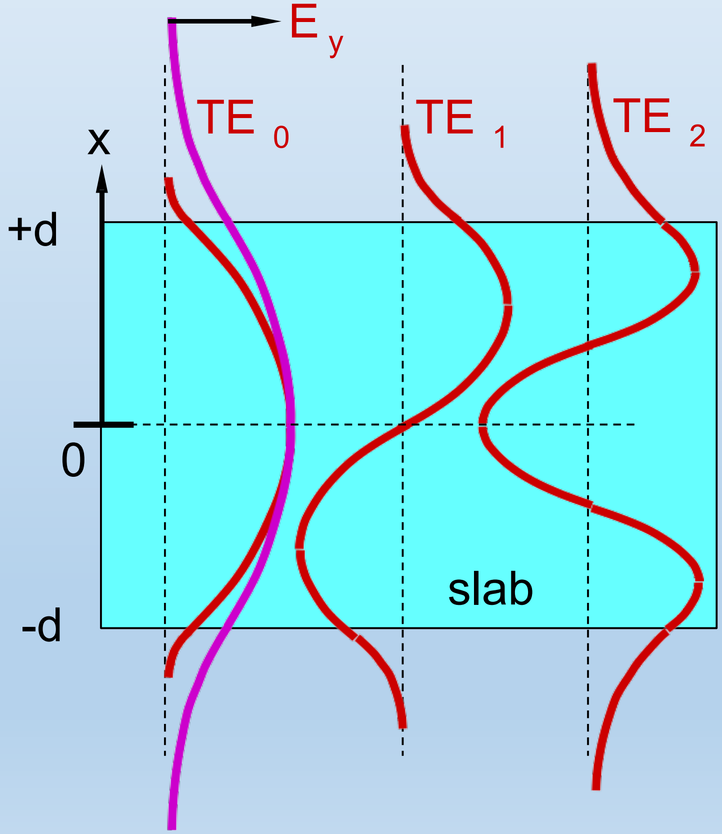
$$\Rightarrow \left(k_x d\right)^2 + \left(\alpha d\right)^2 = \left(n_1^2 - n_2^2\right)\left(k_0 d\right)^2$$

Guidance Condition

$$\boxed{\alpha d = k_x d \tan\left(k_x d - \frac{m\pi}{2}\right)}$$

$$\alpha d = k_x d \tan(k_x d) \qquad \textbf{(TE even)}$$

$$\alpha d = -k_x d \cot(k_x d) \qquad \textbf{(TE odd)}$$



Slab Dielectric Waveguide – $TE_{even,n}$

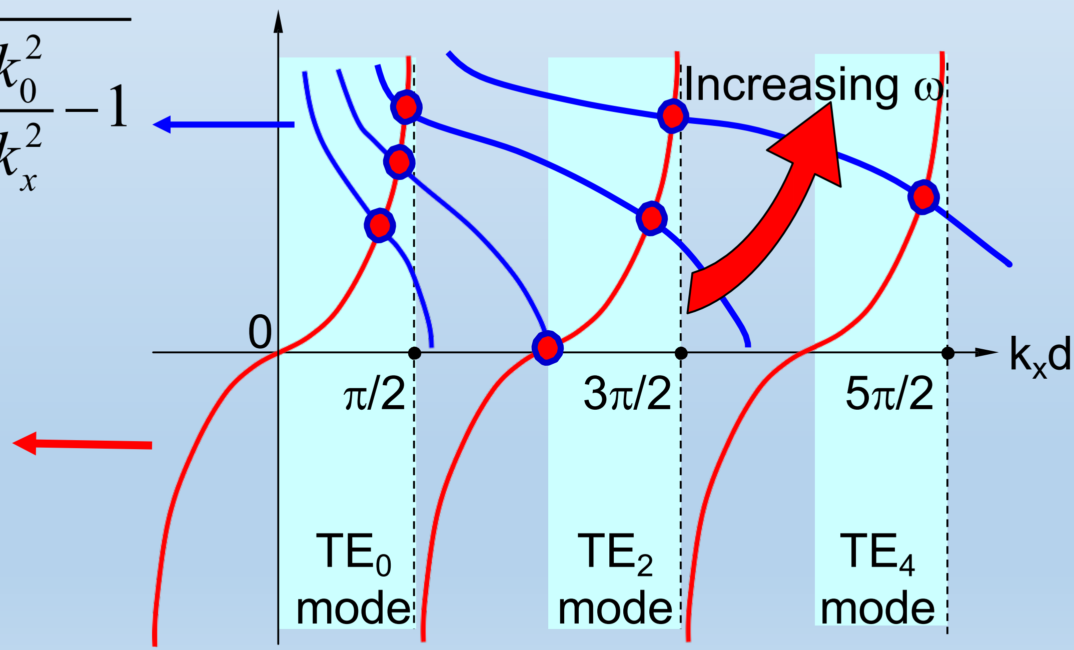
$$k_x^2 + \alpha_x^2 = \left(n_1^2 - n_2^2\right) k_0^2$$

$$\alpha d = k_x d \tan\left(k_x d - \frac{m\pi}{2}\right)$$

$$\tan\left(k_x d - \frac{m\pi}{2}\right) = \sqrt{(n_1^2 - n_2^2)\frac{k_0^2}{k_x^2} - 1}$$

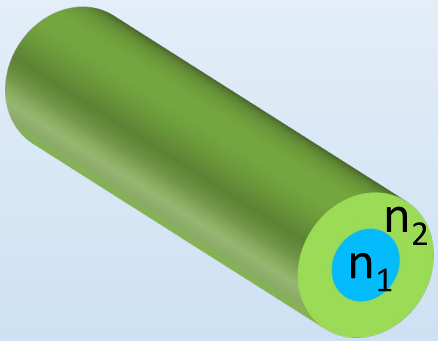
$$\sqrt{\left(n_1^2 - n_2^2\right)\frac{k_0^2}{k_x^2} - 1}$$

$$\tan\left(k_x d\right)$$

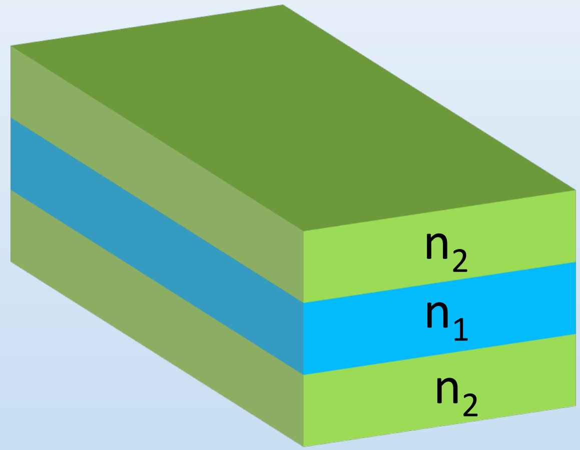


Optical Waveguides

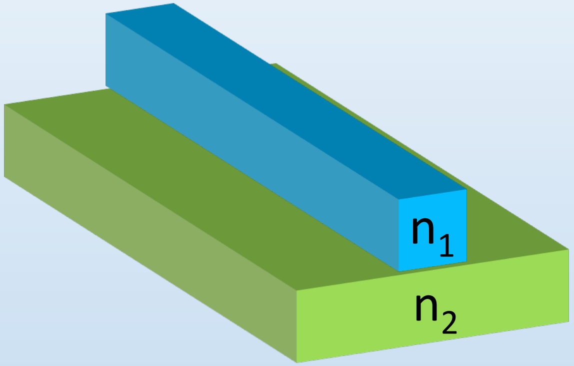
Optical fiber



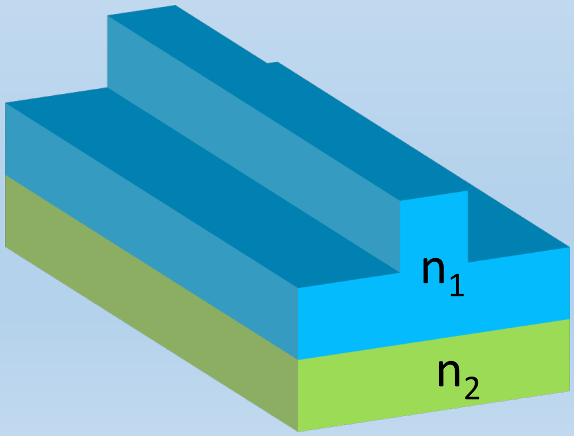
Slab waveguide



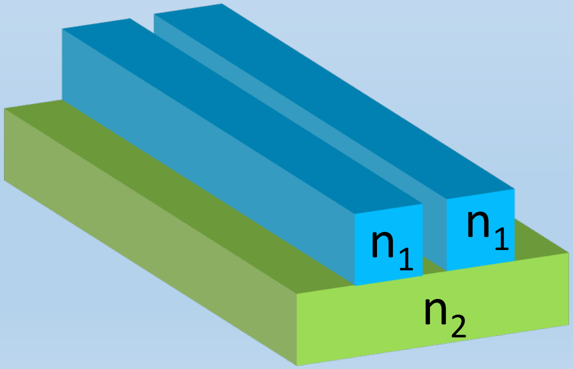
Strip waveguide



Rib waveguide

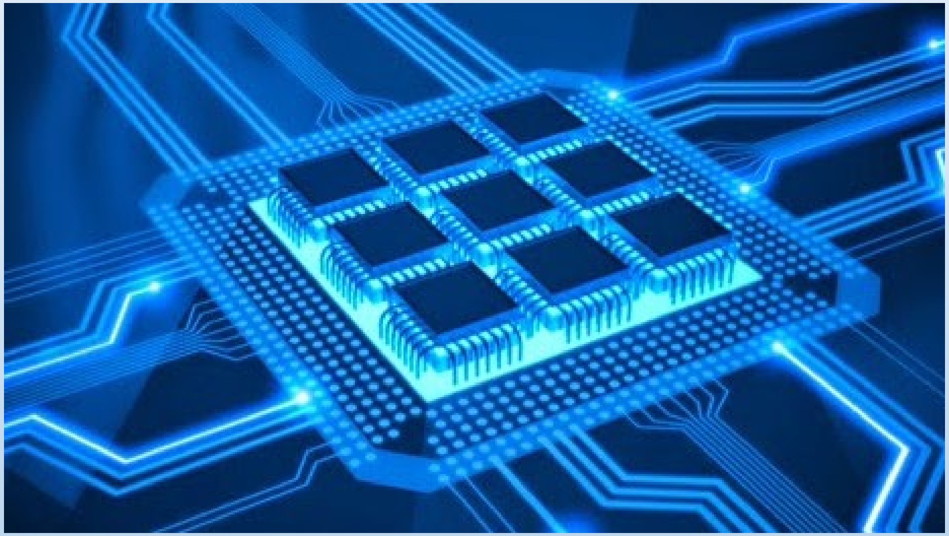


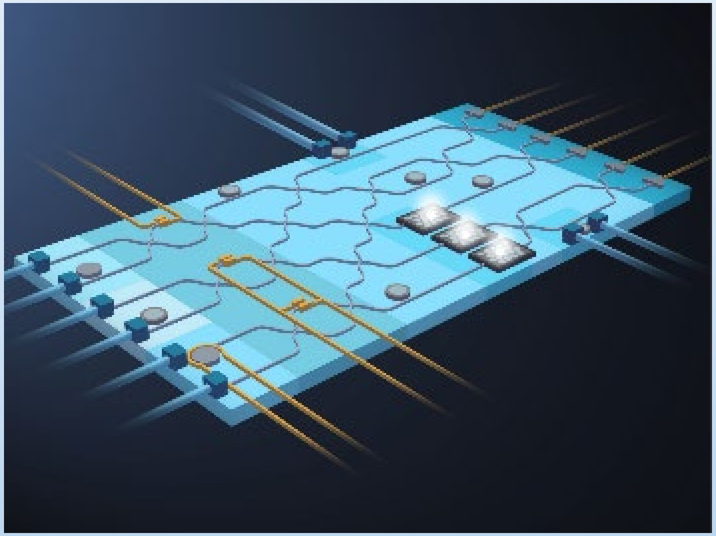
Slot waveguide

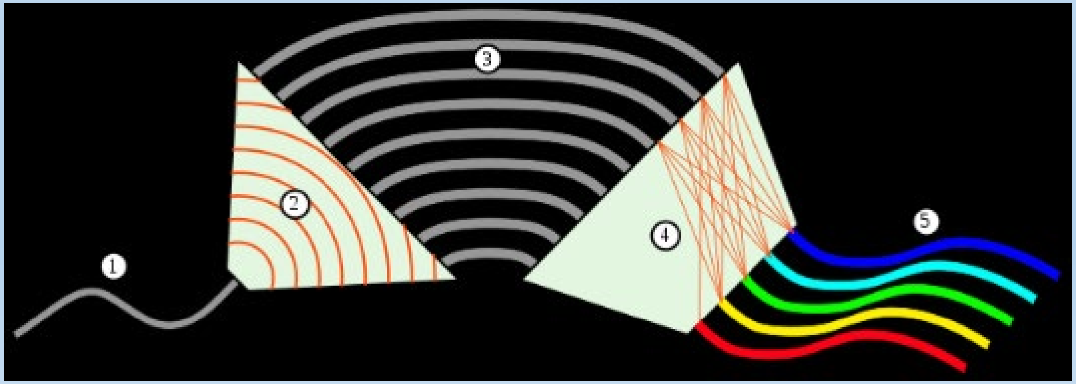


Photonic Integrated Circuits

A **photonic integrated circuit** (**PIC**) or **integrated optical circuit** is a device that integrates multiple (at least two) photonic functions and as such is similar to an electronic integrated circuit.







Electromagnetic spectrum