ECE 451
Advanced Microwave Measurements

Waveguides

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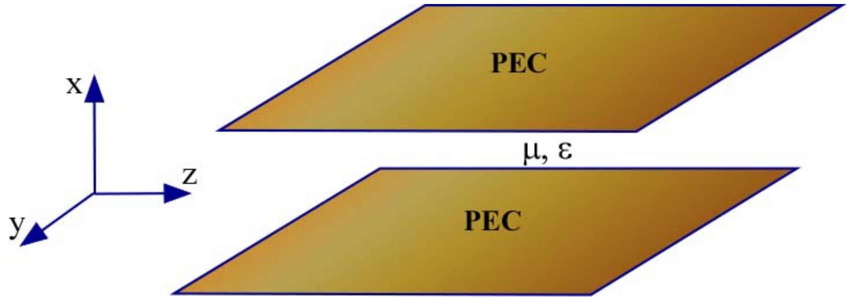
Parallel-Plate Waveguide

Maxwell's Equations ➔ $\nabla^2\mathbf{E} + \omega^2\mu\varepsilon\mathbf{E} = \mathbf{0}$

$$\frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} = -\omega^2\mu\varepsilon E_x$$

$$\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial y^2} + \frac{\partial^2 E_y}{\partial z^2} = -\omega^2\mu\varepsilon E_y$$

$$\frac{\partial^2 E_z}{\partial x^2} + \frac{\partial^2 E_z}{\partial y^2} + \frac{\partial^2 E_z}{\partial z^2} = -\omega^2\mu\varepsilon E_z$$



TE Modes

For a parallel-plate waveguide, the plates are infinite in the *y*-extent; we need to study the propagation in the *z*-direction. The following assumptions are made in the wave equation

$$\Rightarrow \frac{\partial}{\partial y} = 0, \text{ but } \frac{\partial}{\partial x} \neq 0 \text{ and } \frac{\partial}{\partial z} \neq 0$$

$$\Rightarrow \text{Assume } E_y \text{ only}$$

These two conditions define the **TE modes** and the wave equation is simplified to read

$$\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial z^2} = -\omega^2 \mu\varepsilon E_y \qquad (¥)$$

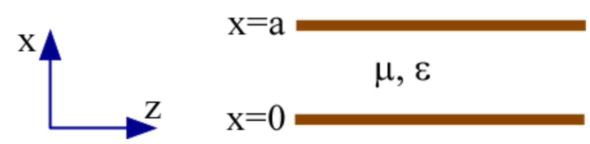
Phasor Solution

General solution (forward traveling wave)

$$E_y(x,z) = e^{-j\beta_z z}\left[Ae^{-j\beta_x x} + Be^{+j\beta_x x}\right]$$

At $x = 0$, $E_y = 0$ which leads to $A + B = 0$. Therefore, $A = -B = E_o/2j$, where E_o is an arbitrary constant

$$E_y(x,z) = E_o e^{-j\beta_z z}\sin\beta_x x$$



a is the distance separating the two PEC plates

Dispersion Relation

At $x = a$, $E_y(x, z) = 0$ ➔ $E_o e^{-j\beta_z z} \sin \beta_x a = 0$

This leads to: $\beta_x a = m\pi$, where $m = 1, 2, 3, \ldots$

$$\beta_x = \frac{m\pi}{a}$$

Moreover, from the differential equation (¥), we get the *dispersion relation*

$$\beta_z^2 + \beta_x^2 = \omega^2 \mu\varepsilon = \beta^2$$

which leads to $\beta_z = \sqrt{\omega^2 \mu\varepsilon - \left(\frac{m\pi}{a}\right)^2}$

Guidance Condition

$$\beta_z = \sqrt{\omega^2 \mu\varepsilon - \left(\frac{m\pi}{a}\right)^2}$$

where m = 1, 2, 3 ... Since propagation is to take place in the z direction, for the wave to propagate, we must have $\beta_z^2 > 0$, or

$$\omega^2 \mu\varepsilon > \left(\frac{m\pi}{a}\right)^2$$

This leads to the following *guidance condition* which will insure wave propagation

$$f > \frac{m}{2a\sqrt{\mu\varepsilon}}$$

Cutoff Frequency

The *cutoff frequency* f_c is defined to be at the onset of propagation

$$f_c = \frac{m}{2a\sqrt{\mu\varepsilon}} \qquad\qquad \lambda_c = \frac{v}{f_c} = \frac{2a}{m}$$

Each mode is referred to as the TE_m mode. It is obvious that there is no TE_0 mode and the first TE mode is the TE_1 mode.

The *cutoff frequency* is the frequency below which the mode associated with the index ***m*** will not propagate in the waveguide. Different modes will have different cutoff frequencies.

Magnetic Field for TE Modes

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

we have $$\mathbf{H} = \frac{-1}{j\omega\mu}\begin{vmatrix} \hat{\mathbf{x}} & \hat{\mathbf{y}} & \hat{\mathbf{z}} \\ \frac{\partial}{\partial x} & 0 & \frac{\partial}{\partial z} \\ 0 & E_y & 0 \end{vmatrix}$$

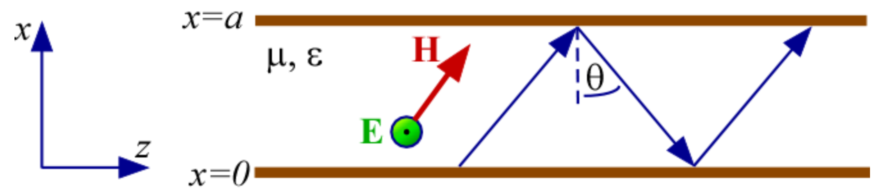
which leads to

$$H_x = -\frac{\beta_z}{\omega\mu}E_o e^{-j\beta_z z}\sin\beta_x x$$

$$H_z = +\frac{j\beta_x}{\omega\mu}E_o e^{-j\beta_z z}\cos\beta_x x$$

The magnetic field for TE modes has 2 components

E & H Fields for TE Modes



As can be seen, there is no H_y component, therefore, the TE solution has E_y, H_x and H_z only.

From the dispersion relation, it can be shown that the propagation vector components satisfy the relations
$\beta_z = \beta \sin\theta$, $\beta_x = \beta \cos\theta$ where θ is the angle of incidence of the propagation vector with the normal to the conductor plates.

Phase and Group Velocities

The phase and group velocities are given by

$$v_{pz} = \frac{\omega}{\beta_z} = \frac{c}{\sqrt{1 - \frac{f_c^2}{f^2}}} \qquad \text{and} \qquad v_g = \frac{\partial \omega}{\partial \beta_z} = c\sqrt{1 - \frac{f_c^2}{f^2}}$$

The effective guide impedance is given by:

$$\eta_{TE} = \frac{E_y}{-H_x} = \frac{\eta_o}{\sqrt{1 - \frac{f_c^2}{f^2}}}$$

Transverse Magnetic (TM) Modes

The magnetic field also satisfies the wave equation:

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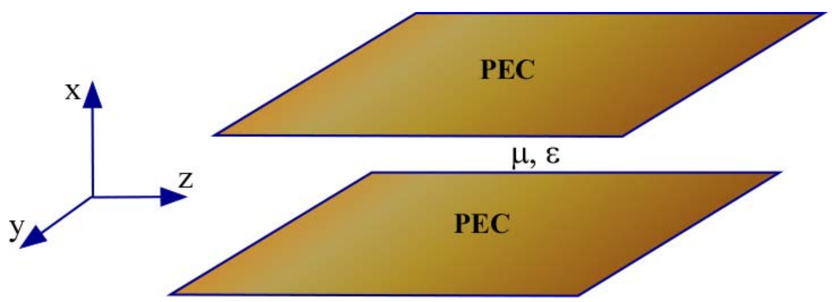
$$\frac{\partial^2 H_x}{\partial x^2} + \frac{\partial^2 H_x}{\partial y^2} + \frac{\partial^2 H_x}{\partial z^2} = -\omega^2 \mu\varepsilon H_x$$

$$\frac{\partial^2 H_y}{\partial x^2} + \frac{\partial^2 H_y}{\partial y^2} + \frac{\partial^2 H_y}{\partial z^2} = -\omega^2 \mu\varepsilon H_y$$

$$\frac{\partial^2 H_z}{\partial x^2} + \frac{\partial^2 H_z}{\partial y^2} + \frac{\partial^2 H_z}{\partial z^2} = -\omega^2 \mu\varepsilon H_z$$



TM Modes

For TM modes, we assume

$$\Rightarrow \frac{\partial}{\partial y} = 0, \text{ but } \frac{\partial}{\partial x} \neq 0 \text{ and } \frac{\partial}{\partial z} \neq 0$$

➔Assume H_y only

These two conditions define the *TM modes* and the equations are simplified to read

$$\frac{\partial^2 H_y}{\partial x^2} + \frac{\partial^2 H_y}{\partial z^2} = -\omega^2 \mu\varepsilon H_y$$

<u>General solution (forward traveling wave)</u>

$$H_y(x,z) = e^{-j\beta_z z}\left[Ae^{-j\beta_x x} + Be^{+j\beta_x x} \right]$$

Electric Field for TM Modes

From $\nabla \times \mathbf{H} = -j\omega\varepsilon\mathbf{E}$

we get $$\mathbf{E} = \frac{1}{j\omega\varepsilon}\begin{vmatrix} \hat{\mathbf{x}} & \hat{\mathbf{y}} & \hat{\mathbf{z}} \\ \frac{\partial}{\partial x} & 0 & \frac{\partial}{\partial z} \\ 0 & H_y & 0 \end{vmatrix}$$

This leads to

$$E_x(x,z) = \frac{\beta_z}{\omega\varepsilon} e^{-j\beta_z z}\left[Ae^{-j\beta_x x} + Be^{+j\beta_x x} \right]$$

$$E_z(x,z) = \frac{\beta_x}{\omega\varepsilon} e^{-j\beta_z z}\left[-Ae^{-j\beta_x x} + Be^{+j\beta_x x} \right]$$

TM Modes Fields

At $x=0$, $E_z = 0$ which leads to $A = B = H_o/2$ where H_o is an arbitrary constant. This leads to

$$H_y(x,z) = H_o e^{-j\beta_z z}\cos\beta_x x$$

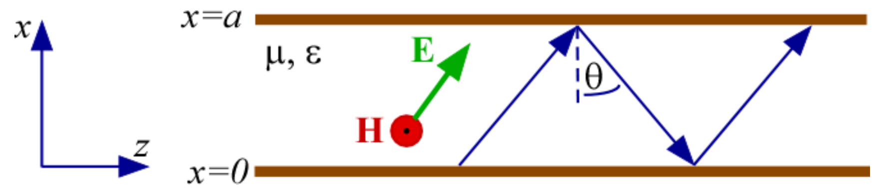
$$E_x(x,z) = \frac{\beta_z}{\omega\varepsilon} H_o e^{-j\beta_z z}\cos\beta_x x$$

$$E_z(x,z) = \frac{j\beta_x}{\omega\varepsilon} H_o e^{-j\beta_z z}\sin\beta_x x$$

At $x = a$, $E_z = 0$ which leads to

$\beta_x a = m\pi$, where $m = 0, 1, 2, 3, \ldots$

E & H Fields for TM Modes



$$\beta_x = \frac{m\pi}{a}$$

This defines the TM modes which have only H_y, E_x and E_z components.

The effective guide impedance is given by:

$$\eta_{TM} = \frac{E_x}{H_y} = \eta_o \sqrt{1 - \frac{f_c^2}{f^2}}$$

The electric field for TM modes has 2 components

E & H Fields for TM Modes

THE DISPERSION RELATION, GUIDANCE CONDITION AND CUTOFF EQUATIONS FOR A PARALLEL-PLATE WAVEGUIDE ARE THE SAME FOR TE AND TM MODES.

This defines the **TM modes**; each mode is referred to as the TM_m mode. It can be seen from that $m=0$ is a valid choice; it is called the TM_0, or *transverse electromagnetic* or TEM mode. For this mode and,

TEM Mode

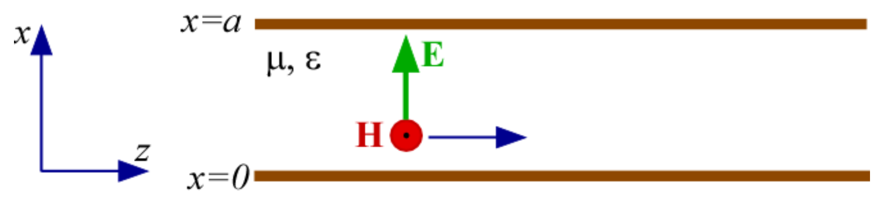
β_x=0 and $\beta_z = \beta$. There are no x variations of the fields within the waveguide. The TEM mode has a cutoff frequency at DC and is always present in the waveguide.

$$H_y = H_o e^{-j\beta_z z}$$

$$E_x = \frac{\beta_z}{\omega\varepsilon} H_o e^{-j\beta_z z} = \sqrt{\frac{\mu}{\varepsilon}} H_o e^{-j\beta_z z}$$

$$E_z = 0$$

The propagation characteristics of the TEM mode do not vary with frequency



The TEM mode is the *fundamental* mode on a parallel-plate waveguide

Power for TE Modes

Time-Average Poynting Vector $\langle \mathbf{P} \rangle = \frac{1}{2}\mathrm{Re}\{\mathbf{E}\times\mathbf{H}^*\}$

<u>TE modes</u>

$$\langle \mathbf{P} \rangle = \frac{1}{2}\mathrm{Re}\left\{\hat{\mathbf{y}}E_y \times \left[\hat{\mathbf{x}}H_x^* + \hat{\mathbf{z}}H_z^*\right]\right\}$$

$$\langle \mathbf{P} \rangle = \frac{1}{2}\mathrm{Re}\left\{\hat{\mathbf{z}}\frac{|E_o|^2}{\omega\mu}\beta_z \sin^2\beta_x x + \hat{\mathbf{x}}j\frac{|E_o|^2}{\omega\mu}\beta_x \cos\beta_x x \sin\beta_x x\right\}$$

$$\langle \mathbf{P} \rangle = \hat{\mathbf{z}}\frac{|E_o|^2}{2\omega\mu}\beta_z \sin^2\beta_x x$$

Power for TM Modes

TM modes

$$\langle \mathbf{P} \rangle = \frac{1}{2}\mathrm{Re}\left\{ \left[\hat{\mathbf{x}} E_x + \hat{\mathbf{z}} E_z \right] \times \hat{\mathbf{y}} H_y^* \right\}$$

$$\langle \mathbf{P} \rangle = \frac{1}{2}\mathrm{Re}\left\{ \hat{\mathbf{z}} \frac{|H_o|^2}{\omega\varepsilon} \beta_z \cos^2 \beta_x x - \hat{\mathbf{x}} j \frac{|H_o|^2}{\omega\varepsilon} \beta_x \sin \beta_x x \cos \beta_x x \right\}$$

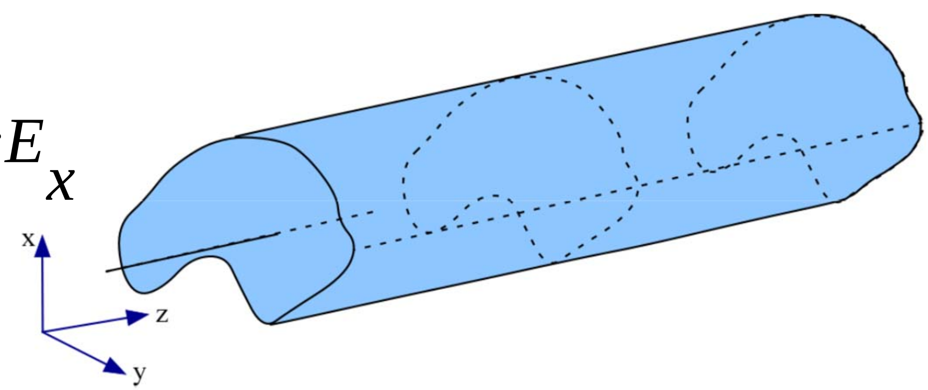
$$\langle \mathbf{P} \rangle = \hat{\mathbf{z}} \frac{|H_o|^2}{2\omega\varepsilon} \beta_z \cos^2 \beta_x x$$

The total time-average power is found by integrating <**P**> over the area of interest.

Waveguide

Maxwell's Equations ➔ $\nabla^2 \mathbf{E} + \omega^2 \mu\varepsilon \mathbf{E} = \mathbf{0}$

$$\frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} = -\omega^2 \mu\varepsilon E_x$$



$$\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial y^2} + \frac{\partial^2 E_y}{\partial z^2} = -\omega^2 \mu\varepsilon E_y$$

$$\frac{\partial^2 E_z}{\partial x^2} + \frac{\partial^2 E_z}{\partial y^2} + \frac{\partial^2 E_z}{\partial z^2} = -\omega^2 \mu\varepsilon E_z$$

Waveguide

Maxwell's Equations ➔ $\nabla^2\mathbf{E} + \omega^2\mu\varepsilon\mathbf{E} = \mathbf{0}$

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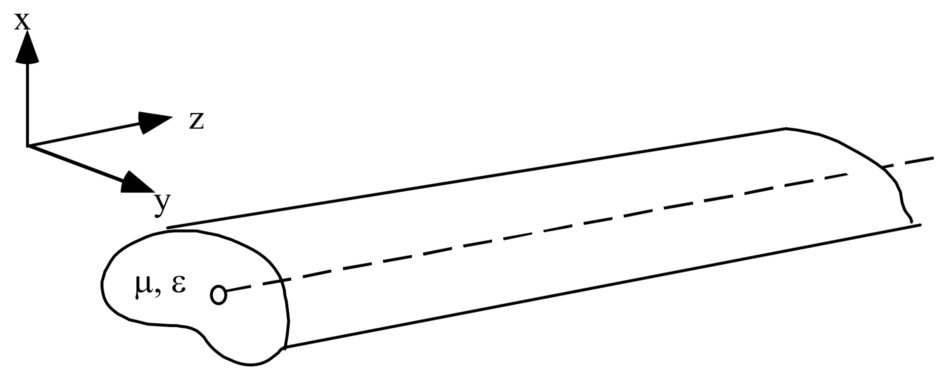


TE Modes

For a waveguide with arbitrary cross section as shown in the above figure, we assume a plane wave solution and as a first trial, we set $E_z = 0$. This defines the TE modes.

From $\nabla \times \mathbf{E} = -\mu \dfrac{\partial \mathbf{H}}{\partial t}$, we have

$$\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} = -\mu \frac{\partial H_x}{\partial t} \Rightarrow + j\beta_z E_y = -j\omega\mu H_x$$

$$\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = -\mu \frac{\partial H_y}{\partial t} \Rightarrow - j\beta_z E_x = -j\omega\mu H_y$$

$$\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = -\mu \frac{\partial H_z}{\partial t} \Rightarrow \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = -j\omega\mu H_z$$

TE Modes

From $\nabla \times \mathbf{H} = j\omega\varepsilon\mathbf{E}$, we get

$$j\omega\varepsilon\mathbf{E} = \begin{vmatrix} \hat{\mathbf{x}} & \hat{\mathbf{y}} & \hat{\mathbf{z}} \\ \dfrac{\partial}{\partial x} & \dfrac{\partial}{\partial y} & \dfrac{\partial}{\partial z} \\ H_x & H_y & H_z \end{vmatrix}$$

$$\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} = j\omega\varepsilon E_x \Rightarrow \frac{\partial H_z}{\partial y} + j\beta_z H_y = j\omega\varepsilon E_x$$

$$\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} = j\omega\varepsilon E_y \Rightarrow -j\beta_z H_x - \frac{\partial H_z}{\partial x} = j\omega\varepsilon E_y$$

$$\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} = 0$$

We want to express all quantities in terms of *H_z*.

TE Modes

From (2), we have $H_y = \frac{\beta_z E_x}{\omega\mu}$ in (4) $\frac{\partial H_z}{\partial y} + j\beta_z^2 \frac{E_x}{\omega\mu} = j\omega\varepsilon E_x$

Solving for E_x $$E_x = \frac{j\omega\mu}{\beta_z^2 - \omega^2 \mu\varepsilon} \frac{\partial H_z}{\partial y}$$

From (1) $H_x = \frac{-\beta_z E_y}{\omega\mu}$ in (5) $j\frac{\beta_z^2 E_y}{\omega\mu} - \frac{\partial H_z}{\partial x} = j\omega\varepsilon E_y$

so that $$E_y = \frac{-j\omega\mu}{\beta_z^2 - \omega^2 \mu\varepsilon} \frac{\partial H_z}{\partial x}$$

TE Modes

$$H_y = \frac{j\beta_z}{\beta_z^2 - \omega^2\mu\varepsilon}\frac{\partial H_z}{\partial y}$$

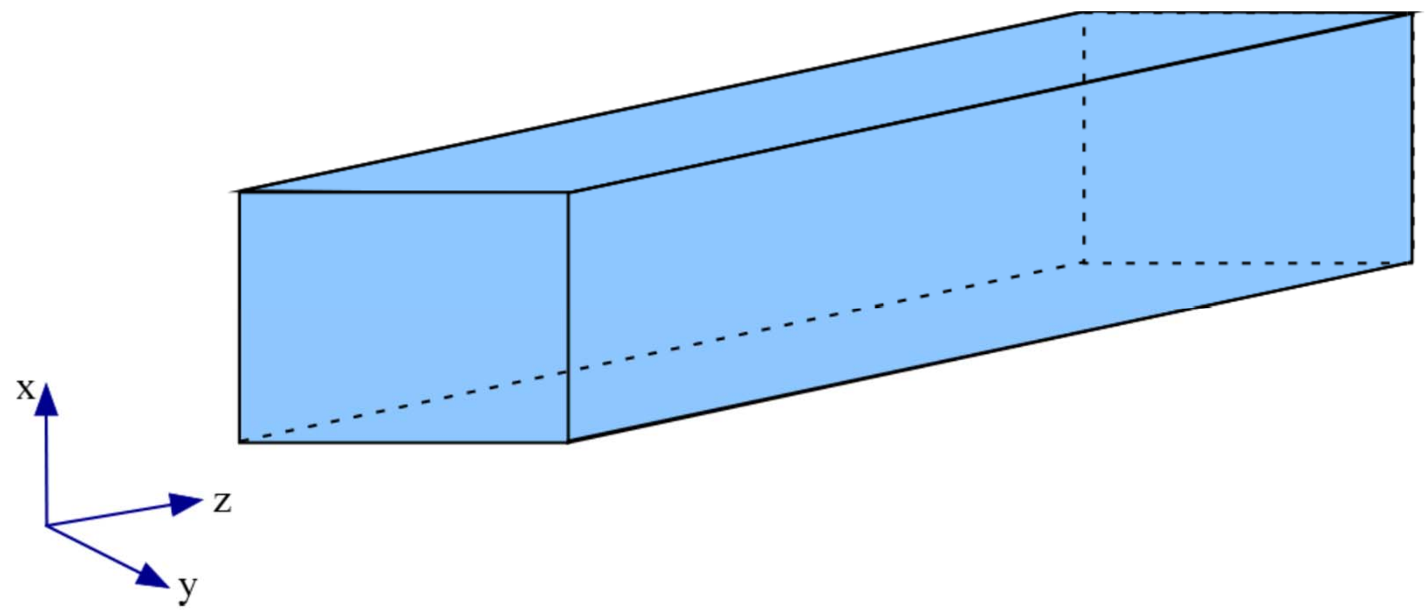
$$H_x = \frac{j\beta_z}{\beta_z^2 - \omega^2\mu\varepsilon}\frac{\partial H_z}{\partial x}$$

$$E_z = 0$$

Combining solutions for E_x and E_y into (3) gives

$$\frac{\partial^2 H_z}{\partial x^2} + \frac{\partial^2 H_z}{\partial y^2} = \left[\beta_z^2 - \omega^2\mu\varepsilon\right]H_z$$

Rectangular Waveguide



$$\frac{\partial^2 H_z}{\partial x^2}+\frac{\partial^2 H_z}{\partial y^2}=\left[\beta_z^2-\omega^2\mu\varepsilon\right]H_z$$

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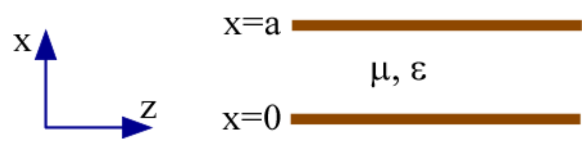

a is the distance separating the two PEC plates

Dispersion Relation

At $x = a$, $E_y(x, z) = 0$ ➔ $E_o e^{-j\beta_z z} \sin \beta_x a = 0$

This leads to: $\beta_x a = m\pi$, where $m = 1, 2, 3, \ldots$

$$\beta_x = \frac{m\pi}{a}$$

Moreover, from the differential equation (¥), we get the *dispersion relation*

$$\beta_z^2 + \beta_x^2 = \omega^2 \mu\varepsilon = \beta^2$$

which leads to $$\beta_z = \sqrt{\omega^2 \mu\varepsilon - \left(\frac{m\pi}{a}\right)^2}$$

Guidance Condition

$$\beta_z = \sqrt{\omega^2 \mu\varepsilon - \left(\frac{m\pi}{a}\right)^2}$$

where m = 1, 2, 3 ... Since propagation is to take place in the z direction, for the wave to propagate, we must have $\beta_z^{\,2} > 0$, or

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$$f > \frac{m}{2a\sqrt{\mu\varepsilon}}$$

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we have $$\mathbf{H} = \frac{-1}{j\omega\mu}\begin{vmatrix} \hat{\mathbf{x}} & \hat{\mathbf{y}} & \hat{\mathbf{z}} \\ \frac{\partial}{\partial x} & 0 & \frac{\partial}{\partial z} \\ 0 & E_y & 0 \end{vmatrix}$$

which leads to

$$H_x = -\frac{\beta_z}{\omega\mu} E_o e^{-j\beta_z z} \sin \beta_x x$$

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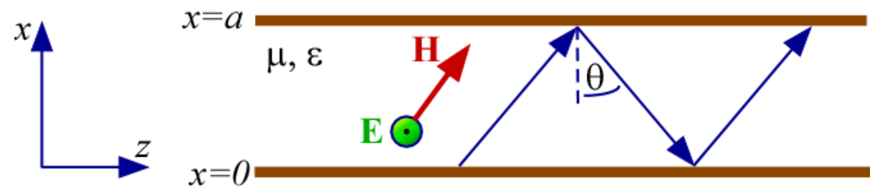
The magnetic field for TE modes has 2 components

E & H Fields for TE Modes



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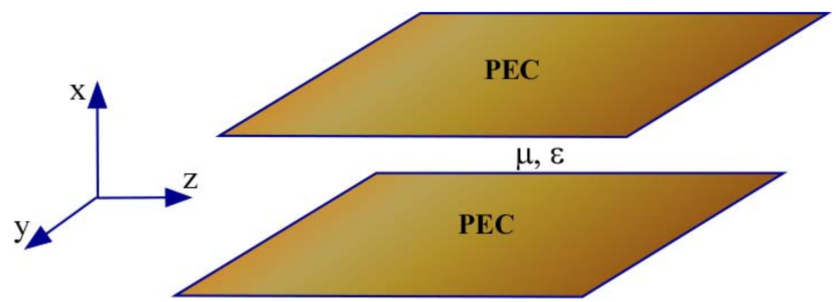

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<u>General solution (forward traveling wave)</u>

$$H_y(x,z) = e^{-j\beta_z z}\left[A e^{-j\beta_x x} + B e^{+j\beta_x x} \right]$$

Electric Field for TM Modes

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we get $$\mathbf{E} = \frac{1}{j\omega\varepsilon}\begin{vmatrix} \hat{\mathbf{x}} & \hat{\mathbf{y}} & \hat{\mathbf{z}} \\ \frac{\partial}{\partial x} & 0 & \frac{\partial}{\partial z} \\ 0 & H_y & 0 \end{vmatrix}$$

This leads to

$$E_x(x,z) = \frac{\beta_z}{\omega\varepsilon} e^{-j\beta_z z}\left[Ae^{-j\beta_x x} + Be^{+j\beta_x x}\right]$$

$$E_z(x,z) = \frac{\beta_x}{\omega\varepsilon} e^{-j\beta_z z}\left[-Ae^{-j\beta_x x} + Be^{+j\beta_x x}\right]$$

TM Modes Fields

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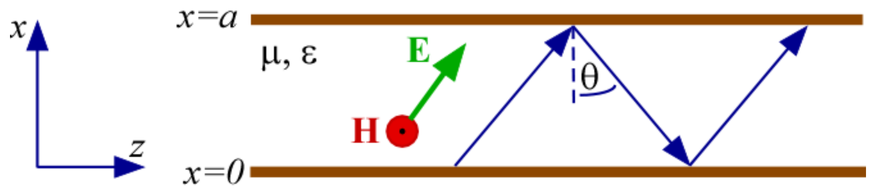
$\beta_x a = m\pi$, where $m = 0, 1, 2, 3, \ldots$

E & H Fields for TM Modes



$$\beta_x = \frac{m\pi}{a}$$

This defines the TM modes which have only H_y, E_x and E_z components.

The effective guide impedance is given by:

$$\eta_{TM} = \frac{E_x}{H_y} = \eta_o \sqrt{1 - \frac{f_c^2}{f^2}}$$

The electric field for TM modes has 2 components

E & H Fields for TM Modes

THE DISPERSION RELATION, GUIDANCE CONDITION AND CUTOFF EQUATIONS FOR A PARALLEL-PLATE WAVEGUIDE ARE THE SAME FOR TE AND TM MODES.

This defines the **TM modes**; each mode is referred to as the TM_m mode. It can be seen from that $m=0$ is a valid choice; it is called the TM_0, or *transverse electromagnetic* or TEM mode. For this mode and,

TEM Mode

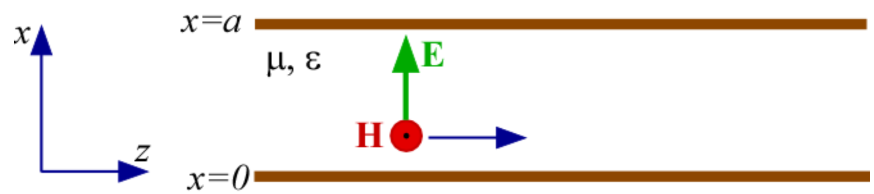
β_x=0 and $\beta_z = \beta$. There are no x variations of the fields within the waveguide. The TEM mode has a cutoff frequency at DC and is always present in the waveguide.

$$H_y = H_o e^{-j\beta_z z}$$

$$E_x = \frac{\beta_z}{\omega\varepsilon} H_o e^{-j\beta_z z} = \sqrt{\frac{\mu}{\varepsilon}} H_o e^{-j\beta_z z}$$

$$E_z = 0$$

The propagation characteristics of the TEM mode do not vary with frequency



The TEM mode is the *fundamental* mode on a parallel-plate waveguide

Power for TE Modes

Time-Average Poynting Vector $\langle \mathbf{P} \rangle = \frac{1}{2}\mathrm{Re}\left\{ \mathbf{E} \times \mathbf{H}^* \right\}$

<u>TE modes</u>

$$\langle \mathbf{P} \rangle = \frac{1}{2}\mathrm{Re}\left\{ \hat{\mathbf{y}} E_y \times \left[\hat{\mathbf{x}} H_x^* + \hat{\mathbf{z}} H_z^* \right] \right\}$$

$$\langle \mathbf{P} \rangle = \frac{1}{2}\mathrm{Re}\left\{ \hat{\mathbf{z}} \frac{|E_o|^2}{\omega\mu} \beta_z \sin^2 \beta_x x + \hat{\mathbf{x}} j \frac{|E_o|^2}{\omega\mu} \beta_x \cos \beta_x x \sin \beta_x x \right\}$$

$$\langle \mathbf{P} \rangle = \hat{\mathbf{z}} \frac{|E_o|^2}{2\omega\mu} \beta_z \sin^2 \beta_x x$$

Power for TM Modes

TM modes

$$\langle \mathbf{P} \rangle = \frac{1}{2}\mathrm{Re}\left\{ \left[\hat{\mathbf{x}}E_x + \hat{\mathbf{z}}E_z \right] \times \hat{\mathbf{y}}H_y^* \right\}$$

$$\langle \mathbf{P} \rangle = \frac{1}{2}\mathrm{Re}\left\{ \hat{\mathbf{z}}\frac{\left|H_o\right|^2}{\omega\varepsilon}\beta_z \cos^2 \beta_x x - \hat{\mathbf{x}}j\frac{\left|H_o\right|^2}{\omega\varepsilon}\beta_x \sin\beta_x x \cos\beta_x x \right\}$$

$$\langle \mathbf{P} \rangle = \hat{\mathbf{z}}\frac{\left|H_o\right|^2}{2\omega\varepsilon}\beta_z \cos^2 \beta_x x$$

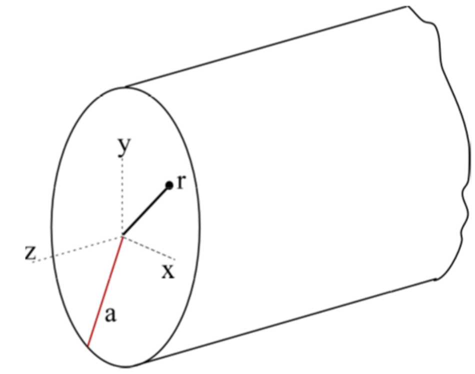
The total time-average power is found by integrating <**P**> over the area of interest.

Circular Waveguide - Fields

For a waveguide with arbitrary cross section, it is known that

TE Modes $$\frac{\partial^2 H_z}{\partial x^2}+\frac{\partial^2 H_z}{\partial y^2}=\left[\beta_z^2-\omega^2\mu\varepsilon\right]H_z \quad \textbf{(1)}$$

TM Modes $$\frac{\partial^2 E_z}{\partial x^2}+\frac{\partial^2 E_z}{\partial y^2}=\left[\beta_z^2-\omega^2\mu\varepsilon\right]E_z \quad \textbf{(2)}$$



We first assume TM modes in cylindrical coordinates:

$$\underbrace{\frac{\partial^2 E_z}{\partial r^2}+\frac{1}{r}\frac{\partial E_z}{\partial r}+\frac{1}{r^2}\frac{\partial^2 E_z}{\partial \phi^2}}_{\nabla_{tr}^2 E_z}+\left(\gamma^2+\omega^2\mu\varepsilon\right)E_z=0$$

$$\gamma=\pm j\beta_z$$

See Reference [6].

Circular Waveguide – TM Modes

Solution will be in the form

$$E_z(r,\phi) = f(r)\,g(\phi)$$

Which after substitution gives

$$\frac{r}{f}\frac{d}{dr}\left(r\frac{df}{dr}\right) + h^2 r^2 = -\frac{1}{g}\frac{d^2 g}{d\phi^2} \qquad \textbf{(3)}$$

where $h^2 = \gamma^2 + \omega^2 \mu\varepsilon$

For equality in (3) to hold, both sides must be equal to the same constant say n^2 where n is an integer in view of the azimuthal symmetry since the fields must be periodic in ϕ.

Circular Waveguide – TM Modes

$$\frac{d^2 g}{d\phi^2} + n^2 g = 0 \qquad \textbf{(4)}$$

$$\frac{d^2 f}{dr^2} + \frac{1}{r}\frac{df}{dr}\left(h^2 - \frac{n^2}{r^2}\right) f = 0 \qquad \textbf{(5)}$$

Solution of (4) is of the form

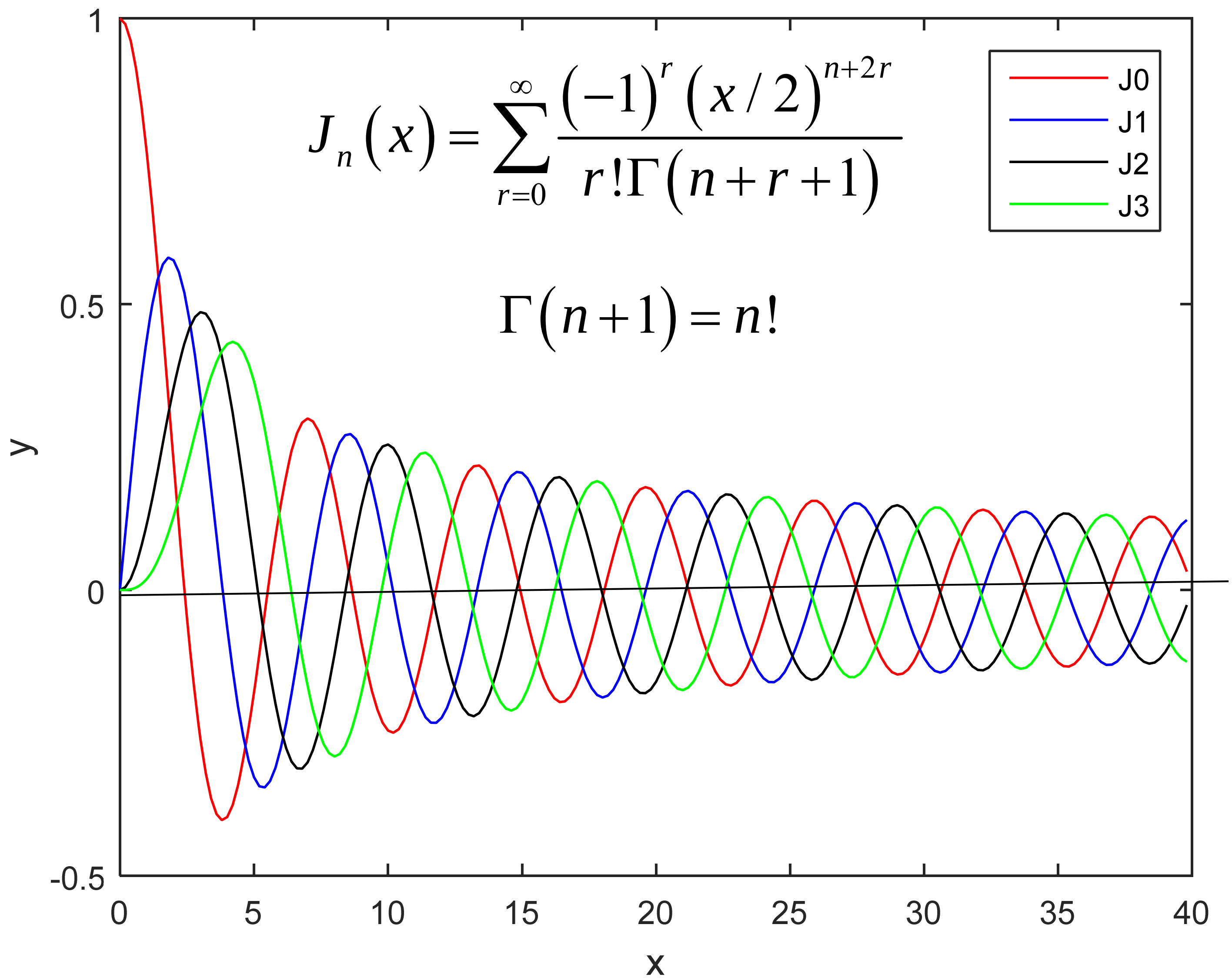
$$g(\phi) = C_1 \cos(n\phi) + C_2 \sin(n\phi) \qquad \textbf{(6)}$$

(5) is Bessel's equation and has solution

$$f(r) = C_3 J_n(hr) + C_4 Y_n(hr) \qquad \textbf{(7)}$$

J_n and Y_n are the n^{th} order Bessel functions of the first and second kinds respectively

Bessel Functions of the First Kind



$$J_n(x) = \sum_{r=0}^{\infty} \frac{(-1)^r (x/2)^{n+2r}}{r!\,\Gamma(n+r+1)}$$

$$\Gamma(n+1) = n!$$

Circular Waveguide – TM Modes

Y_n has singularity at 0 and must consequently be discarded ➔ $C_4 = 0$. The general solution then becomes

$$E_z(r,\phi) = C_3 J_n(hr)\left[C_1 \cos(n\phi) + C_2 \sin(n\phi)\right]$$

Since the origin for ϕ is arbitrary, the expression can be written as:

$$E_z(r,\phi) = C_n J_n(hr)\cos(n\phi)$$

where C_n is a constant. The boundary condition $E_{tan} = 0$ requires that

$$E_z(r,\phi) = 0 \;\; for\; r = a$$

Solution exists for only discrete values of h such that

$$J_n(ha) = 0$$

Circular Waveguide – TM Modes

ha **must be a root of the n^{th} order Bessel function. If we assume that t_{nl} is the l^{th} root of J_n, we can define a set of eigenvalues h_{nl} for the TM modes so that:**

$$h_{TM_{nl}} = \frac{t_{nl}}{a}$$

l^{th} root of $J_n(.)=0$

$n \rightarrow$, $l \downarrow$

l \ n	0	1	2
1	2.405	3.832	5.136
2	5.520	7.016	8.417
3	8.654	13.323	11.620

Each choice of *n* and *l* specifies a particular solution or *mode*

n **is related to the number of circumferential variations and *l* describes the number of radial variations of the field.**

Circular Waveguide – TM Modes

The propagation constant of the nl^{th} propagating TM mode is:

$$\beta_{TM_{nl}} = \left[\omega^2 \mu\varepsilon - \left(\frac{t_{nl}}{a} \right)^2 \right]^{1/2}$$

The propagation occurs for $\lambda < \lambda_{cTMnl}$ or $f > f_{cTMnl}$ where the cutoff frequency and wavelength can be found from $\gamma = 0$ as:

$$\lambda_{cTMnl} = \frac{2\pi a}{t_{nl}} \qquad f_{cTMnl} = \frac{t_{nl}}{2\pi a\sqrt{\mu\varepsilon}}$$

The other field components can be obtained from E_z

$$E_z = C_n J_n \left(\frac{t_{nl}}{a} r \right) \cos(n\phi) e^{-j\beta_{nl} z}$$

Circular Waveguide – TE Modes

The solutions for the TE modes can be found in a similar manner except that we solve for $H_z(r,\phi)$ to get:

$$H_z(r,\phi) = C_n J_n(hr)\cos(n\phi)$$

To apply the boundary condition $E_{tan} = 0$, we require

$$\frac{\partial H_z}{\partial r} \text{ to be 0 at } r = a$$

We must have $\hat{n}\cdot\nabla_{tr}H_z = \dfrac{\partial H_z}{\partial r} = 0 \quad at \quad r = a$

For this, we need the zeros of $J_n'(u)$ given by s_{nl}. The propagation constant, cutoff frequency and wavelength have the same expressions as in the TM case with $t_{nl} \rightarrow s_{nl}$.

Circular Waveguide – TE Modes

The propagation constant of the *nl*th propagating TE mode is:

$$\beta_{TE_{nl}} = \left[\omega^2 \mu\varepsilon - \left(\frac{s_{nl}}{a}\right)^2\right]^{1/2}$$

***l*th root of $J_n'(.)=0$**

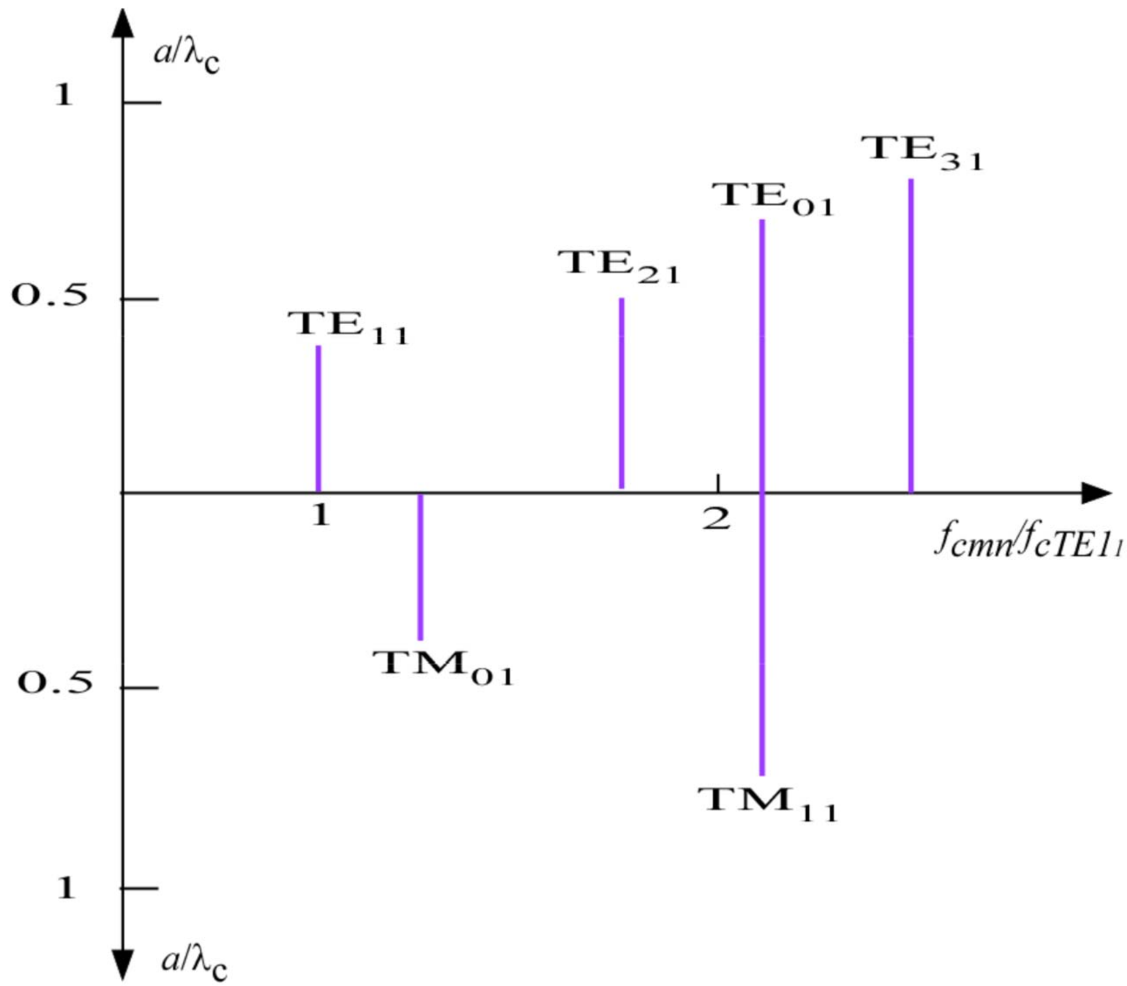
n → / l ↓	0	1	2
1	3.832	1.841	3.054
2	7.016	5.331	6.706
3	10.173	8.536	9.969

From the tables, it can be seen that the lowest cutoff frequency is the TE_{11} mode.

and for TE modes,

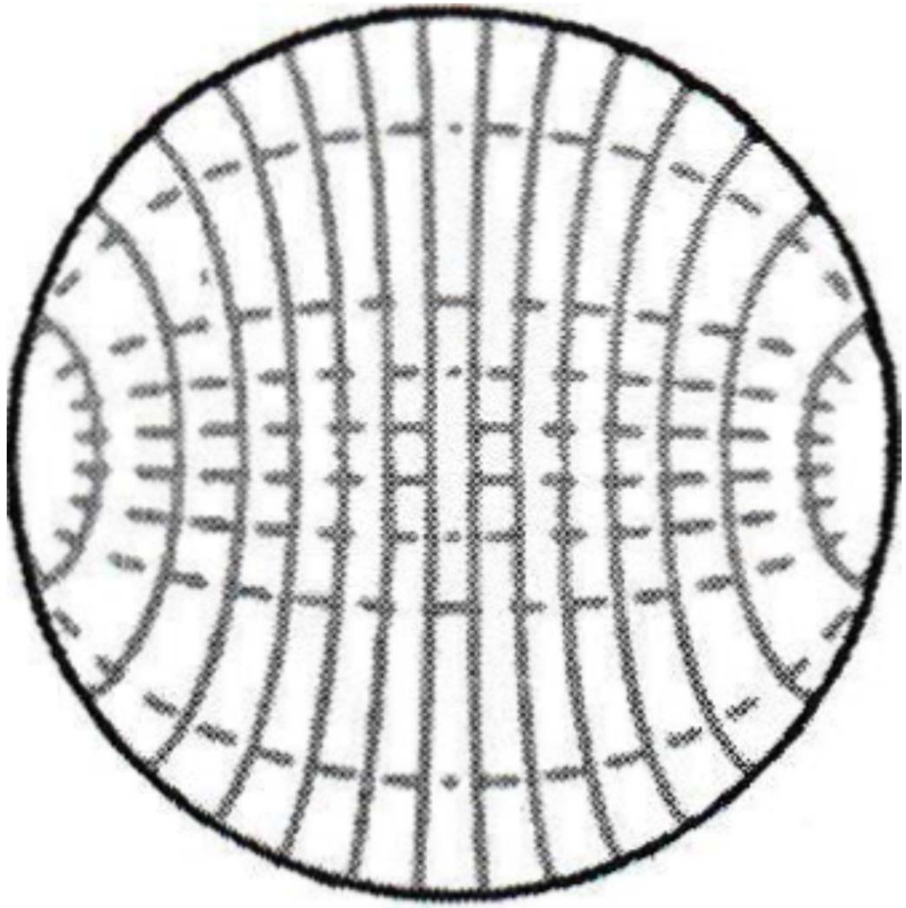
$$H_z = C_n J_n\left(\frac{s_{nl}}{a} r\right)\cos(n\phi)e^{-j\beta_{nl}z}$$

Circular Waveguide – TE & TM Modes



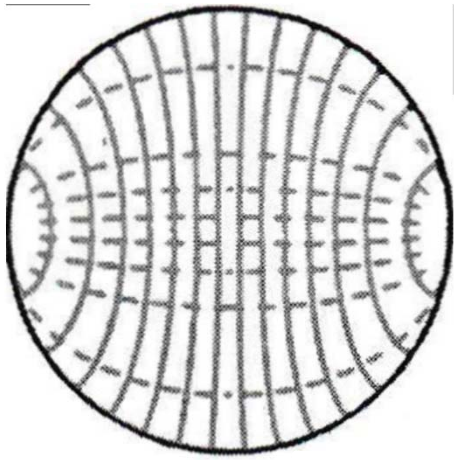
See Reference [6].

TE_{11} Mode in Circular Waveguide

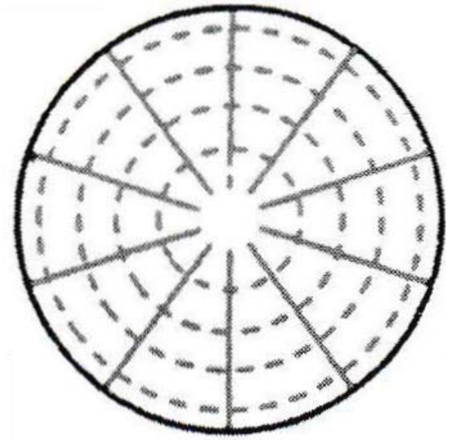


See Reference [1].

Modes in Circular Waveguide



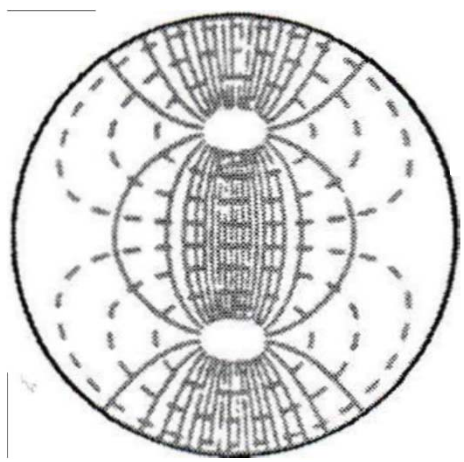
TE_{11}



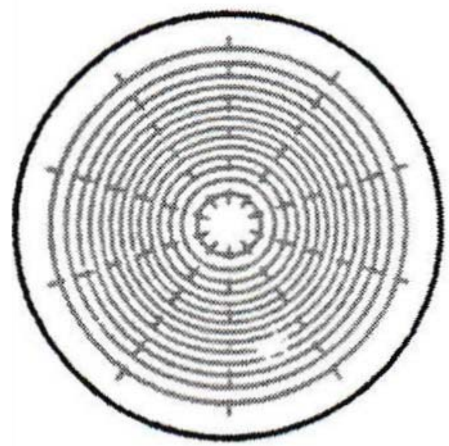
TM_{01}

E ———

H - - - - -



TM_{11}



TE_{01}

See Reference [1].

Example: Circular Waveguide Design

Design an air-filled circular waveguide such that only the dominant mode will propagate over a bandwidth of 10 GHz.

Solution: the cutoff frequency of the TE_{11} mode is the lower bound of the bandwidth.

$$f_{cTE_{11}} = \frac{1.8412c}{2\pi a}$$

The next mode is the TM_{01} with cutoff frequency:

$$f_{cTM_{01}} = \frac{2.4049c}{2\pi a}$$

Example: Circular Waveguide Design

The BW is the difference between these two frequencies

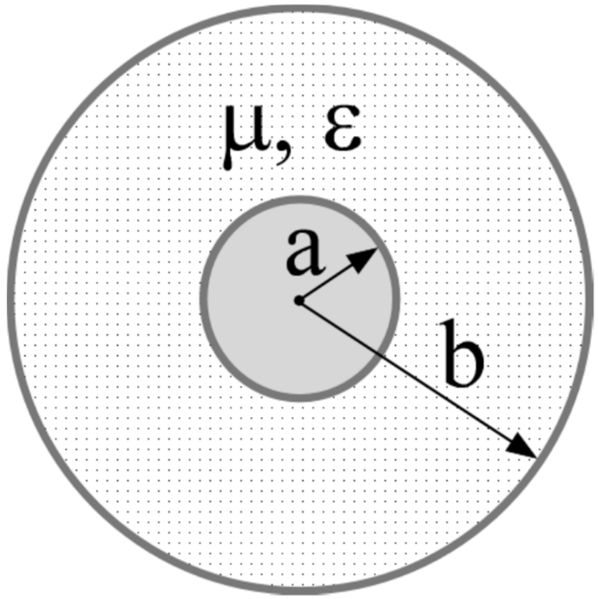
$$BW = f_{cTM_{01}} - f_{cTE_{11}} = \frac{c}{2\pi a}\left(2.4049 - 1.8412\right) = 10GHz$$

From which we find *a* = 0.269 cm

So that

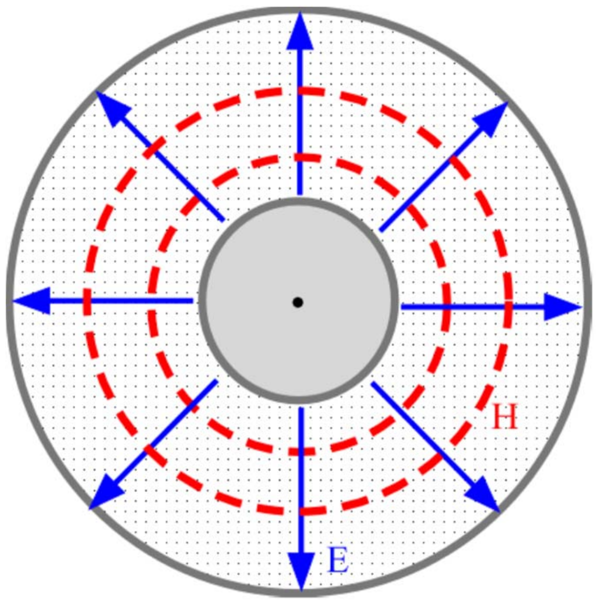
$$f_{cTE_{11}} = 32.7\ GHz\ and\ \ f_{cTM_{11}} = 42.76\ GHz$$

Coaxial Waveguide



- **Most common two-conductor transmission system**
- **Dielectric filling in most microwave applications is polyethylene or Teflon**

Coaxial Waveguide – TEM Mode



- Two-conductor system ➔ Dominant mode is TEM
- Tangential E-field and normal H field must be 0 in conductor surfaces

$$E_\phi = 0 \text{ and } H_r = 0 \text{ at } r = a, b$$

Coaxial Waveguide – TEM Mode

TEM solution can exist only with

$$E = \hat{r}E_r\left(r,z\right) \quad \text{and} \quad H = \hat{\phi}H_\phi\left(r,z\right)$$

with no ϕ dependence because of azimuthal symmetry

we get

$$-\frac{\partial H_\phi}{\partial z} = j\omega E_r \rightarrow j\beta H_\phi^o\left(r\right) = j\omega\varepsilon E_r^o\left(r\right)$$

$$-\frac{1}{r}H_\phi + \frac{\partial H_\phi}{\partial r} = 0 \rightarrow -\frac{1}{r}H_\phi^o\left(r\right) + \frac{\partial H_\phi^o}{\partial r} = 0$$

Where propagation in z direction is assumed.

Coaxial Waveguide – TEM Mode

We get

$$\mathbf{H} = \hat{\phi}\frac{H_o}{r}e^{-j\beta z} \qquad \mathbf{E} = \hat{r}\frac{H_o\eta}{r}e^{-j\beta z}$$

where H_o is a constant. No cutoff condition for TEM mode.

The voltage between the two conductors is given by

$$V(z) = -\eta H_o \ln(b/a)e^{-j\beta z}$$

The current in the inner conductor is given by

$$I(z) = 2\pi H_o e^{-j\beta z}$$

The characteristic impedance Z_o is thus given by

$$Z_o = \eta\frac{\ln(b/a)}{2\pi}$$

Coaxial Waveguide – TE and TM Modes

TE and TM modes may also exist in addition to TEM. In a coaxial line, they are generally undesirable.

For TM modes, we have:

$$E_z^o(r,\phi) = \left[C_3 J_n(hr) + C_4 Y_n(hr)\right]\cos(n\phi)$$

For TE modes, we have:

$$H_z^o(r,\phi) = \left[C_3' J_n(hr) + C_4' Y_n(hr)\right]\cos(n\phi)$$

With boundary conditions at *r* =*a, b* of

$$E_z(r,\phi) = 0 \quad \text{for TM modes}$$

$$\frac{\partial H_z}{\partial r} = 0 \quad \text{for TE modes}$$

Coaxial Waveguide – TE and TM Modes

These conditions lead to

$$J_n(ha)Y_n(hb) = J_n(hb)Y_n(ha) \quad \text{for TM modes}$$

$$J_n'(ha)Y_n'(hb) = J_n'(hb)Y_n'(ha) \quad \text{for TE modes}$$

Solutions of these transcendental equations determine the eigenvalues of *h* for given *a, b*. As in the circular waveguide case, the modes for coaxial waveguide are denoted TE_{nl} and TM_{nl}.

Coaxial Waveguide – TE and TM Modes

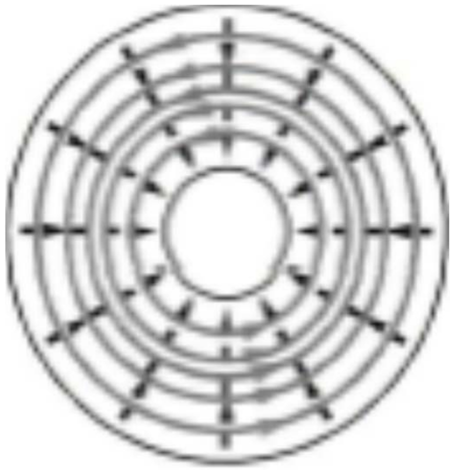
The mode with the lowest cutoff frequency is the TE_{11} mode for which the eigenvalue *h* is approximated as:

$$h = \frac{2}{a+b}$$

The cutoff frequency and cutoff wavelength are given by

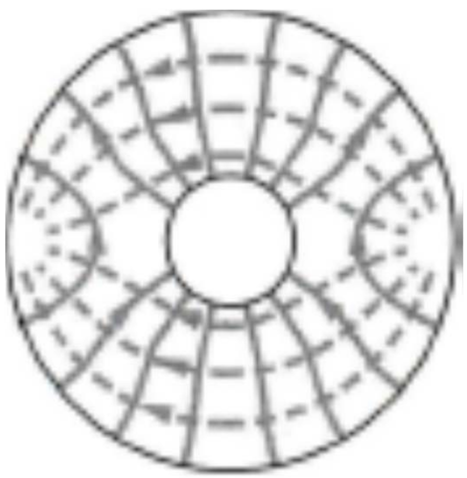
$$\lambda_{c11} = \frac{2\pi}{h} \simeq \pi\left(a+b\right) \quad \text{and} \quad f_{c11} \simeq \frac{1}{\pi\left(a+b\right)\sqrt{\mu\varepsilon}}$$

Coaxial Waveguide – TE and TM Modes

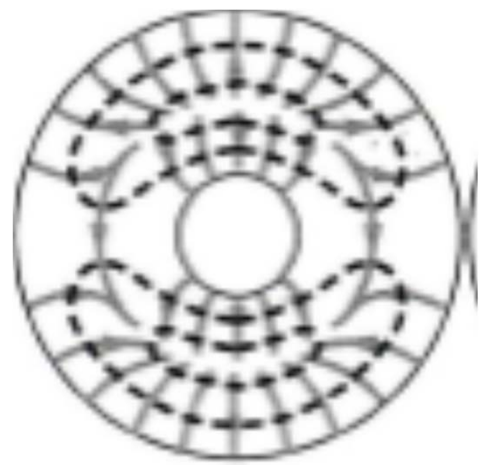


TE_{01}

TM_{01}



TE_{11}



TM_{11}

See Reference [3].

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