Microwave Waveguides and Cavities

- **A hollow metallic tube of the uniform cross section for transmitting electromagnetic waves by successive reflections from the inner walls of the tube is called as a Waveguide.**

- **Microwaves propagate through microwave circuits, components and devices, which act as a part of Microwave transmission lines, broadly called as Waveguides.**

- **A waveguide is generally preferred in microwave communications. A waveguide is a special form of a transmission line, which is a hollow metal tube. Unlike the transmission line, the waveguide has no center conductor.**

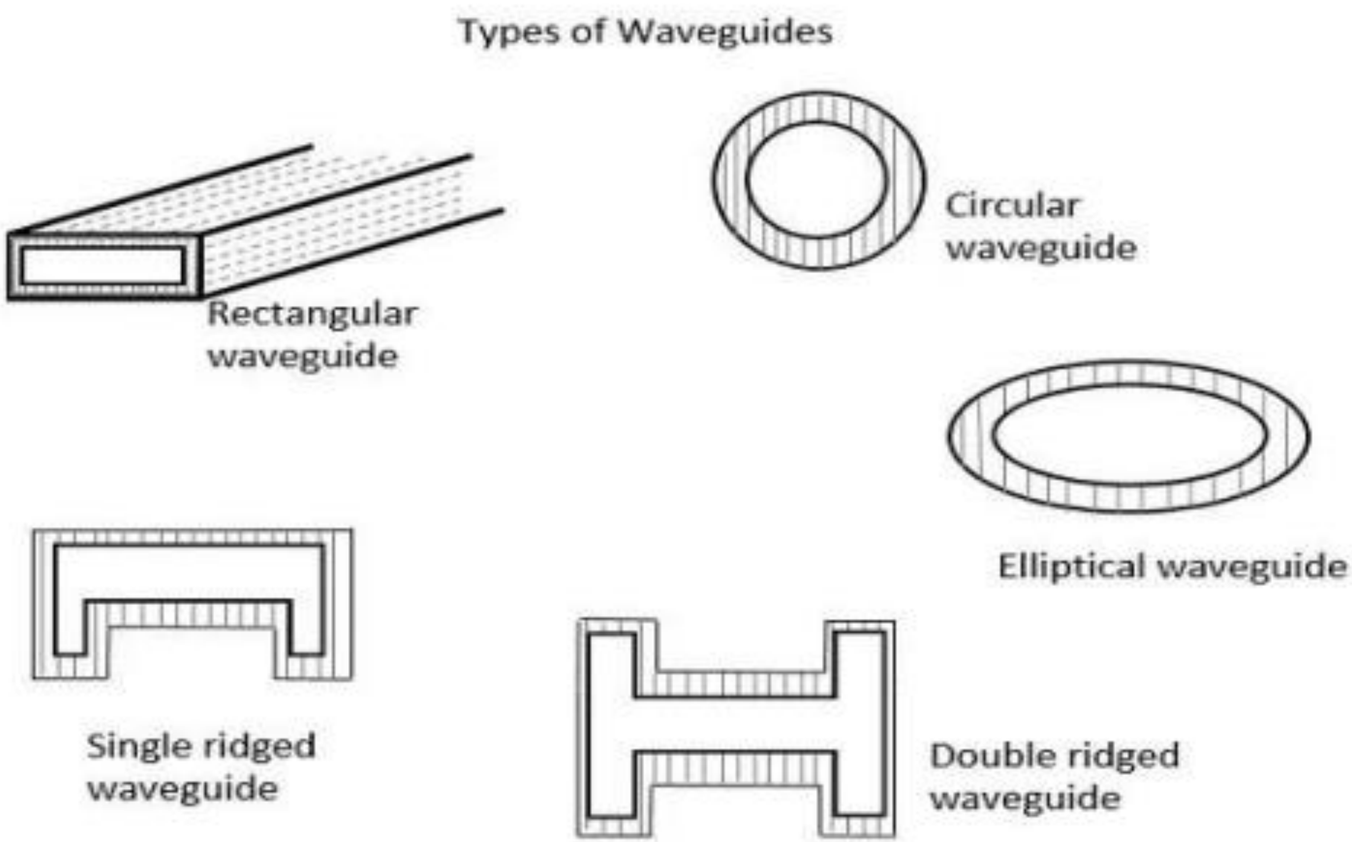
Advantages of Waveguides

- **Waveguides are easy to manufacture.**
- **They can handle very large power (in kilowatts).**
- **Power loss is very negligible in waveguides.**
- **They offer very low loss (low value of alpha-attenuation).**
- **The microwave energy when travels through the waveguide, experiences lower losses than a coaxial cable.**

Types of waveguides

- **There are five types of waveguides. They are:**
- **Rectangular waveguide**
- **Circular waveguide**
- **Elliptical waveguide**
- **Single ridged waveguide**
- **Double ridged waveguide**

Types of waveguides



Transmission Lines Vs Waveguide

The main difference between a transmission line and a wave guide is –

➢A two conductor structure that can support a TEM wave is a transmission line.

➢A one conductor structure that can support a TE wave or a TM wave but not a TEM wave is called as a waveguide.

Transmission Lines	Waveguides
Supports TEM wave	Cannot support TEM wave
All frequencies can pass through	Only the frequencies that are greater than cut-off frequency can pass through
One conductor transmission	Two conductor transmission
Reflections are less	Wave travels through reflections from the walls of waveguide
It has characteristic impedance	It has wave impedance

Transmission Lines Vs Waveguide

Propagation of waves is according to "Circuit theory"	Propagation of waves is according to "Field theory"
It has a return conductor to earth	Return conductor is not required as the body of the waveguide acts as earth
Bandwidth is not limited	Bandwidth is limited
Waves do not disperse	Waves get dispersed

Transverse Electro Magnetic (TEM) wave: Here both electric and magnetic fields are directed components. (i.e.) Ez=0 and Hz =0

Transverse Electric (TE) wave: Here only the electric field is purely transverse to the direction of propagation and the magnetic field is not purely transverse. i.e Ez =0 and Hz is not equal to zero.

Transverse Magnetic (TM) wave: Here only magnetic field is transverse to the direction of propagation and the electric field is not purely transverse. i.e Ez is not equal to zero and Hz=0.

Hybrid (HE) wave: Here neither electric nor magnetic fields are purely transverse to the direction of propagation i.e Ez is not equal to zero or Hz is not equal to zero.

- **The electromagnetic wave inside a waveguide can have an infinite number of patterns which are called modes.**

- **The electric field cannot have a component parallel to the surface i.e. the electric field must always be perpendicular to the surface at the conductor.**

- **The magnetic field on the other hand always parallel to the surface of the conductor and cannot have a component perpendicular to it at the surface.**

- **Dominant Mode: The dominant mode in a particular guide is the mode having the lowest cutoff frequency.**

- **Degenerate Modes: Two or more modes having the same cut-off frequency are called 'Degenerate modes'**

- Rectangular waveguides are the one of the earliest type of the transmission lines.
- They are used in many applications. A lot of components such as isolators, detectors, attenuators, couplers and slotted lines are available for various standard waveguide bands between 1 GHz to above 220 GHz.
- A rectangular waveguide supports TM and TE modes but not TEM waves because we cannot define a unique voltage since there is only one conductor in a rectangular waveguide.
- The shape of a rectangular waveguide is as shown below . A material with permittivity e and permeability m fills the inside of the conductor.
- A rectangular waveguide cannot propagate below some certain frequency . This frequency is called the cut-off frequency.
- The U.S. standard rectangular waveguide WR-90 has an inner width of 2.286 cm (0.9 in.) and an inner height of 1.016 cm (0.4 in.); but its outside dimensions are 2.54 cm (1 in.) wide and 1.27 cm (0.5 in.)
- high.

A rectangular waveguide is a hollow metallic tube with a rectangular cross section. The conducting walls of the guide confine the electromagnetic fields and thereby guide the electromagnetic wave. A number of distinct field configurations or modes can exist in waveguides. When the waves travel longitudinally down the guide, the plane waves are reflected from wall to wall. This process results in a component of either electric or magnetic field in the direction of propagation of the resultant wave; therefore the wave is no longer a *transverse electromagnetic* (TEM) wave. Figure 4-1-1 shows that any uniform plane wave in a lossless guide may be resolved into TE and TM waves.

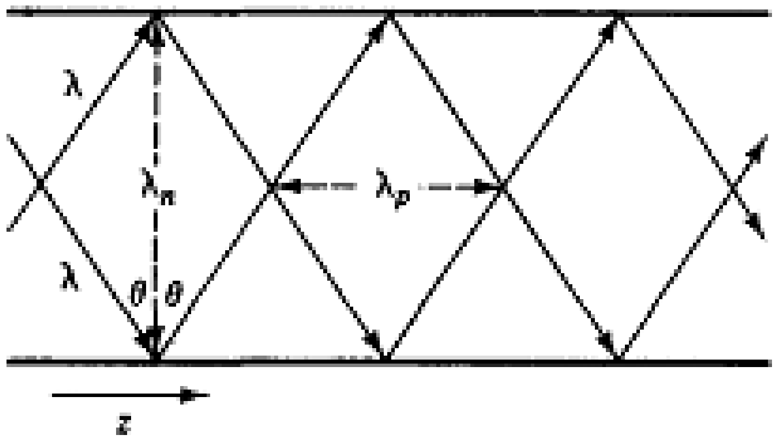


Figure 4-1-1 Plane wave reflected in a waveguide.

It is clear that when the wavelength λ is in the direction of propagation of the incident wave, there will be one component λ_n in the direction normal to the reflecting plane and another λ_p parallel to the plane. These components are

$$\lambda_n = \frac{\lambda}{\cos\theta} \tag{4-1-1}$$

$$\lambda_p = \frac{\lambda}{\sin\theta} \tag{4-1-2}$$

where θ = angle of incidence
λ = wavelength of the impressed signal in unbounded medium

A plane wave in a waveguide resolves into two components: one standing wave in the direction normal to the reflecting walls of the guide and one traveling wave in the direction parallel to the reflecting walls. In lossless waveguides the modes may be classified as either *transverse electric* (TE) mode or *transverse magnetic* (TM) mode. In rectangular guides the modes are designated TE_{mn} or TM_{mn}. The integer m denotes the number of half waves of electric or magnetic intensity in the x direction, and n is the number of half waves in the y direction if the propagation of the wave is assumed in the positive z direction.

As stated previously, there are time-domain and frequency-domain solutions for each wave equation. However, for the simplicity of the solution to the wave equation in three dimensions plus a time-varying variable, only the sinusoidal steady-state or the frequency-domain solution will be given. A rectangular coordinate system is shown in Fig. 4-1-2.

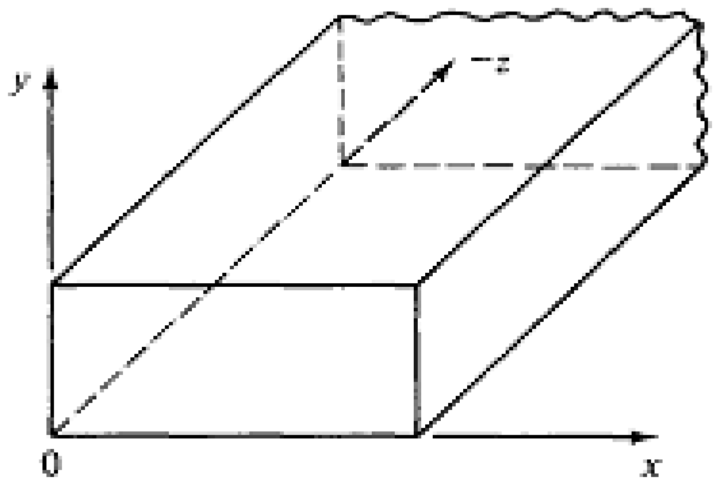


Figure 4-1-2 Rectangular coordinates.

The electric and magnetic wave equations in frequency domain in Eqs. (2-1-20) and (2-1-21) are given by

$$\nabla^2 \mathbf{E} = \gamma^2 \mathbf{E} \tag{4-1-3}$$

$$\nabla^2 \mathbf{H} = \gamma^2 \mathbf{H} \tag{4-1-4}$$

where $\gamma = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)} = \alpha + j\beta$. These are called the *vector wave equations*.

The Helmholtz equation in rectangular coordinates is

$$\frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2} + \frac{\partial^2\psi}{\partial z^2} = \gamma^2\psi \qquad (4\text{-}1\text{-}6)$$

This is a linear and inhomogeneous partial differential equation in three dimensions. By the method of separation of variables, the solution is assumed in the form of

$$\psi = X(x)Y(y)Z(z) \qquad (4\text{-}1\text{-}7)$$

where $X(x)$ = a function of the x coordinate only
$Y(y)$ = a function of the y coordinate only
$Z(z)$ = a function of the z coordinate only

The total solution of the Helmholtz equation in rectangular coordinates is

$$\psi = [A \sin(k_x x) + B \cos(k_x x)][C \sin(k_y y) + D \cos(k_y y)]$$
$$\times [E \sin(k_z z) + F \cos(k_z z)] \tag{4-1-16}$$

The propagation of the wave in the guide is conventionally assumed in the positive z direction. It should be noted that the propagation constant γ_g in the guide differs from the intrinsic propagation constant γ of the dielectric. Let

$$\gamma_g^2 = \gamma^2 + k_x^2 + k_y^2 = \gamma^2 + k_c^2 \tag{4-1-17}$$

where $k_c = \sqrt{k_x^2 + k_y^2}$ is usually called the *cutoff wave number*. For a lossless dielectric, $\gamma^2 = -\omega^2 \mu\epsilon$. Then

$$\gamma_g = \pm\sqrt{\omega^2 \mu\epsilon - k_c^2} \tag{4-1-18}$$

There are three cases for the propagation constant γ_g in the waveguide.

Case I. There will be no wave propagation (evanescence) in the guide if $\omega_c^2 \mu\epsilon = k_c^2$ and $\gamma_g = 0$. This is the critical condition for cutoff propagation. The cutoff frequency is expressed as

$$f_c = \frac{1}{2\pi\sqrt{\mu\epsilon}}\sqrt{k_x^2 + k_y^2} \qquad (4\text{-}1\text{-}19)$$

Case II. The wave will be propagating in the guide if $\omega^2\mu\epsilon > k_c^2$ and

$$\gamma_g = \pm j\beta_g = \pm j\omega\sqrt{\mu\epsilon}\sqrt{1 - \left(\frac{f_c}{f}\right)^2} \qquad (4\text{-}1\text{-}20)$$

This means that the operating frequency must be above the cutoff frequency in order for a wave to propagate in the guide.

Case III. The wave will be attenuated if $\omega^2\mu\epsilon < k_c^2$ and

$$\gamma_g = \pm\alpha_g = \pm\omega\sqrt{\mu\epsilon}\sqrt{\left(\frac{f_c}{f}\right)^2 - 1} \qquad (4\text{-}1\text{-}21)$$

This means that if the operating frequency is below the cutoff frequency, the wave will decay exponentially with respect to a factor of $-\alpha_g z$ and there will be no wave propagation because the propagation constant is a real quantity. Therefore the solution to the Helmholtz equation in rectangular coordinates is given by

$$\psi = [A\sin(k_x x) + B\cos(k_x x)][C\sin(k_y y) + D\cos(k_y y)]e^{-j\beta_g z} \qquad (4\text{-}1\text{-}22)$$

There are two types of power losses in a rectangular waveguide:

1. Losses in the dielectric
2. Losses in the guide walls

Example 4-1-1, Example 4-1-2

For a circular waveguide with a radius of 1cm and a desired frequency of operation of 10GHz (for dominant mode), determine:

(a) cut-off frequency
(b) cut-off wavelength
(c) group velocity
(d) phase velocity
(e) propagation wavelength in the waveguide
(f) characteristics impedance

Repeat example 1 for a circular waveguide with a radius of 2.5cm and a desired frequency of operation of 7GHz.

Example 4-1-1, Example 4-1-2

For a circular waveguide with a radius of 1cm and a desired frequency of operation of 10GHz (for dominant mode), determine:
(a) cut-off frequency
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Repeat example 1 for a circular waveguide with a radius of 2.5cm and a desired frequency of operation of 7GHz.