PROPAGATION OF GUIDED WAVES

ECE 524E – MICROWAVE ENGINEERING

Thursday, 08 February 2024

WHERE ARE WE IN THE SYLLABUS?

Course Content:

Introduction: Components of RF and microwave design, Behaviour of passive components, Propagation of guided waves. Micro-stripline circuits; Evaluation of attenuation constant for the rectangular waveguide. Waveguides and Components: Review of electromagnetic (EM) spectrum. Rectangular waveguides, Circular Waveguides, Microwave cavities. Microwave antennas: electromagnetic horns; reflector antennas; micro-strip antennas; phased arrays. Micro Strip Antenna. Directional couplers. Circulators, isolators. Wave guide couplings, bends and twists, Transitions, hybrid couplers, Matched load, Attenuators and phase shifters, E-plane, H-plane and Hybrid Tees, Hybrid ring. Waveguide discontinuities: Windows, Irises and Tuning screws, Detectors, wave meters. Strip Lines: Microstrip lines. Parallel strip lines. Coplanar strip lines. Shielded strip lines. Microwave Active circuits: Microwave transistors and tunnel diodes. Microwave FETs. Transferred electron devices: Avalanche transit time devices. Microwave linear beam tubes. Microwave crossed-field tubes. Microwave Communication Systems. Effect of Biological Exposure to microwave radiation. Microwave tubes: Klystron, Reflex Klystron, Magnetron, TWT, BWO: Their schematic, Principle of operation, performance characteristics and application. Microwave semiconductor devices: PIN diode, Tunnel diode, LSA diode, varactor diode, Gunn Devices, IMPATT and TRAPATT, their Principal of operation, characteristics and applications. Microwave Relays: Line-of-site path characteristics, FM radio stations and repeaters, FM microwave systems, analogue FM/AM, analogue versus digital switching arrangements.

ADVANTAGES & DISADVANTAGES OF WAVEGUIDES

Waveguides have the following advantages:

1. High-power handling capability.
2. High-frequency application.
3. Signal attenuation is very low compared to other transmission lines.
4. Installation is easy in a microwave system.

Disadvantages of waveguides are:

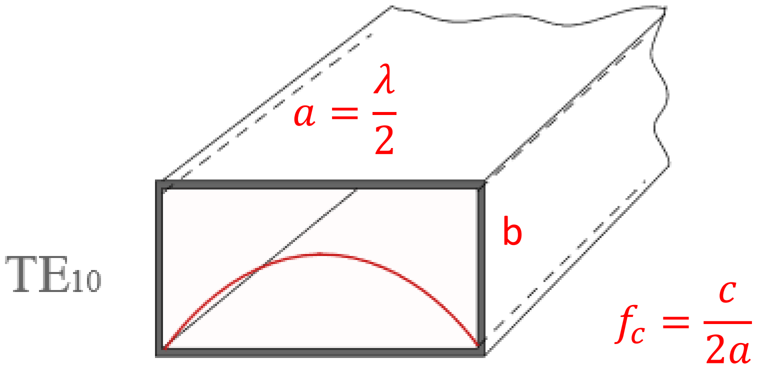
1. Attenuation of low-frequency signals
2. Large size and weight
3. TEM Mode not supported
4. Costly
5. Only suitable for special purpose design/application

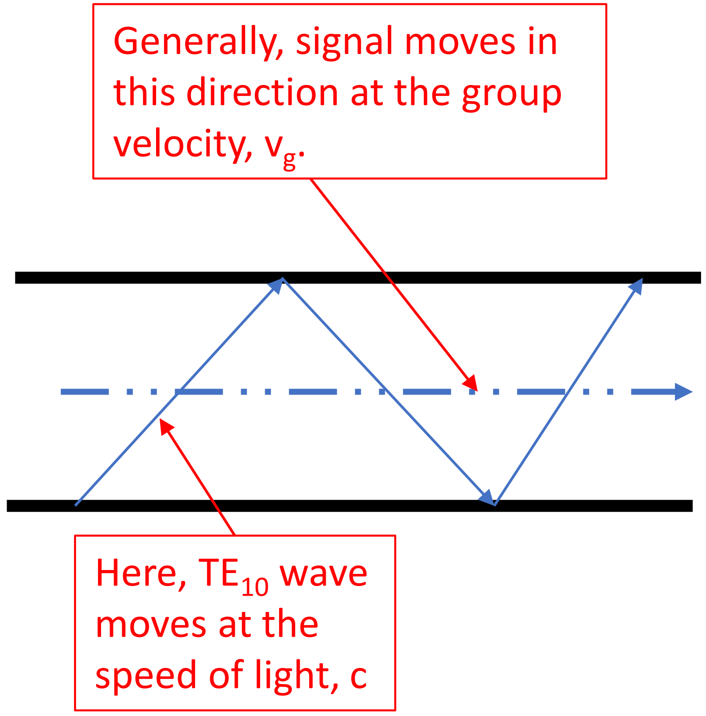
DIFFERENCES BETWEEN WAVEGUIDES & TRANSMISSION LINES

TRANSMISSION LINES	WAVEGUIDES
1. Supports TEM wave	Cannot support TEM wave
2. All frequencies can pass through	Only the frequencies that are greater than cut-off frequency can pass through
3. Two conductor transmission	One conductor transmission
4. Reflections are less	A wave travels through reflections from the walls of the waveguide
5. It has a characteristic impedance	It has wave impedance
6. Propagation of waves is according to "Circuit theory"	Propagation of waves is according to "Field theory"
7. It has a return conductor to earth	Return conductor is not required as the body of the waveguide acts as earth
8. Bandwidth is not limited	Bandwidth is limited

CHARACTERISTICS OF A WAVEGUIDE (1)

1. **Critical (cut-off) frequency, f_c(Hz):** the lowest frequency for which a mode will propagate in a waveguide.
2. **Critical (cut-off) wavelength, λ_c (m/cycle):** the largest wavelength that can propagate in the waveguide without any / minimum attenuation (or the smallest free space wavelength that is just unable to propagate in the waveguide).
3. **Group velocity (v_g, m/s):**
   a) The velocity at which a wave propagates in a waveguide.
   b) Refers to the velocity of a group of waves.
   c) It is also the velocity at which information signals or energy is propagated.





CHARACTERISTICS OF A WAVEGUIDE (2)

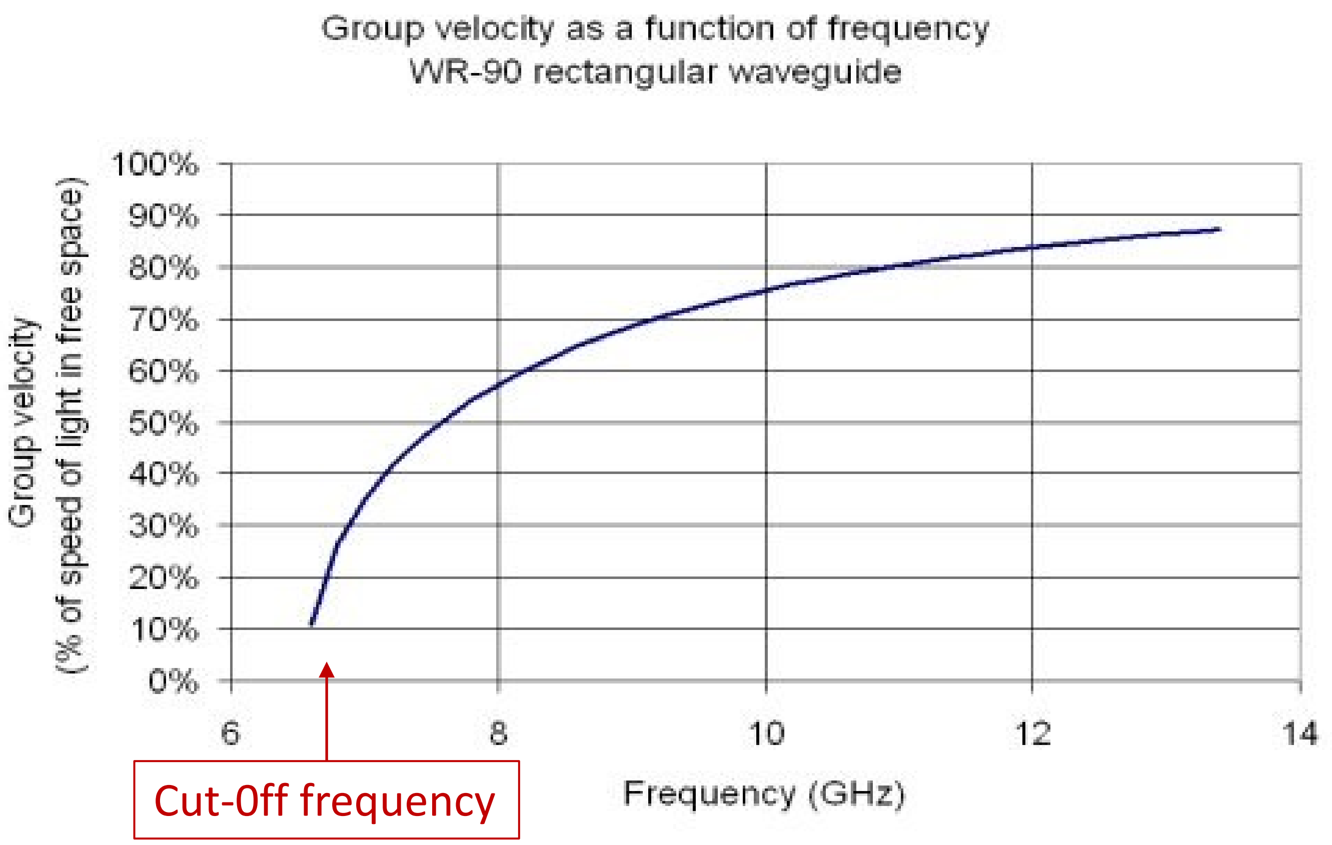
4. Phase velocity (v_p, m/s):

a) The velocity at which the wave changes phase in the waveguide.
b) It is the apparent velocity of the wave (i.e.: max electric intensity point).
c) v_p always equal to or greater than v_g ($v_p \geq v_g$).
d) It may exceed the velocity of light (velocity in free space).

- In theory: $v_g < c \leq v_p$.
- The relationship between v_g, v_p and speed of light, C is given by:

$$c^2 = v_g * v_p$$

GROUP VELOCITY VS SPEED OF LIGHT



Note:

1. Characteristic is determined by the fundamental relationship

$$V_g = \frac{c^2}{v_p}$$

2. The cut-off frequency is given by

$$f_c = \frac{c}{2a} = \frac{3 \times 10^8}{2 \times 2.286 \times 10^{-2}}$$

= 6.56 GHz

- Dimensions of WR Waveguide are 0.8 x 0.4 inches (2.286 x 1.016 cm)
- The recommended operating band of WR-90 is from 8.2 to 12.4 GHz.
- At 8.2 GHz the signal is slowed to 60% of the free-space speed of light.

CHARACTERISTICS OF A WAVEGUIDE (3)

5. <u>Propagation wavelength in the waveguide (λ_g, m/s):</u>

Wavelength of travelling wave that propagates down the waveguide.

λ_g is greater in the waveguide than in free space (λ_o).

MEASURING WAVEGUIDE IMPEDANCE

1. To determine the waveguide impedance by using the voltage to be the potential difference between the top and bottom walls in the middle of the waveguide, and then take the value of current to be the integrated value across the top wall.
2. Measure the voltage between the top and bottom walls and then use the power flow within the waveguide.
3. Take the ratio of the electric field to the magnetic field at the centre of the waveguide.

WAVEGUIDE IMPEDANCE

6. Waveguide characteristic impedance (Z_o, Ω):

a) It depends on the cut-off frequency, which in turn is determined by the guide dimension.

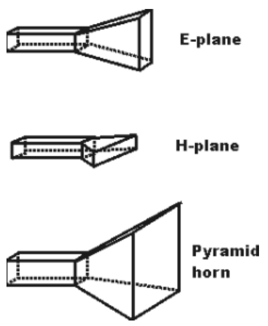
b) It is also closely related to the characteristic impedance of free space (377 Ω).

c) Generally, $190\Omega < Z_o < 750\ \Omega$

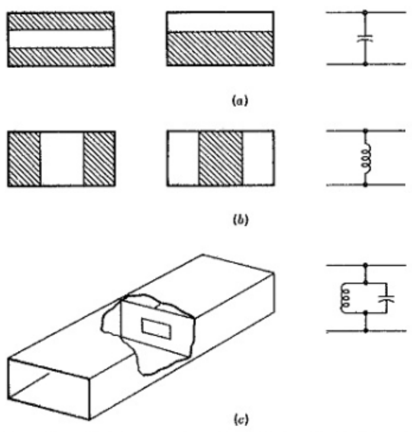
WAVEGUIDE IMPEDANCE MATCHING

The main methods of impedance matching are

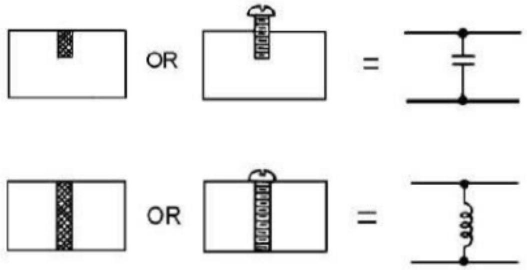
1. **Use a gradual change in dimensions of waveguide**. Example is the horn antennas - these are funnel shaped antennas that provide the waveguide impedance match between the waveguide itself and free space.



2. **Use of a waveguide iris** which is an obstruction within the waveguide that provides a capacitive or inductive element . The element is able to provide the required matching of the characteristic impedance of the waveguide.



3. **Use of a waveguide post or screw** made from a conductive material. To make the post or screw inductive, it should extend through the waveguide completely making contact with both top and bottom walls. For a capacitive reactance the post or screw should only extend part of the way through.



RECTANGULAR WAVEGUIDE TE/TM CALCULATIONS (1)

1. Dominant mode (mode with lowest cutoff frequency) for rectangular waveguide is TE_{10}
2. A waveguide acts as a high-pass filter in that it passes only those frequencies above the cutoff frequency.

$$v_g v_p = c^2 \qquad \lambda_g = \lambda_o \frac{v_p}{c}$$

Where λ_0 is the wavelength is free space.

RECTANGULAR WAVEGUIDE TE/TM CALCULATIONS (2)

$$f_c = \frac{c}{2a} = \frac{c}{\lambda_c}$$

$$v_p = \frac{c(\lambda_g)}{\lambda_o} = \frac{c}{\sqrt{1-\left(f_c/f\right)^2}}$$

$$Z_o = \frac{377}{\sqrt{1-\left(f_c/f\right)^2}} = 377\frac{\lambda_g}{\lambda_o}(TE\ \mathrm{mod}e)$$

$$Z_o = 377\frac{\lambda_o}{\lambda_g}(TM\ \mathrm{mod}e)$$

TYPICAL QUESTIONS

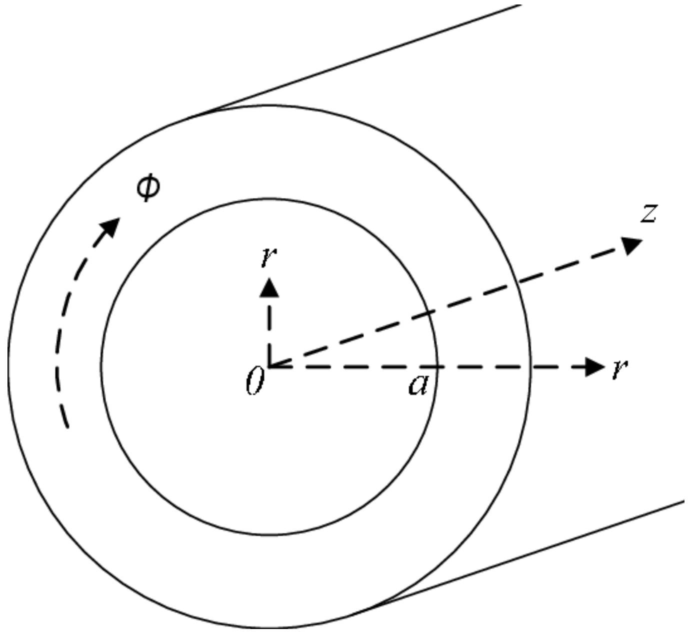
1. For a rectangular waveguide with a width of 3 cm and a desired frequency of operation of 6 GHz (for dominant mode), determine:
   a) Cut-off frequency
   b) Cut-off wavelength
   c) Group velocity
   d) Phase velocity
   e) Propagation wavelength in the waveguide
   f) Characteristic impedance
2. Repeat Example 1 for a rectangular waveguide with a width of 2.5 cm and a desired frequency of operation of 7 GHz.

CIRCULAR WAVEGUIDE TE/TM CALCULATIONS(1)

- Dominant mode for circular waveguide is TE_{11}.

Cut-off frequency, $f_c = \frac{Cx_{np}}{2\pi a} = \frac{1.8412c}{2\pi a}$

Where a is the radius of the waveguide
x_{np} is a cut-off phase constant



$$\lambda_c = \frac{2\pi a}{x_{np}}$$

$$v_p = \frac{c}{\sqrt{1-(f_c/f)^2}}$$

$$v_g v_p = c^2$$

CIRCULAR WAVEGUIDE TE/TM CALCULATIONS(2)

$$\lambda_g = \frac{\lambda_o}{\sqrt{1-\left(f_c/f\right)^2}}$$

$$Z_o = 377\frac{\lambda_g}{\lambda_o}(TE\ \text{mode})$$

$$Z_o = 377\frac{\lambda_o}{\lambda_g}(TM\ \text{mode})$$

TYPICAL QUESTIONS

1. For a circular waveguide with a radius of 1 cm and a desired frequency of operation of 10 GHz (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) Characteristic impedance
2. Repeat Example 1 for a circular waveguide with a radius of 2.5 cm and a desired frequency of operation of 7 GHz.