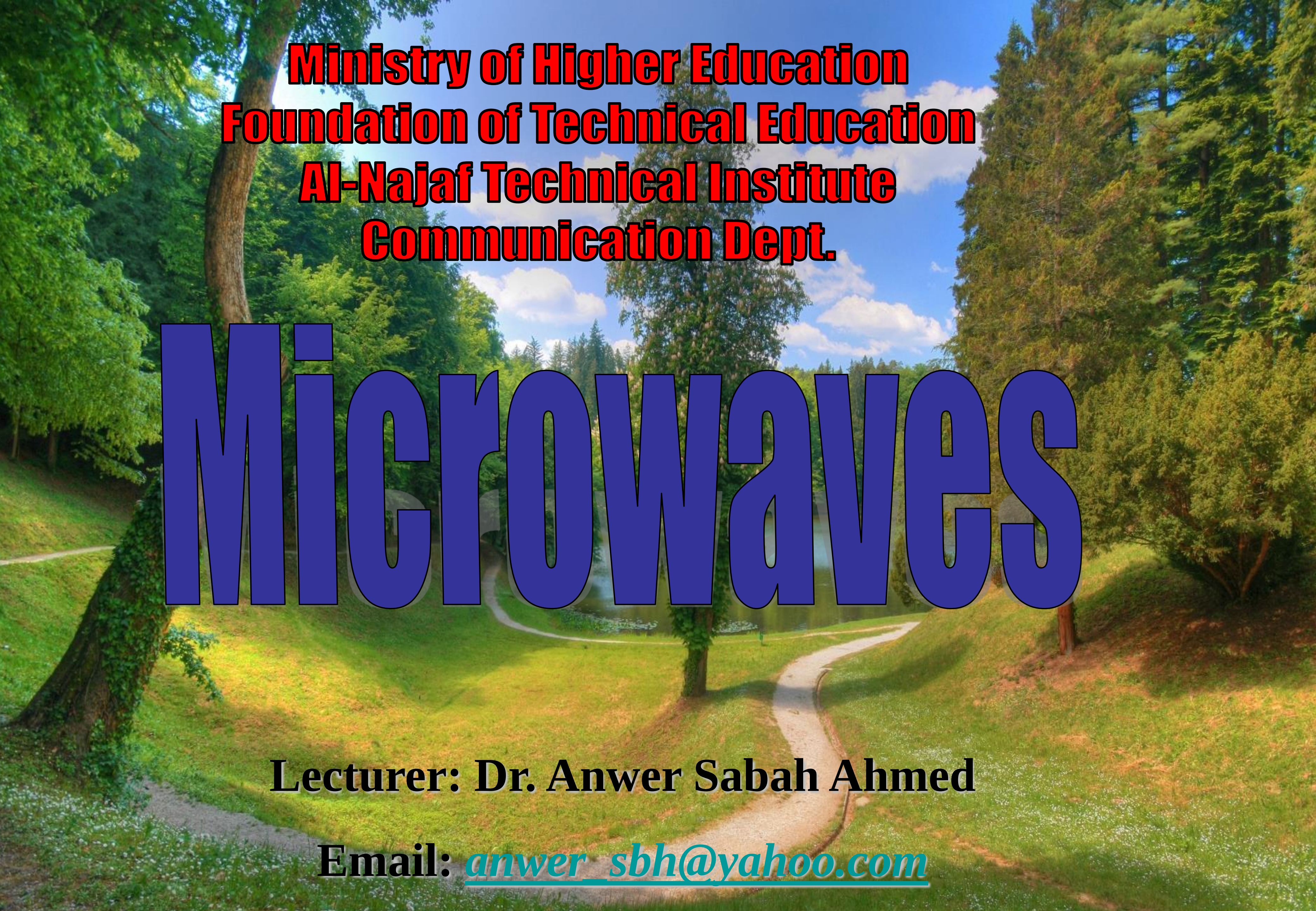

Ministry of Higher Education
Foundation of Technical Education
Al-Najaf Technical Institute
Communication Dept.

Microwaves

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Course Syllabus

Week	Details
1	Introduction to Microwave , Spectral of Electromagnetic wave , Microwave bands, and Applications of Microwaves .
2	Maxwells Equations.
3-4	- Fields in media and boundary conditions includes: - Fields in general material interface - Fields at a dielectric interface, - Fields at the interface with a perfect conductor(Electrical wall) -the magnetic wall boundary condition , -the radiation condition.
5-7	Transmission Lines:Coaxial cable , Flexible coaxial cable , Semirigid cable Stripline ,Microstrip, Waveguide – Rectangular Waveguide – Circular Waveguide
8	Transmission modes (TEM ,TEmn and TMmn)
9-10	Smith chart , matching , mismatching , stand wave ratio
11-12	Microwave components, directional components, attenuators, - Mixers ,and duplexers, Resonators, cavities, Hybrids,Terminals.
13-14	Microwave sources : - Solid state source:- varactor diode , Tuned diode and gun oscillator. - Microwave tubes:- Klystron , Magnetron.

15-16	Microwave Path loss :- - Line of sight microwave propagation, - wave propagation equation ,(Friis equation)
17	Principles of antennas and Radiation pattern directivity and antenna gain
18-19	Horn antenna , Helix antenna , Parabolic antenna , Micro strip antenna
20	Doppler effect.
21-22	Microwave filters
23-24	Satellite communication systems ,
25-27	Modulation and multiplexing -ASK , FSK and PSK -Space Division Multiple access (SDMA) -Frequency Division Multiple access (FDMA) -Time Division Multiple access (TDMA) -CDMA code division Multiple access
28-29	Basic principles of Radar systems
30	Biological effects of microwaves

Grading

Student achievement in the course objectives will be assessed using a combination of homework and exams as well as class attendance and participation. Your course grade will be determined by your weighted performance in the following categories:

Homework	5%
Participation	5%
Midterm Exam #1	20%
Midterm Exam #2	20%
Final Exam	50%

References

1. D. M. Pozar, *Microwave engineering*. Hoboken, Nj: Wiley, 2012.
2. F. Gustrau, RF and Microwave Engineering. John Wiley & Sons, 2012.

Lecture-1-

Microwave Introduction

Waves

In physics, a **wave** is disturbance or oscillation that travels through matter or space, accompanied by a .transfer of energy

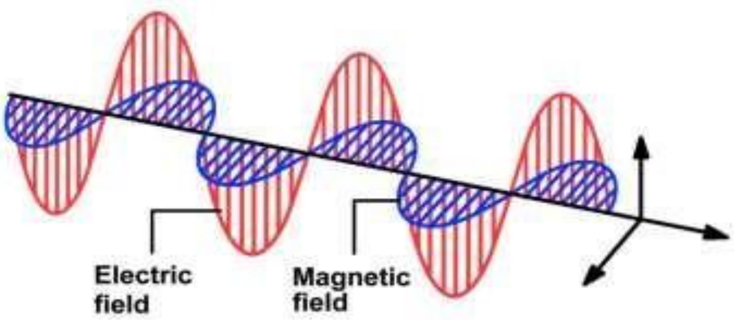
There are two main . types of waves

Mechanical Waves

Electromagnetic Waves

- Radio waves
- Microwaves
- Infrared radiation
- Visible light
- Ultraviolet radiation

Microwaves



Microwaves are electromagnetic waves

Frequency range

300MHz-300Ghz

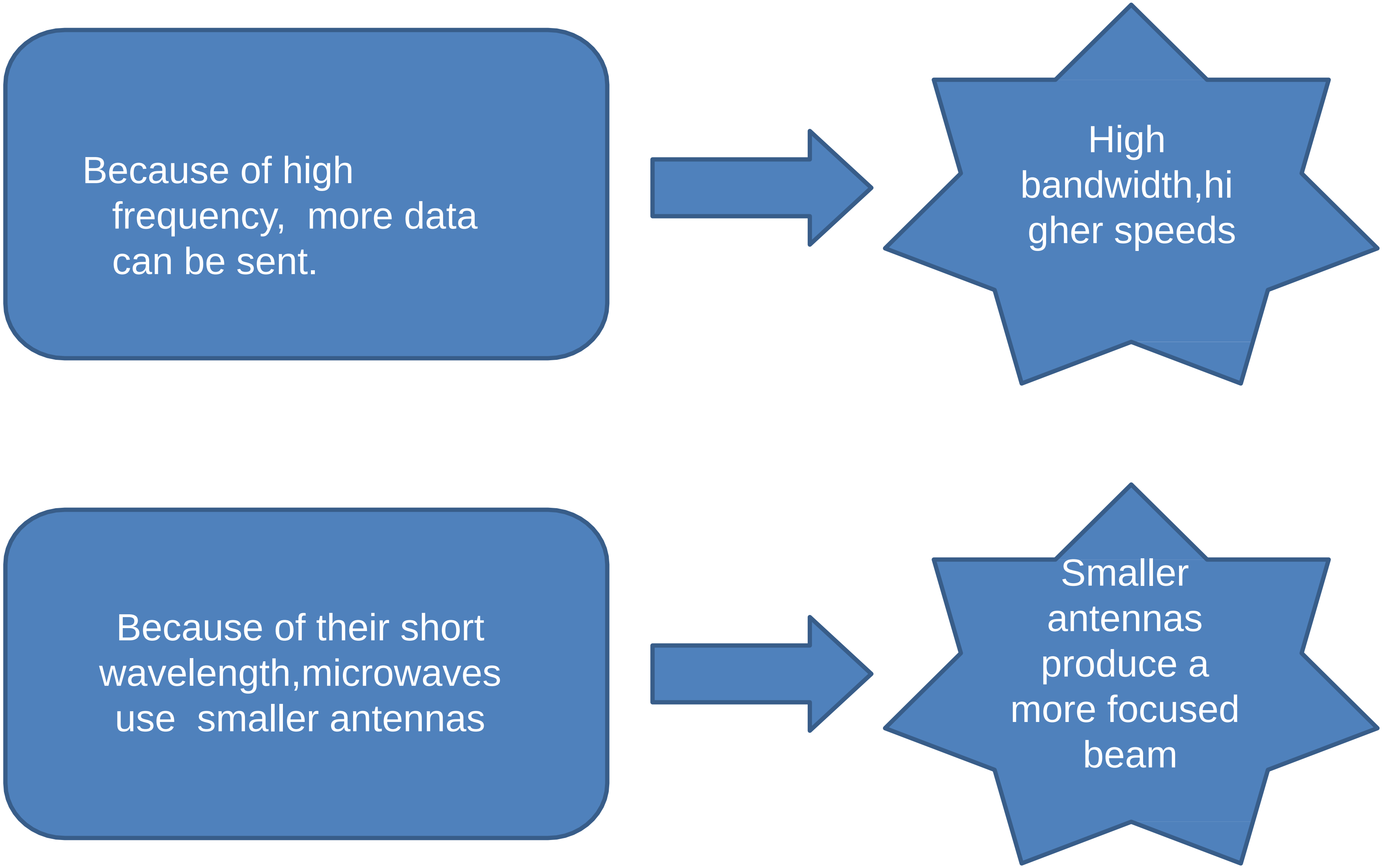
Wavelengths range in air

100cm-1mm

The word microwave means "very short wave"

Microwaves is the shortest wavelength region of the radio spectrum and a part of the electromagnetic spectrum

Advantages of Microwave communication



Because of high frequency, more data can be sent.

High bandwidth,higher speeds

Because of their short wavelength,microwaves use smaller antennas

Smaller antennas produce a more focused beam

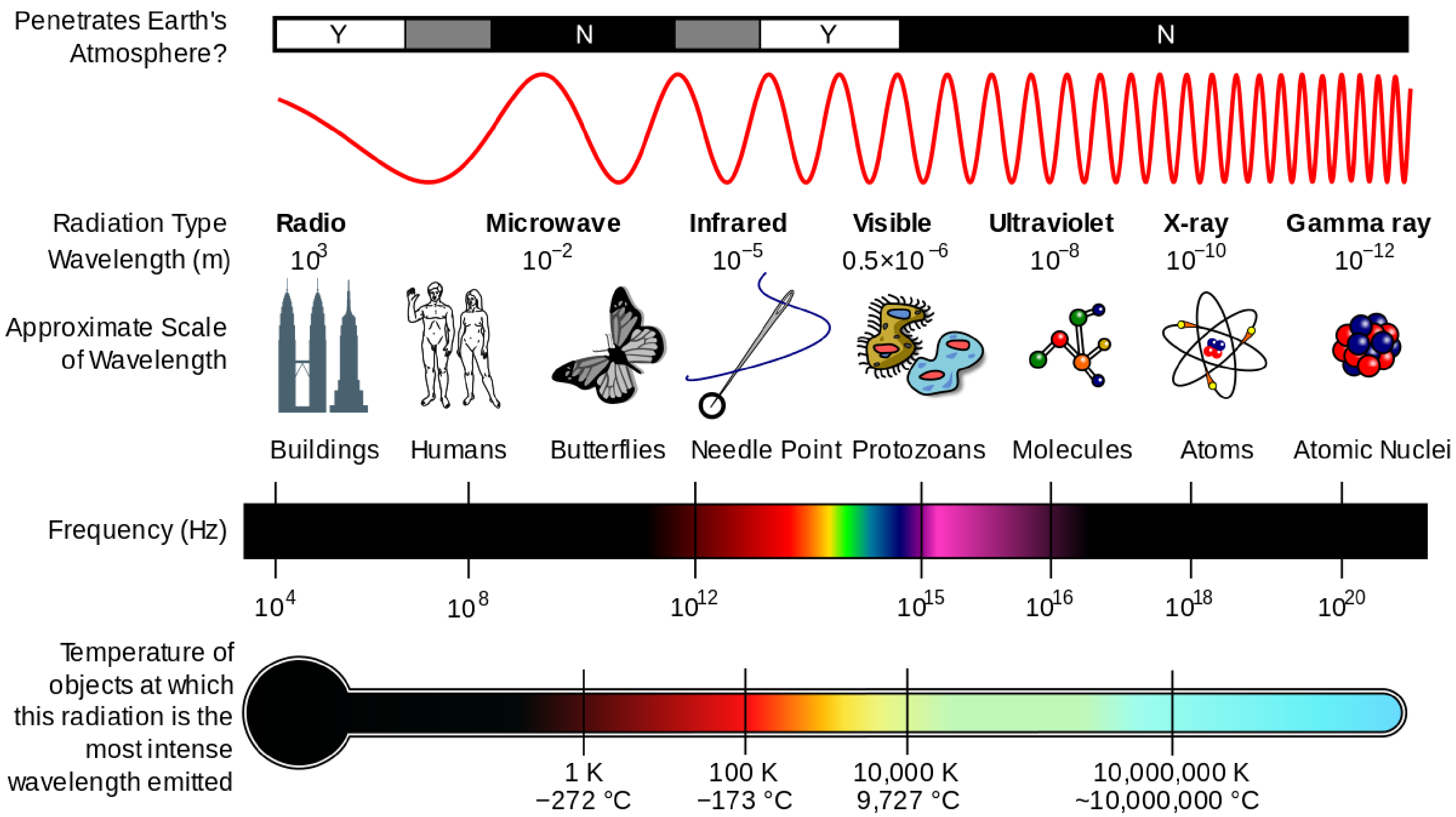
Disadvantages of microwave communication

- They require no obstacle is present in the transmission path

- The cost of implementing the communication infrastructure is high

- Microwaves are susceptible to rain,snow,electromagnetic interference

Basic Principle Of Microwave



Basic Principle Of Microwave

For a typical microwave radio link, information originates and terminates at the terminal stations, while repeaters simply relay the information to the next downlink microwave station. Stations must be placed in a way that the terrain such as mountains, buildings and lakes, do not interfere with the transmission of signals. Geographic location of stations must be carefully selected in such a way that natural and man-made barriers do not interfere with propagation between stations.

Basic Principle Of Microwave

Types of Microwave Systems

- Intrastate or feeder service microwave systems - generally categorized as short haul since they are used to carry information for relatively short distances, such as between cities within the same state.
- Long haul microwave systems - used to carry information for long distances.

Basic Principle Of Microwave

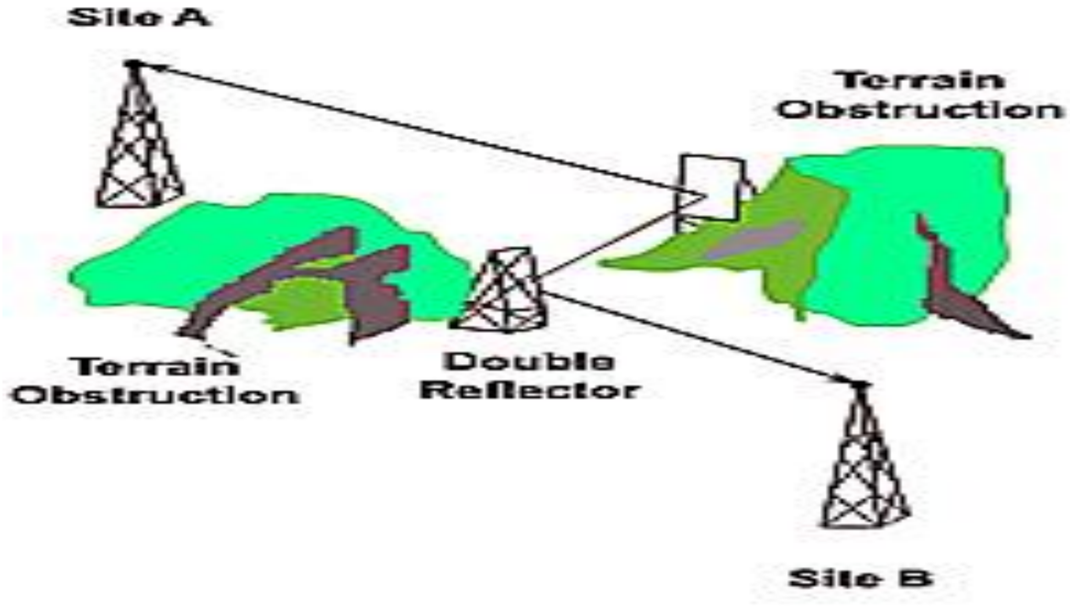
Microwave Repeaters

Microwave communications requires the line-of-sight or space wave propagation method. There are some instances where barriers are inevitable which cause obstructions between the transmitter and receiver. This kind of problem is best resolved by repeaters.

Basic Principle Of Microwave

Passive Repeater

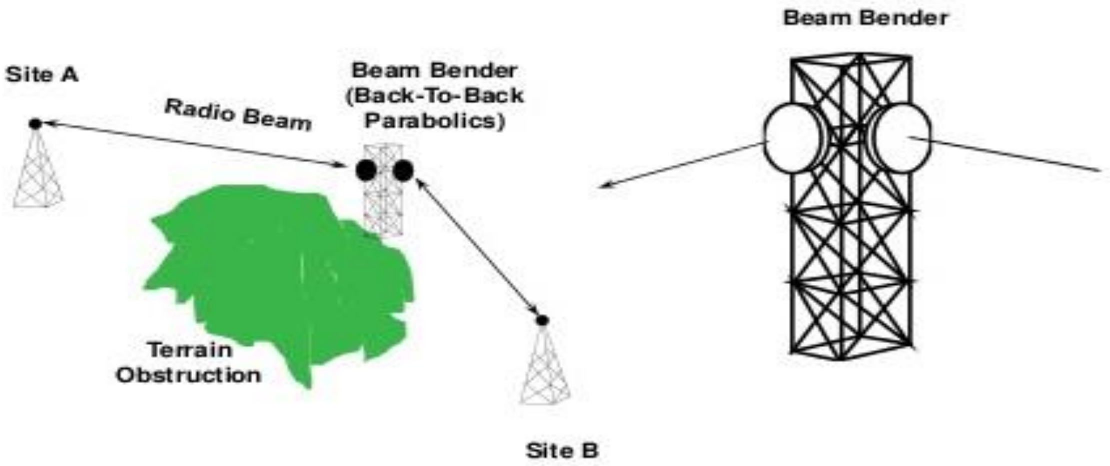
It is a device used to re-radiate the intercepted microwave energy without the use of additional electronic power. It also has the ability to redirect intercepted microwave radars to the other direction.



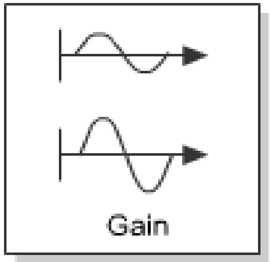
Basic Principle Of Microwave

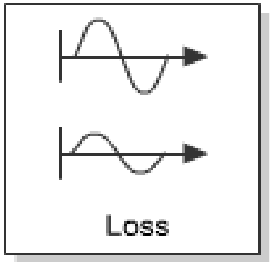
Active Repeater

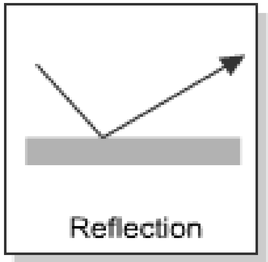
It is a receiver and a transmitter placed back to back or in tandem with microwave repeaters. There are two types of active repeater namely: baseband and heterodyne or IF. It receives the signal, amplifies and reshapes it, then retransmits the signal to the next station.

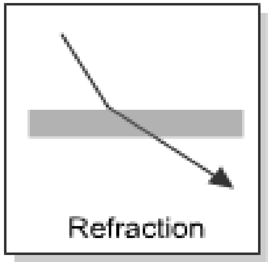


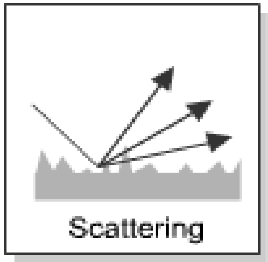
Microwave signal attenuation

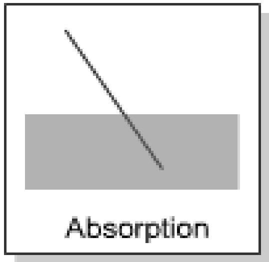

Gain


Loss


Reflection


Refraction

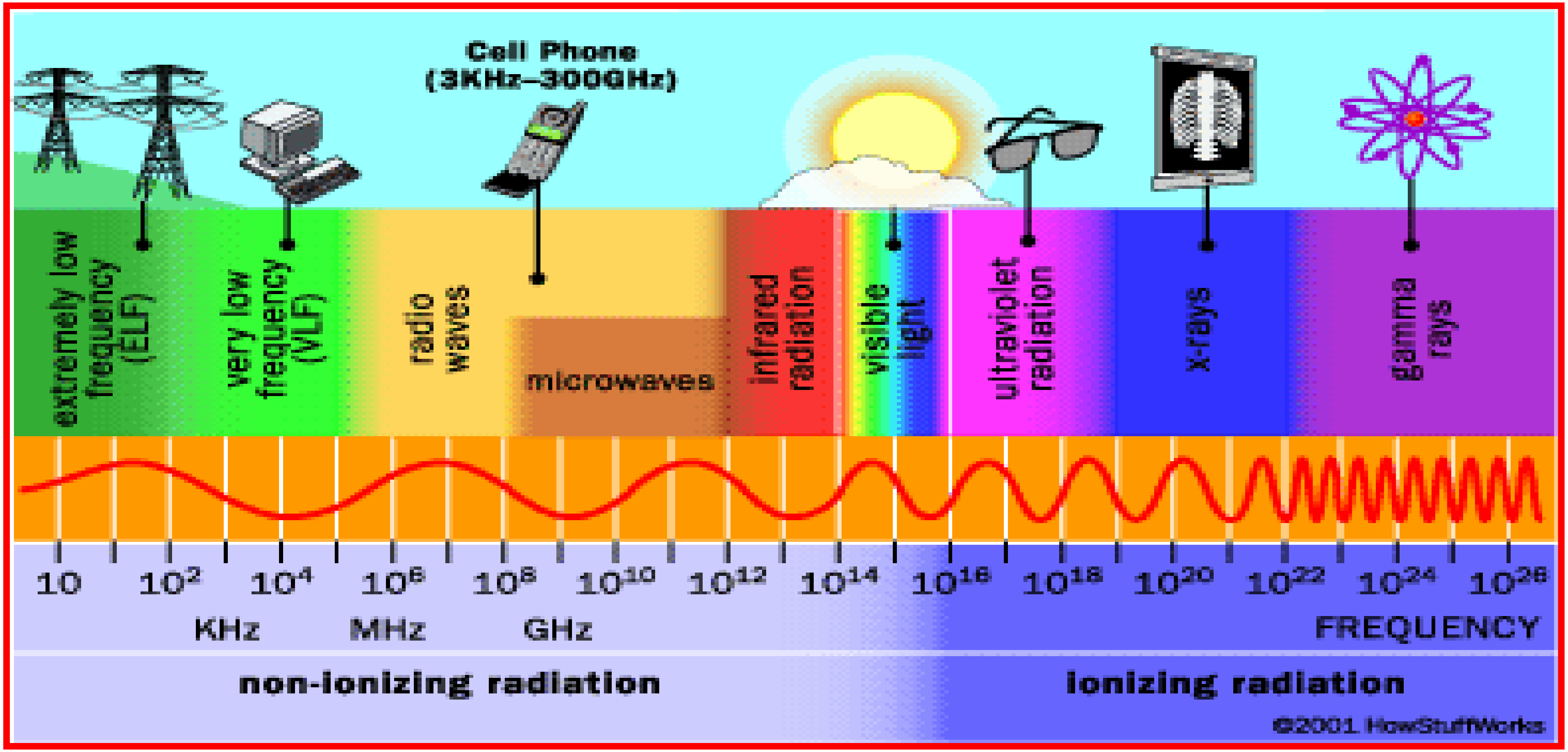

Scattering


Absorption

Properties of Microwaves

- Microwave is an electromagnetic radiation of short wavelength.
- They can reflect by conducting surfaces just like optical waves since they travel in straight line.
- Microwave currents flow through a thin outer layer of an ordinary cable.
- Microwaves are easily attenuated within short distances.
- They are not reflected by ionosphere.

Ionizing and non – ionizing radiations of electromagnetic energy



Ionizing radiation

- Ionization is a process by which electrons are stripped from atoms and molecules and this can produce molecular changes that can lead to damage in biological tissue, including effects on DNA, the genetic material.

- This process requires interaction with high levels of electromagnetic energy to ionize biological material, this include X-radiation and gamma radiation.

- The energy levels associated with RF and microwave radiations are not great enough to cause the ionization of atoms and molecules, therefore, it is a type of non-ionizing radiation.

Non ionizing radiation

- Microwave energy is non-ionizing electromagnetic radiation.
- Ionizing radiation messes up molecules, non-ionizing radiation merely heats them.
- In general, it does not have sufficient energy to kick an electron off an atom thus producing charged particle in a body and cause biological damage.
- The only proven harmful effect from exposure to microwave (or RF) radiation is thermal.
- RF radiation can enter deep into the body and heat human organs.

Effect of microwaves in human body

- The blood vessels are dilating and the blood flow increases substantially as the thermoregulatory mechanism is activated in order to keep the body temperature constant.

- With rising body temperature the metabolic rate rises, which may lead to Stress-Adaptation-Fatigue Syndrome.

Effects produced by the electromagnetic waves at different frequency level

- Above 10 GHz (3 cm wavelength or less) heating occurs mainly in the outer skin surface.
- From 3 GHz to 10 GHz (10 cm to 3 cm) the penetration is deeper and heating higher
- From 150 MHz to about 1 GHz (200 cm to 25 cm wavelength), penetration is even deeper and because of high absorption, deep body heating can occur.
- Any part of the body that cannot dissipate heat efficiently or is heat sensitive may be damaged by microwave radiation of sufficient power.

Measurement of Microwave exposure

- The microwave energy exposure is measured in terms of SAR (Specific Absorption Rate) or PD (Power Density).

- SAR is the energy which is absorbed in a unit of mass or volume of the body per unit time.

- The standards that limit microwave exposure were set at 0.4 W/kg SAR for occupational and 0.08W/Kg for public exposure.

- The averaging time for determination of SAR was 6 minutes. Power density is the energy absorbed per unit area in unit time. The high power microwaves definitely cause some adverse effects in the human system.

Effects of Microwave energy

Power level (mW /cm2)	Long-term effect on human body	Remarks
0.01	Nothing	
0.1	Nothing	
1	Nothing	
5	Nothing	Accepted standard for microwave oven leakage
10	Nothing	Accepted standard for maximum continuous exposure to radiated emissions (cell phones, etc.)
30	You can feel heat	
100	Cataracts can be produced	Summer sunlight is at this level
1000	Pain is induced	

Do you know YOUR Brain can be FRIED???

What do Microwave Ovens, Cell Phones and Cordless Phones have in common?

They all emit... **Dangerous Microwave Radiation!**

The **GOOD NEWS** is... with Microwave radiation you can...

- Boil water
- Cook meat
- Fry eggs

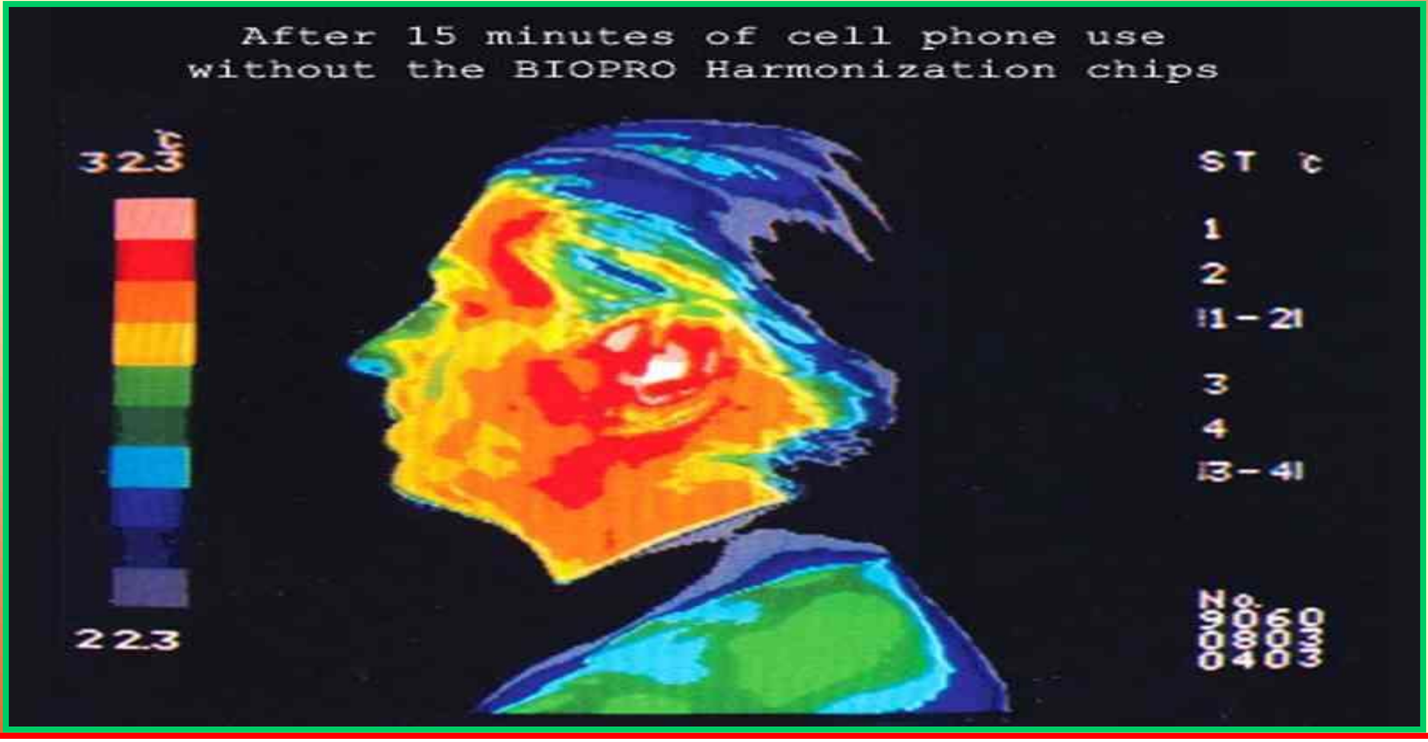
The **BAD NEWS** is...
with Microwave radiation you can...

Fry Your Brain

Your head and brain heat up significantly when you talk on your cell phone or cordless phone.

Want proof?

After 15 minutes of using a cell phone, the ***orange, red and pink show significant, dangerous HEAT*****.** Most heat is generated in your ear canal, which is directly connected to YOUR BRAIN



Proof enough?

Some scientists estimate that you are now exposed daily to 100 million times the electromagnetic frequency (Micro wave) radiation of your grandparents.

So….

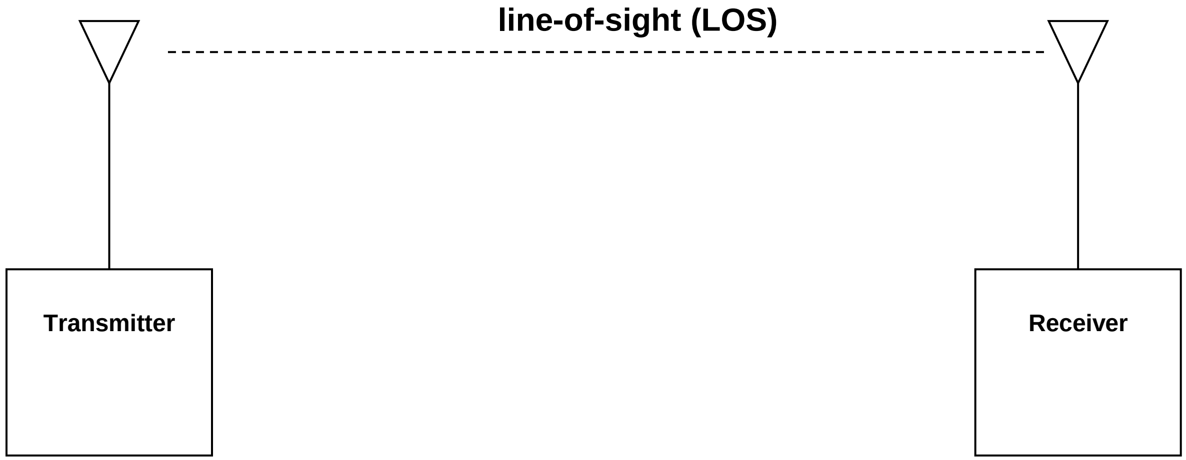
AVOID FREQUENT USE OF CELL PHONES!!!

Lecture-3-

TRANSMISSION IMPAIRMENT (PROBLEMS)

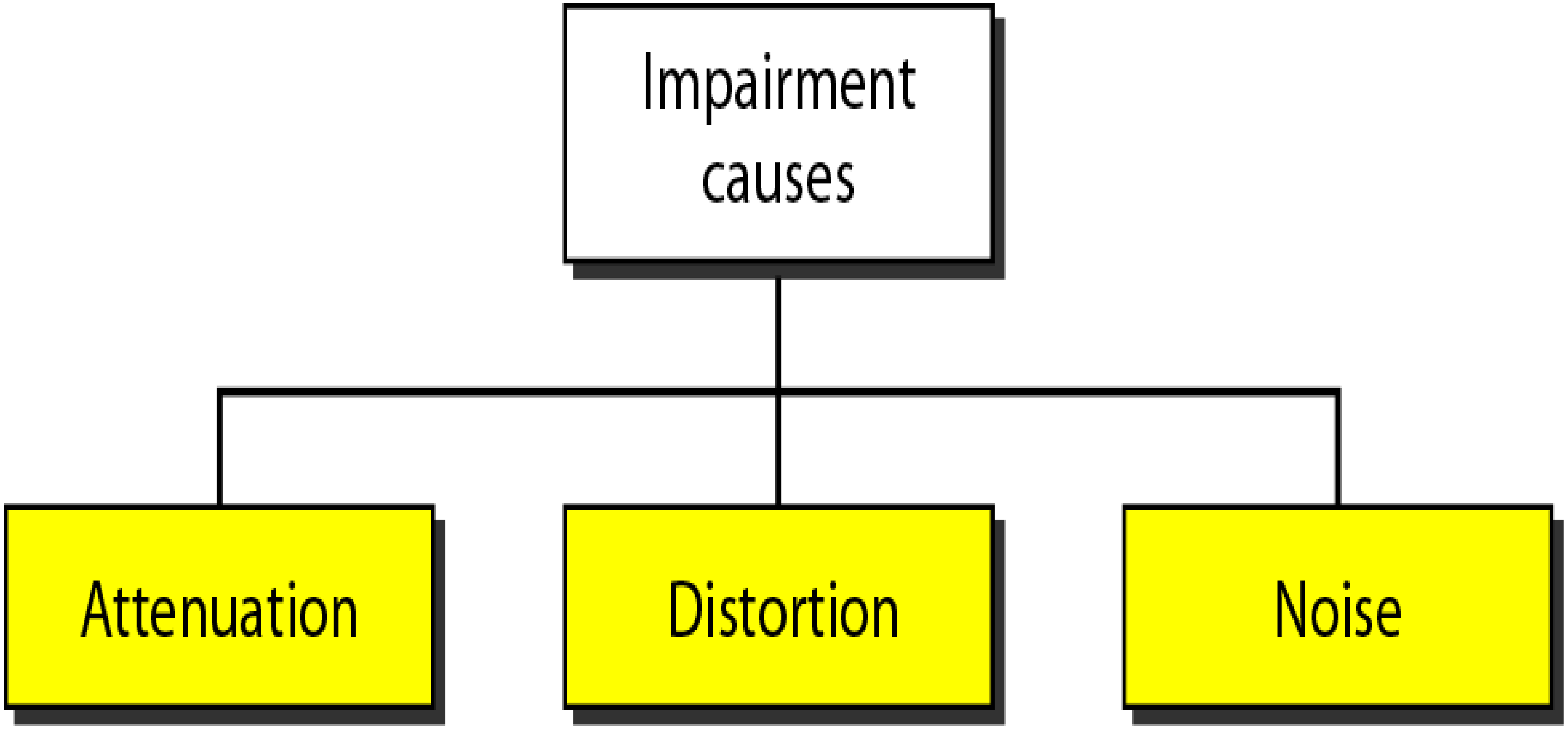
Wireless Communication Channel

In the channel on which wireless communication signals travel, the signal experiences attenuation, distortion, and noise. The path through which the signal propagates from the transmitter to the receiver may be a line-of-sight (LOS).Signals travel through transmission media, which are not perfect. The imperfection causes signal impairment. This means that the signal at the beginning of the medium is not the same as the signal at the end of the medium. What is sent is not what is received.



- For analog signal, these impairments cause various modifications that degrade the signal quality.

- For digital signal, due to bit error a binary 1 maybe changed into binary 0 and vice versa.



Impairment causes

Attenuation

Distortion

Noise

Attenuation

- Means loss of energy, thus weaker signal.
- When a signal travels through a medium it loses energy overcoming the resistance of the medium.
- Amplifiers are used to compensate for this loss of energy by amplifying the signal.

Measurement of Attenuation

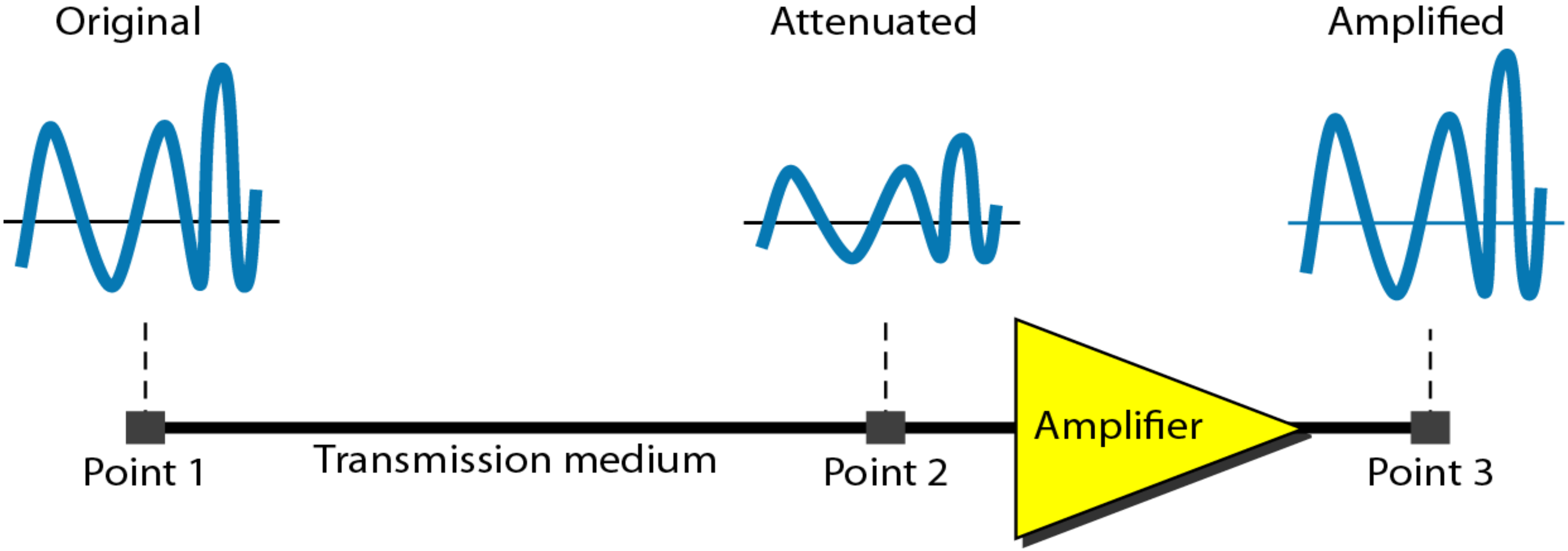
- To show the loss or gain of energy the unit “decibel” is used.

$$dB = 10\log_{10}P_2/P_1$$

P_1 - input signal

P_2 - output signal

In the Medium



Example-1

Suppose a signal travels through a transmission medium and its power is reduced to one-half. This means that P_2 is $(1/2)P_1$. In this case, the attenuation (loss of power) can be calculated as

$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{0.5 P_1}{P_1} = 10 \log_{10} 0.5 = 10(-0.3) = -3 \text{ dB}$$

Example-2

A signal travels through an amplifier, and its power is increased 10 times. This means that $P_2 = 10P_1$. In this case, the amplification (gain of power) can be calculated as

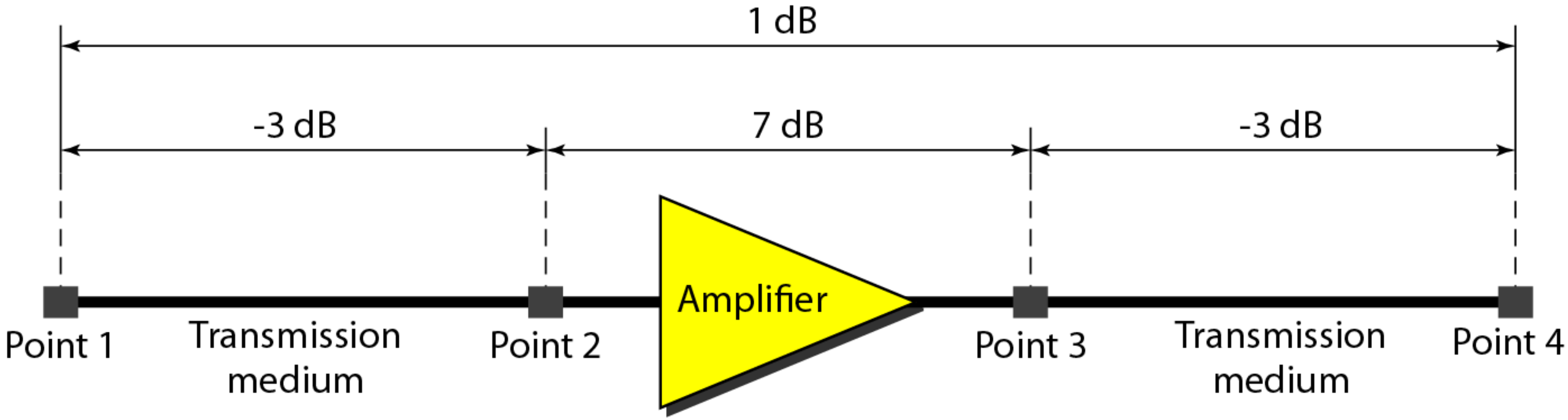
$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{10P_1}{P_1}$$

$$= 10 \log_{10} 10 = 10(1) = 10 \text{ dB}$$

Example -3

One reason that engineers use the decibel to measure the changes in the strength of a signal is that decibel numbers can be added (or subtracted) when we are measuring several points (cascading) instead of just two. In the figure below a signal travels from point 1 to point 4. In this case, the decibel value can be calculated as:

$$\boxed{dB = -3 + 7 - 3 = +1}$$

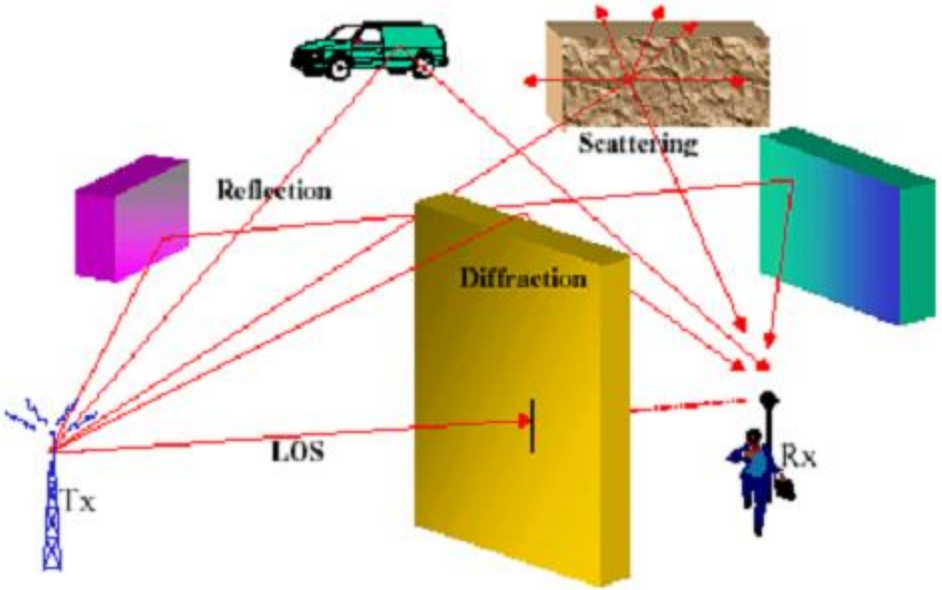


Fading

In wireless communications, fading is variation of the attenuation of a signal with various variables. These variables include time, geographical position, and radio frequency. Fading is often modeled as a random process. A fading channel is a communication channel that experiences fading. In wireless systems, fading may either be due to multipath propagation, referred to as multipath induced fading, weather (particularly rain), or shadowing from obstacles affecting the wave propagation, sometimes referred to as shadow fading.

The presence of reflectors in the environment surrounding a transmitter and receiver create multiple paths that a transmitted signal can traverse. As a result, the receiver sees the superposition of multiple copies of the transmitted signal, each traversing a different path. Each signal copy will experience differences in attenuation, delay and phase shift while travelling from the source to the receiver. This can result in either constructive or destructive interference, amplifying or attenuating the signal power seen at the receiver. Strong destructive interference is frequently referred to as a deep fade and may result in temporary failure of communication due to a severe drop in the channel signal-to-noise ratio.

- **Reflection - caused by smooth surface with very large dimensions compared to avelength.**
- **Diffraction- Obstruction caused by a dense body with large dim. > wavelength. EM waves get bend around objects. Reason for shadowing and RF energy being present without LOS.**
- **Scattering- Large rough surface with dim. ~wavelength**



Causes of Attenuation

Long distance Attenuation

The signal gets attenuated as it propagates through the medium and longer the distance it travels the more it gets attenuated and finally after propagating through a long distance, the signal get vanished completely.

So, as the signal travels, it gets attenuated exponentially. In general, the maximum transmission distance between two stations is 50 km but when the signal propagates through the reflected surfaces such as rivers, oceans, lakes, sea etc., then the maximum distance it can propagate is only about 35 km.

Atmospheric Attenuation

- *Rain Attenuation*

Another important source of microwave signal attenuation is rain. When the rain rate intensity is high, then the microwave signal gets significantly attenuated. For example, it is observed that at high rain intensity (150 mm/hr), the fading of RF signal at 2.4 GHz reached the value 0.02 dB/km.

- *Attenuation due to fog, wind, snow, hurricane etc…*

There are other factors that affect the signal degradation such as fog, wind, hurricane etc. but these effects are not that much significant.

- *Attenuation due to trees*

Another factor that engenders the signal attenuation is the tree. The signal often has to propagate via dense forest. The absorption of signal is significant while propagating through the dense forest. Isolated trees are not the problem for microwave signal as their individual effect of attenuation is very small.

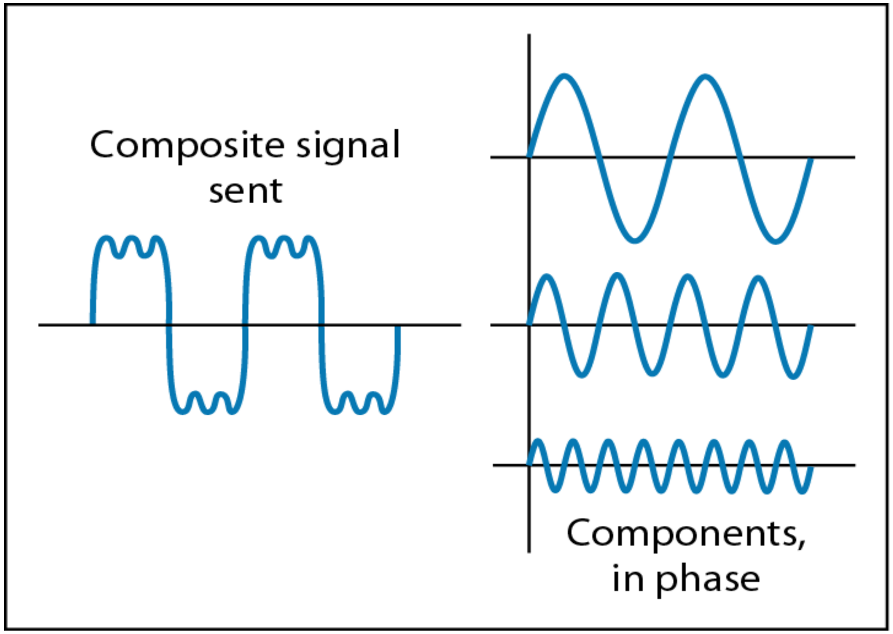
In one experiment, it is observed that the trees having wet leaves can cause huge attenuation as compared to the trees bearing the dry leaves. It is observed that the signal can get attenuated up to 0.4 dB/m at 3 GHz. So there is a huge path loss if the signal passes through several hundreds meters through the jungle.

- *Attenuation due to defective parts of microwave communication system*

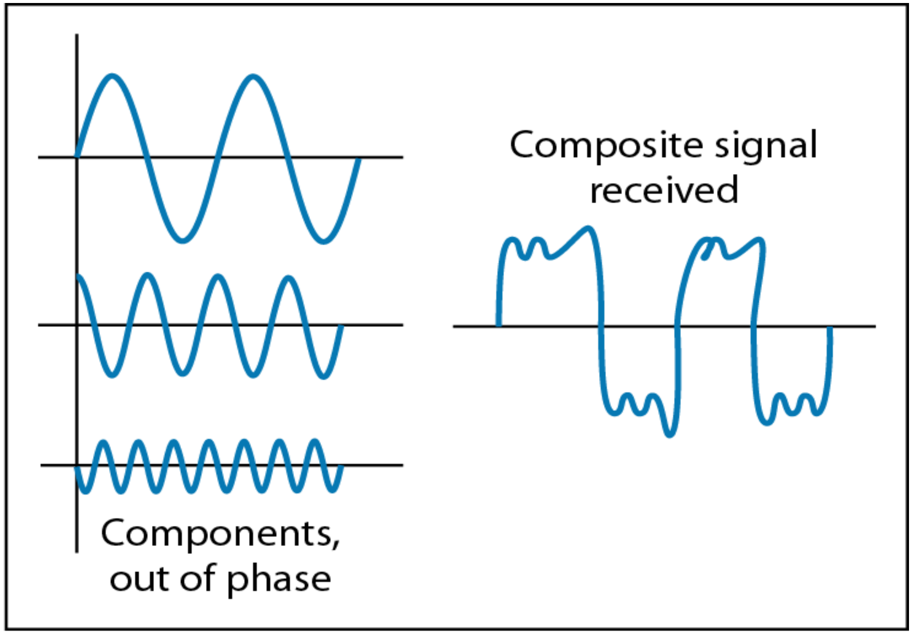
Attenuation can also be occurred due to the defective parts of microwave communication system such as microwave antenna, ODU (Outdoor Unit), IF cable (the cable connecting ODU and the IDU (Indoor Unit), connectors etc.

Distortion

- ***Means that the signal changes its form or shape***
- ***Distortion occurs in composite signals***
- ***Each frequency component has its own propagation speed traveling through a medium.***
- ***The different components therefore arrive with different delays at the receiver.***
- ***That means that the signals have different phases at the receiver than they did at the source.***



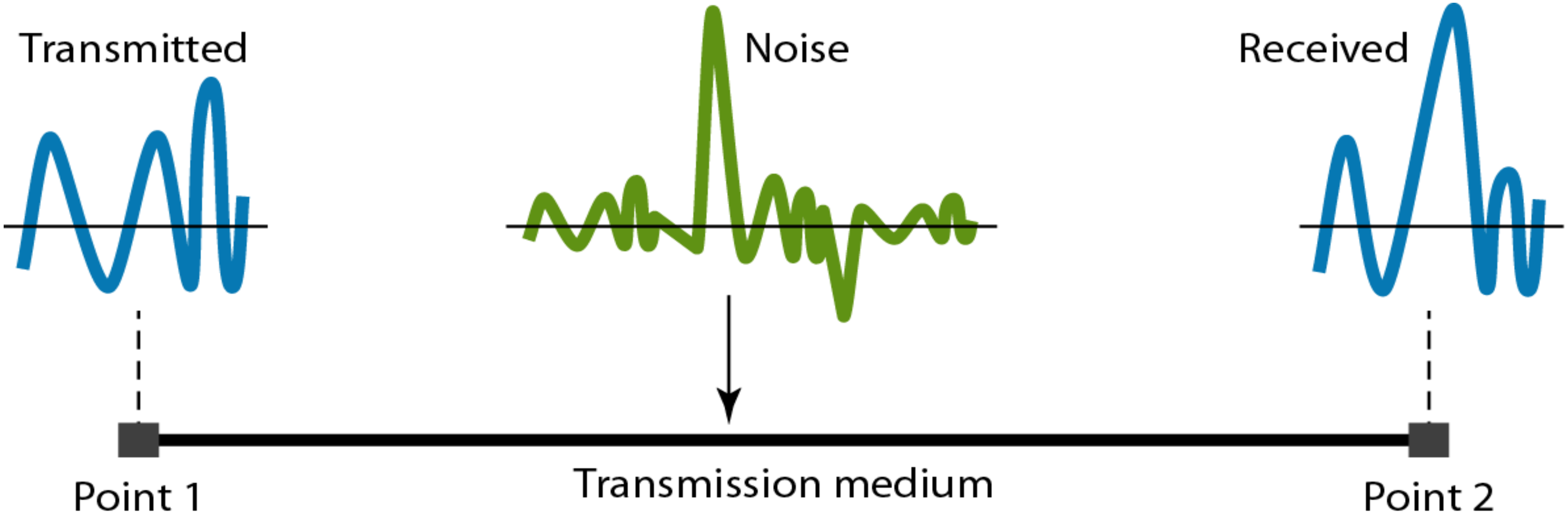
At the sender



At the receiver

Noise

- **There are different types of noise**
  - **Thermal - Random motion of electrons in the wire creates an extra signal.**
  - **Induced - From motors and appliances, devices act are transmitter antenna and medium as receiving antenna.**
  - **Crosstalk - Same as above but between two wires .**
  - **Impulse - Spikes that result from power lines, lightning, etc.**


Transmitted
Noise
Received
Point 1
Transmission medium
Point 2

Signal to Noise Ratio (SNR)

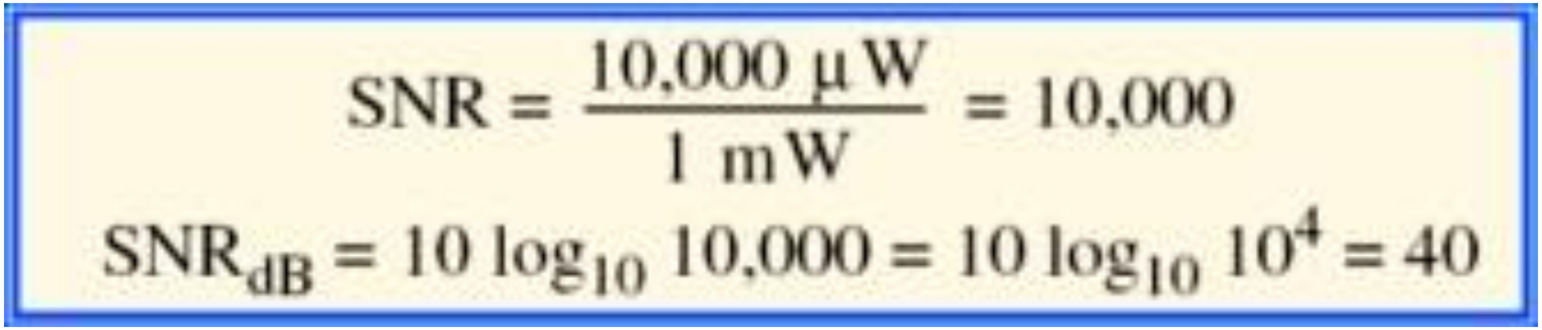
- ***To measure the quality of a system the SNR is often used. It indicates the strength of the signal wrt the noise power in the system.***
- ***It is the ratio between two powers.***
- ***It is usually given in dB and referred to as $SNR_{dB.}$***

Example-4

The power of a signal is 10 mW and the power of the noise is 1 μW; what are the values of SNR and SNR_{dB} ?

Solution

The values of SNR and SNR_{dB} can be calculated as follows:



$$\mathrm{SNR} = \frac{10{,}000\ \mu\mathrm{W}}{1\ \mathrm{mW}} = 10{,}000$$

$$\mathrm{SNR}_{\mathrm{dB}} = 10 \log_{10} 10{,}000 = 10 \log_{10} 10^4 = 40$$

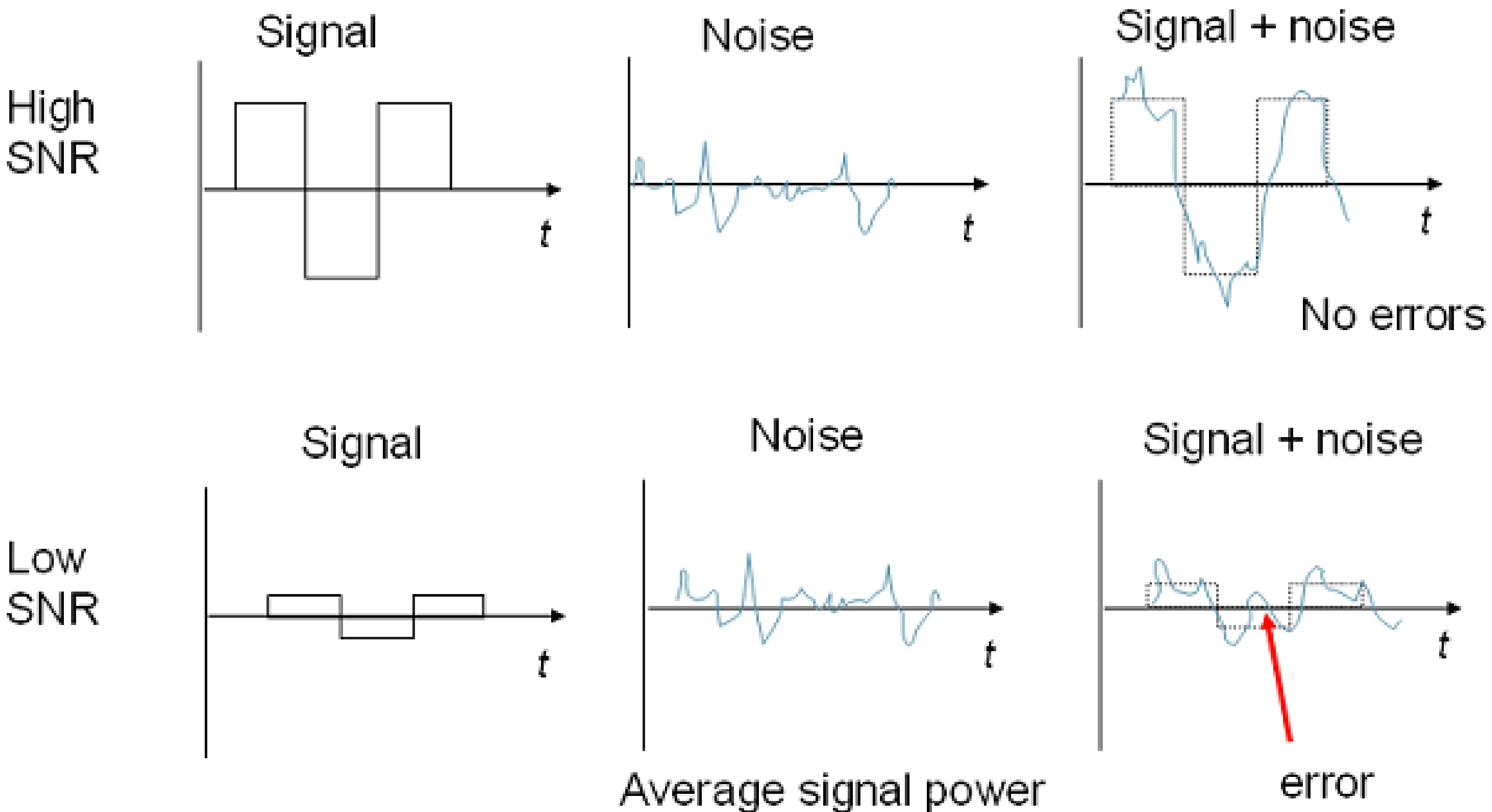
Example -5

The values of SNR and SNR$_{dB}$ for a noiseless channel are

$$\text{SNR} = \frac{\text{signal power}}{0} = \infty$$

$$\text{SNR}_{\text{dB}} = 10 \log_{10} \infty = \infty$$

We can never achieve this ratio in real life; it is an ideal.



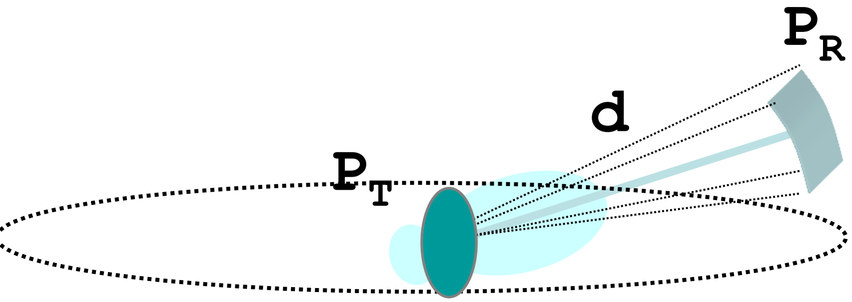
$$\text{SNR} = \frac{\text{Average signal power}}{\text{Average noise power}}$$

Lecture-4-

Free Space Losses

In telecommunication, free-space path loss (FSPL) is the loss in signal strength of an electromagnetic wave that would result from a line-of-sight path through free space (usually air), with no obstacles nearby to cause reflection or diffraction. It does not include factors such as the gain of the antennas used at the transmitter and receiver, nor any loss associated with hardware imperfections. A discussion of these losses may be found in the article on link budget.

Free Space Propagation Model



$$P_{Di} = \frac{P_T}{4\pi d^2} \; W/m^2$$

Isotropic power density

$$P_D = \frac{P_T G_T}{4\pi d^2}$$

Power density along the direction of maximum radiation

$$P_R = P_D A_{eff}$$

Power received by Antenna

$$P_R = \frac{P_T G_T}{4\pi d^2} A_{eff}$$

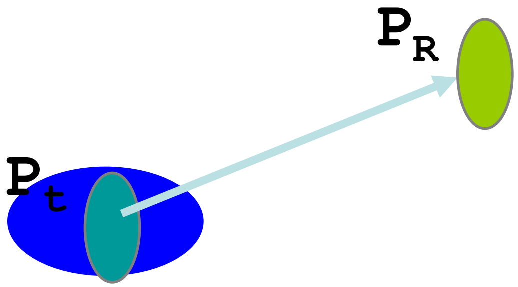
$$\frac{A_{eff}}{G} = \frac{\lambda^2}{4\pi}$$

Predict received signal strength when the transmitter and receiver have a clear line-of-sight path between them

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d} \right)^2$$

Also known as Friis free space formula

Path Loss (relative measure)



$$\frac{P_R}{P_T} = G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2$$

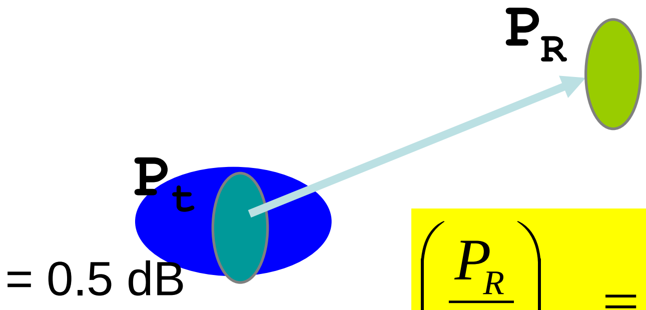
$$\frac{P_R}{P_T} = G_T G_R \frac{0.57*10^{-3}}{(df)^2}$$

f is in MHz
d is in Km

$$\left(\frac{P_R}{P_T}\right)_{dB} = (G_T)_{dB} + (G_R)_{dB} - (32.5 + 20\log_{10} d + 20\log_{10} f)$$

Path Loss represents signal attenuation (measured on dB) between the effective transmitted power and the receive power (excluding antenna gains)

Path Loss (Example)



Assume that antennas are isotropic.
Calculate receive power (in dBm) at free space distance of 100m from the antenna. What is P_R at 10Km? f= 900 MHz.

$$\left(\frac{P_R}{P_T}\right)_{dB} = (G_T)_{dB} + (G_R)_{dB} - (32.5 + 20\log_{10} d + 20\log_{10} f)$$

$$\left(\frac{P_R}{P_T}\right)_{dB} = 0 + 0 - (32.5 + 20\log_{10} 0.1 + 20\log_{10} 900)$$

59

-20 (for d = 0.1)

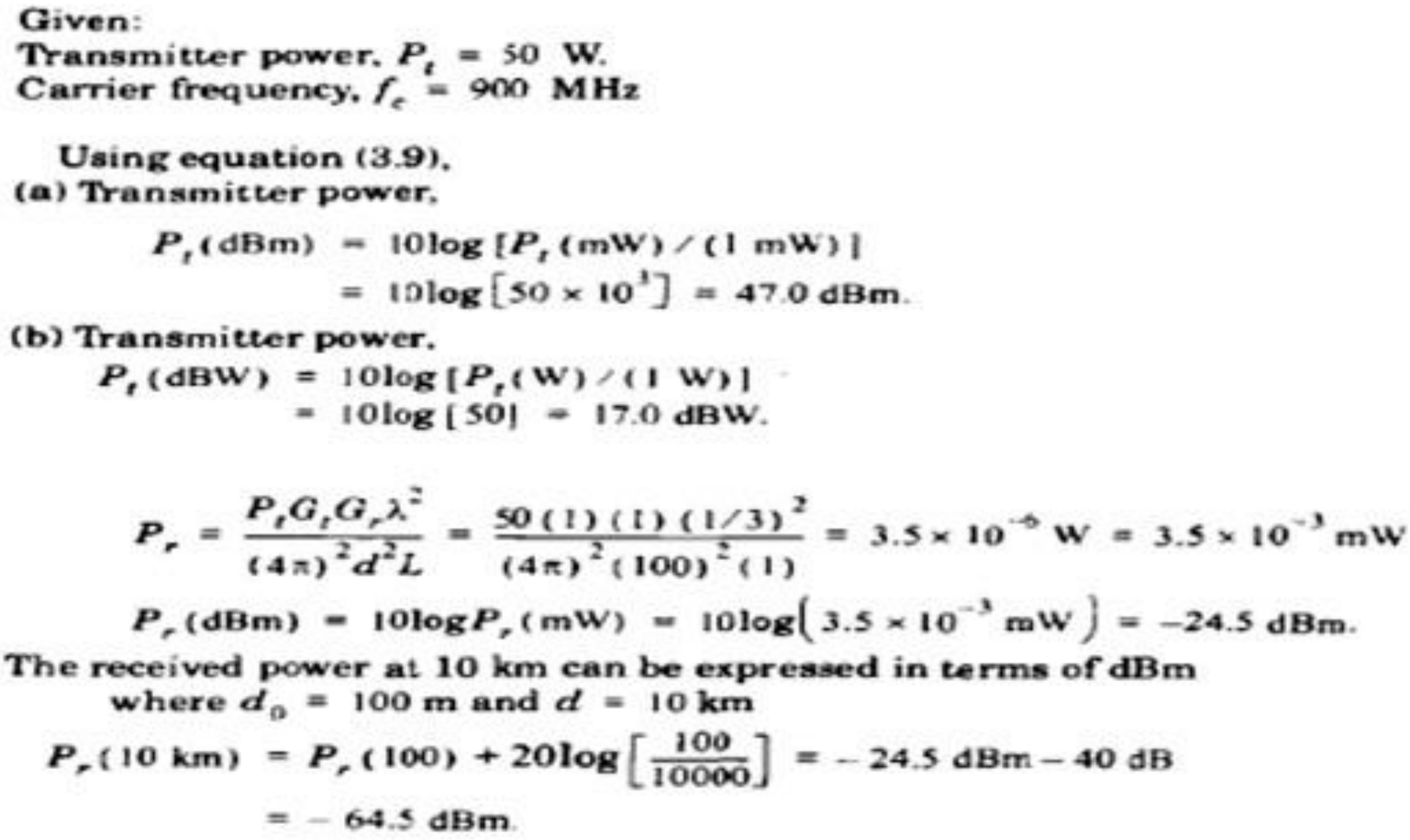
$$\left(\frac{P_R}{P_T}\right)_{dB} = -71.5dB$$

20 (for d = 10)

$$\left(\frac{P_R}{P_T}\right)_{dB} = -111.5dB$$

Example: If a transmitter produces 50 watts of power, express the transmit power in units of (a) dBm, and (b) dBW. If 50 watts is applied to a unity gain antenna with a 900 MHz carrier frequency, find the received power in dBm at a free space distance of 100 m from the antenna, What is P_r (10 km)? Assume unity gain for the receiver antenna.

Solution



Given:
Transmitter power, $P_t = 50$ W.
Carrier frequency, $f_c = 900$ MHz

Using equation (3.9),
(a) Transmitter power,

$$P_t(\text{dBm}) = 10\log[P_t(\text{mW})/(1\text{ mW})]$$
$$= 10\log\left[50 \times 10^3\right] = 47.0\text{ dBm.}$$

(b) Transmitter power,

$$P_t(\text{dBW}) = 10\log[P_t(\text{W})/(1\text{ W})]$$
$$= 10\log[50] = 17.0\text{ dBW.}$$

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} = \frac{50(1)(1)(1/3)^2}{(4\pi)^2(100)^2(1)} = 3.5 \times 10^{-6}\text{ W} = 3.5 \times 10^{-3}\text{ mW}$$

$$P_r(\text{dBm}) = 10\log P_r(\text{mW}) = 10\log\left(3.5 \times 10^{-3}\text{ mW}\right) = -24.5\text{ dBm.}$$

The received power at 10 km can be expressed in terms of dBm where $d_0 = 100$ m and $d = 10$ km

$$P_r(10\text{ km}) = P_r(100) + 20\log\left[\frac{100}{10000}\right] = -24.5\text{ dBm} - 40\text{ dB}$$
$$= -64.5\text{ dBm.}$$

Lecture-5-

Transmission Line

Transmission Lines

- A transmission line (TL) is a distributed-parameter network, where voltages and currents can vary in magnitude and phase over the length of the line.

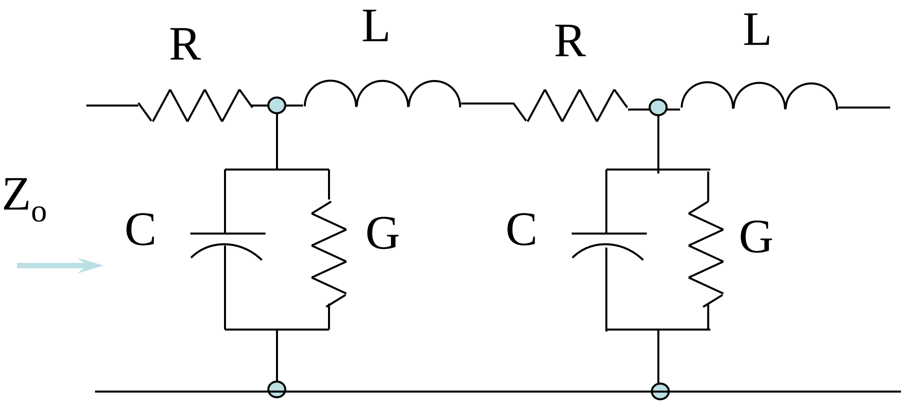
- TL has two conductors in parallel with a dielectric separating them.

- They transmit TEM waves inside the lines.

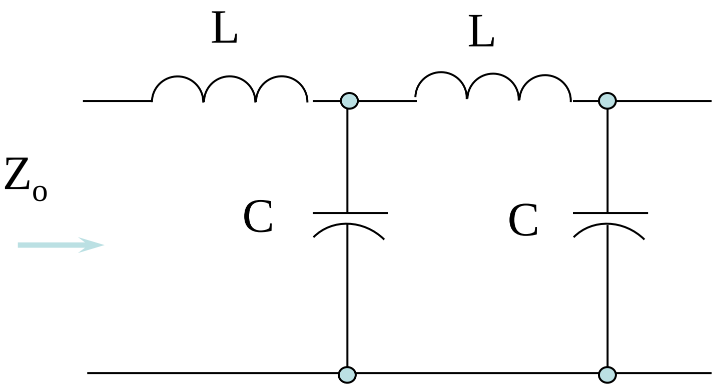
Lumped Element Model for a Transmission Line

- Transmission lines usually consist of 2 parallel conductors.
- A short segment Δz of transmission line can be modeled as a lumped-element circuit.

Transmission Line Equivalent Circuit



“Lossy” Line



Lossless Line

$$Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

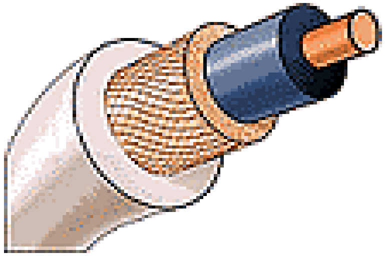
$$Z_o = \sqrt{\frac{L}{C}}$$

R = series resistance per unit length for both conductors.
L = series inductance per unit length for both conductors.
G = shunt conductance per unit length.
C = shunt capacitance per unit length.

Types of Transmission Lines

- Differential or balanced lines (where neither conductor is grounded): e.g. twin lead, twisted-cable pair, and shielded-cable pair.

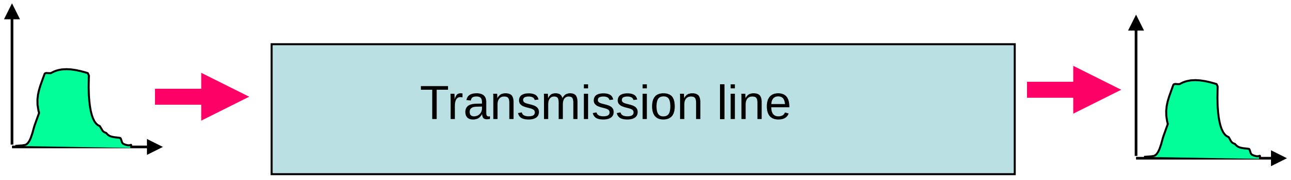
- Single-ended or unbalanced lines (where one conductor is grounded): e.g. concentric or coaxial cable.



- Transmission lines for microwave use: e.g. striplines, microstrips, and waveguides.

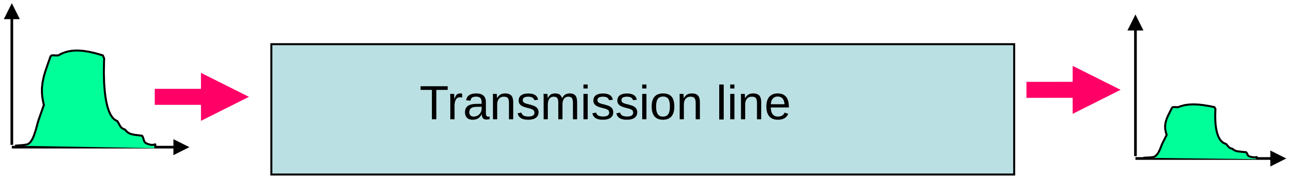
Different cases of TL

- Lossless



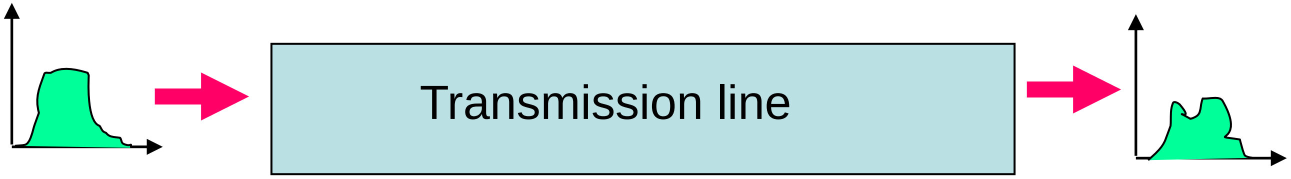
Transmission line

- Distortionless



Transmission line

- Lossy



Transmission line

Notes on Transmission Line

- Characteristics of a line is determined by its primary electrical constants or distributed parameters: R (Ω/m), L (H/m), C (F/m), and G (S/m).
- Characteristic impedance, Z_o, is defined as the input impedance of an infinite line or that of a finite line terminated with a load impedance, $Z_L = Z_o$.
- The characteristic impedance of a **lossless** transmission line is purely **real** (i.e., Im{Z0} =0).

Transmission-Line Wave Propagation

Electromagnetic waves travel at < c in a transmission line because of the dielectric separating the conductors. The velocity of propagation is given by:

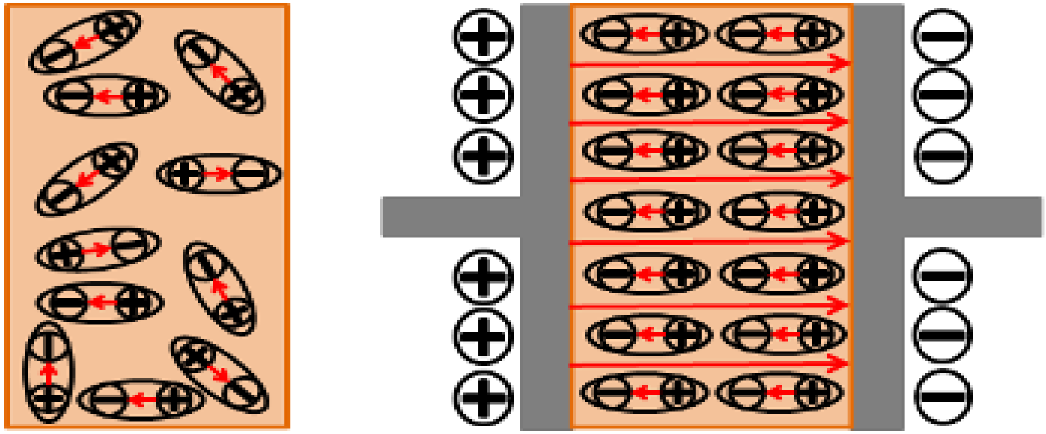
$$v = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\varepsilon_r}} \quad \text{m/s}$$

Velocity factor, VF, is defined as:

$$VF = \frac{v}{c} = \frac{1}{\sqrt{\varepsilon_r}}$$

Electric Permittivity

- A material with high permittivity polarizes more in response to an applied electric field than a material with low permittivity, thereby storing more energy in the material.
- The molecules normally align randomly with each other in a substance, but when an external electric field is introduced they align themselves in such a way that the electric field their dipole moments produce resists the external electric field.



Incident & Reflected Waves

- For an infinitely long line or a line terminated with a matched load, no incident power is reflected. The line is called a flat or nonresonant line.
- For a finite line with no matching termination, part or all of the incident voltage and current will be reflected.

Reflection Coefficient

The reflection coefficient is defined as:

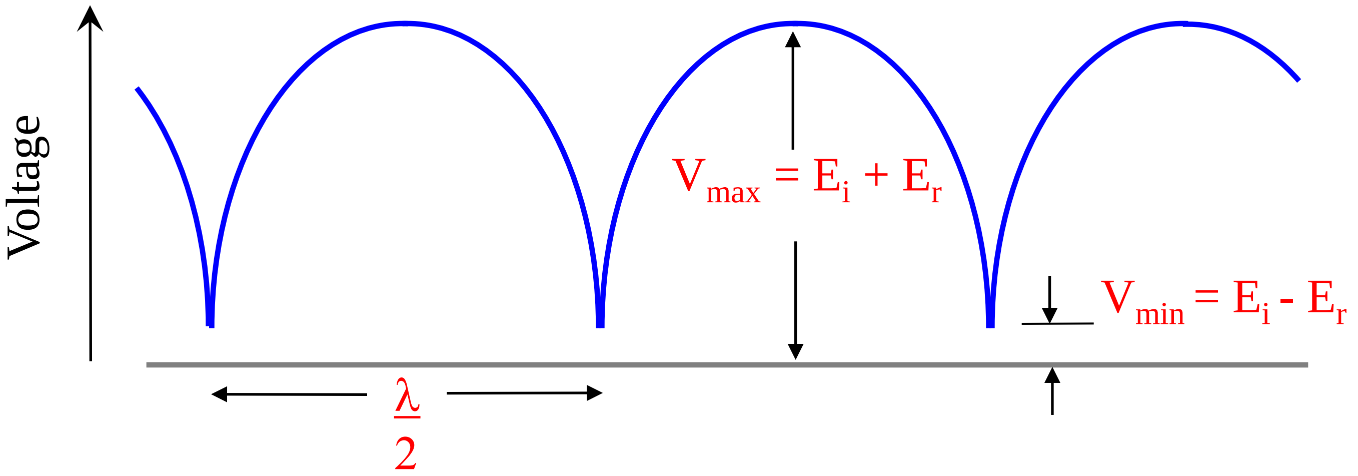
$$\Gamma = \frac{E_r}{E_i} \quad or \quad \frac{I_r}{I_i}$$

It can also be shown that:

$$\Gamma = \frac{Z_L - Z_o}{Z_L + Z_o} = |\Gamma| \angle \phi$$

Note that when $Z_L = Z_o$, $\Gamma = 0$; when $Z_L = 0$, $\Gamma = -1$; and when Z_L = open circuit, $\Gamma = +1$.

Standing Waves



With a mismatched line, the incident and reflected waves set up an interference pattern on the line known as a standing wave (1< VSWR<∞). the distance between 2 successive voltage maxima (or minima) is $l = \lambda/2$, while the distance between a maximum and a minimum is $l = \lambda/4$.

The standing wave ratio is :

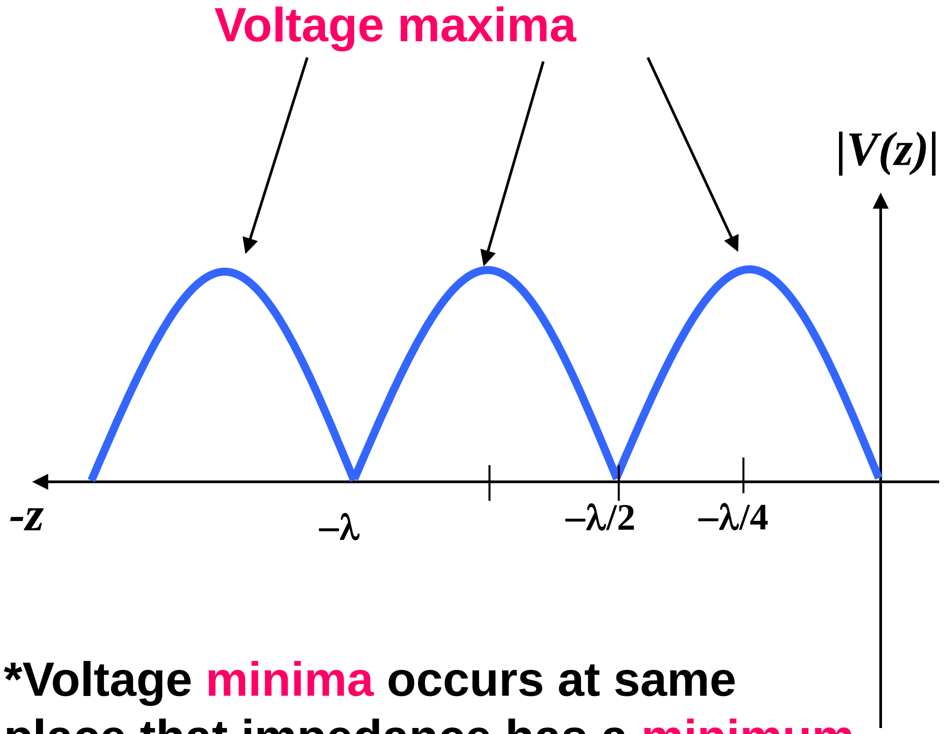
$$SWR = \frac{V_{max}}{V_{min}} = \frac{1+|\Gamma|}{1-|\Gamma|}$$

and

$$|\Gamma| = \frac{VSWR-1}{VSWR+1}$$

Standing Waves -Short

Shorted Line ($Z_L=0$), we had

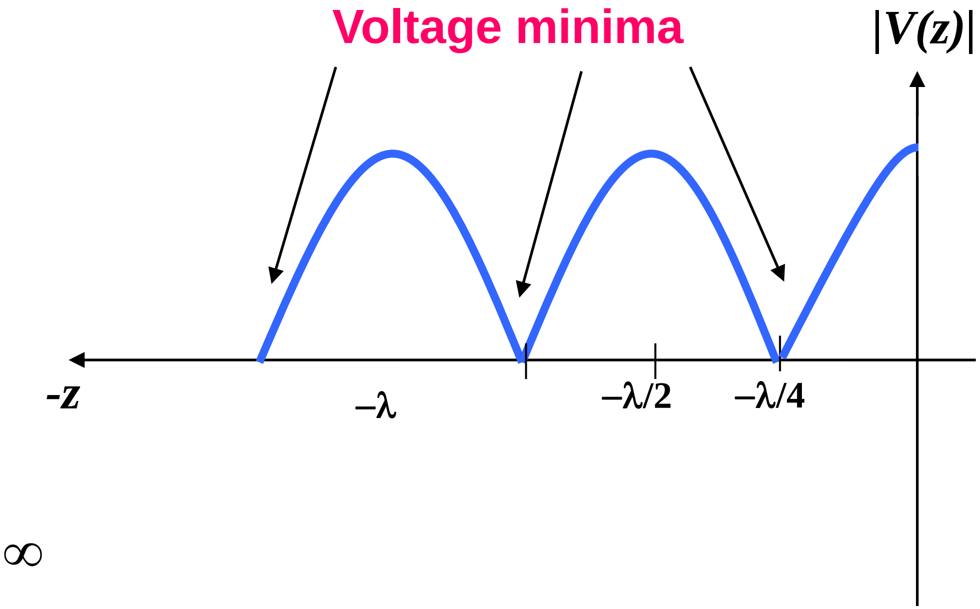


***Voltage minima occurs at same place that impedance has a minimum on the line**

Standing Waves -Open

Open Line ($Z_L = \infty$) ,we had

- So substituting in $V(z)$

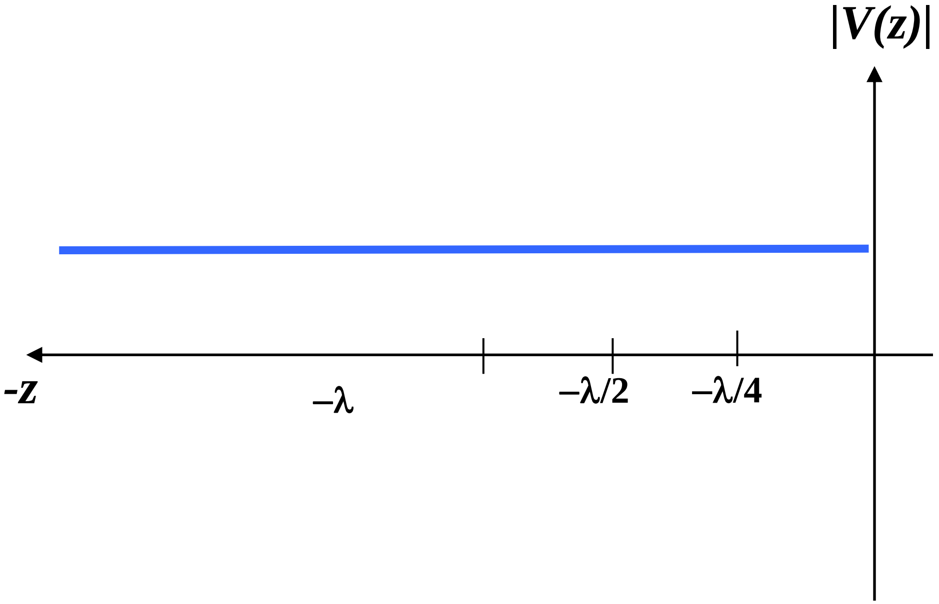


$$Z_{in} = -jZ_o \cot \beta l\,, \quad \Gamma_L = +1, \quad SWR = \infty$$

Standing Waves -Matched

Matched Line ($Z_L = Z_o$), we had

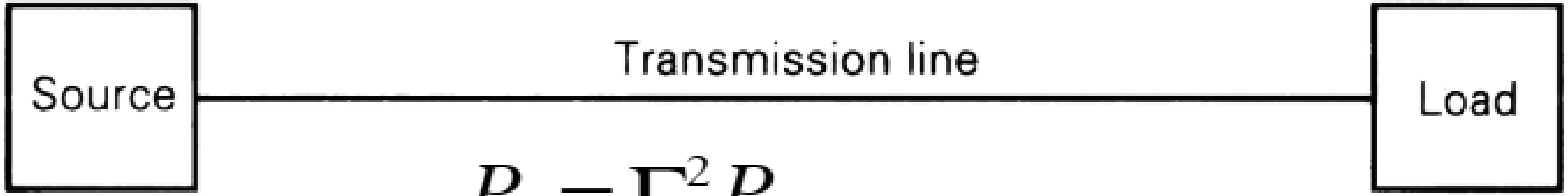
$$Z_{in} = Z_o\ , \quad \Gamma_L = 0, \quad SWR = 1$$



Example: Evaluate the VSWR for the coaxial cable has the reflection coefficient (Γ = -0.1).

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} = \frac{1+|-0.1|}{1-|-0.1|} = 1.2$$

Note: if two cables were matched, the *VSWR* would be 1.



$$P_r = \Gamma^2 P_i$$

$$P_L = P_i(1-\Gamma^2)$$

$$P_L = \frac{4SWR}{(1+SWR)^2} P_i$$

P_r = reflected power
P_i = incident power
P_L = power delivered to load

Other Formulas

When the load is purely resistive:
(whichever gives an SWR > 1)

$$SWR = \frac{Z_L}{Z_o} \; or \; \frac{Z_o}{Z_L}$$

Return Loss, RL = Fraction of power reflected
= $|\Gamma|^2$, or -20 log $|\Gamma|$ dB
So, $P_r = |\Gamma|^2 P_i$

Mismatched Loss, ML = Fraction of power transmitted/absorbed = 1 - $|\Gamma|^2$ or -10 log$(1-|\Gamma|^2)$ dB
So, $P_t = P_i (1 - |\Gamma|^2) = P_i - P_r$

Transmission-Line Input Impedance

The input impedance at a distance ℓ from the load is:

$$Z_i = Z_o \frac{Z_L + jZ_o \tan(\beta l)}{Z_o + jZ_L \tan(\beta l)}$$

When the load is a short circuit, $Z_i = jZ_o \tan(\beta \ell)$.

For $0 \longrightarrow \ell < \lambda/4$, shorted line is inductive.

For $\ell = \lambda/4$, shorted line = a parallel resonant circuit.

For $\lambda/4 < \ell \longrightarrow \lambda/2$, shorted line is capacitive.

T-L Input Impedance (cont'd)

When the load is an open circuit, $Z_i = -jZ_o \cot(\beta\ell)$

For $0 < \ell < \lambda/4$, open circuited line is capacitive.

For $\ell = \lambda/4$, open-line = series resonant circuit.

For $\lambda/4 < \ell < \lambda/2$, open-line is inductive.

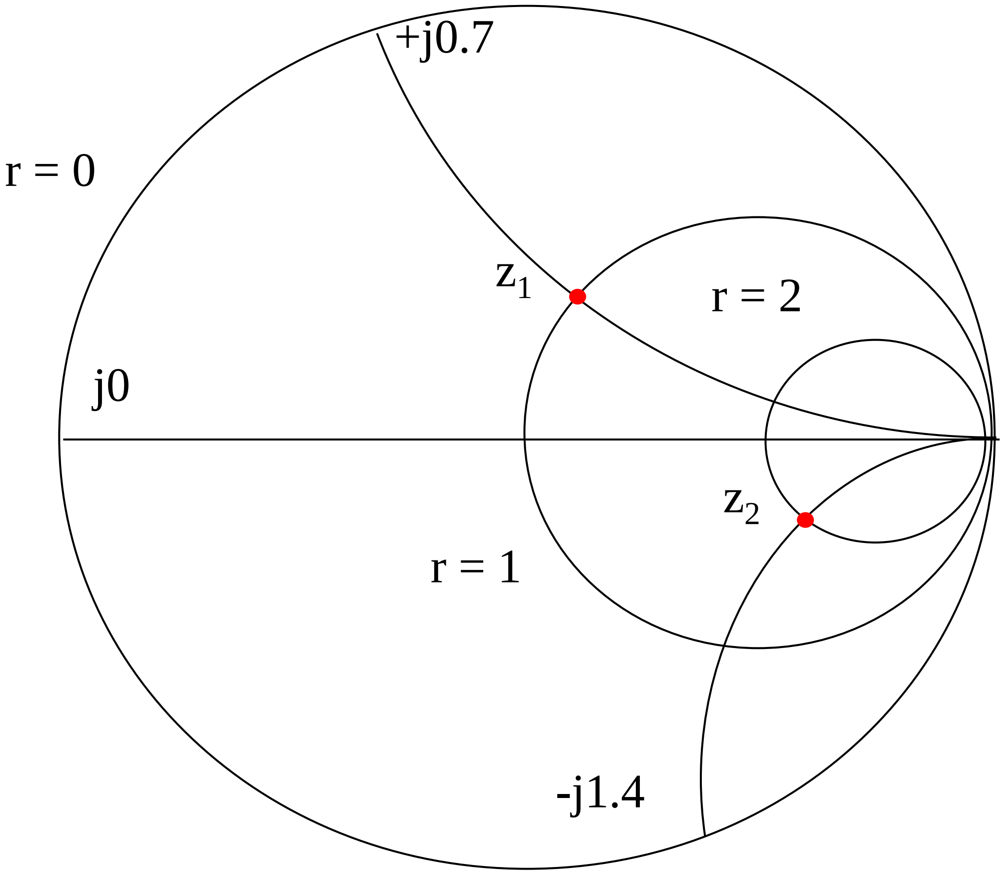
- A $\lambda/4$ line with characteristic impedance, Z_o , can be used as a matching transformer between a resistive load, Z_L, and a line with characteristic impedance, Z_o, by choosing:

$$Z_o' = \sqrt{Z_o Z_L}$$

Smith Chart

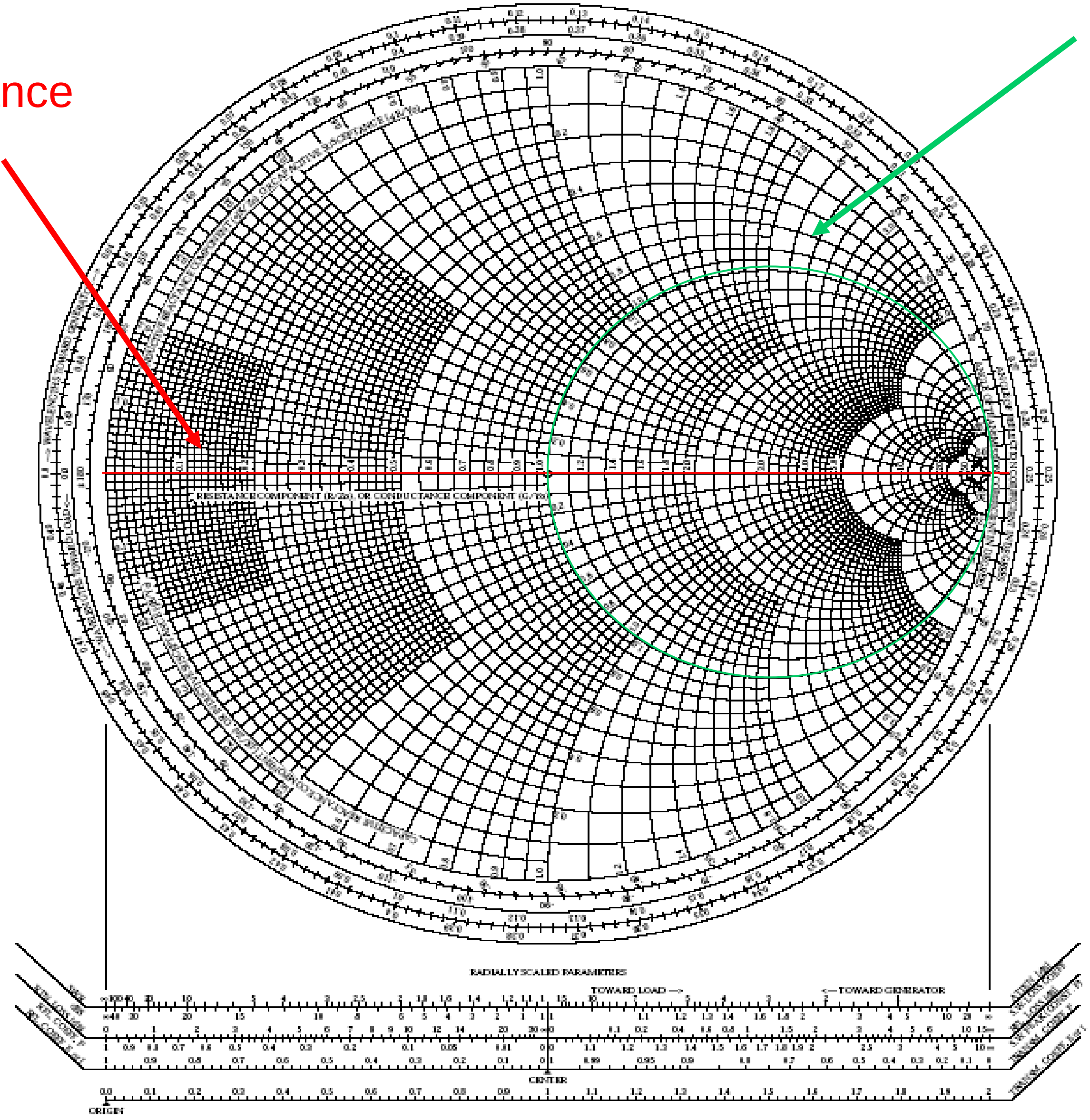
- The Smith chart is a clever graphical tool for solving transmission-line impedance problems.
- The coordinates on the chart are based on the intersection of two sets of orthogonal circles.
- One set represents the normalized resistive component, r (= R/Z_o), and the other the normalized reactive component, ± jx (= $\pm jX/Z_o$).
- The outside of the chart shows location on the line in wavelengths

Smith Chart Basics



z_1 = 1+j0.7

z_2 = 2-j1.4



Real Impedance Axis

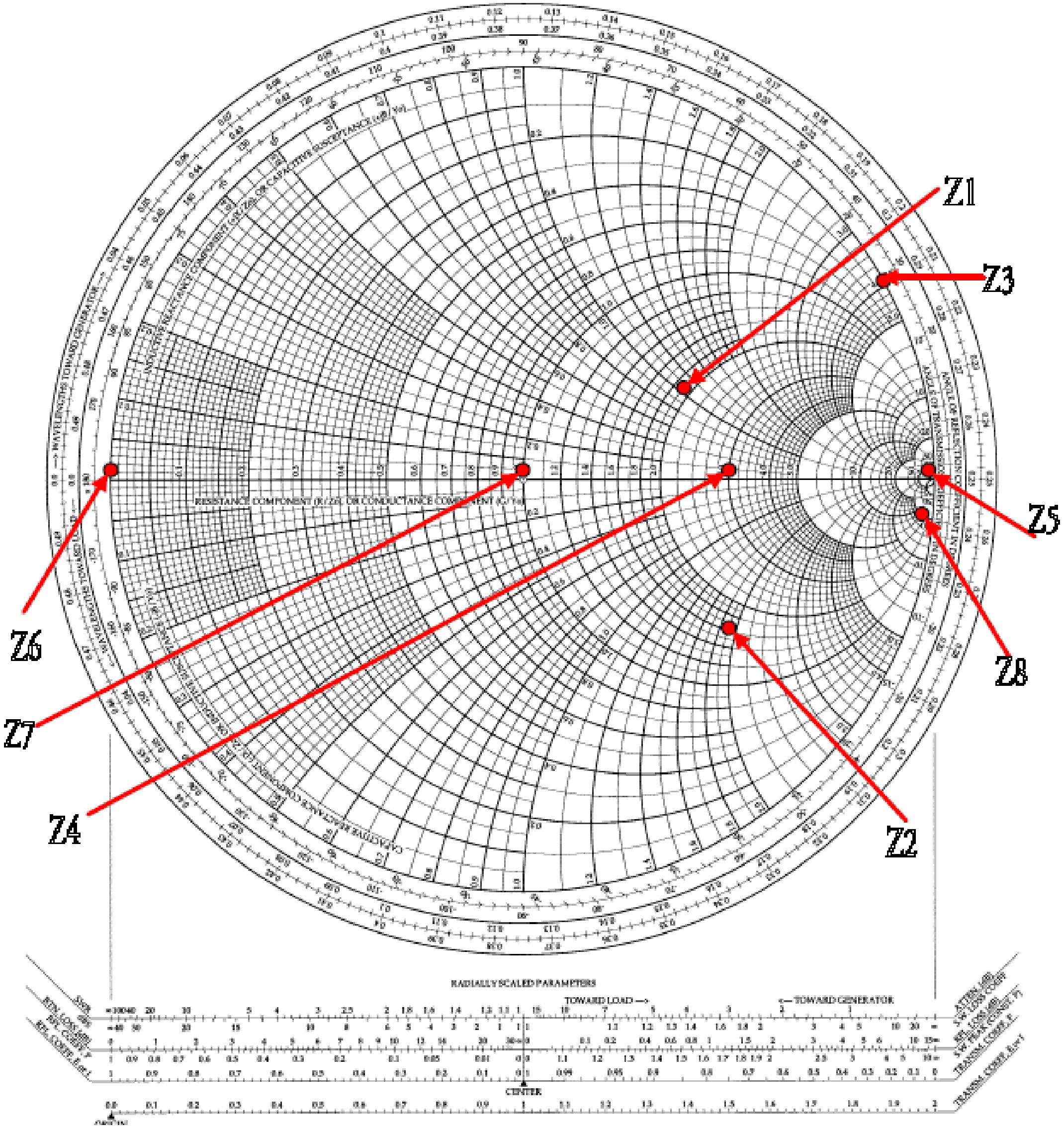
Imaginary Impedance Axis

Applications of The Smith Chart

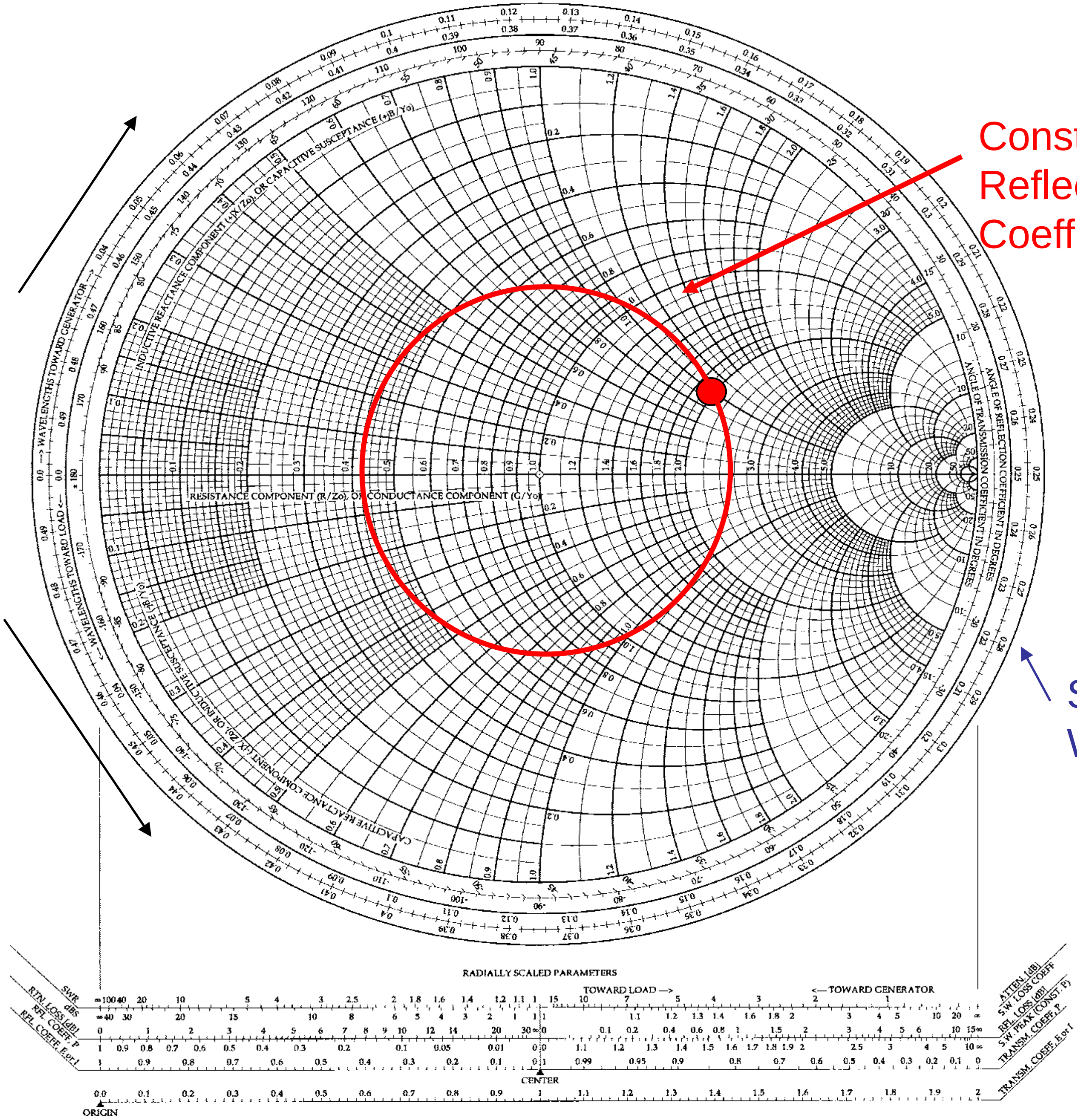
- Applications to be discussed in this course:
  - Find SWR, $|\Gamma|\angle\phi$, RL
  - Find Y_L
  - Find Z_i of a shorted or open line of length ℓ
  - Find Z_i of a line terminated with Z_L
  - Find distance to V_{max} and V_{min} from Z_L
  - Solution for quarter-wave transformer matching
  - Solution for parallel single-stub matching

- Impedance divided by line impedance   (50 Ohms)
  - Z1 = 100 + j50
  - Z2 = 75 -j100
  - Z3 = j200
  - Z4 = 150
  - Z5 = infinity (an open circuit)
  - Z6 = 0 (a short circuit)
  - Z7 = 50
  - Z8 = 184 -j900

- Then, normalize and plot. The points are plotted as follows:
  - z1 = 2 + j
  - z2 = 1.5 -j2
  - z3 = j4
  - z4 = 3
  - z5 = infinity
  - z6 = 0
  - z7 = 1
  - z8 = 3.68 -j18S



- Thus, the first step in analyzing a transmission line is to locate the normalized load impedance on the chart.
- Next, a circle is drawn that represents the reflection coefficient or SWR. The center of the circle is the center of the chart. The circle passes through the normalized load impedance.
- Any point on the line is found on this circle. Rotate clockwise to move toward the generator (away from the load).
- The distance moved on the line is indicated on the outside of the chart in wavelengths.



Toward Generator

Away From Generator

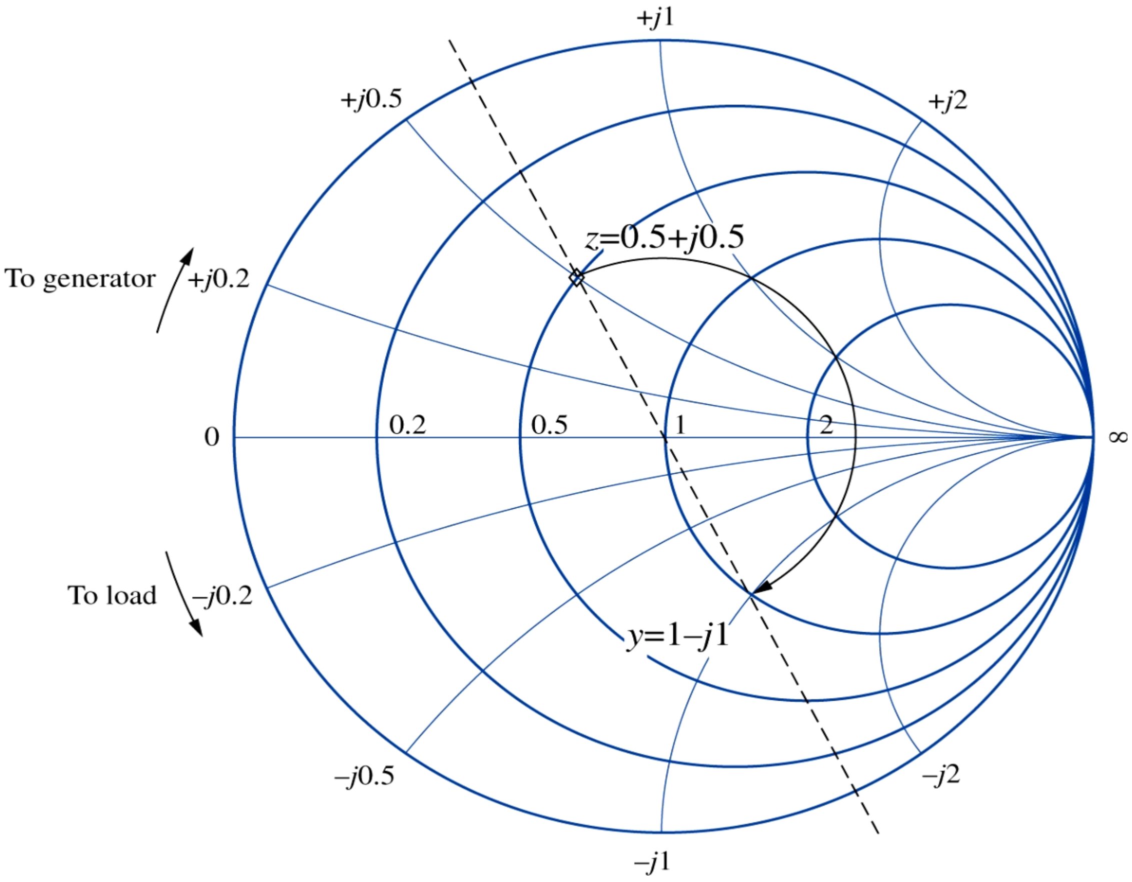
Constant Reflection Coefficient Circle

Scale in Wavelengths

For example, the impedance
$z = 0.5 + j\,0.5$
corresponds to the admittance

$$y = \frac{1}{0.5 + j0.5} = 1 - j1$$

Surprisingly, this calculation can be done graphically using the Smith chart! First, we locate the normalized impedance on the chart.
Second, we draw a circle (or a semicircle "to generator") centered at the center of the Smith chart and passing through the impedance.



Third, we plot a straight line through the center of the Smith chart and through this impedance. The intersection of the line with the semicircle yields the value for the admittance.

Example: Load Impedance

Z_R= 50 +j100 Ω on a 50 Ω line.

Solution:-

i. Normalize the Impedance; z = 1 +j2.0 Ω.

ii. On horizontal Resistance line move from zero to 1.0 on the right.

iii. Follow resistance circle upward.

iv. Locate point where crosses reactance circle j2.0

v. Point of intersection is z = 1.0 + j2.0 Ω.

Example:-Voltage Standing Wave Ratio:

Z_R=100 – j50Ω on a 50Ω line. Find SWR?

Solution:

- Normalize Z…z_R= 2 – j1.0 Ω
- Plot it on the chart
- Draw a circle with center at point (1,0)through point z_R
- VSWR is 2.6

Example: Reflection Coefficient:-

Z_R= 100 + j75Ω on a 50Ω line Find $|\Gamma|$?

Solution:

- Normalize Load $z_R = 2 + j1.5\ \Omega$
- Plot the z_R on the chart
- Draw VSWR circle through z_R, read SWR…= 3.3
- $|\Gamma| = (swr - 1)/(swr + 1)$?
- $|\Gamma| = 0.535$
- Draw a radial line through z_R to meet the phase line…. $\Gamma = 0.535\angle 30^0$

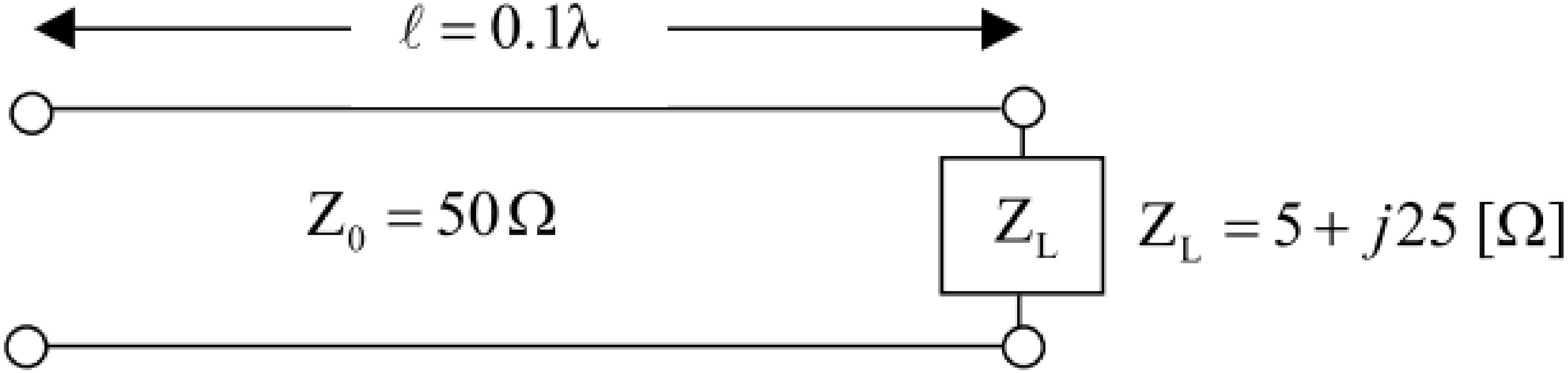
Example: Reflection Coefficient:-

$Z_R = 100 + j75\Omega$ on a 50Ω line Find $|\Gamma|$?

Solution:

- Normalize Load $z_R = 2 + j1.5\ \Omega$
- Plot the z_R on the chart
- Draw VSWR circle through z_R, read VSWR…= 3.3
- $|\Gamma| = (swr - 1)/(swr + 1)$?
- $|\Gamma| = 0.535$
- Draw a radial line through z_R to meet the phase line…. $\Gamma = 0.535\angle 30^0$

Example: The 0.1λ length line shown has a characteristic impedance of 50 and is terminated with a load impedance of Z_L=5+j25.



a) Locate $z_L = Z_L / Z_0 = 0.1 + j0.5$ on the Smith chart. See the point plotted on the Smith chart.

b) What is the impedance at $\ell = 0.1\lambda$? Since we want to move toward the generator, read 0.074λ on the wavelengths toward generator scale and add $\ell = 0.1\lambda$ to obtain 0.174λ on the wavelengths toward generator scale. A radial line from the center of the chart intersects the constant reflection coefficient magnitude circle at $z=0.38+j1.88$. Hence

$Z_L = z \times Z_0 = 50 \times (0.38+j1.88) = 19+j94\Omega$.

c) What is the VSWR on the line? Find SWR = z_{max} = 13 on the horizontal line to the right of the chart's center. Or use the SWR scale on the chart.

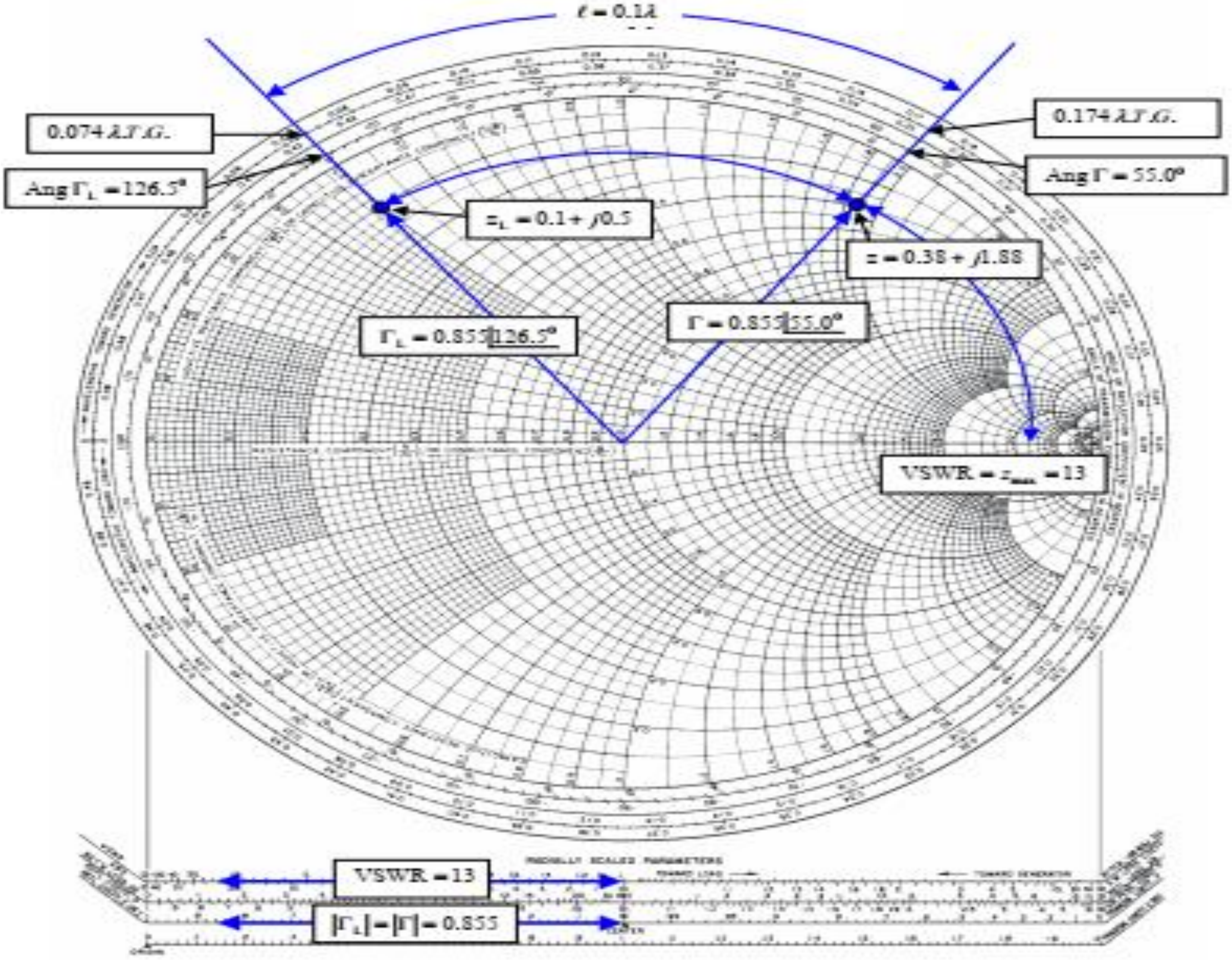
d) What is Γ_L?

From the reflection coefficient scale below the chart, find $|\Gamma_L|$ = 0:855. From the angle of reflection coefficient scale on the perimeter of the chart, fnd the angle of Γ_L = 126.5^o.

Hence $\Gamma_L = 0.855\ e^{(j126.5)}$.

e) What is Γ at $\ell = 0.1\lambda$ from the load?

Note that $|\Gamma| = |\Gamma_L| = 0.855$. Read the angle of the reflection coefficient from the ANGLE OF REFLECTION COEFFICIENT scale as 55.0°. Hence $\Gamma = 0.855e^{j55.0^\circ}$.

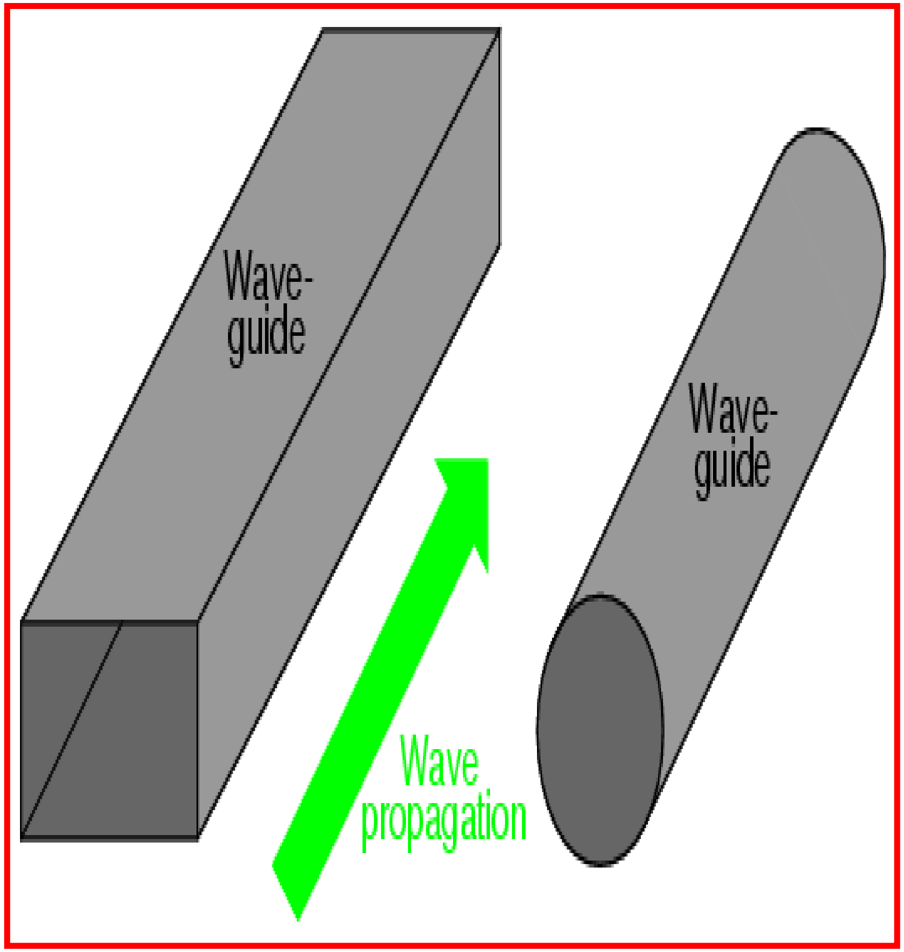

ℓ = 0.1λ
0.074 λ.T.G.
Ang Γ_L = 126.5°
z_L = 0.1 + j0.5
0.174 λ.T.G.
Ang Γ = 55.0°
z = 0.38 + j1.88
Γ_L = 0.855∠126.5°
Γ = 0.855∠55.0°
VSWR = z_max = 13
RADIALLY SCALED PARAMETERS
VSWR = 13
|Γ_L| = |Γ| = 0.855

Lecture-6-

Waveguides

Definition

- A Hollow metallic tube of uniform cross section for transmitting electromagnetic waves by successive reflections from the inner walls of the tube is called ***waveguide***.



- Pipe through which waves propagate.
- Can have various cross sections:
  - Rectangular
  - Circular
  - Elliptical
- Can be rigid or flexible.
- Waveguides have very low loss.

- At frequencies higher than 3 GHz, transmission of electromagnetic energy along the transmission lines and cables becomes difficult.

- This is due to the losses that occur both in the solid dielectric needed to support the conductor and in the conductors themselves.

- A metallic tube can be used to transmit electromagnetic wave at the above frequencies

Basic features

- Waveguides may be used to carry energy between pieces of equipment or over longer distances to carry transmitter power to an antenna or microwave signals from an antenna to a receiver

- Waveguides are made from copper, aluminum or brass. These metals are extruded into long rectangular or circular pipes.

- An electromagnetic energy to be carried by a waveguide is injected into one end of the waveguide.

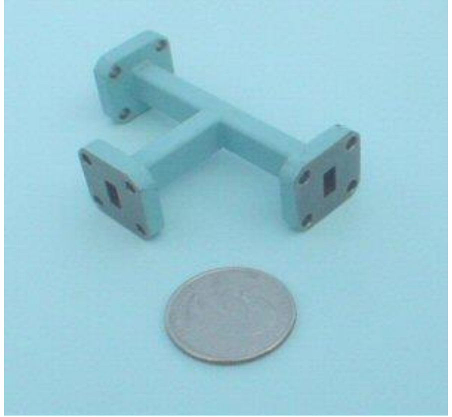
- The electric and magnetic fields associated with the signal bounce off the inside walls back and forth as it progresses down the waveguide.

Waveguide components

Rectangular waveguide

Waveguide to coax adapter

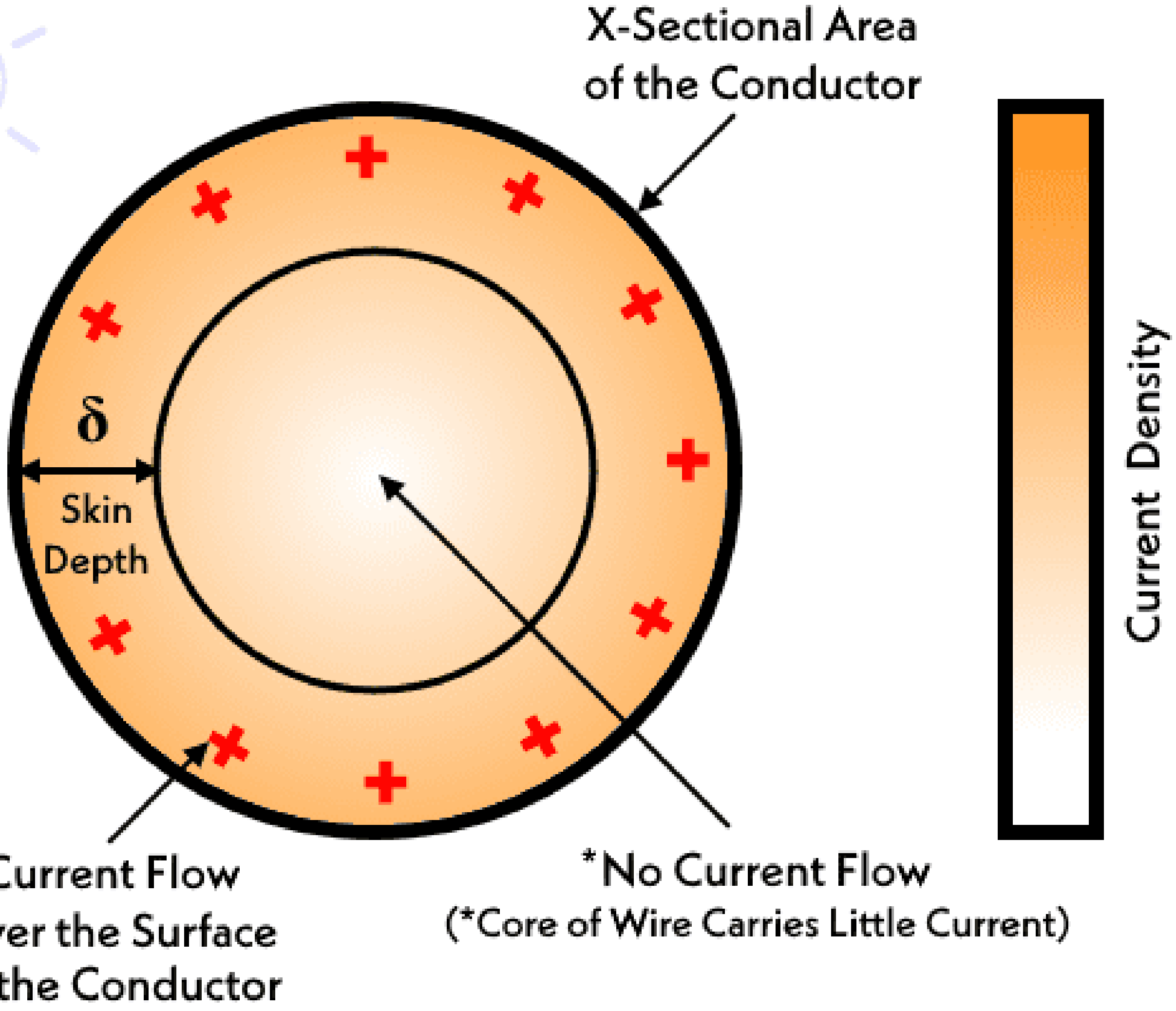
Waveguide bends



E-tee

Why Waveguide

- When an alternating current “AC” flows through a conductor, it is distributed non-uniformly throughout the conductor and tends to stay more near the surface of the conductor. This phenomenon is called Skin Effect.
- The resistance of the wire increases, causing an increase in line losses. The line losses occur in the form of heat which further increases the resistance of the conductor. It reduces the efficiency of the transmission line.


X-Sectional Area
of the Conductor
δ
Skin
Depth
Current Density
Current Flow
Over the Surface
of the Conductor
*No Current Flow
(*Core of Wire Carries Little Current)

Factors Affecting Skin Effect

- Frequency

The current frequency is the main factor affecting skin effect and it is directly proportional to the skin effect. As we know that inductive reactance is given by

$$X_L = 2\pi f L$$

Increasing the frequency increases the reactance and decreases the skin depth of the conductor. Thus the current stays more to the surface or the skin effect increases.

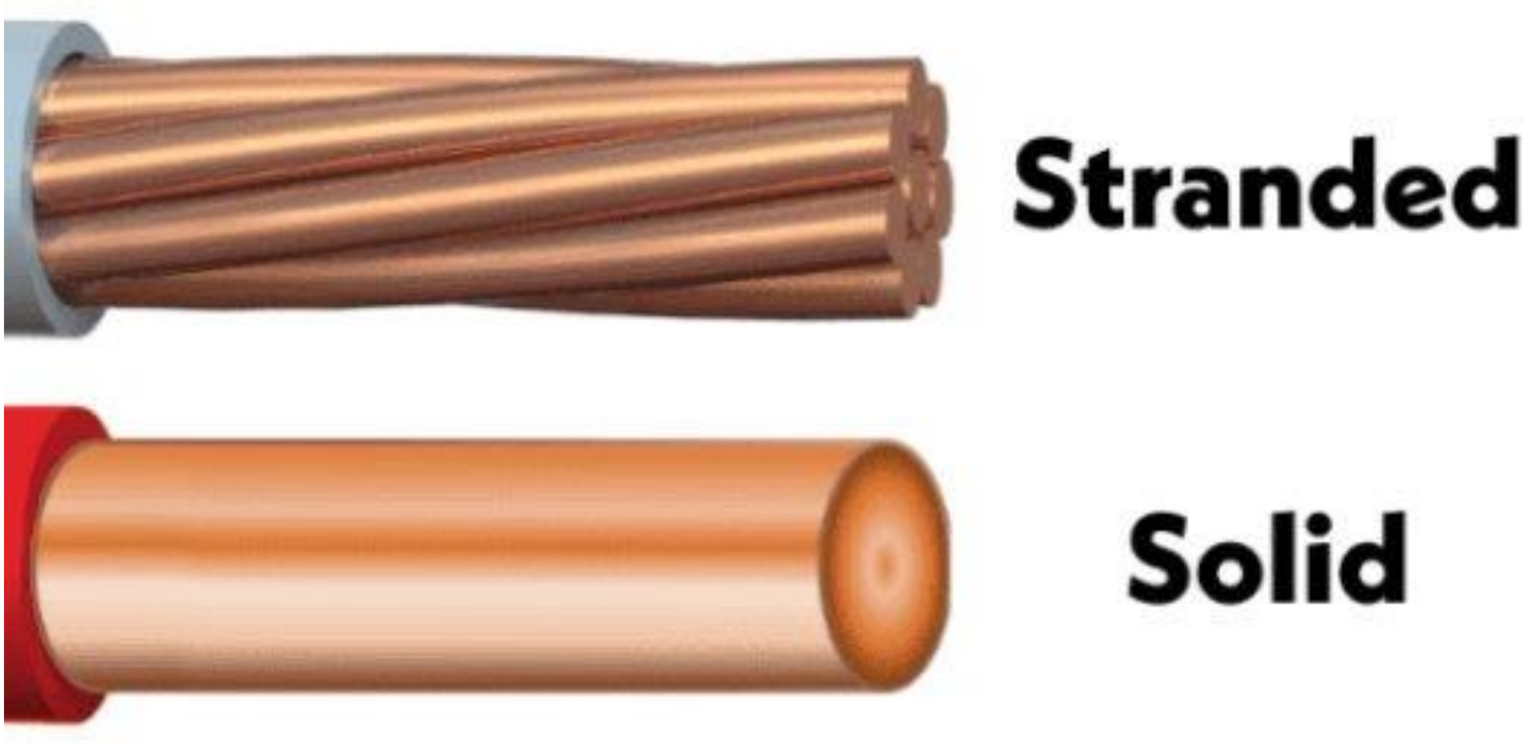
Since DC has no frequency, its reactance is zero and the current is distributed uniformly throughout the conductor.

Factors Affecting Skin Effect

- Shape of Conductor

The skin effect also depends on the shape of the conductor. Conductors are either solid or stranded. The stranded conductor has a greater surface area as compared to a solid conductor of the same size. As the AC tends to stay at the surface, the stranded conductor has a less skin effect as compared to the solid conductor. It means AC is more efficient for transmission in stranded conductors than in solid conductors.

Factors Affecting Skin Effect



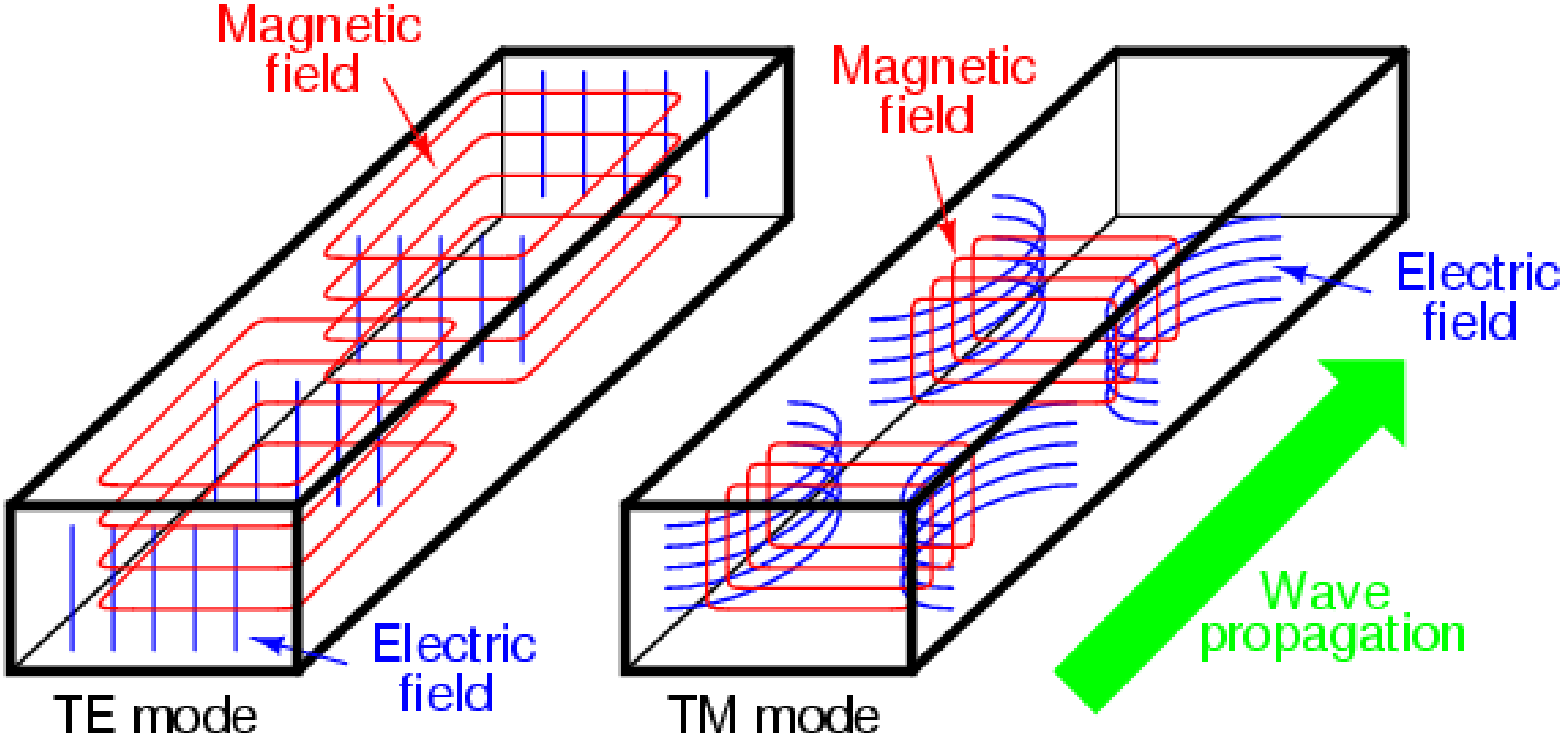
Factors Affecting Skin Effect

- Diameter of Conductor

The skin effect is directly proportional to the diameter of a conductor. It increases with an increase in diameter. It means it is minimum in conductors having a smaller diameter. As a matter of fact, if the radius of the conductor remains smaller than the skin depth, there will be no or minimum skin effect.

Modes

- Waves can propagate in various ways.
- Time taken to move down the guide varies with the mode.
- Each mode has a cutoff frequency below which it won’t propagate.
- Mode with lowest cutoff frequency is **dominant mode.**



Magnetic flux lines appear as continuous loops

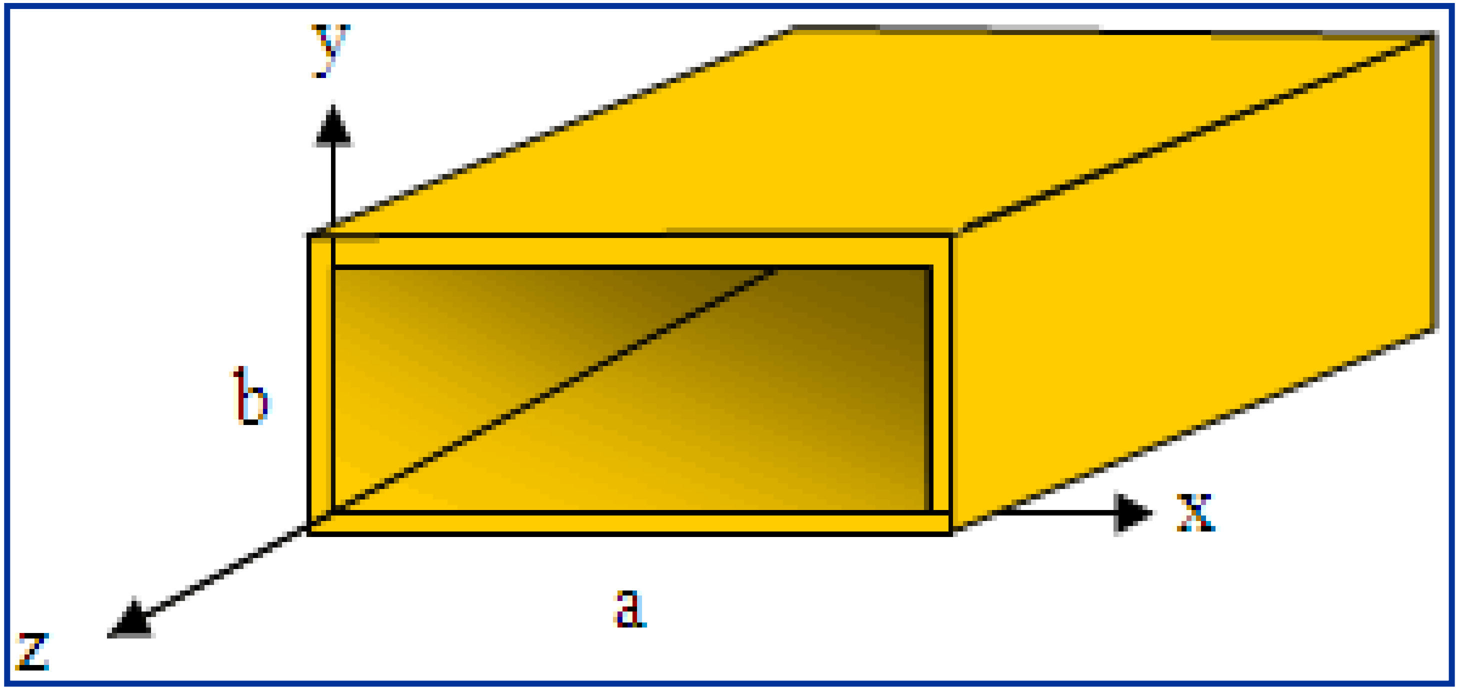
Electric flux lines appear with beginning and end points

Rectangular Waveguides

- Any shape of cross section of a waveguide can support electromagnetic waves of which rectangular and circular waveguides have become more common.

- A waveguide having rectangular cross section is known as *Rectangular waveguide*

Rectangular waveguide

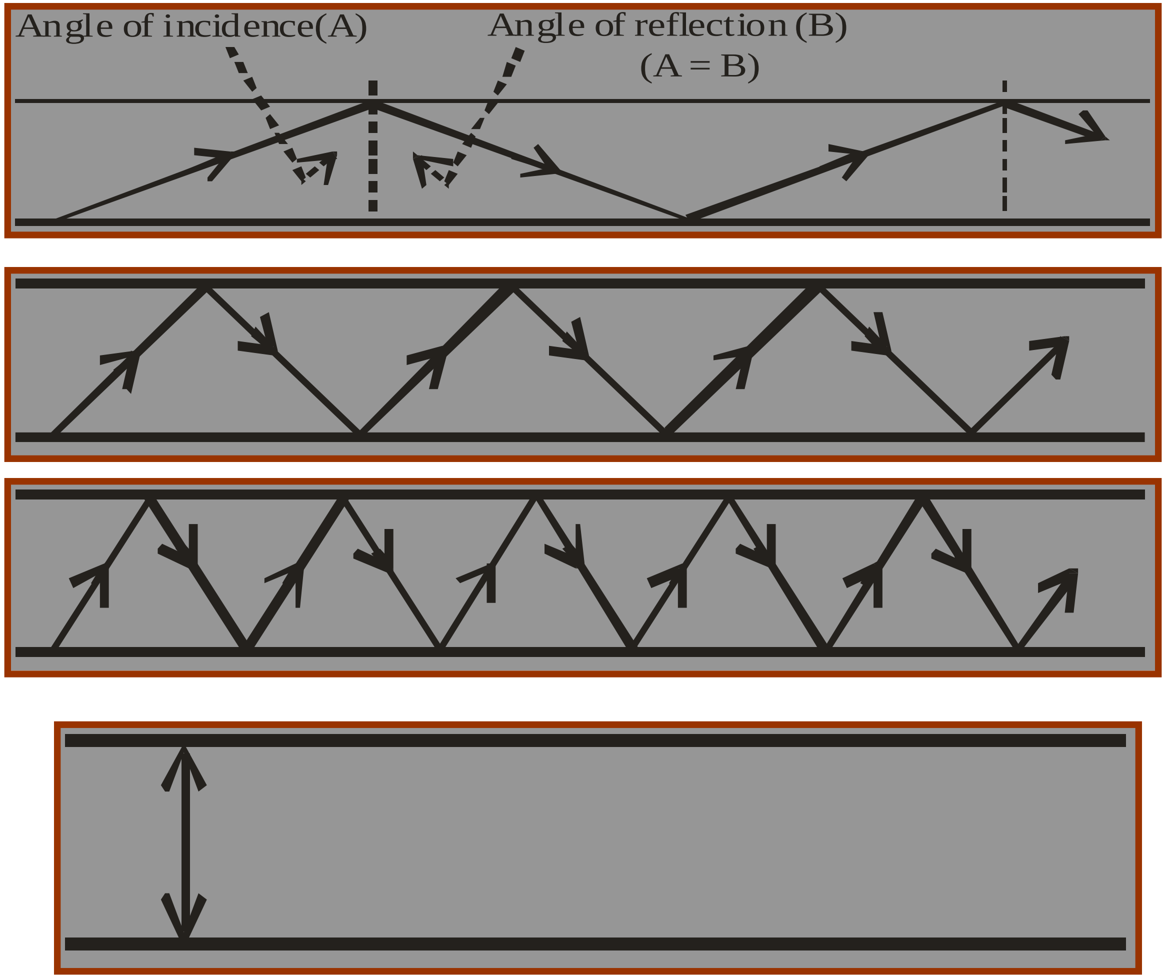


Dimensions of the waveguide which determines the operating frequency range

Dimensions of the waveguide which determines the operating frequency range:

1. The size of the waveguide determines its operating frequency range.
2. The frequency of operation is determined by the dimension ‘a’.
3. This dimension is usually made equal to one – half the wavelength at the lowest frequency of operation, this frequency is known as the waveguide *cutoff frequency.*
4. At the cutoff frequency and below, the waveguide will not transmit energy. At frequencies above the cutoff frequency, the waveguide will propagate energy.

Wave paths in a waveguide at various frequencies



(a)At high frequency

(b) At medium frequency

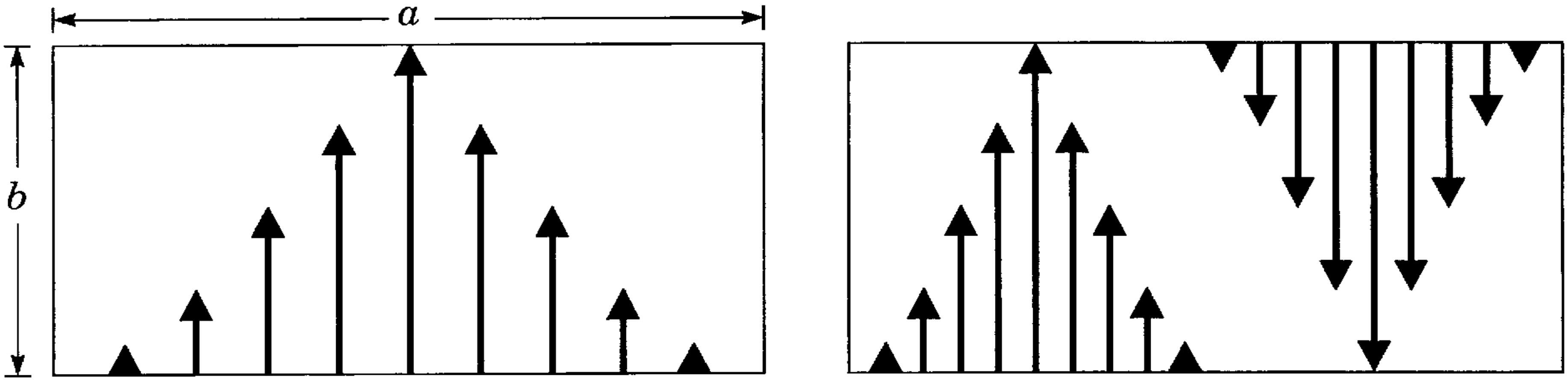
(c) At low frequency

(d) At cutoff frequency

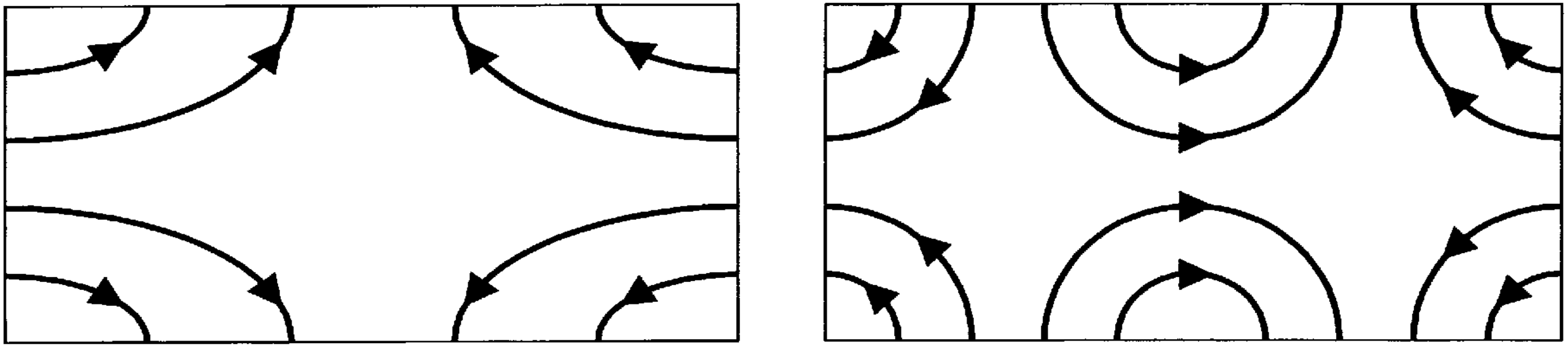
Representation of modes

- The general symbol of representation will be $TE_{m, n}$ or $TM_{m, n}$ where the subscript *m* indicates the number of half wave variations of the electric field intensity along the a (wide) dimension of the waveguide.
- The second subscript *n* indicates the number of half wave variations of the electric field in the *b* (narrow) dimension of the guide.
- The $TE_{1, 0}$ mode has the longest operating wavelength and is designated as the dominant mode. It is the mode for the lowest frequency that can be propagated in a waveguide.

TE Modes in Rectangular Waveguide



(a) TE$_{10}$ (b) TE$_{20}$



(c) TE$_{11}$ (d) TE$_{21}$

Expression for cut off wavelength

- For a standard rectangular waveguide, the cutoff frequency is given by,

$$f_{c_{mn}} = \frac{c}{2\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$

Where a and *b* are measured in centimeters

Rectangular Waveguides

- Dominant mode is TE_{10}
  - 1 half cycle along long dimension (a)
  - No half cycles along short dimension (b)
  - Cutoff for $a = \lambda_c/2$
- Modes with next higher cutoff frequency are TE_{01} and TE_{20}
  - Both have cutoff frequency twice that for TE_{10}

Example: A rectangular air – filled waveguide has a cross section of 4 $cm \times 10\ cm$. Calculate the minimum frequency which can propagation in the waveguide.

Solution:

A rectangular waveguide air filled with a = 10 cm , b = 4 cm.

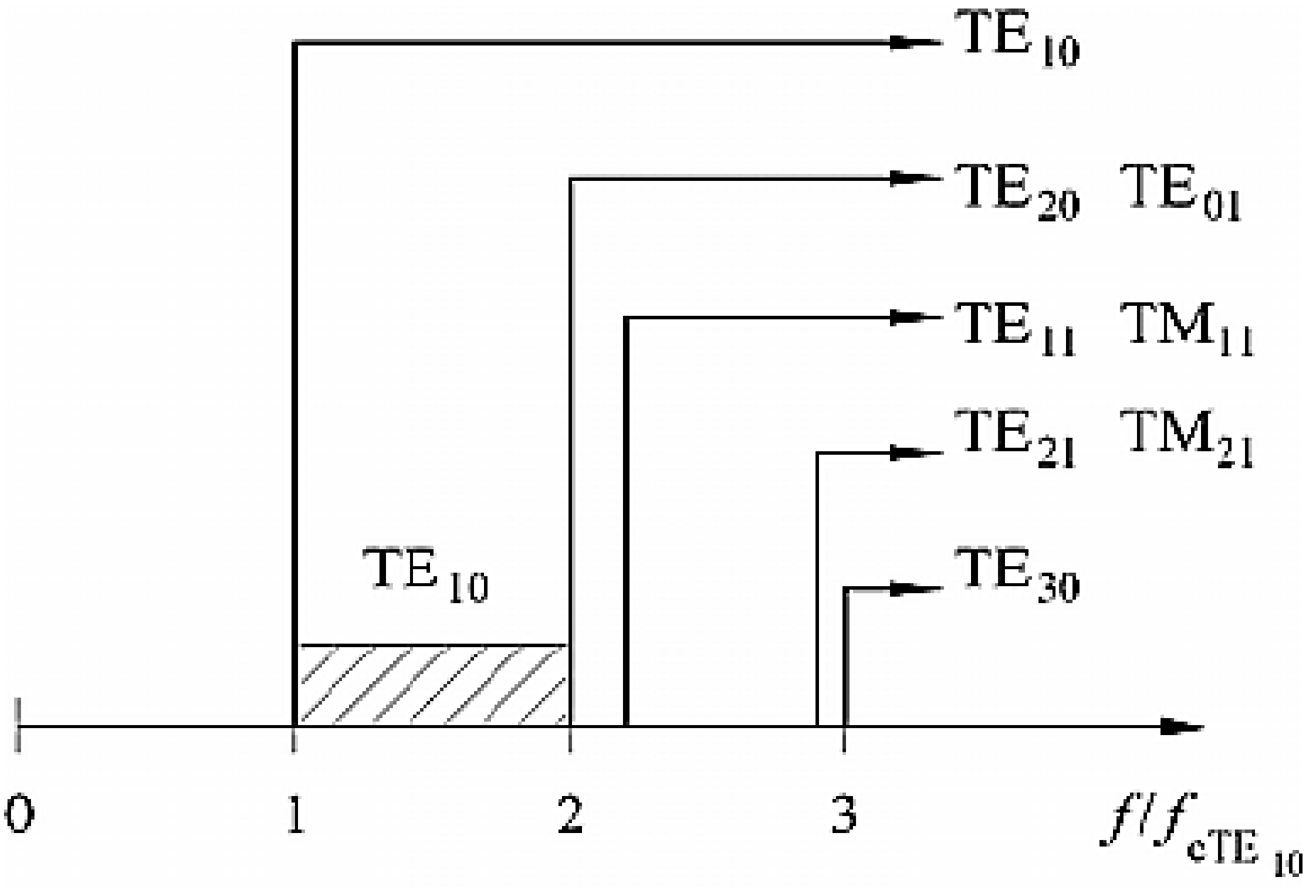
Waveguide acts as a high pass filter with cut off frequency of

$$f_{c_{mn}} = \frac{c}{2\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$

$$\boldsymbol{f_{c_{10}} = 1.5 \times 10^8 \sqrt{\frac{1}{100} \times 10^4}\ Hz}$$

$$\boldsymbol{= 1.5\ GHz}$$

The sequence of propagating modes in a rectangular waveguide



Rectangular Waveguide

Example

Let us calculate the cutoff frequency for the first four modes of WR284 waveguide. The guide dimensions are a = 7.214 cm and b = 3.404 cm.

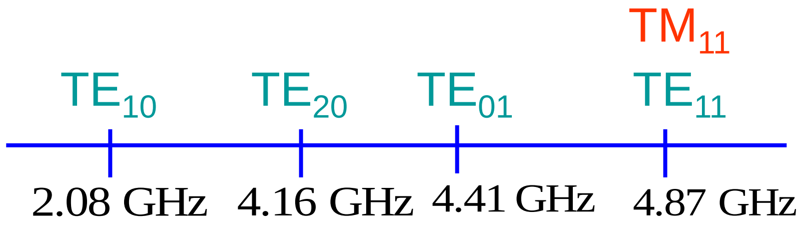
$$f_{c_{mn}} = \frac{c}{2\sqrt{\mu_r \varepsilon_r}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \qquad \text{where } c = 3\times 10^8 \text{ m/s}$$

TE$_{10}$: $$f_{c10} = \frac{c}{2a} = \frac{3x10^8\ {}^{m}\!/_{s}}{2(7.214cm)}\frac{100cm}{1m} = 2.08\text{ GHz}$$

TE$_{01}$: $$f_{c01} = \frac{c}{2b} = \frac{3x10^8\ {}^{m}\!/_{s}}{2(3.404cm)}\frac{100cm}{1m} = 4.41\text{ GHz}$$

TE$_{20}$: $$f_{c20} = \frac{c}{a} = 4.16\text{ GHz}$$

TE$_{11}$: $$f_{c11} = \frac{3x10^8\ {}^{m}\!/_{s}}{2}\sqrt{\left(\frac{1}{7.214cm}\right)^2 + \left(\frac{1}{3.404cm}\right)^2}\,\frac{100cm}{1m} = 4.87\text{ GHz}$$



Group Velocity (V_g)

- Waves propagate at speed of light *c* in guide.
- Waves don’t travel straight down guide.
- Speed at which signal moves down guide is the group velocity and is always less than *c.*

$$v_g = c\sqrt{1-\left(\frac{f_c}{f}\right)^2}\ m/s$$

Assuming an air dielectric, the wave travels inside the waveguide at the speed of light. However, it does not travel straight down the guide but reflects back and forth from the walls. The actual speed at which a signal travels down the guide is called the group velocity, and it is considerably k than the speed of light. The group velocity in a rectangular waveguide is given by the equation

$$v_g = c\sqrt{1 - \left(\frac{\lambda}{2a}\right)^2}$$

where v_g = group velocity

λ = free-space wavelength

a = larger dimension of the interior cross section

From the above equation. it can be seen that the group velocity is a function of frequency and becomes zero at the cutoff frequency. At frequencies below cut-off. course, there is no propagation. so the equation does not apply. The physical explanation of the variation of group velocity is that the angle the wave makes with the wall of the guide varies with frequency. At frequencies near the cutoff value, the wave moves back and forth across the guide more often while traveling a given distance down the guide than it does at higher frequencies.

Example: Find the group velocity for the waveguide has (f_c=3.75) GHz and operating frequency (f=5 GHz).

$$v_g = c\sqrt{1-\left(\frac{f_c}{f}\right)^2}$$

$$= (300\times10^6\,\mathrm{m/s})\sqrt{1-\left(\frac{3.75}{5}\right)^2}$$

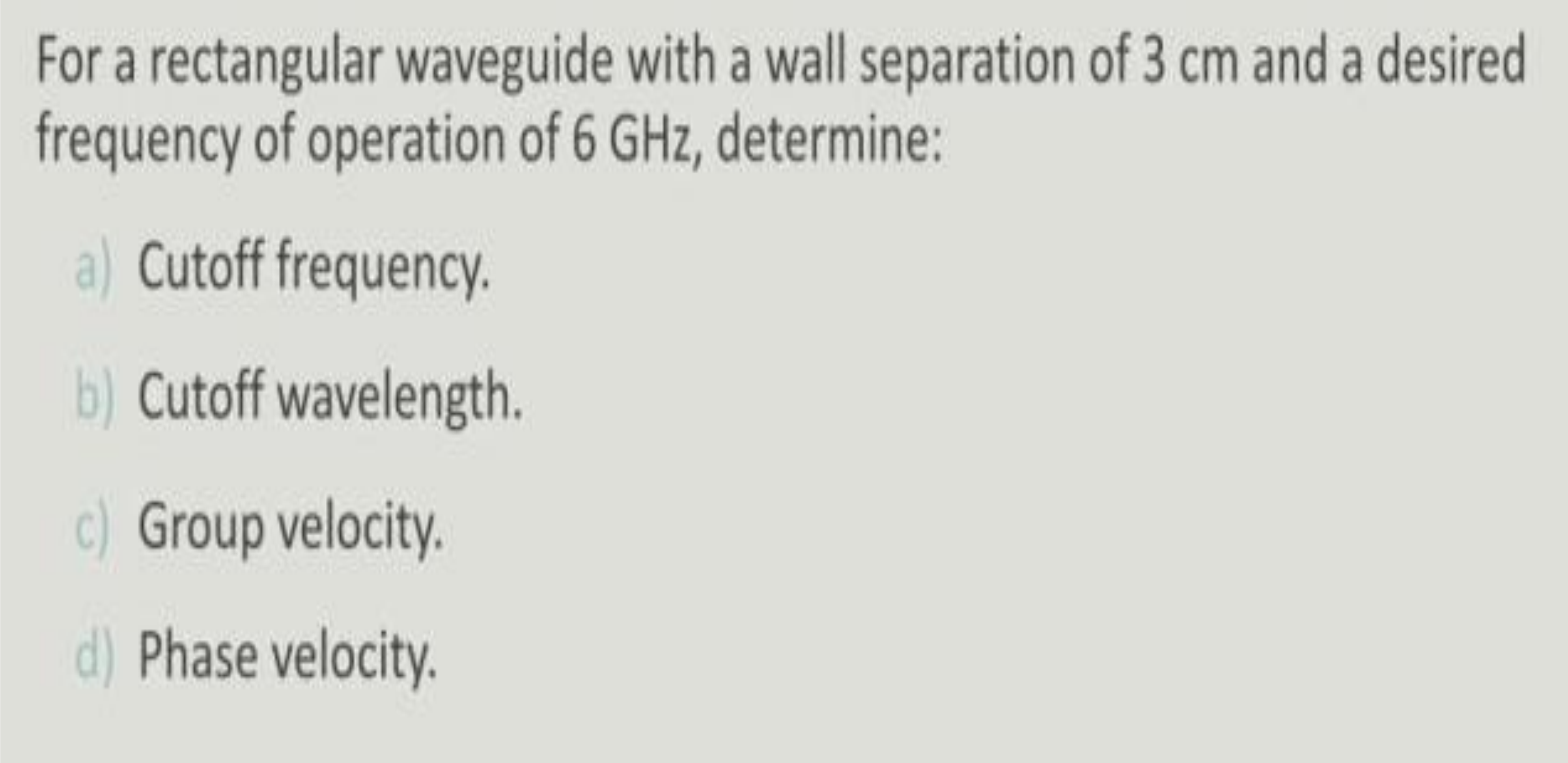
$$= 198\times10^6\,m/s$$

Phase Velocity (*V_p*)

- The velocity at which the wave changes its phase.
- V_p always equal to or greater than (v_g).
- It may exceed the velocity of light (velocity in free space).

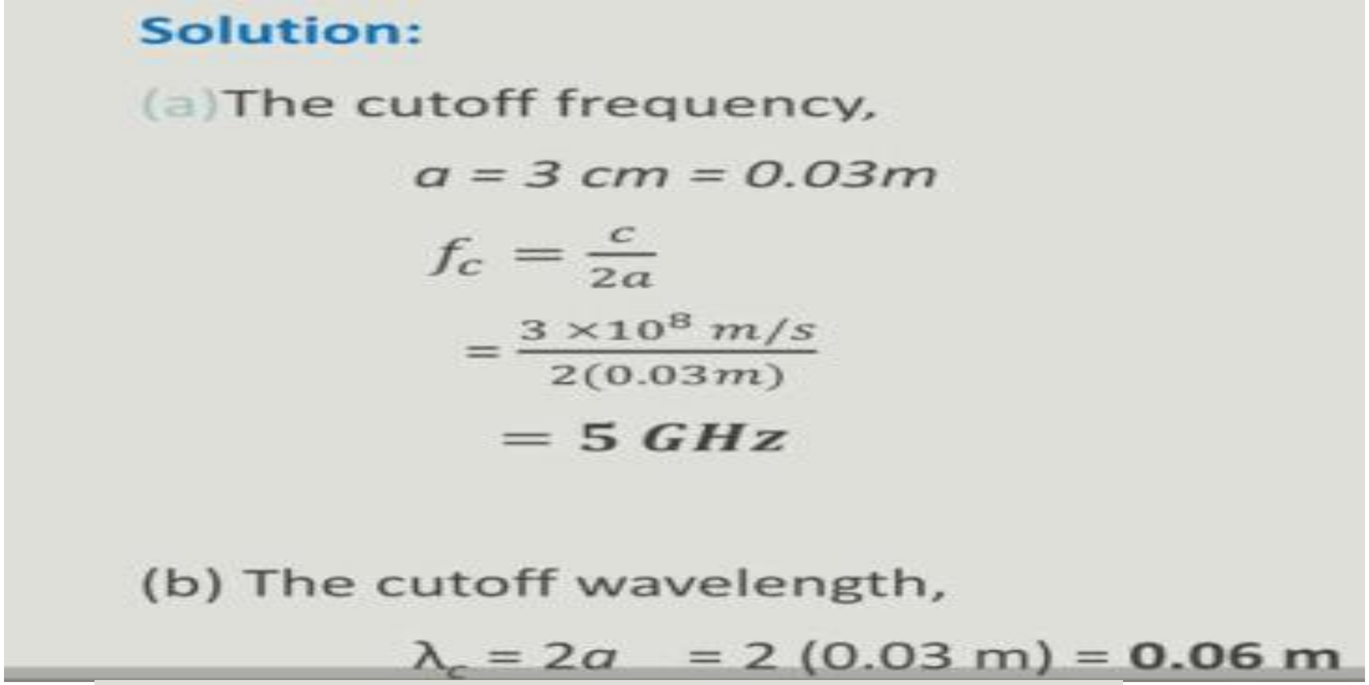
$$v_p = \frac{c}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}} \quad m/s$$

Example



For a rectangular waveguide with a wall separation of 3 cm and a desired frequency of operation of 6 GHz, determine:

a) Cutoff frequency.
b) Cutoff wavelength.
c) Group velocity.
d) Phase velocity.



Solution:

(a) The cutoff frequency,

$$a = 3\ cm = 0.03m$$

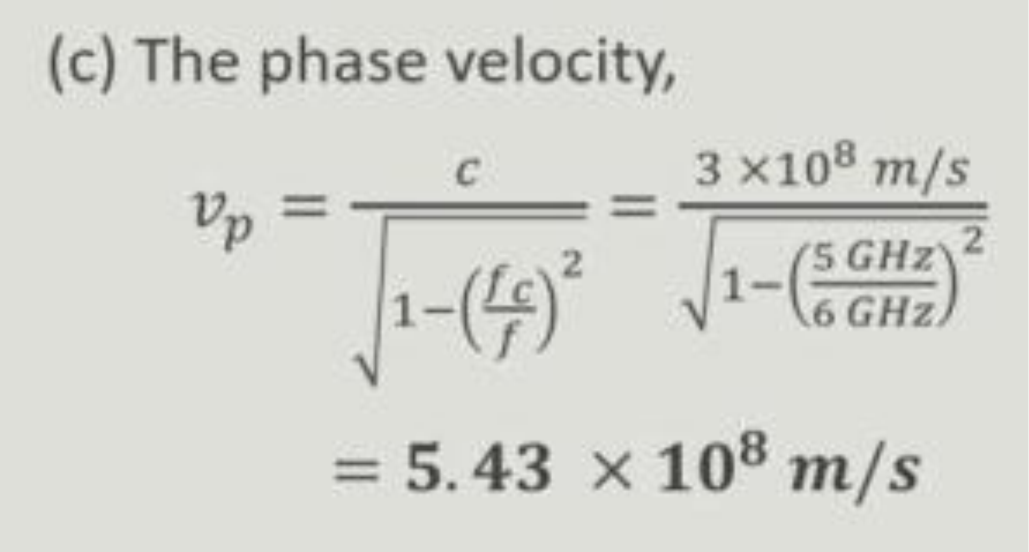
$$f_c = \frac{c}{2a}$$

$$= \frac{3 \times 10^8\ m/s}{2(0.03m)}$$

$$= \mathbf{5\ GHz}$$

(b) The cutoff wavelength,

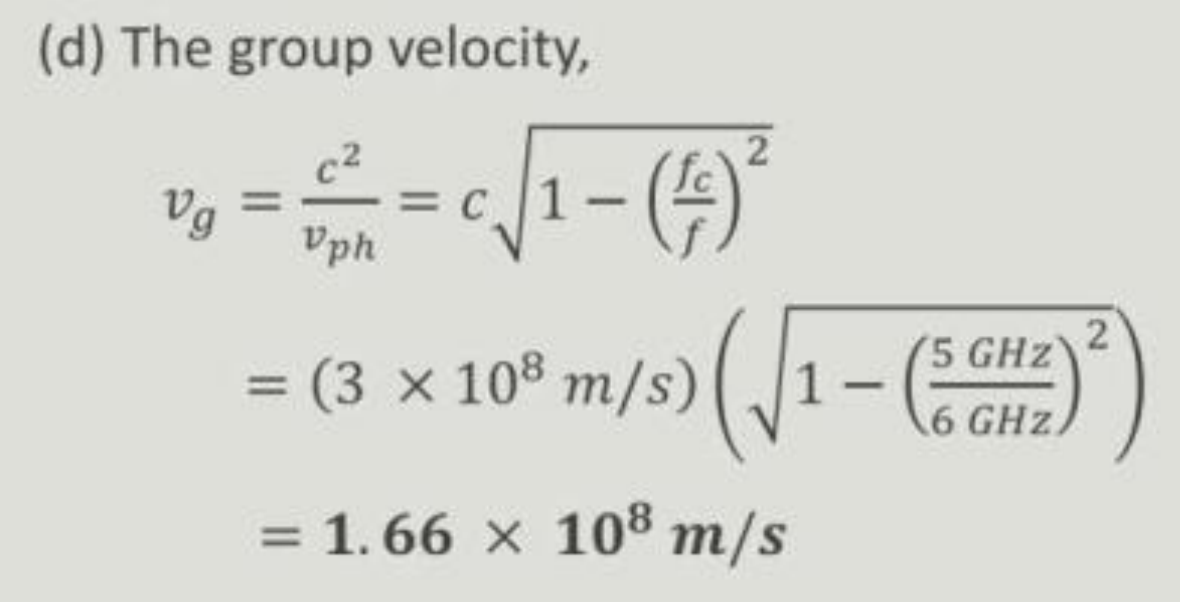
$\lambda_c = 2a \quad = 2\ (0.03\ m) = \mathbf{0.06\ m}$



(c) The phase velocity,

$$v_p = \frac{c}{\sqrt{1-\left(\frac{f_c}{f}\right)^2}} = \frac{3 \times 10^8\ m/s}{\sqrt{1-\left(\frac{5\ GHz}{6\ GHz}\right)^2}}$$

$$= \mathbf{5.43\ \times 10^8\ m/s}$$



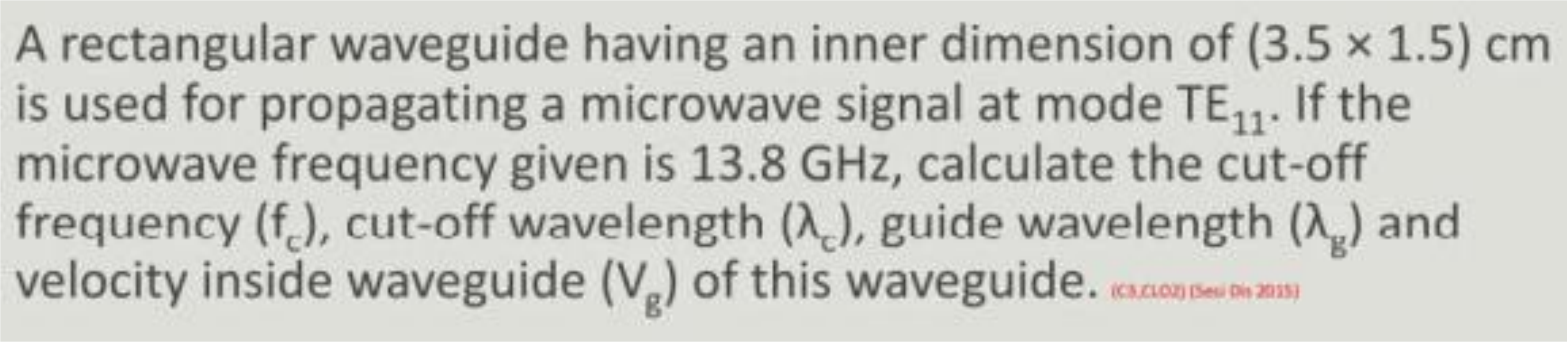
(d) The group velocity,

$$v_g = \frac{c^2}{v_{ph}} = c\sqrt{1-\left(\frac{f_c}{f}\right)^2}$$

$$= (3 \times 10^8\ m/s)\left(\sqrt{1-\left(\frac{5\ GHz}{6\ GHz}\right)^2}\right)$$

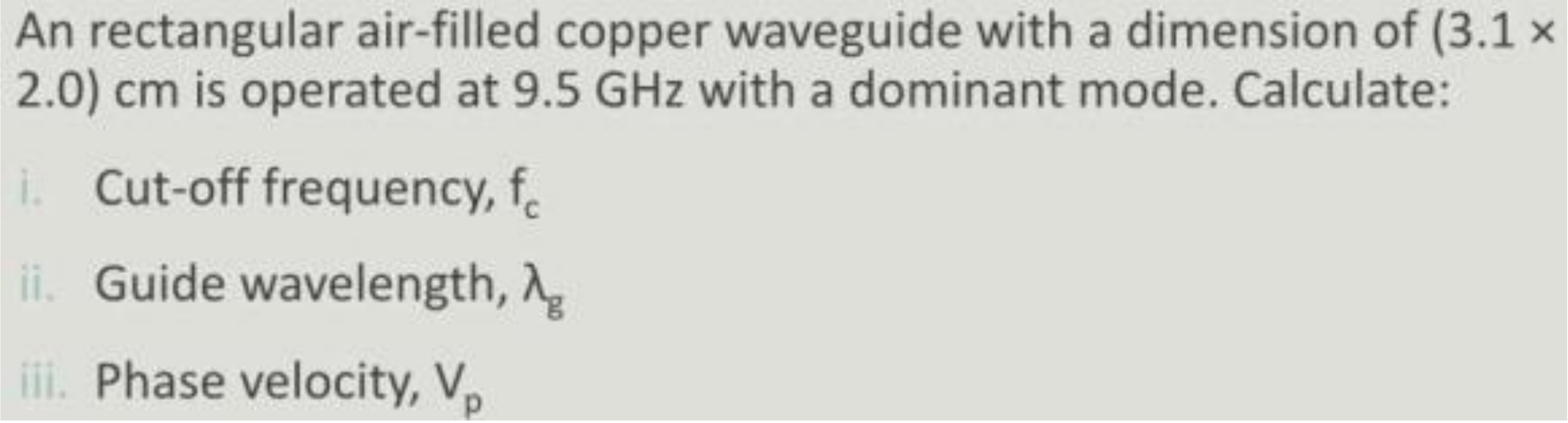
$$= \mathbf{1.66 \times 10^8\ m/s}$$

Problem 1



A rectangular waveguide having an inner dimension of (3.5 × 1.5) cm is used for propagating a microwave signal at mode TE_{11}. If the microwave frequency given is 13.8 GHz, calculate the cut-off frequency (f_c), cut-off wavelength (λ_c), guide wavelength (λ_g) and velocity inside waveguide (V_g) of this waveguide. (C3,CLO2) (Sesi Dis 2015)

Problem 2



An rectangular air-filled copper waveguide with a dimension of (3.1 × 2.0) cm is operated at 9.5 GHz with a dominant mode. Calculate:

i. Cut-off frequency, f_c

ii. Guide wavelength, λ_g

iii. Phase velocity, V_p

Lecture-6-

Magnetron Oscillator

Conventional Tubes

- Conventional Device tubes cannot be used for frequencies above 100MHz.
- Interelectrode capacitance (stray capacitance), this occurs due to the close proximity of electrical devices or electrodes.
- Lead Inductance effect.
- Transit time effect.
- Gain Bandwidth limitation.
- Effect of RF losses (Conductance, dielectric).
- Effect due to radiation losses.

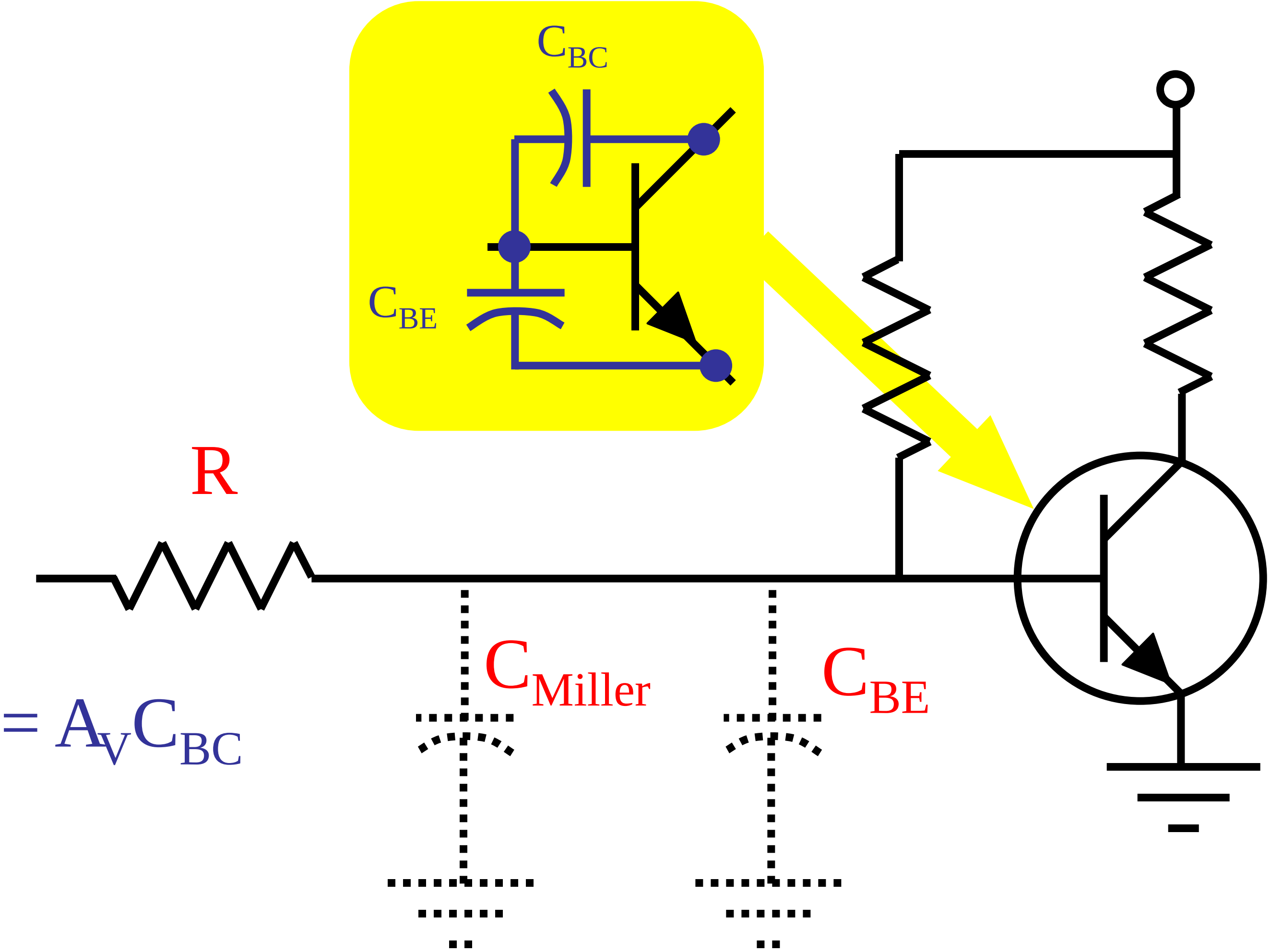
Frequency Limitations of Conventional Tubes

Three characteristics of ordinary vacuum tubes become increasingly important as frequency rises. These characteristics are:

- Interelectrode Capacitance
- Lead Inductance
- Electron Transit Time.

Interelectrode Capacitance

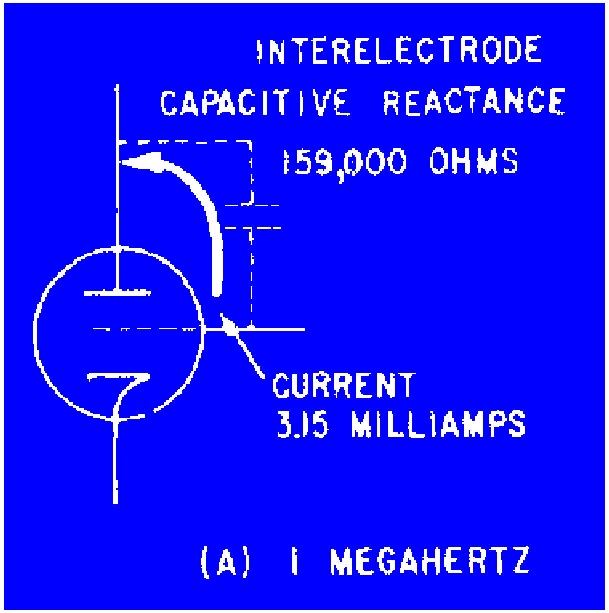
The interelectrode capacitances in a vacuum tube, at low or medium radio frequencies, produce capacitive reactances that are so large that no serious effects upon tube operation are noticeable. However, as the frequency increases, the reactances become small enough to materially affect the performance of a circuit. For example, in figure below, view (A), a 1-picofarad capacitor has a reactance of 159,000 ohms at 1 megahertz.



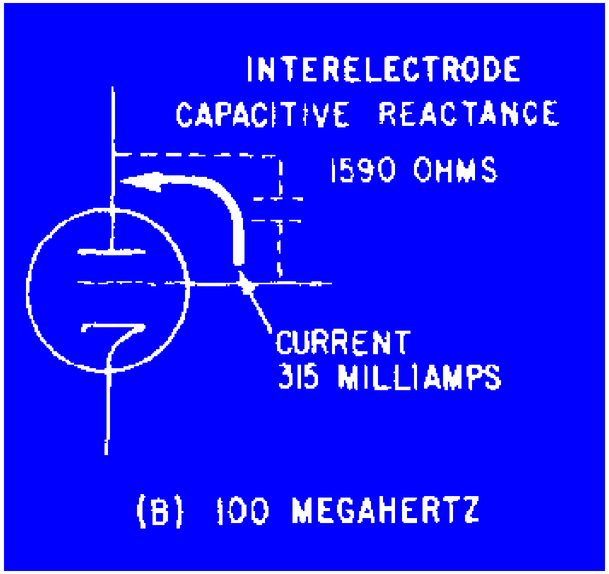
$$C_{Miller} = A_V C_{BC}$$

$$C_{Input} = C_{Miller} + C_{BE}$$

$$f_b = \frac{1}{2\pi R C_{Input}}$$


INTERELECTRODE
CAPACITIVE REACTANCE
159,000 OHMS
CURRENT
3.15 MILLIAMPS
(A) 1 MEGAHERTZ

A


INTERELECTRODE
CAPACITIVE REACTANCE
1590 OHMS
CURRENT
315 MILLIAMPS
(B) 100 MEGAHERTZ

B

Lead Inductance

Another frequency-limiting factor is the lead inductance of the tube elements. since the lead inductances within a tube are effectively in parallel with the interelectrode capacitance, the net effect is to raise the frequency limit. however, the inductance of the cathode lead is common to both the grid and plate circuits. This provides a path for degenerative feedback which reduces overall circuit efficiency.

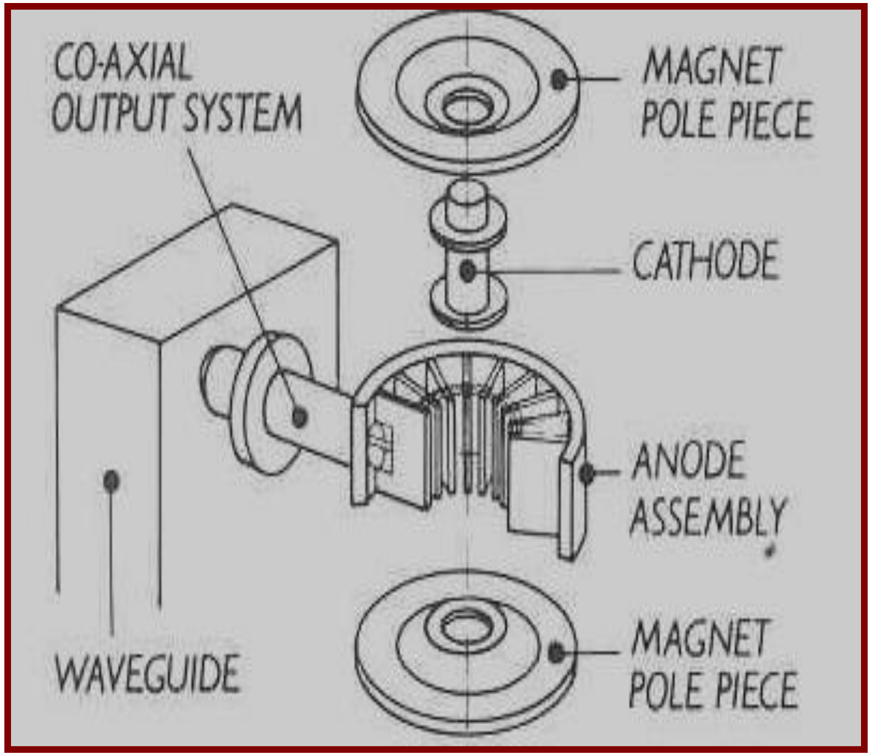
Transit Time

Transit time is the time required for electrons to travel from the cathode to the plate. While some small amount of transit time is required for electrons to travel from the cathode to the plate, the time is insignificant at low frequencies. In fact, the transit time is so insignificant at low frequencies that it is generally not considered to be a hindering factor. However, at high frequencies, transit time becomes an appreciable portion of a signal cycle and begins to hinder efficiency.

Magnetron Oscillator

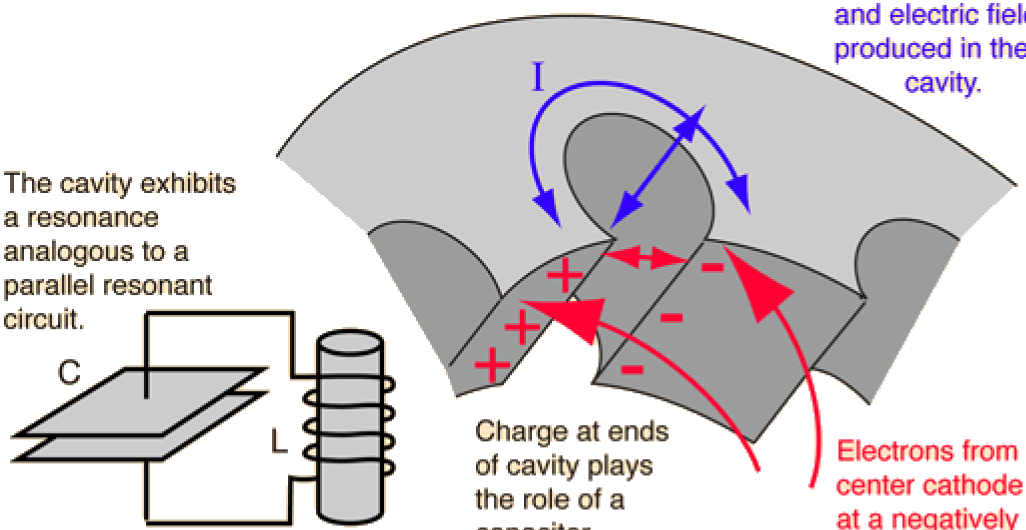
- The **magnetron** is a high-powered vacuum tube.
- Crossed electron and magnetic fields are used in the magnetron to produce the high-power output.

- These multi-cavity devices may be used in radar transmitters as either pulsed or cw oscillators at frequencies ranging from approximately 600 to 30,000 megahertz.



Physical construction of a magnetron

The 8 up to 20 cylindrical holes around its circumference are resonant cavities. A narrow slot runs from each cavity into the central portion of the tube dividing the inner structure into as many segments as there are cavities. Each cavitiy work like a parallel resonant circuit. The rear wall of the structure of the anode bloc may be considered to as the inductive portion (a coil with a single turn). The resonant frequency of a microwave cavity is thereby determined by the physical dimension of the resonator. If a single resonant cavity oscillates, then it excites the next one to oscillate too. This one oscillates at a phase delay of 180 degrees and excites the next resonant cavity, and so on. From a resonant cavity to the next always occurs this delay of 180 degrees.



Current around the cavity plays the role of an inductor.

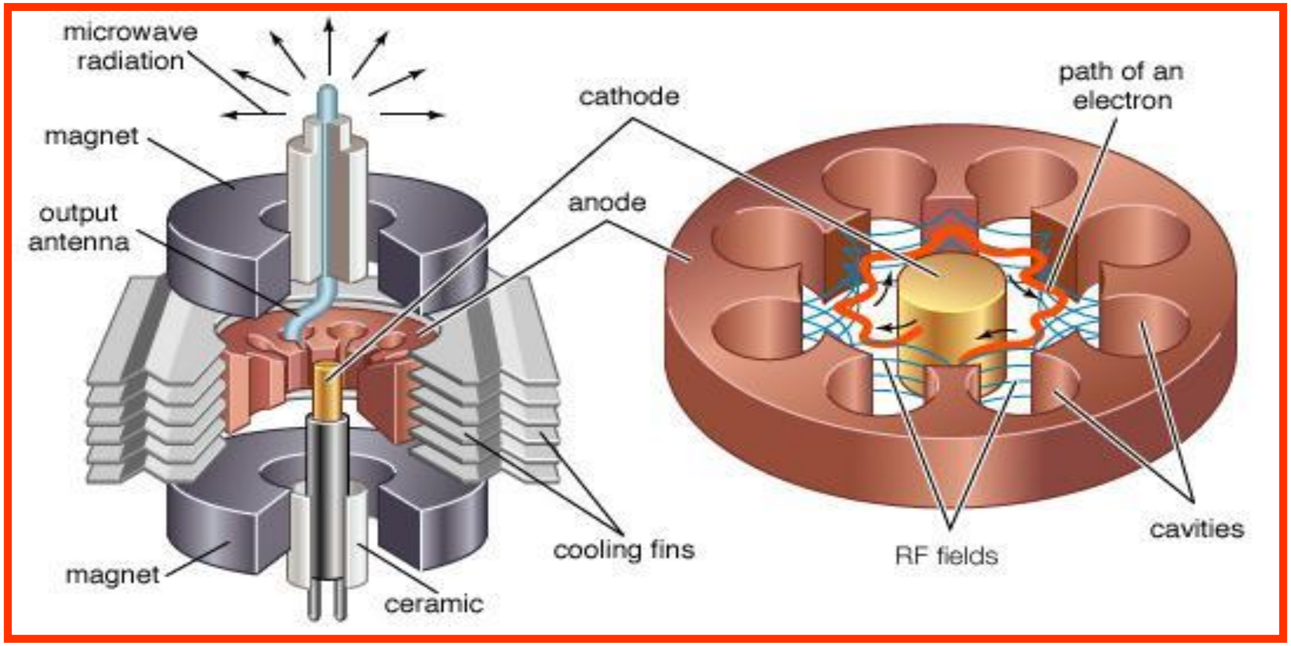
Oscillating magnetic and electric fields produced in the cavity.

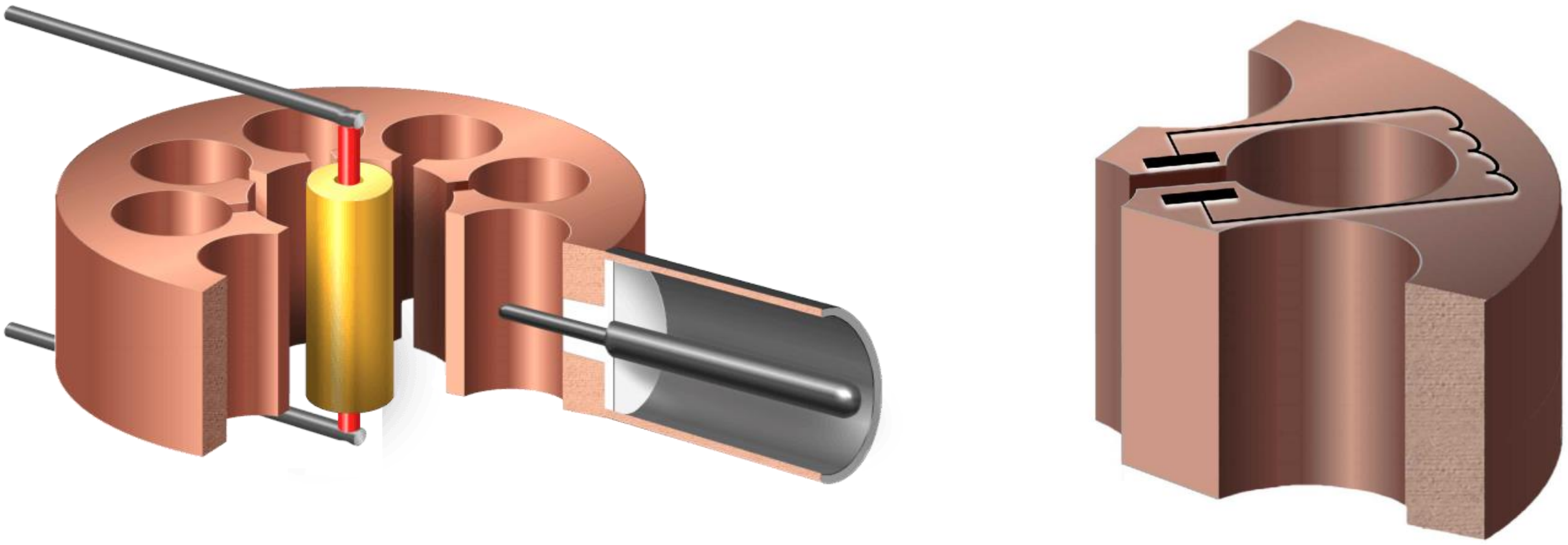
The cavity exhibits a resonance analogous to a parallel resonant circuit.

Charge at ends of cavity plays the role of a capacitor.

Electrons from the hot center cathode arriving at a negatively charged region tend to drive it back around the cavity, "pumping" the natural resonant frequency.

$$f_{resonance} \approx \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

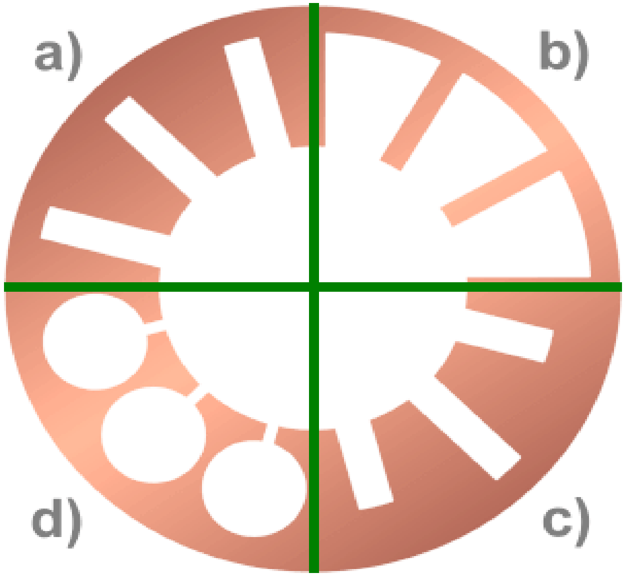

microwave radiation
magnet
output antenna
magnet
cathode
anode
cooling fins
ceramic
path of an electron
cavities
RF fields



The open space between the anode block and the cathode is called the interaction space. In this space the electric and magnetic fields interact to exert force upon the electrons. The magnetic field is usually provided by a strong, permanent magnet mounted around the magnetron so that the magnetic field is parallel with the axis of the cathode.

It generally consists of an even number of microwave cavities arranged in radial fashion. The form of the cavities varies, shown in the figure.

A. slot- type
B. vane- type
C. rising sun- type
D. hole-and-slot- type



Magnetron Basic Operation

As when all velocity-modulated tubes the electronic events at the production microwave frequencies at a magnetron can be subdivided into four phases too:

phase: Production and acceleration of an electron beam in a dc field

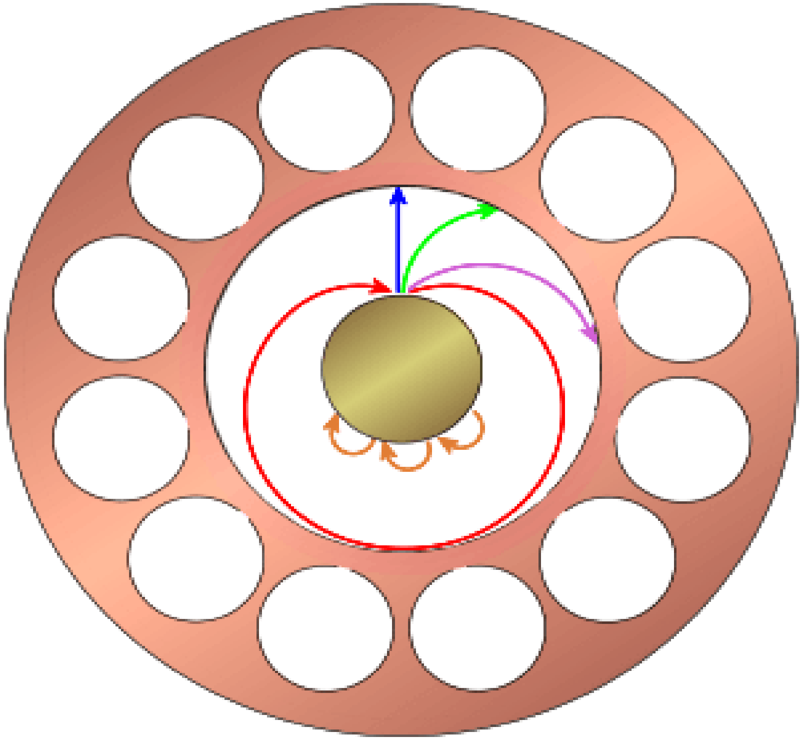
phase: Velocity-modulation of the electron beam

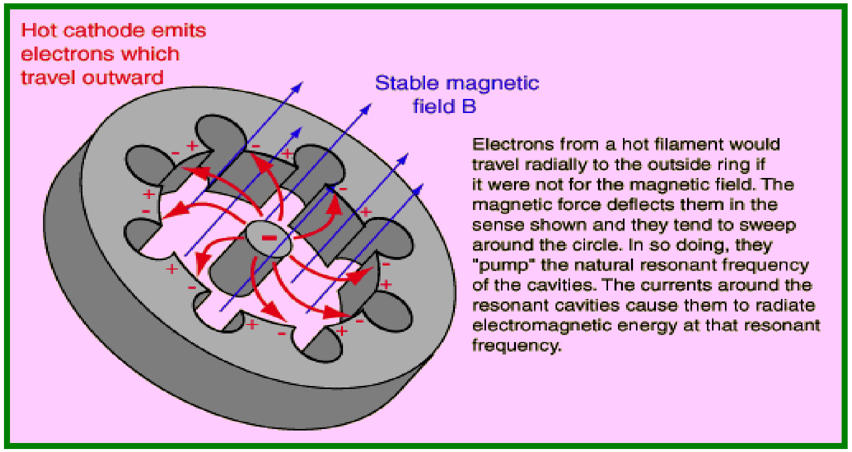
phase: Formation of electron bunches by velocity modulation (here in form of a “Space-Charge Wheel”)

phase: Dispense energy to the ac field

Production and acceleration of an electron beam

When no magnetic field exists, heating the cathode results in a uniform and direct movement of the electron from the cathode to the anode block (the blue path in the figure). A weak permanent magnetic field B perpendicular to the electric field bends the electron path as shown with the green path in the figure . If the electron flow reaches the anode, so a large amount of plate current is flowing. If the strength of the magnetic field is increased, the path of the electron will have a sharper bend. When the field strength is made still greater, the plate current drops to zero.





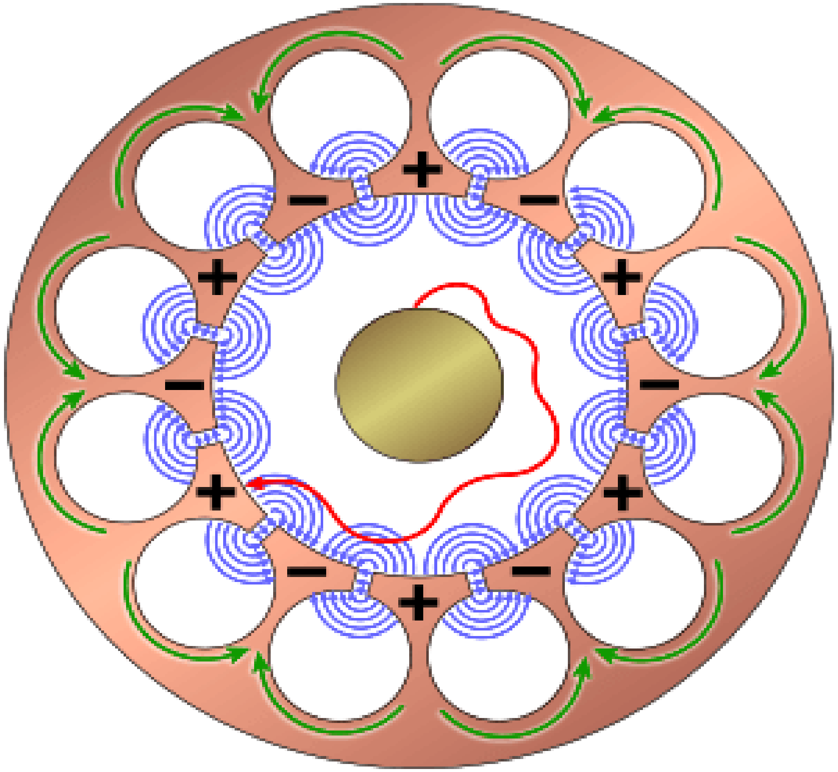
Electrons from a hot filament would travel radially to the outside ring if it were not for the magnetic field. The magnetic force deflects them in the sense shown and they tend to sweep around the circle. In so doing, they "pump" the natural resonant frequency of the cavities. The currents around the resonant cavities cause them to radiate electromagnetic energy at that resonant frequency.

Velocity-modulation of the electron beam

The electric field in the magnetron oscillator is a product of AC and DC fields. The DC field extends radially from adjacent anode segments to the cathode. The AC fields, extending between adjacent segments, are shown at an instant of maximum magnitude of one alternation of the RF oscillations occurring in the cavities.

This AC field work in addition to the to the permanently available DC field. The AC field of each individual cavity increases or decreases the DC field like shown in the figure.

Well, the electrons which fly toward the anode segments loaded at the moment more positively are accelerated in addition. These get a higher tangential speed. On the other hand the electrons which fly toward the segments loaded at the moment more negatively are slow down.

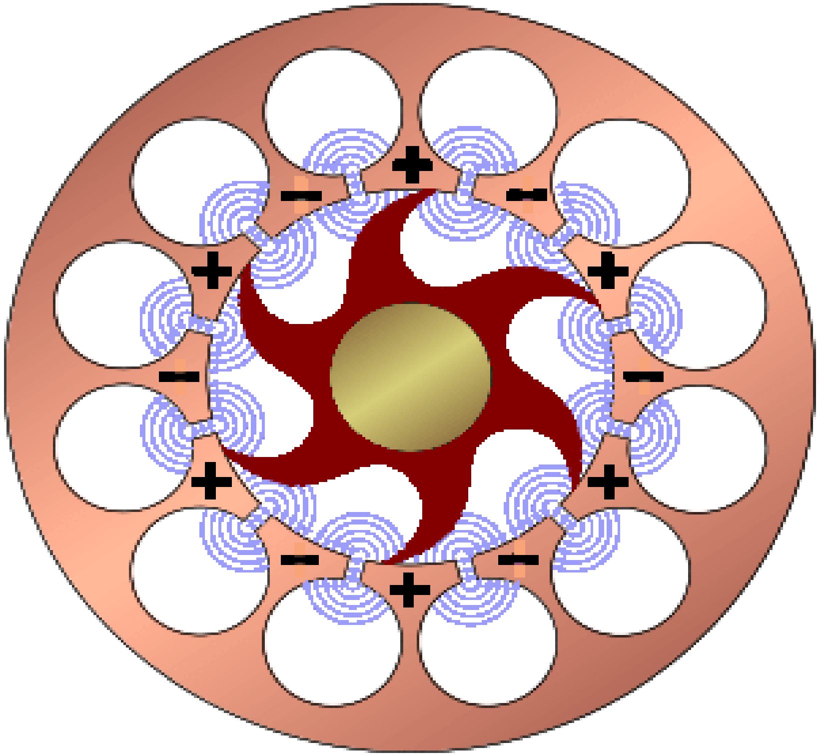


Forming of a Space-Charge Wheel

On reason the different speeds of the electron groups the velocity modulation leads to a density modulation therefore.

The cumulative action of many electrons returning to the cathode while others are moving toward the anode forms a pattern resembling the moving spokes of a wheel known as a “Space-Charge Wheel”. The space-charge wheel rotates about the cathode at an angular velocity of 2 poles (anode segments) per cycle of the AC field. This phase relationship enables the concentration of electrons to continuously deliver energy to sustain the RF oscillations.

The electrons are slowed down and pass her energy on to the AC field. This state isn't static, because both the AC- field and the wire wheel permanently circulate. The tangential speed of the electron spokes and the cycle speed of the wave must be brought in agreement so.

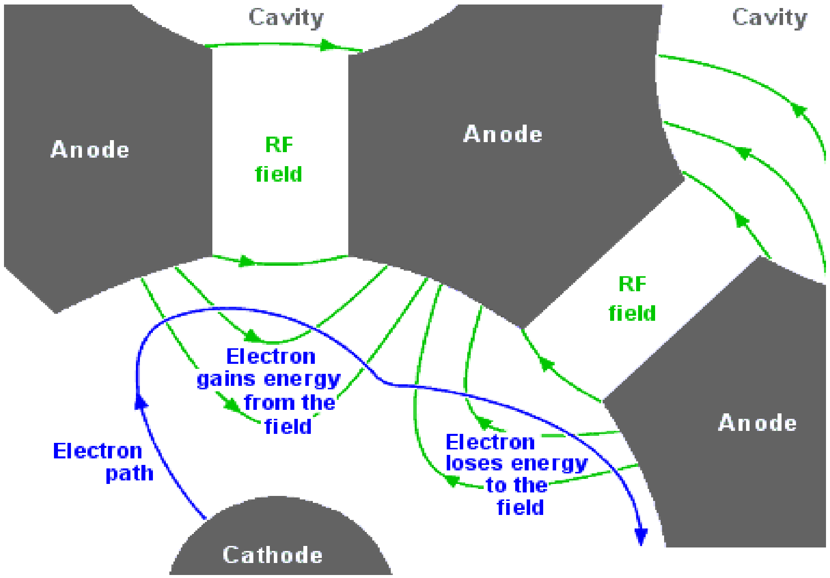


In other words, the electron current is noisy. It contains energy at all sorts of frequencies. And this noisy current is circulating close to a series of resonant cavities, which act as tuned circuits. If they see energy at frequencies near their resonant frequency, they seize it, and store it, swapping the energy between their electric and magnetic fields just like any other tuned circuit.

The energy oscillating around inside each cavity establishes its own field - the RF field - which itself now interacts with the circulating electron current.

Electrons passing though the RF field may give up some of their energy to it, slowing them down and leaving them to fall into the anode. Or they may gain energy from it, sending them back towards the cathode.

The effect is to thin out the cloud, causing the electrons to collect into bunches that rotate like the sails of a windmill (but not really).

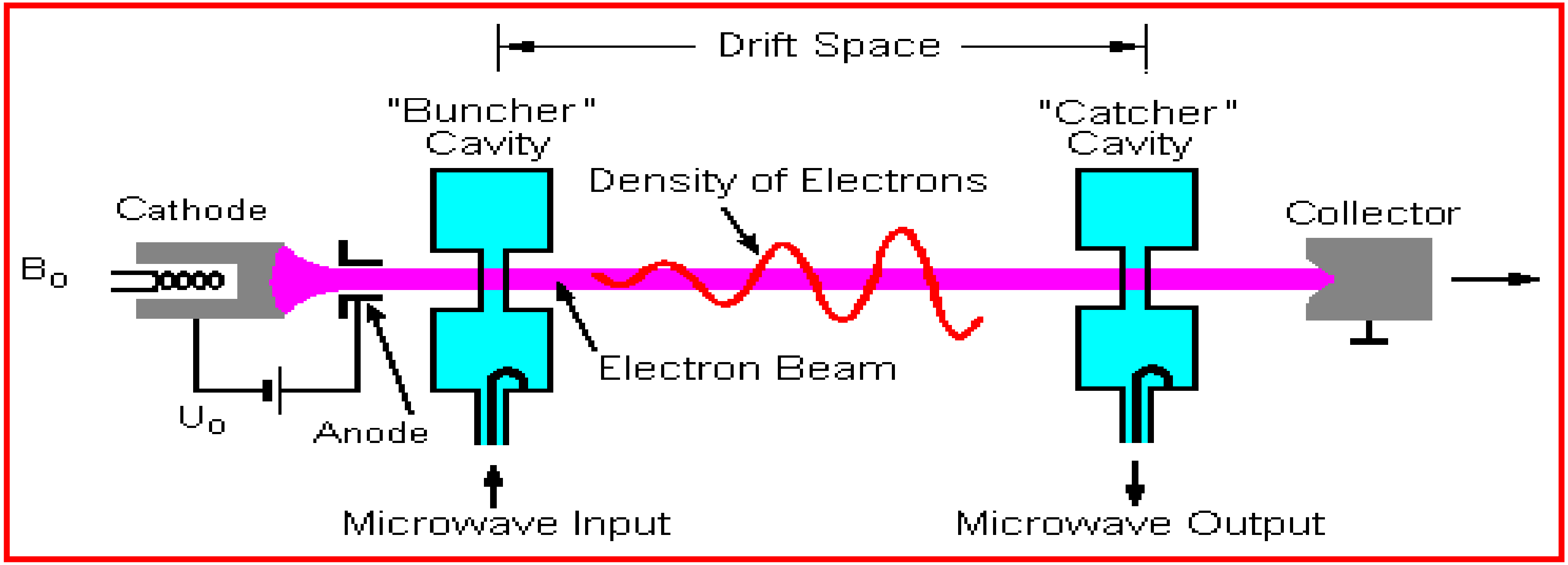


Lecture-7-

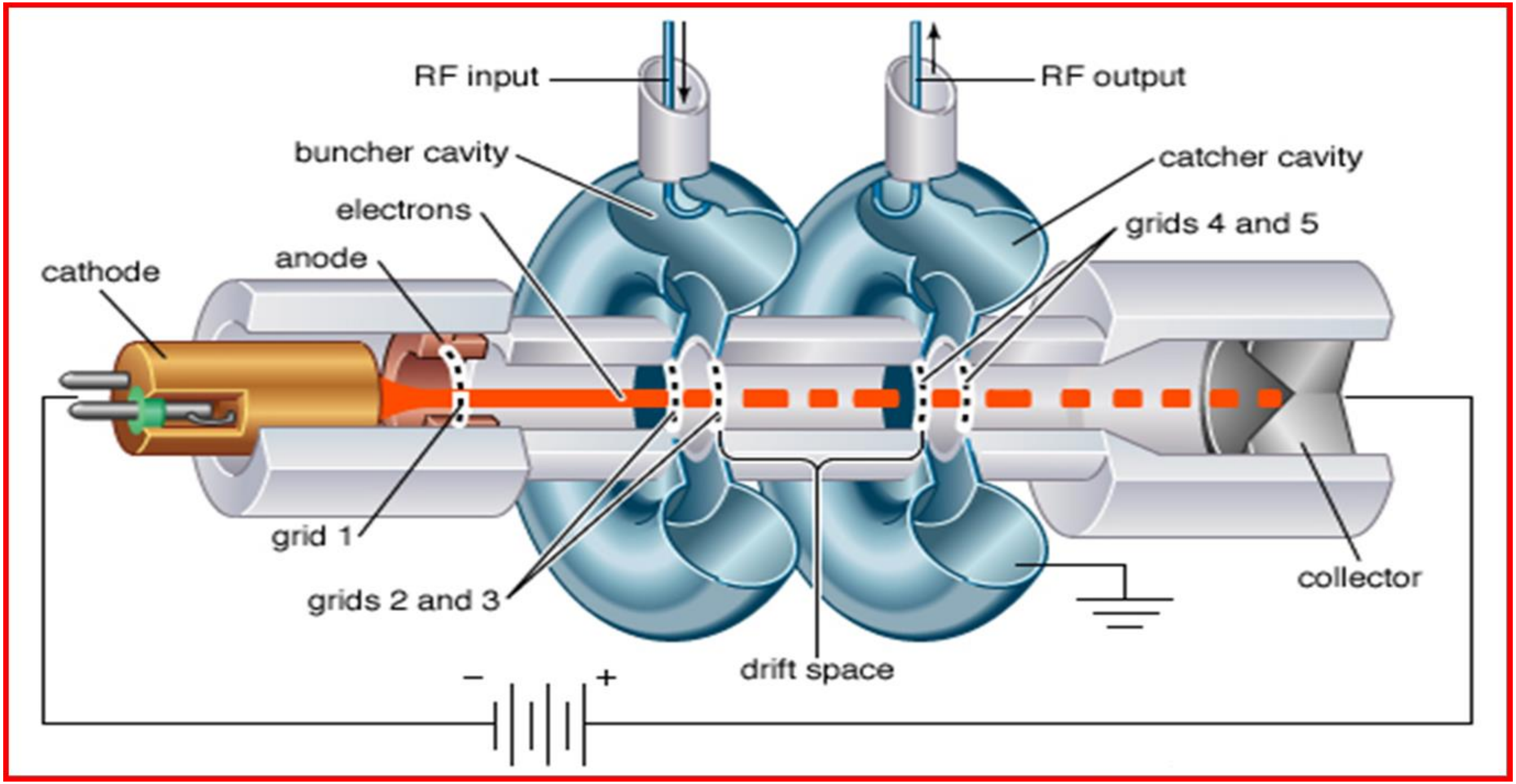
Klystron

Klystron Oscillator

A klystron is a vacuum tube that can be used either as a generator or as an amplifier of power, at microwave frequencies.



Two cavity Klystron Amplifier

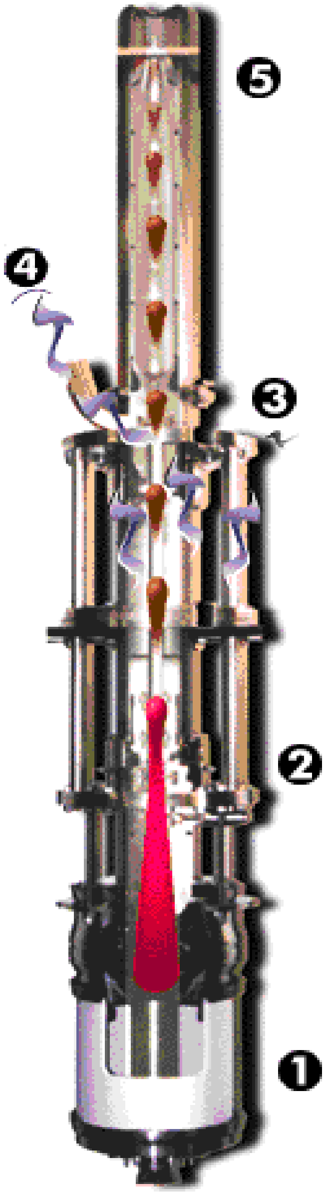


Applications

- **As power output tubes**
  1. in UHF TV transmitters.
  2. in troposphere scatter transmitters.
  3. satellite communication ground station.
  4. radar transmitters.
- **As power oscillator** (5 – 50 GHz), if used as a klystron oscillator.

In a klystron:

1. The electron gun produces a flow of electrons .
2. The bunching cavities regulate the speed of the electrons so that they arrive in bunches at the output cavity.
3. The bunches of electrons excite microwaves in the output cavity of the klystron.
4. The microwaves flow into the waveguide, which transports them to the accelerator .
5. The electrons are absorbed in the beam stop.



Example: The parameters of a two cavity Klystron are:

Input power = 10 mW
Voltage gain = 20 dB
R_{sh}(Input cavity) = 25 kΩ
R_{sh}(Output cavity) = 35 kΩ
Load resistance = 40 kΩ
Calculate (a) Input voltage (b) Output voltage (c) Power output .

Solution:

$$P_{ac\ in} = \frac{V_1^2}{Rshin}$$

$$V_1 = \sqrt{Pacin * Rshin} = \sqrt{250} = 15.81\ \text{V}$$

$$A_v = 20 \log \frac{V_2}{V_1} = 20\ \text{dB}$$

$$\log \frac{V_2}{V_1} = 1, \quad \frac{V_2}{V_1} = 10, \quad V_2 = 158.1\ \text{V}$$

$$\text{Power output} = \frac{V_2^2}{RL\ ||R_{shout}} = 1.339\ \text{W}$$

Reflex Klystrons

- The reflex klystron has been the most used source of microwave power in laboratory applications.

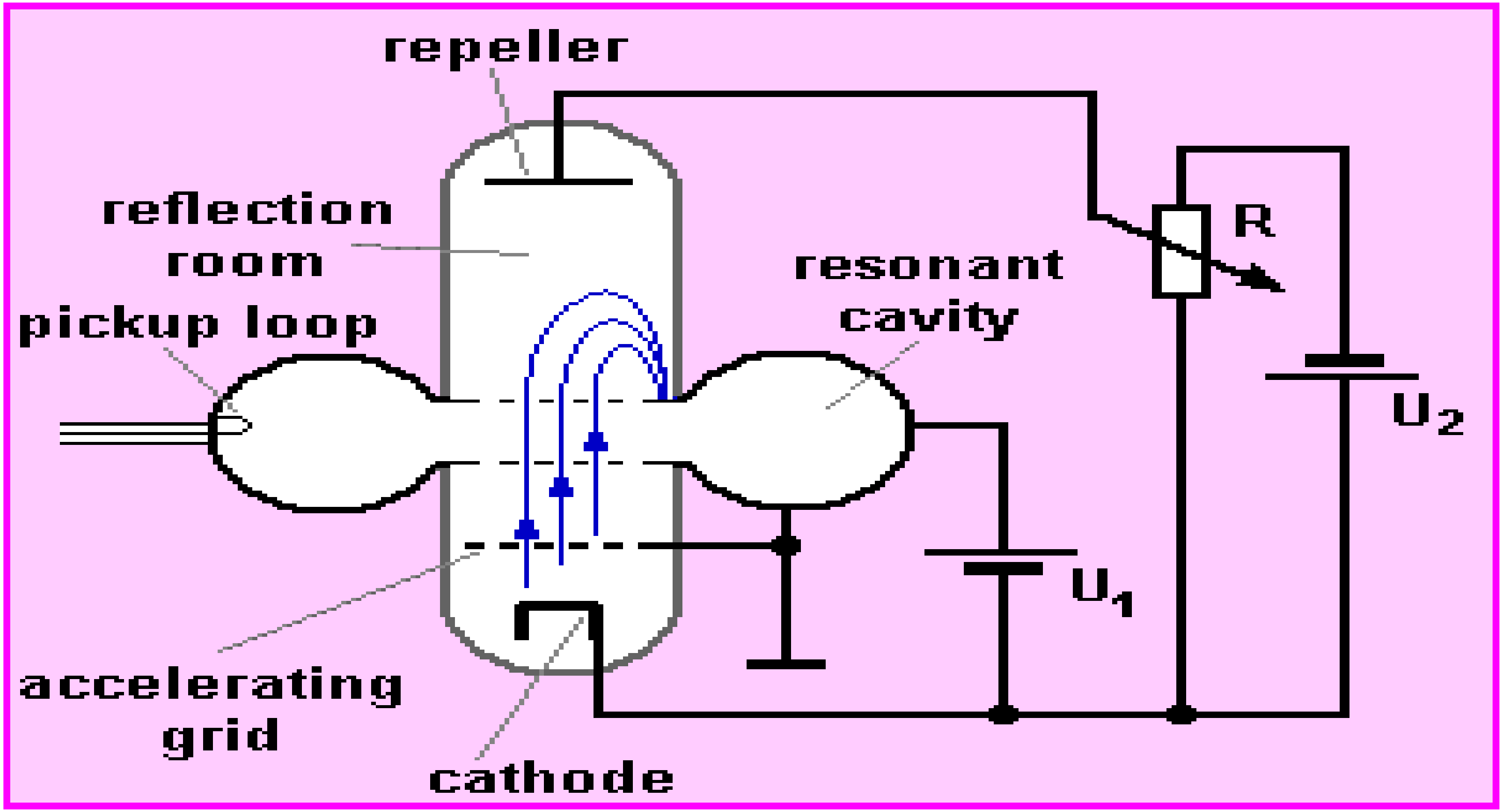
Construction

- A reflex klystron consists of an electron gun, a cavity with a pair of grids and a repeller plate as shown in the above diagram.
- In this klystron, a single pair of grids does the functions of both the buncher and the catcher grids.
- The main difference between two cavity reflex klystron amplifier and reflex klystron is that the output cavity is omitted in reflex klystron and the repeller or reflector electrode, placed a very short distance from the single cavity, replaces the collector electrode.

Working

- The cathode emits electrons which are accelerated forward by an accelerating grid with a positive voltage on it and focused into a narrow beam.
- The electrons pass through the cavity and undergo velocity modulation, which produces electron bunching and the beam is repelled back by a repeller plate kept at a negative potential with respect to the cathode.
- On return, the electron beam once again enters the same grids which act as a buncher, therby the same pair of grids acts simultaneously as a buncher for the forward moving electron and as a catcher for the returning beam.

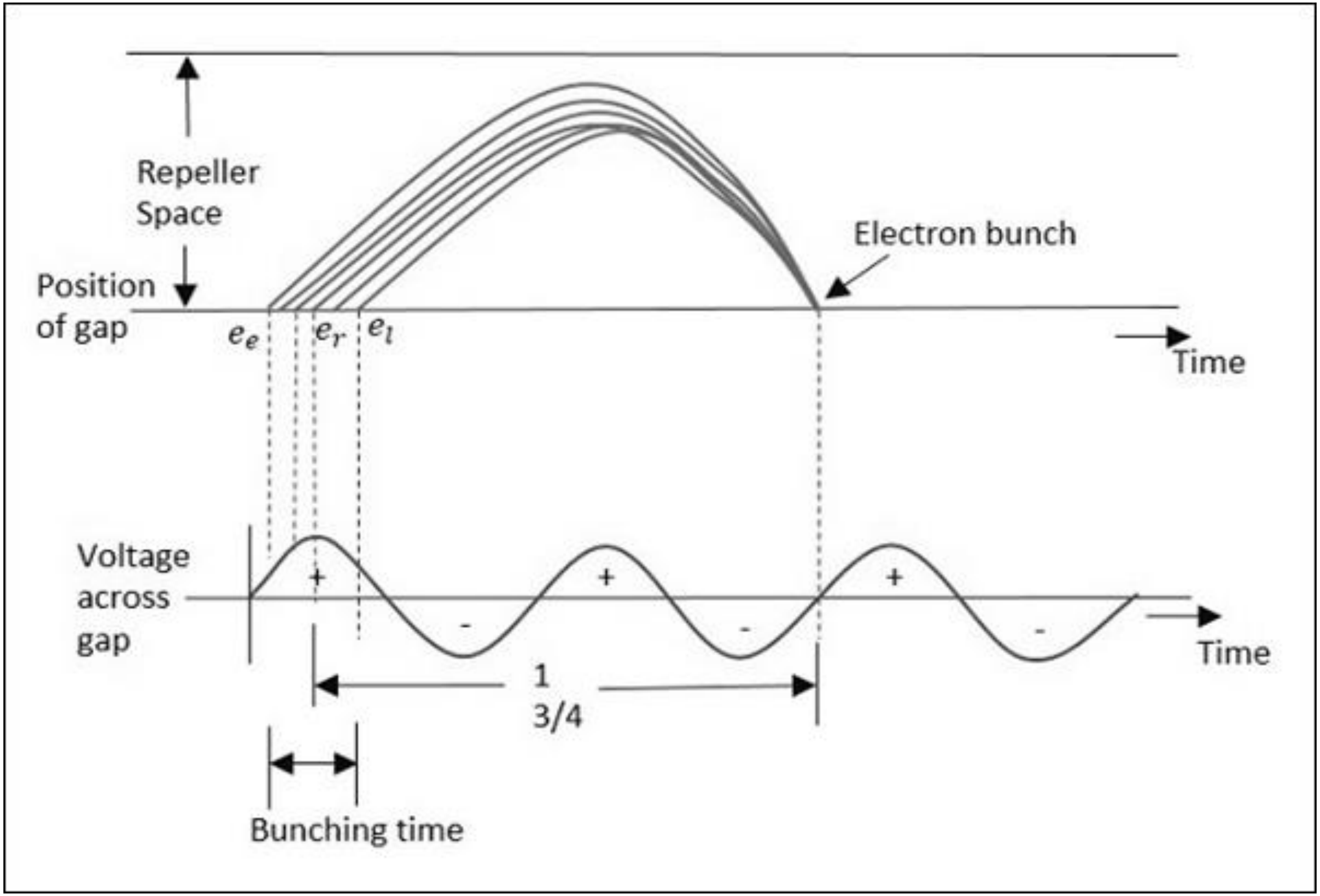
Reflex Klystron oscillator



Working

- The feedback necessary for electrical oscillations is developed by reflecting the electron beam, the velocity modulated electron beam does not actually reach the repeller plate, but is repelled back by the negative voltage.
- The point at which the electron beam is turned back can be varied by adjusting the repeller voltage.
- Thus the repeller voltage is so adjusted that complete bunching of the electrons takes place at the catcher grids, the distance between the repeller and the cavity is chosen such that the repeller electron bunches will reach the cavity at proper time to be in synchronization.
- Due to this, they deliver energy to the cavity, the result is the oscillation at the cavity producing RF frequency.

Applegate Diagram



Mode of Oscillation

- The electrons should return after 1¾, 2 ¾ or 3 ¾ cycles – most optimum departure time.
- If **T is the time period at the resonant frequency**, t_o is the time taken by the reference electron to travel in the repeller space between entering the repeller space and returning to the cavity at positive peak voltage on formation of the bunch

Then, $t_o = (n + \frac{3}{4})T = NT$

Where $N = n + \frac{3}{4}$, n = 0,1,2,3…….

N – mode of oscillation.

Applications

- The reflex klystrons are used in

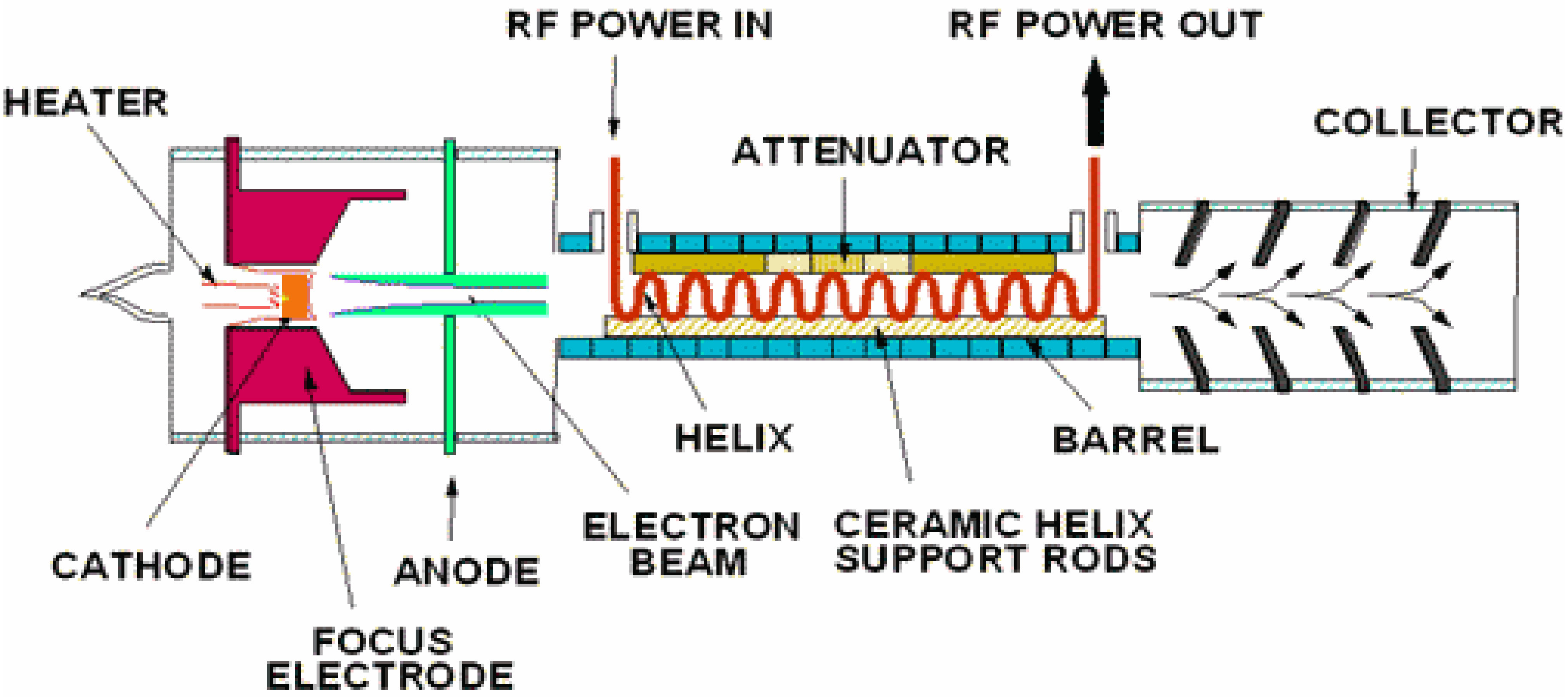
1. Radar receivers
2. Local oscillator in microwave receivers
3. Signal source in microwave generator of variable frequency
4. Portable microwave links
5. Pump oscillator in parametric amplifier

Traveling Wave Tube (TWT)

- Traveling Wave Tube (TWT) is the most versatile microwave RF power amplifiers.

- The main virtue of the TWT is its extremely wide band width of operation.

BASICS of Traveling Wave Tube (TWT) Amplifier



Basic structure

- The basic structure of a TWT consists of a cathode and filament heater plus an anode that is biased positively to accelerate the electron beam forward and to focus it into a narrow beam.
- The electrons are attracted by a positive plate called the collector, which has given a high dc voltage.
- The length of the tube is usually many wavelengths at the operating frequency.
- Surrounding the tube are either permanent magnets or electromagnets that keep the electrons tightly focused into a narrow beam.

Functioning

- The passage of the microwave signal down the helix produces electric and magnetic fields that will interact with the electron beam.
- The electromagnetic field produced by the helix causes the electrons to be speeded up and slowed down, this produces velocity modulation of the beam which produces density modulation.
- Density modulation causes bunches of electrons to group together one wavelength apart and these bunch of electrons travel down the length of the tube toward the collector.

Functioning

- The electron bunches induce voltages into the helix which reinforce the voltage already present there. Due to that the strength of the electromagnetic field on the helix increases as the wave travels down the tube towards the collector.
- At the end of the helix, the signal is considerably amplified. Coaxial cable or waveguide structures are used to extract the energy from the helix.

Advantages

1. TWT has extremely wide bandwidth. Hence, it can be made to amplify signals from UHF to hundreds of gigahertz.
2. Most of the TWT’s have a frequency range of approximately 2:1 in the desired segment of the microwave region to be amplified.
3. The TWT’s can be used in both continuous and pulsed modes of operation with power levels up to several thousands watts.

Key Notes of TWTA:

- Heater/Filament is closest to Cathode Voltage.
- Heater and Cathode act as electron gun, and they are on the side RF Input.
- Collectors sits on RF output.
- Electrons are fired from Cathode and received from Collectors.
- RF signal is amplified through bunching effect after traveling along the path of Helix coil.
- Higher Cathode voltage → Higher RF Power.
- Advantage of TWTA (over solid state amplification) is the linearity and output power.
- TWTA Efficiency: 50% to 60% vs. Solid State: 25% to 30%
- Ranges of Frequency for TWTA: 1Ghz – 40 Ghz.

Microwave Devices

Microwave Concepts

Microwave Communication Systems

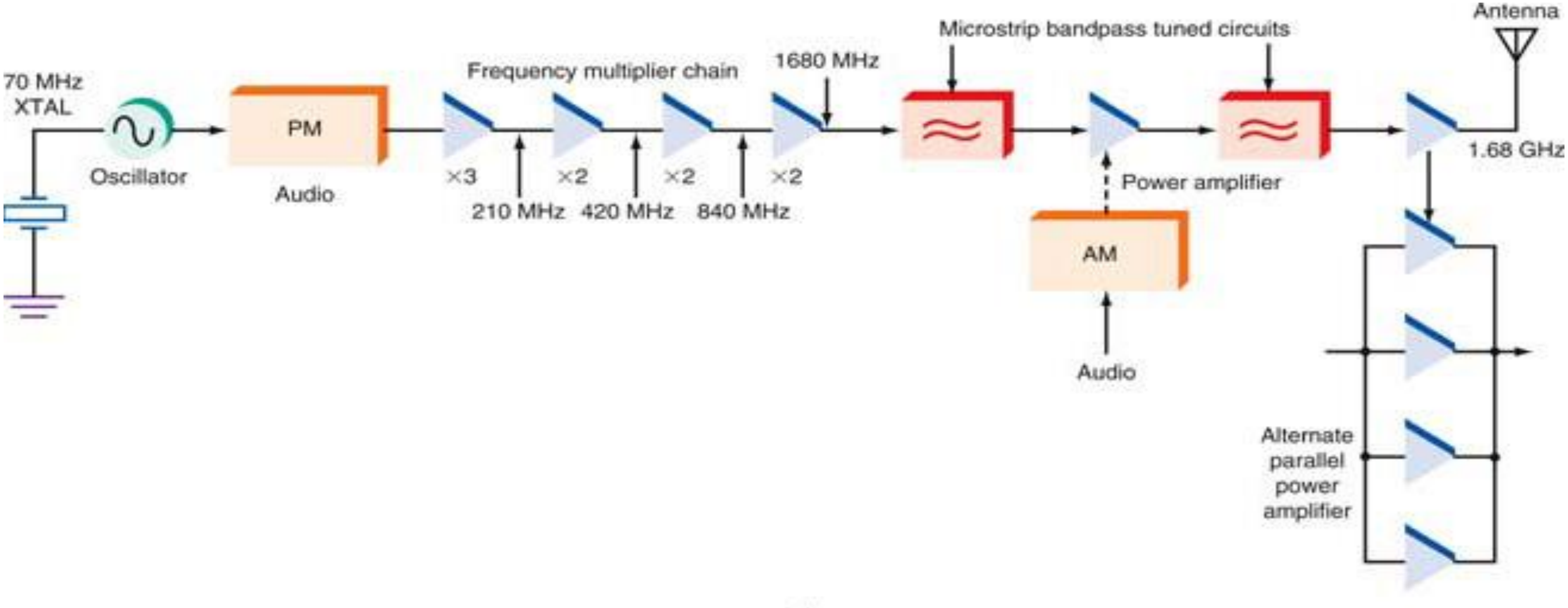
- Like any other communication system, a microwave communication system uses transmitters, receivers, and antennas.
- The same modulation and multiplexing techniques used at lower frequencies are also used in the microwave range.
- The RF part of the equipment, however, is physically different because of the special circuits and components that are used to implement the components.

Microwave Concepts

Microwave Communication Systems: Transmitters

- Like any other transmitter, a microwave transmitter starts with a carrier generator and a series of amplifiers.
- It also includes a modulator followed by more stages of power amplification.
- The final power amplifier applies the signal to the transmission line and antenna.
- A transmitter arrangement could have a mixer used to up-convert an initial carrier signal with or without modulation to the final microwave frequency.

Microwave Concepts



(a)

Microwave transmitters using frequency multipliers to reach the microwave frequency. The shaded stages operate in the microwave region.

Microwave Concepts

Microwave Communication Systems: Receivers

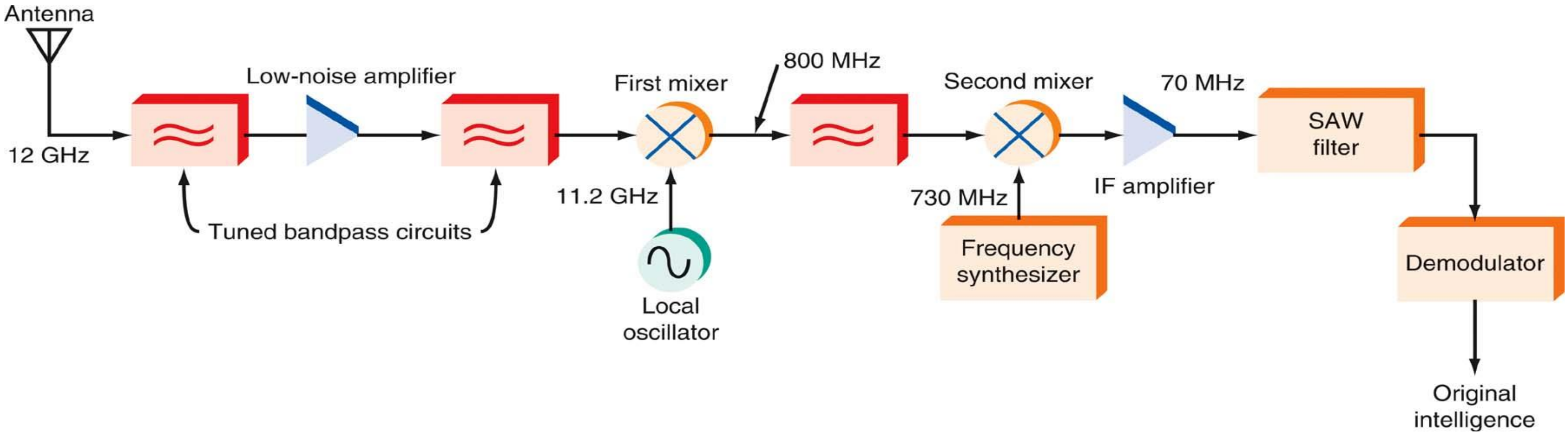
- Microwave receivers, like low-frequency receivers, are the superheterodyne type.
- Their front ends are made up of microwave components.
- Most receivers use double conversion.

Microwave Concepts

Microwave Communication Systems: Receivers

- The antenna is connected to a tuned circuit, which could be a cavity resonator or microstrip or stripline tuned circuit.
- The signal is then applied to a special RF amplifier known as a low-noise amplifier (LNA).
- Another tuned circuit connects the amplified input signal to the mixer.
- The local oscillator signal is applied to the mixer.
- The mixer output is usually in the UHF or VHF range.
- The remainder of the receiver is typical of other superheterodynes.

Microwave Concepts



A microwave receiver

Microwave Concepts

Microwave Communication Systems: Transmission Lines

- Coaxial cable, most commonly used in lower-frequency communication has very high attenuation at microwave frequencies and conventional cable is unsuitable for carrying microwave signals.
- Special microwave coaxial cable that can be used on bands L, S, and C is made of hard tubing. This low-loss coaxial cable is known as **hard line cable.**
- At higher microwave frequencies, a special hollow rectangular or circular pipe called **waveguide** is used for the transmission line.

Microwave Concepts

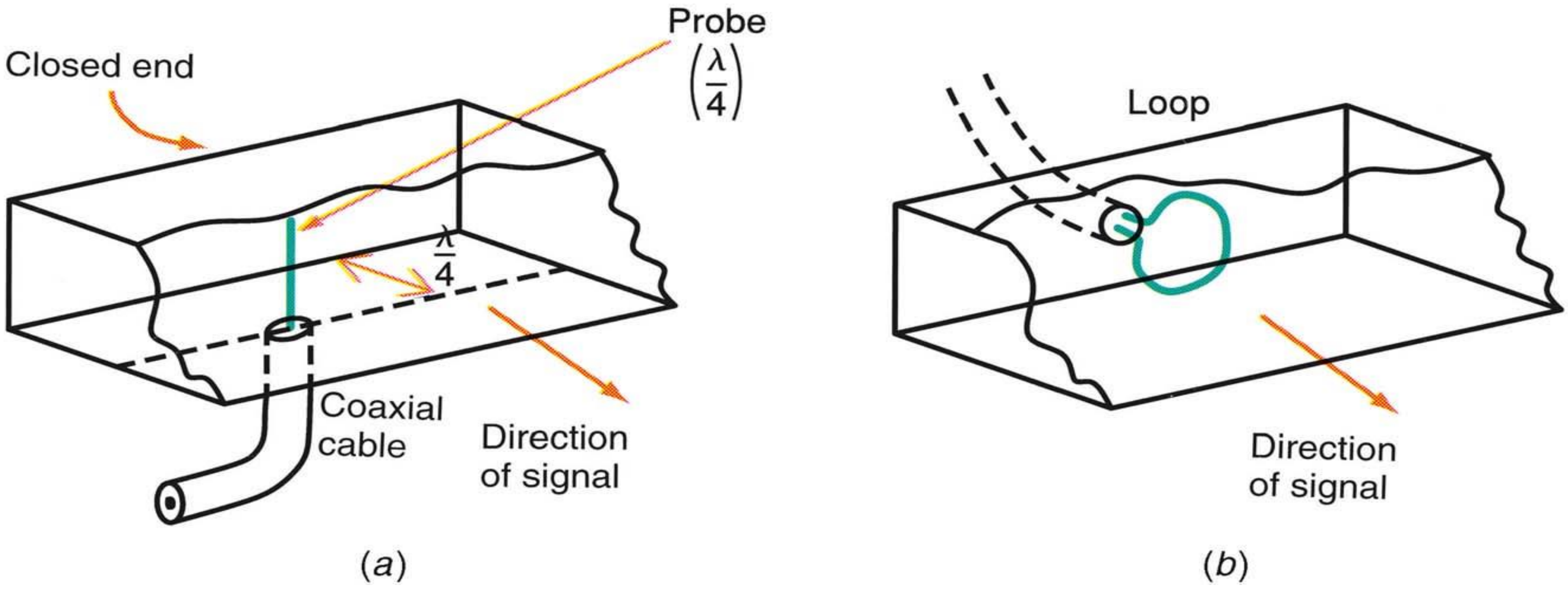
Microwave Communication Systems: Antennas

- At low microwave frequencies, standard antenna types, including the simple dipole and one-quarter wavelength vertical antenna, are still used.
- At these frequencies antennas are very small; for example, a half-wave dipole at 2 GHz is about 3 inch.
- At higher microwave frequencies, special antennas are generally used.

Waveguides: Signal Injection and Extraction

- A microwave signal to be carried by a waveguide is introduced into one end of the waveguide with an antennalike probe.
- The probe creates an electromagnetic wave that propagates through the waveguide.
- The electric and magnetic fields associated with the signal bounce off the inside walls back and forth as the signal progresses down the waveguide.
- The waveguide totally contains the signal so that none escapes by radiation.

Waveguides: Signal Injection and Extraction



Injecting a sine wave into a waveguide and extracting a signal.

Waveguides: Signal Injection and Extraction

Waveguides: Signal Injection and Extraction

- Probes and loops can be used to extract a signal from a waveguide.
- When the signal strikes a probe or a loop, a signal is induced which can then be fed to other circuitry through a short coaxial cable.

Waveguide Hardware and Accessories

A **directional coupler** is a 4-port network that is designed to **divide** and **distribute** power.

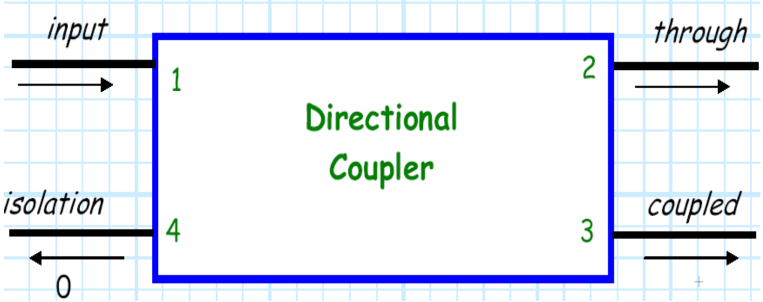
Although this would seem to be a particularly **mundane** and simple task, these devices are both very **important** in microwave systems, and very **difficult** to design and construct.

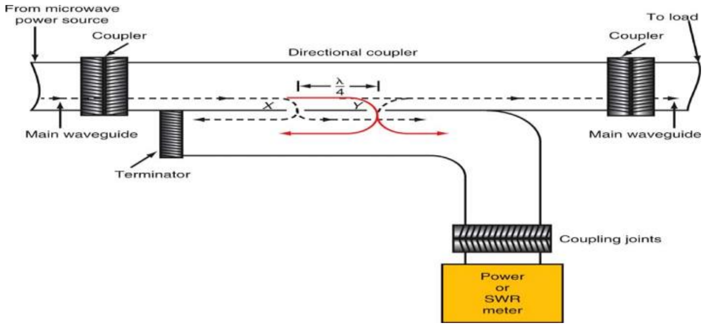
Two of the **reasons** for this difficulty are our desire for the device to be:

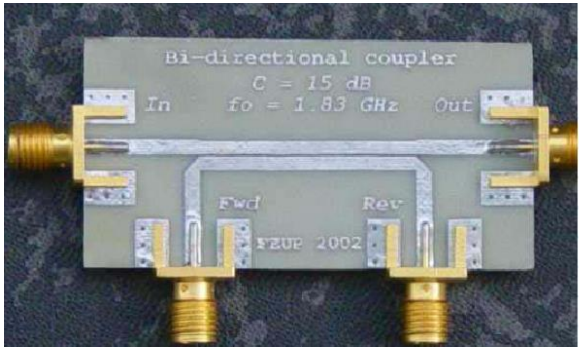
1. Matched

2. Lossless

In the terminology of the directional coupler, we say that port 1 is the **input** port, port 2 is the **through** port, port 3 is the **coupled** port, and port 4 is the **isolation** port. Note however, that **any** of the coupler ports can be an input, with a different through, coupled and isolation port for each case.







Waveguide Hardware and Accessories

Thus, from the scattering matrix of a directional coupler, we can form the following table:

Input	Through	Coupled	Isolation
Port 1	Port 2	Port 3	Port 4
Port 2	Port 1	Port 4	Port 3
Port 3	Port 4	Port 1	Port 2
Port 4	Port 3	Port 2	Port 1

Coupling (C)

The **coupling** value is the ratio of the coupled output power (P3) to the input power (P1), expressed in decibels:

$$C\,(dB) = 10\log_{10}\left[\frac{P_1}{P_3}\right]$$

This is the **primary** specification of a directional coupler. Note the **larger** the coupling value, the **smaller** the coupled power.

Directivity (D)

The **directivity** is the ratio of the power **out** of the coupling port (P3) to the power **out** of the isolation port (P4), expressed in decibels.

$$D\,(dB) = 10\log_{10}\left[\frac{P_3}{P_4}\right]$$

This value indicates how effective the device is in “**directing**” the coupled energy into the correct port (i.e., into the coupled port, **not** the isolation port).

Ideally this is infinite (i.e., P4=0) , so the **higher** the directivity, the **better**.

Isolation I

Isolation is the ratio of the **input power** (P1) to the power out of the **isolation** port (P4), expressed in decibels.

$$I(dB) = 10\log_{10}\left[\frac{P_1}{P_4}\right]$$

This value indicates how “isolated” the isolation port actually is. **Ideally** this is infinite (i.e., P4=0), so the **higher** the isolation, the better. Note that isolation, directivity, and coupling are **not** independent values! **You** should be able to quickly show that:

$$I(dB) = C(dB) + D(dB)$$

Mainline Loss ML

The **mainline loss** is the ratio of the **input** power (P1)to the power out of the **through** port (P2), expressed in decibels.

$$ML(dB) = 10\log_{10}\left[\frac{P_1}{P_2}\right]$$

It indicates how much power the signal **loses** as it travels from the input to the through port.

Coupling Loss ML

The **coupling loss** indicates the **portion** of the mainline loss that is due to coupling some of the input power into the coupling port.

$$CL(dB) = 10\log_{10}\left[\frac{P_1}{P_1^{+} - P_3^{-}}\right]$$

Insertion Loss IL

Q: But wait, shouldn’t (P1-P3=P2), meaning the coupling loss and the mainline loss will be the **same exact value**?

A: Ideally this would be true.

But, the reality is that couplers are **not perfectly lossless**, so there will additionally be loss due to **absorbed** energy (i.e., heat). This loss is called **insertion loss** and is simply the **difference** between the mainline loss and coupling loss:

$$IL(dB) = ML(dB) - CL(dB)$$

The insertion loss thus indicates the portion of the mainline loss that is **not** due to coupling some input power to the coupling port. This insertion loss **is** avoidable, and thus the **smaller** the insertion loss, the better**.** For couplers with **very small coupling** coefficients (e.g.,C (dB) >20) the coupling loss is so small that the mainline loss is almost entirely due to insertion loss (i.e., ML = IL)often then, the two terms are used **interchangeably**.

Lecture-10-

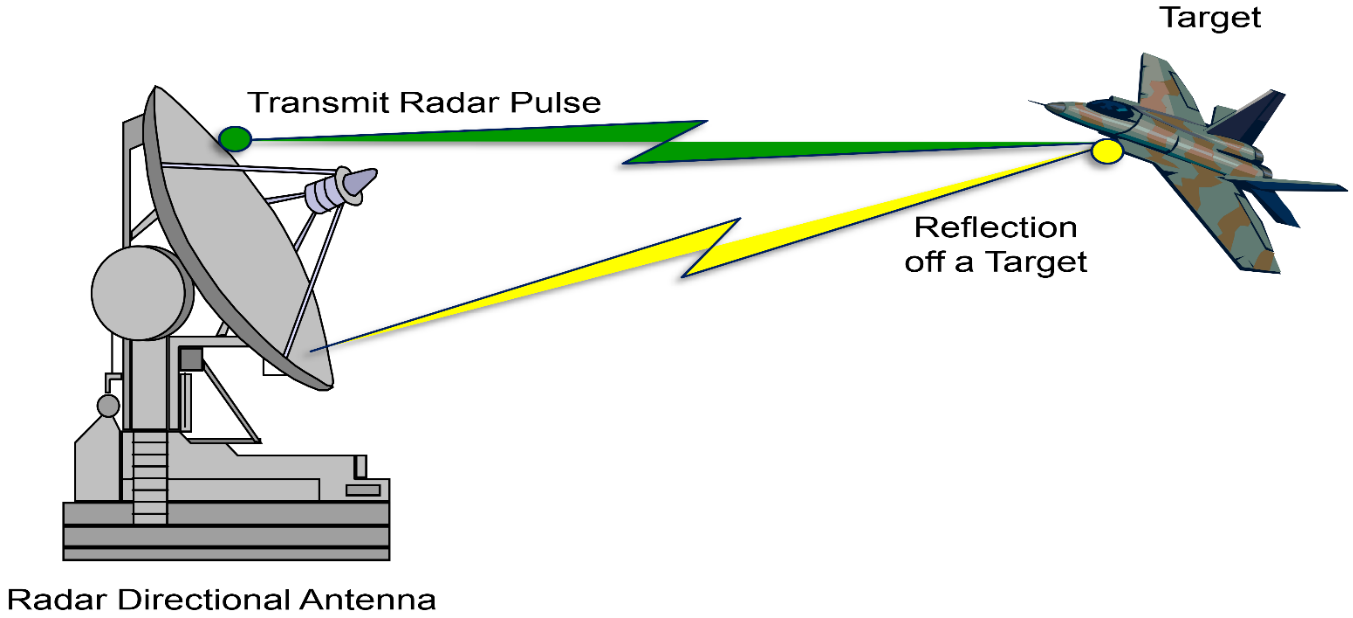
Radar , Microwave oven, Stealth

Introduction to RADAR

RADAR is a method of using electromagnetic waves to determine the position (range and direction), velocity and identifying characteristics of targets.

Radar is used to expand the individual's ability to perceive the environment, especially vision. The value of radar is not to replace the eyes, but to do things that the eyes cannot do.

The advantage of radar is that it can measure the distance or range to an object. This may be its most important attribute.



Radar Applications

- Military

– Search and Detection
– Targeting and Target Tracking
– Missile Guidance
– Fire Control – Acquisition, Track
– Airborne Intercept
– Ground and Battle field Surveillance
– Air Mapping Systems
– Submarine and Sub-Chasers

- Commercial

– Weather, Navigation, Air Traffic Control
– Space and Range
– Road and Speeding
– Biological Research – Bird and Insect Surveillance and Tracking
– Medical – diagnosis, organ movements, water condensation in the lungs, monitor heart rate and pulmonary motion, range(distance), remote sensor of heart and respiration rates without electrodes, patient movement and falls in the home
– Miniature – Seeing aids, early warning collision detection and situational awareness

Two Basic Radar Types

- Pulse Radar
  - Transmits a pulse stream with a low duty cycle
  - Receives reflected pulses during the time off or dead time between pulses
  - Single Antenna
  - Determines Range and Altitude
  - Susceptible To Jamming
  - Physical Range Determined By PW and PRF
  - Low average power
  - Time synchronization

- Continuous Wave CW Radar
  - Transmits a CW signal and receives a Doppler frequency for moving targets
  - Frequency Modulated CW FM-CW also provides both range and velocity
  - Requires 2 Antennas and high SNR
  - More Difficult to Jam But Easily Deceived
  - Simpler to operate, timing not required

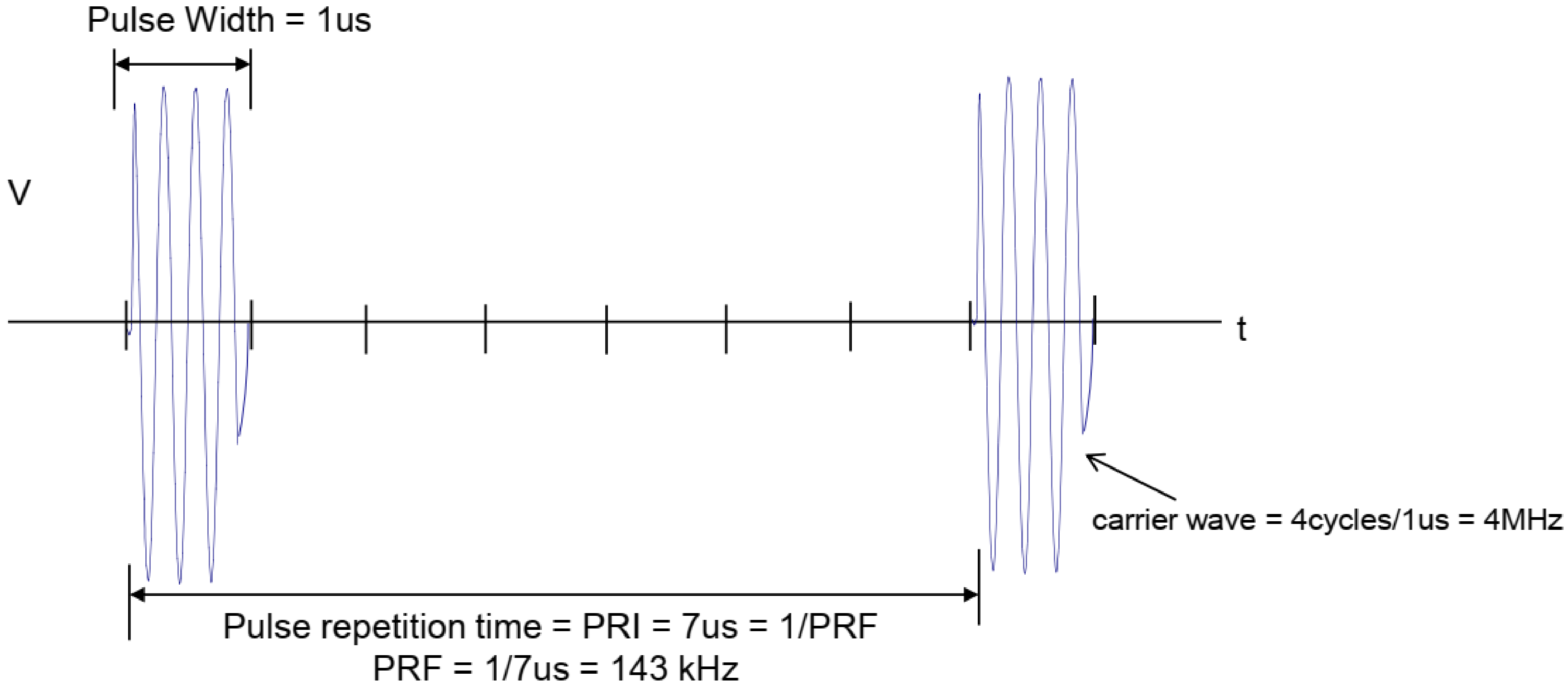
Pulsed Radar

- Most radar systems are pulsed.
- Transmit a pulse and then listen for receive signals, or echoes.
- Avoids problem of a sensitive receiver simultaneously operating with a high power transmitter.
- Radar transmits a low duty cycle, short duration high-power RF pulses.
- Time synchronization between the transmitter and receiver of a radar set is required for range measurement.
- Returns that come from the 1st pulse causes distortion in the returns after the next pulse.

Radar Modulation

- 100% Amplitude Modulation AM, ON/OFF keying
  - Turns on/off a carrier frequency
- Pulse Width PW amount of time that the radar is on for one pulse
  - Determines the minimum range resolution
- Pulse Repetition Frequency PRF = number of pulses per second
- Pulse Repetition Interval PRI is the time between the start of the pulses
- Pulse Repetition Time PRT = Pulse Repetition Interval PRI =1/PRF
- PRF can determine the radar’s maximum detection range

Radar Turns on/off the Carrier Frequency



Pulse Width = 1us

V

t

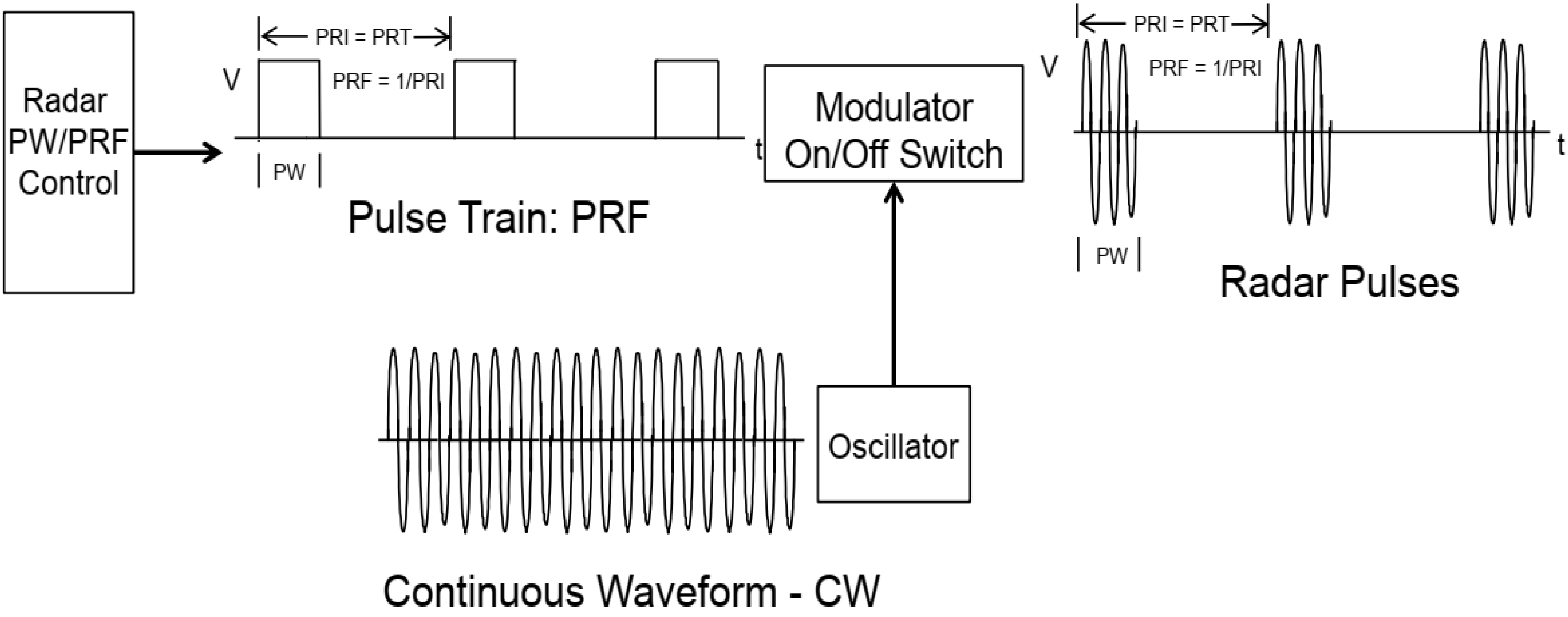
carrier wave = 4cycles/1us = 4MHz

Pulse repetition time = PRI = 7us = 1/PRF

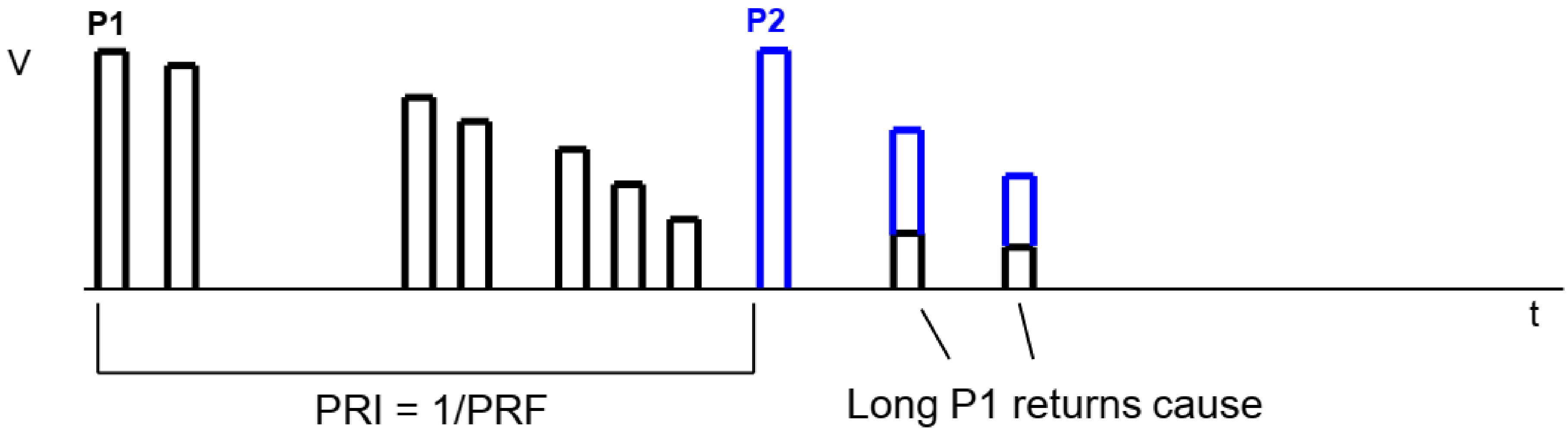
PRF = 1/7us = 143 kHz

- Burst of Carrier Frequency – Radar burst
- Low duty cycle, high power
- Duty cycle = PW/PRI x 100 = 1us/7us x 100 = 14%

Basic Radar Uses On/Off Keying of a CW Waveform

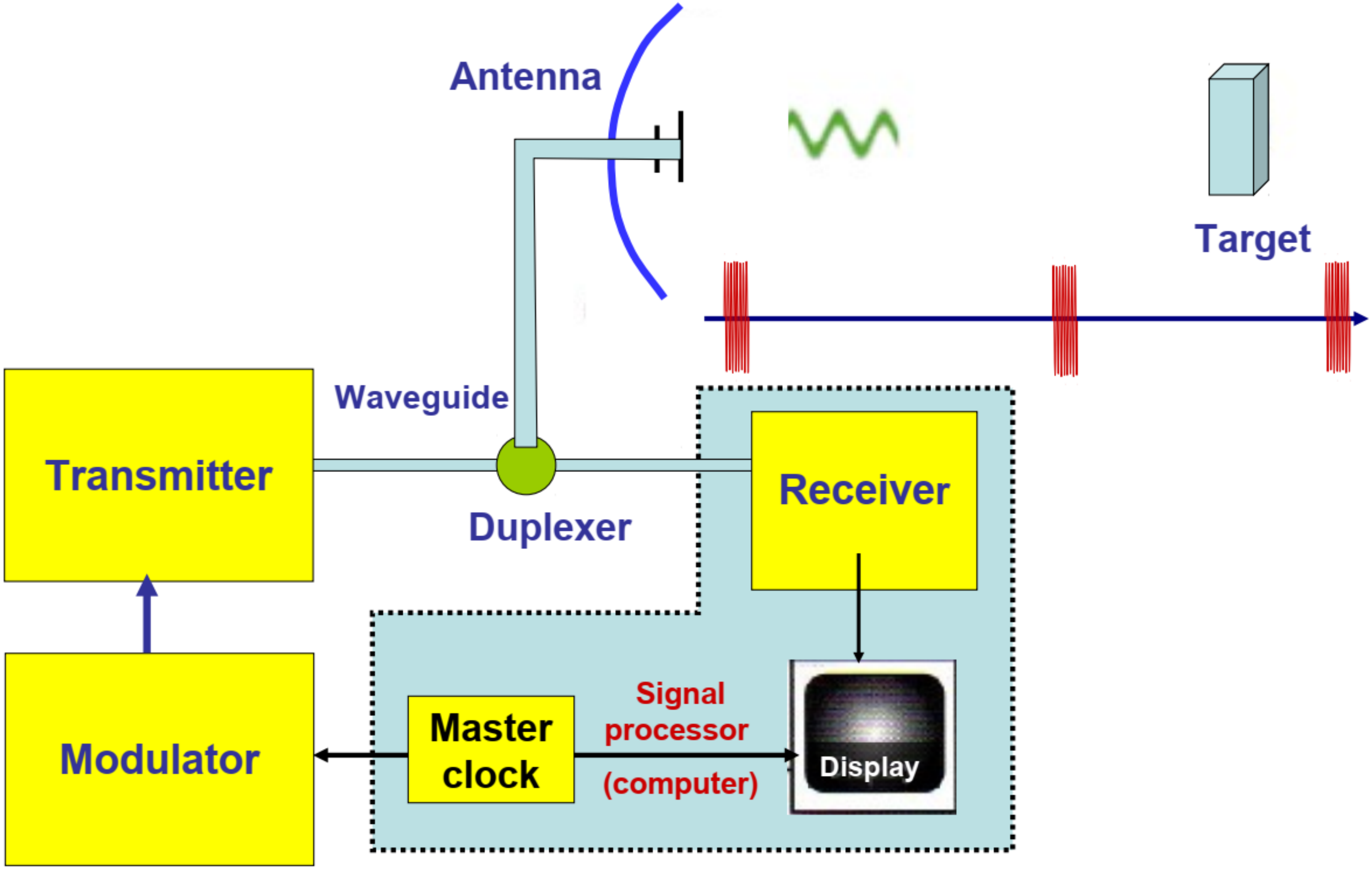


Pulse Distortion



Long returns from P1 causes distortion to the returns of P2

Basic Radar Diagram



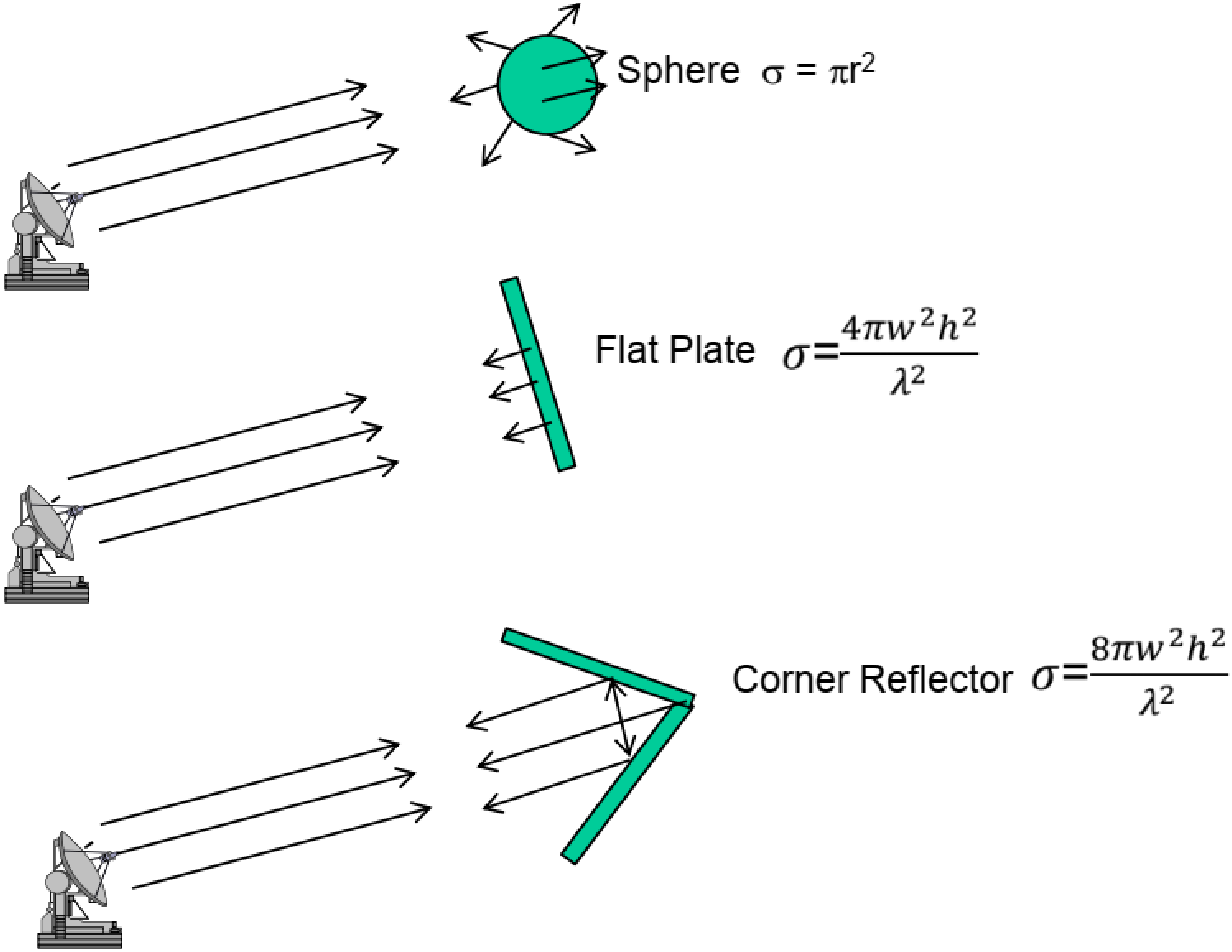
Radar Cross Section RCS

- RCS (s) - size and ability of a target to reflect radar energy m^2
- RCS(s) = Projected cross section x Reflectivity x Directivity
- The target radar cross sectional area depends on:
  - Target’s physical geometry and exterior features
  - Direction of the illuminating radar
  - Transmitted frequency,
  - Material types of the reflecting surface.

- Difficult to estimate
  - Equals the target’s cross-sectional area theoretically
  - Not all reflected energy is distributed in all directions
  - Some energy is absorbed
  - Usually measured for accurate results

Radar RCS Patterns

Similar to Antenna Gains



Sphere $\sigma = \pi r^2$

Flat Plate $\sigma = \frac{4\pi w^2 h^2}{\lambda^2}$

Corner Reflector $\sigma = \frac{8\pi w^2 h^2}{\lambda^2}$

RADAR Equation to Assess Radar Performance

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L_s}$$

P_r = Radar received power
P_t = Radar transmitted power
G_t = Transmitter antenna gain
G_r = Receiver antenna gain
$G^2 = G_r G_t$ assumes the same antenna at the radar
λ = wavelength
R = slant range
L_s = total two-way additional losses
σ = radar cross section of the target RCS

Radar Range Calculation

- Radar uses electromagnetic energy pulses
- Pulse travel at the speed of light c_o
- Reflects off of a surface and returns an echo back to the radar
- Calculates the two-way distance or slant range
- Slant range = line-of-sight distance from radar to target
- Takes in account the angle from the earth
- Ground range = horizontal distance from radar to target
- Slant range calculated using ground range and elevation
- Radar energy to the target drops proportional to range squared.
- Reflected energy to the radar drops by a factor of range squared
- Received power drops with the fourth power of the range

– Need very large dynamic ranges in the receive signal processing

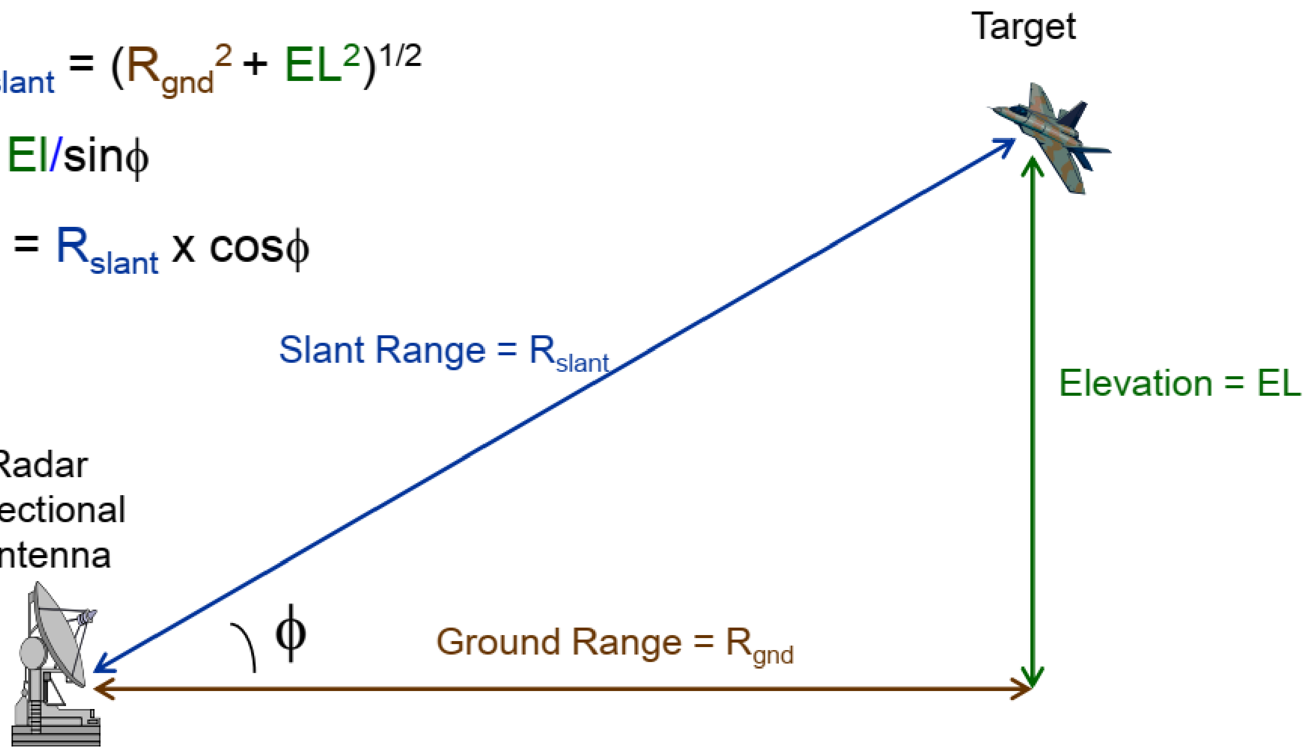
- Need to detect very small signals in the presence of large interfering signals

Slant Range

$R_{slant}^2 = R_{gnd}^2 + EL^2$: $R_{slant} = (R_{gnd}^2 + EL^2)^{1/2}$

$\text{Sin}\phi = El/R_{slant}$: $R_{slant} = El/\sin\phi$

$\text{Cos}\phi = R_{gnd}/R_{slant}$: $R_{gnd} = R_{slant} \text{ x } \cos\phi$



Given:
Elevation = 5000 ft
Angle = 30^0

Calculate Slant Range =
$R_{slant} = El/\sin\phi = 5000/\sin(30) = 10{,}000$ ft

What is the Ground Range =
$R_{gnd} = R_{slant} \times \text{cosf} = 10{,}000 \text{ x } \cos(30) = 8660.25$ ft
$R_{slant}^2 = R_{gnd}^2 + EL^2$: $R_{gnd} = (R_{slant}^2 - EL^2)^{1/2} = (10{,}000^2 - 5000^2)^{1/2} = 8660.25$ft

Range Calculation

Electromagnetic energy pulse travels at the speed of light c_o

$$R = \frac{(t_{delay} * c_0)}{2}$$

R = slant range

t_{delay} = two way time delay – Radar-Target-Radar

c_o = speed of light = 3×10^8 m/s

Given: t_{delay} = 1ms

Calculate Slant Range

R = (1ms x $^{-3}$ 3×10^8 m/s)/2 = 150km

Range Ambiguity

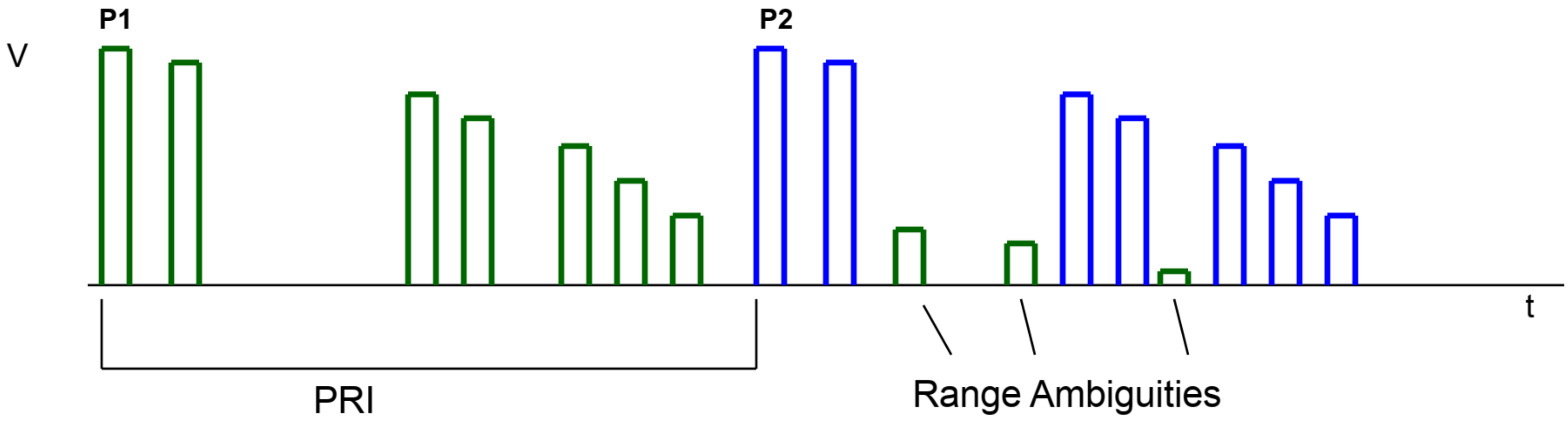
- Caused by strong targets at a range in excess of the pulse repetition interval or time
- Pulse return from the first pulse comes after the second pulse is sent
- This causes the range to be close instead of far away
- Radar does not know which pulse is being returned
- Large pulse amplitude and higher PRF amplifies the problem
- The maximum unambiguous range for given radar system can be determined by using the formula:

$$R_{max} = (PRI - T)\frac{c_0}{2}$$

PRI = pulse repetition interval
T = pulse width time
c_o = speed of light

Example: PRI = 1msec, T = 1μs
Calculate Max unambiguous Range = (1ms – 1μs) × 3 × $10^8/2$ = 149.9km

Range Ambiguity



$$R_{max} = (PRI - PW)\frac{c_0}{2}$$