# Doppler Weather Radar Technology

भारत मौसम विज्ञान विभाग
INDIA METEOROLOGICAL DEPARTMENT

# RADAR

An acronym for

**Radio**

**Detection**

**And**

**Ranging**

# History of RADARs

**The term RADAR-RAdio Detection And Ranging proposed by US Navy (SM Taylor & FR Furth) in 1940s has become a common practice still now; this acronym can be attributed to the generic term radio waves then commonly used for EM-waves.**

# History of RADARs

**The principle of RADAR one can attribute to the confirmative test of electromagnetic waves by Tesla in 1900. However the possible detection demonstration in the form of patent document “Hertzian wave projecting and receiving apparatus adopted to indicate or give warning of the presence of a metallic body, such as a ship or a train in the line of projection of such waves” of Christian Hulsmeyer 1904 is considered as the early invention of radar.**

# History of RADARs

A systematic wooden ship detection at NRL in 1922 was performed by Taylor and Young. Further deduction capability was also demonstrated in 1924 as a beat frequency pattern in ionosphere studies by Appleton, Barnett using FM-CW equipment separately at London.

# History of RADARs

**This paved to the work of Watson-Watt to demonstrate detection of Aircraft during 1935 leading to the chain home radar network, and the reply to the CSSAD, harnessed him with the title “Father of Radars”**

# History of RADARs

It is a well-known fact with the global conflict at its peak, many a scientific labs devoted much to the integral development of the radar technology, preferred to keep it has a closed secret.

# History of RADARs

**High powered compact radar systems came in vogue in 1940s when Magnetrons (Randall & Booth) capable of producing 400W continuous power became a reality.**

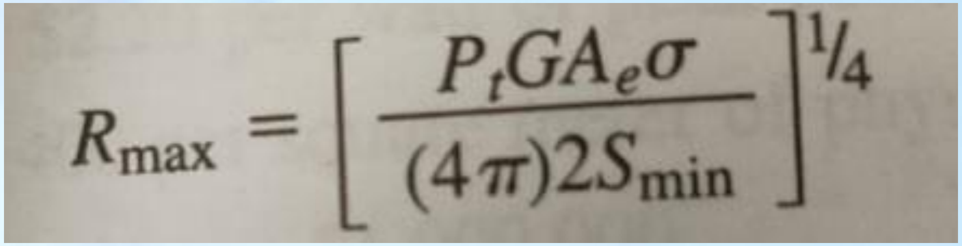
# History of RADARs

**The focal point of major radar development efforts happened in MIT from 1940s nick named Radiation Laboratory. The work got compiled in 27 volumes called the Radiation Laboratory Series**

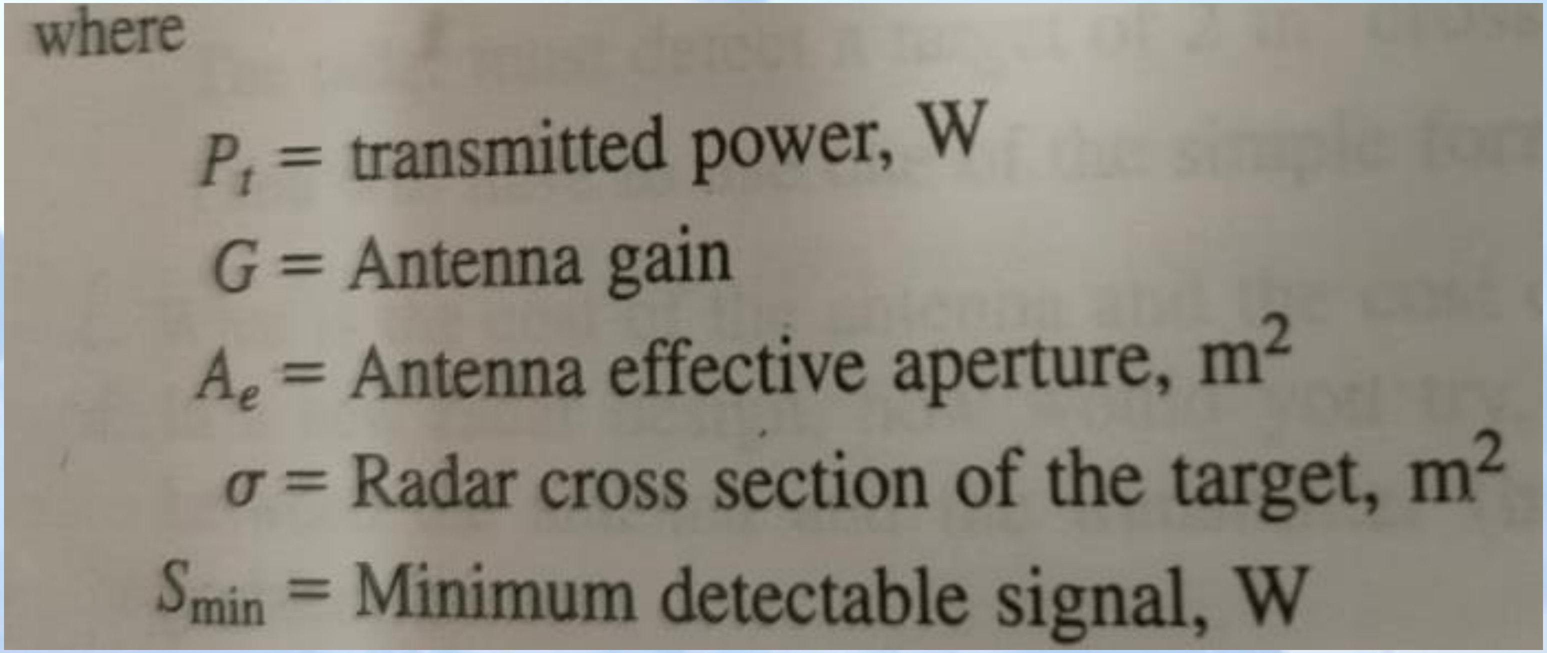
# Radar – Frequency bands

| Band Designation | Frequency | Wavelength |
|---|---|---|
| HF | 3 – 30 MHz | 100 – 10m |
| VHF | 30-300MHz | 10-1 m |
| UHF | 300 - 1000MHz | 1 - 0.3 m |
| L | 1-2 GHz | 30-15 cm |
| **S** | **2-4 GHz** | **15-8 cm** |
| **C** | **4-8 GHz** | **8-4 cm** |
| **X** | **8-12 GHz** | **4-2.5 cm** |
| Ku | 12-18 GHz | 2.5-1.7 cm |
| K | 18-27 GHz | 1.7-1.2 cm |
| Ka | 27-40 GHz | 1.2-0.75 cm |
| mm or W | 40-300 GHz | 7.5 – 1mm |

# RADAR EQUATION



$$R_{\max} = \left[ \frac{P_t G A_e \sigma}{(4\pi)2S_{\min}} \right]^{1/4}$$



where

$P_t$ = transmitted power, W

$G$ = Antenna gain

$A_e$ = Antenna effective aperture, $m^2$

$\sigma$ = Radar cross section of the target, $m^2$

$S_{\min}$ = Minimum detectable signal, W

# Is the simple form of radar equation adequate for range calculations??

## NO. This is because:-

- The statistical nature of the minimum detectable signal(usually determined by receiver noise).
- Fluctuations and uncertainties in the target’s radar cross section.
- The losses experienced throughout the system.
- The propagation effects caused by the earth’s surface and atomosphere.

The statistical nature of the receiver noise and the targets' cross section requires that the maximum radar range be described probabilistically rather than by a single number.

# Why is the simple form of radar equation used then?

- **Assessing the performance of the radar.**
- **Determining the system trade-offs that must be considered while designing a new radar system.**
- **Aiding in generating the technical requirements for a new radar procurement.**

# Detection of signals in Noise

## MDS( Minimum Detectable Signal)

**The weakest signal that can be detected by a receiver is the minimum detectable signal.**

**Detection of radar signals is based on establishing a threshold at the output of the receiver.**

**If the receiver output is large enough to exceed the threshold, a target is said to be present.**

- **If the receiver output is not of sufficient amplitude to cross the threshold, only the noise is to be present. This is called Threshold Detection.**
- **False Alarm**
- **Missed Detection**

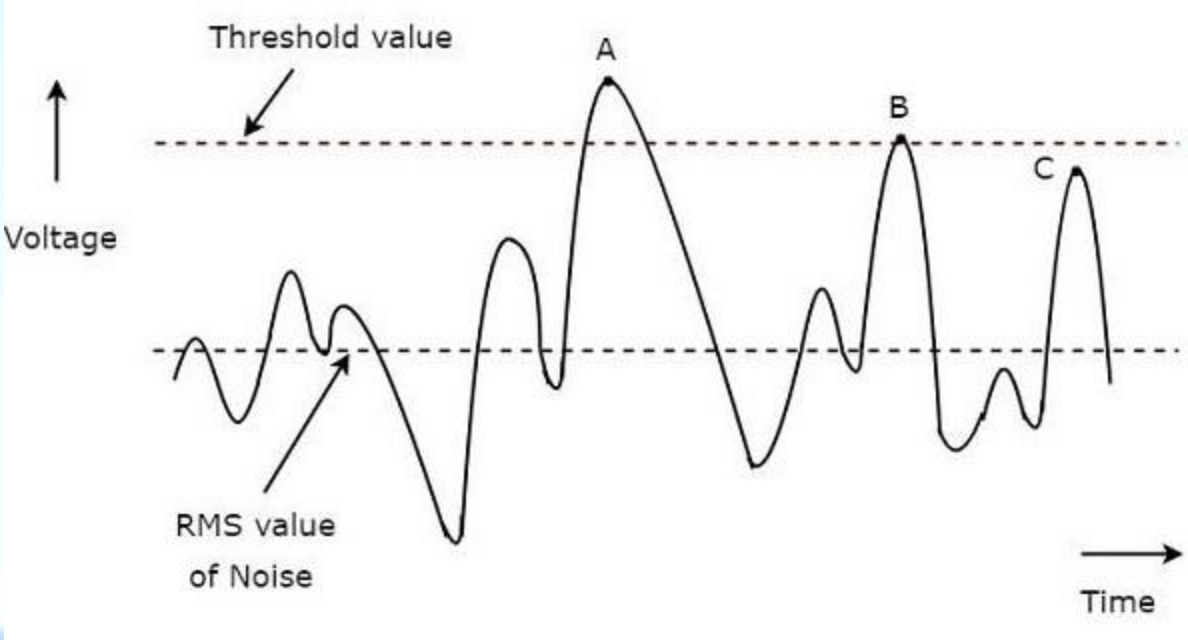
**False Alarm:**

If the threshold level is set too low, noise might exceed it and is mistaken for a target.

**Missed Detection:**

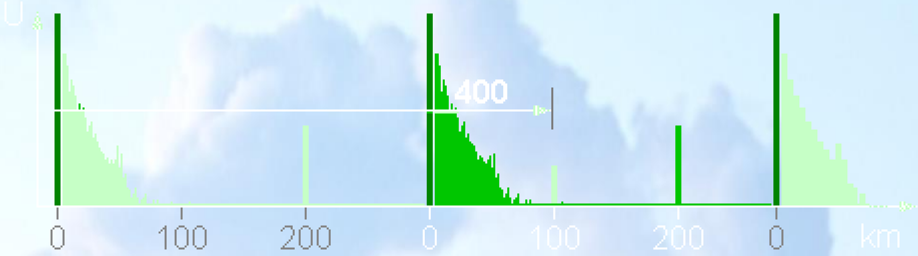
If the threshold is set too high, noise might not be large enogh to cause false alarms, but weak

**target echoes might not exceed the threshold and would not be detected. When this occurs, This is called Missed Detection.**


Threshold value
A
B
C
Voltage
RMS value
of Noise
Time

# Staggered PRT

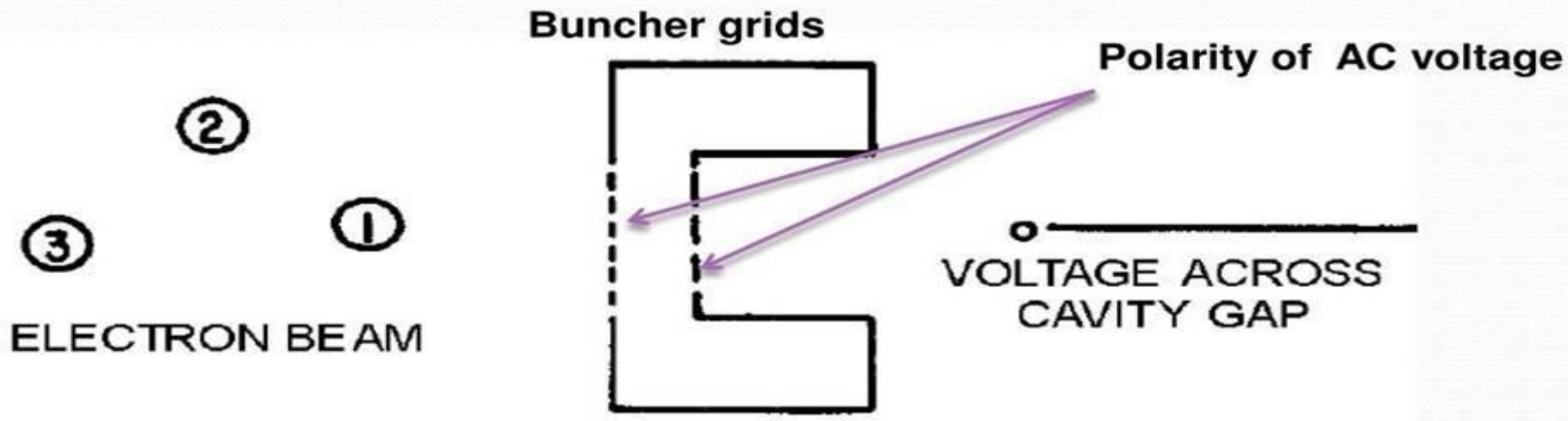
By employing staggered PRT the target ambiguous return isn't represented any more by small arc on an analog display. This movement or instability of the ambiguous return is represented typically as a collection of points in certain equipment because of the change in reception times from impulse to impulse. With this distinction, a computer controlled signal processing can calculate the actual distance.


U
400
0
100
200
0
100
200
0
km

# MICROWAVE TUBES

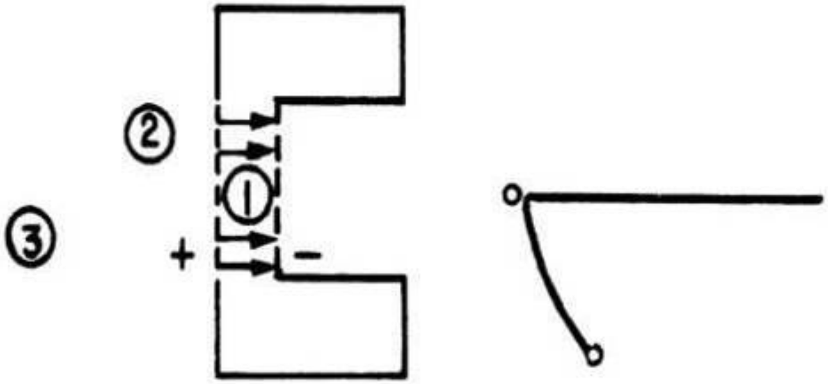
# Velocity Modulation

- Velocity modulation is defined as the variation in the velocity of a beam of electrons caused by the alternate speeding up and slowing down of the electrons in the beam.
- the electron beam passes through a pair of closely spaced grids, called the Buncher grids

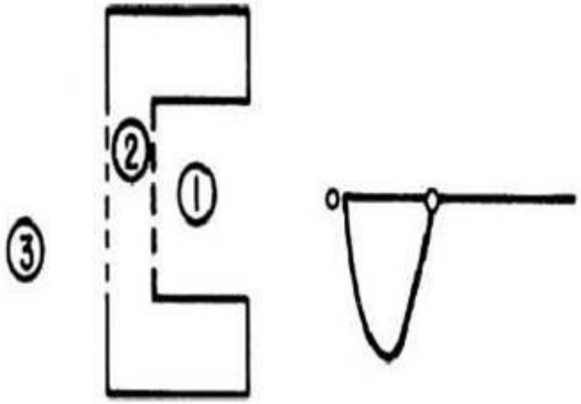


Buncher cavity action. BUNCHER CAVITY.

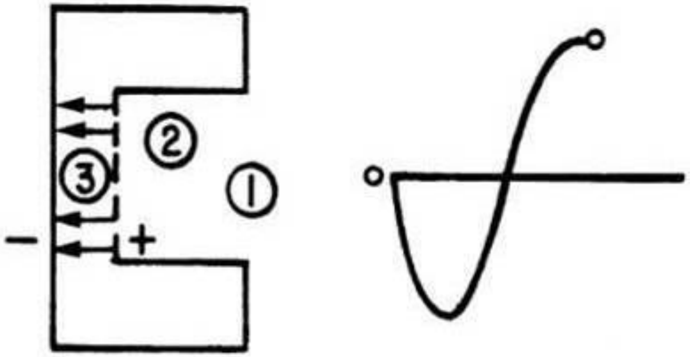
# Electron Beam via Buncher Grids



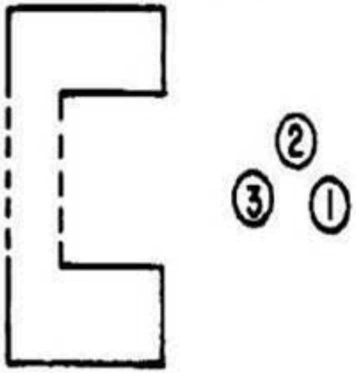
Buncher cavity action. ELECTRON #1 DECELERATED.



Buncher cavity action. ELECTRON #2 VELOCITY UNCHANGED.

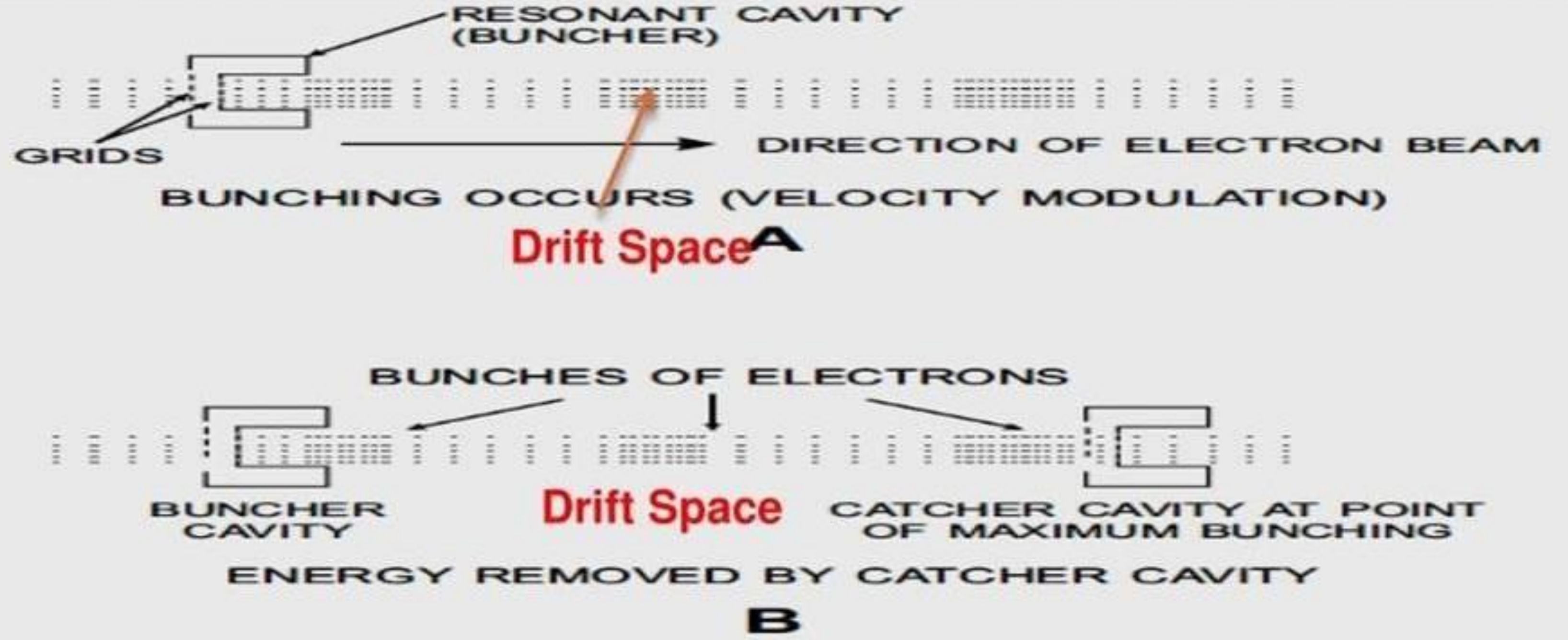


Buncher cavity action. ELECTRON #3 ACCELERATED.



Buncher cavity action. ELECTRONS BEGINNING TO BUNCH, DUE TO VELOCITY DIFFERENCES.

# Buncher and Catcher Cavities



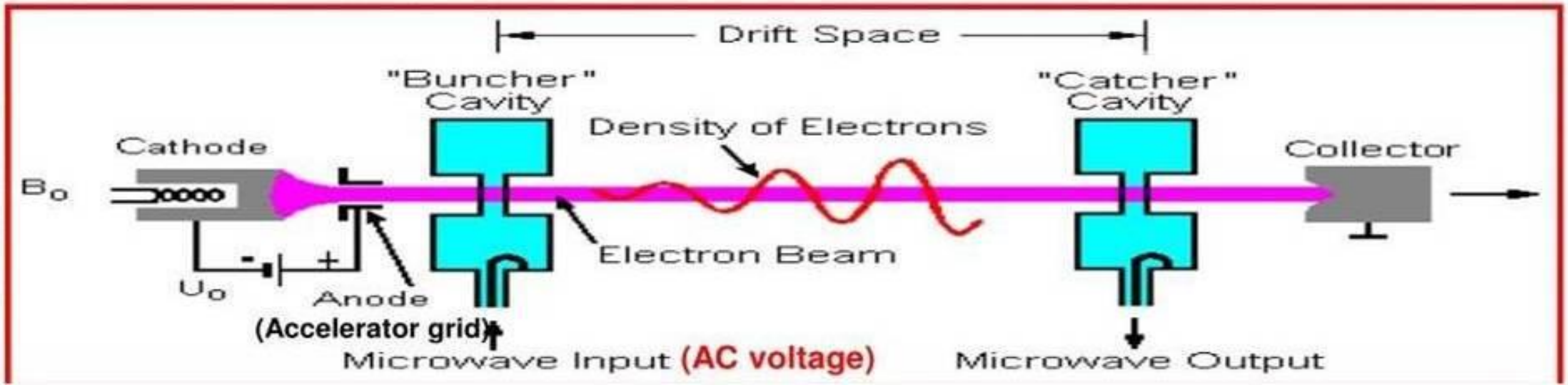
-Removing energy from a velocity-modulated beam.

- The energy gained by the accelerated electrons is balanced by the energy lost by the decelerated electrons.

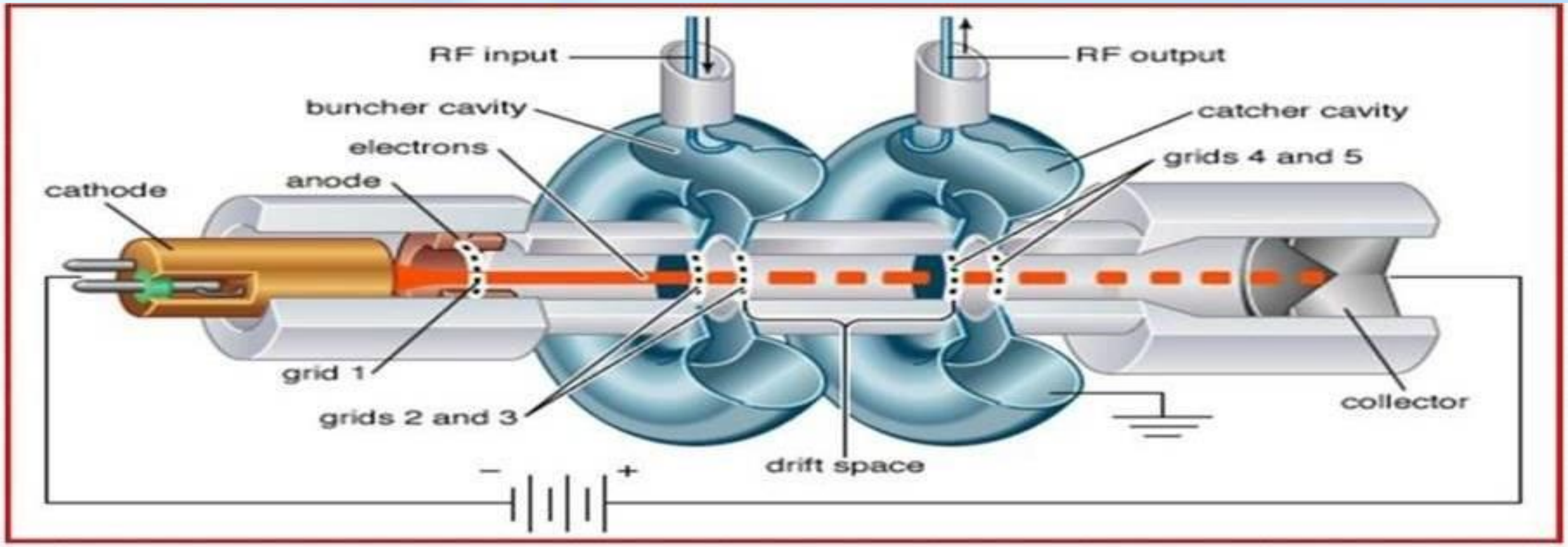
- A new and useful beam distribution will be formed if the velocity modulated electrons are allowed to drift into an area that has no electrostatic field.

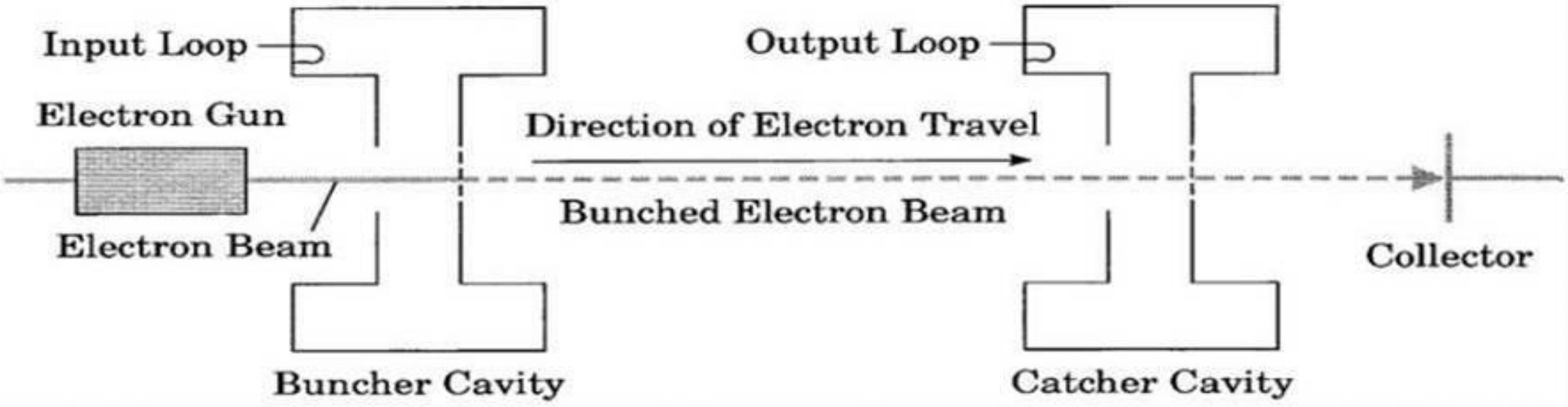
# Two Cavity Kylstron Amplifier

- A klystron is a microwave vacuum tube using cavity resonators to produce velocity modulation of the electron beam and to produce amplification.
- Input cavity (buncher cavity) RF energy is coupled in, and the electron beam is velocity modulated .
- Output cavity (catcher cavity) the RF energy is coupled through the electron beam by placing the second cavity into the proper position at an optimum distance.
- The RF interacting with the electron beam causes a kinetic energy loss from the beam that result in gain.



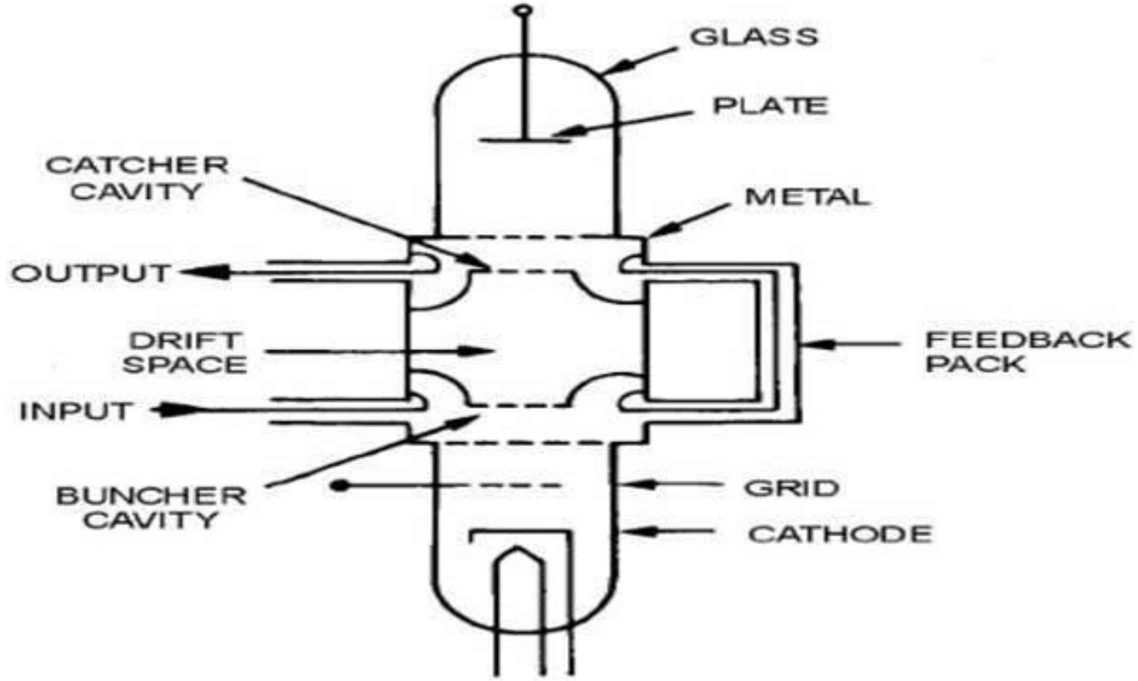
# Two Cavity Klystron Amplifier





# Two Cavity Klystron Amplifier

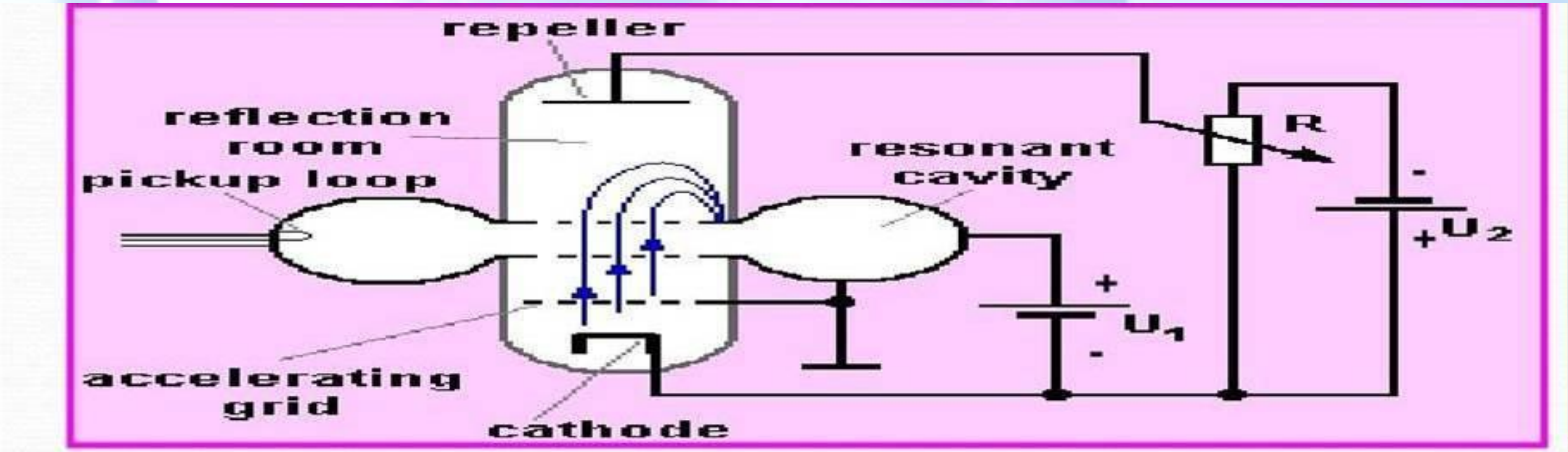
The two-cavity amplifier klystron is readily turned into an oscillator klystron by providing a feedback loop between the input and output cavities.



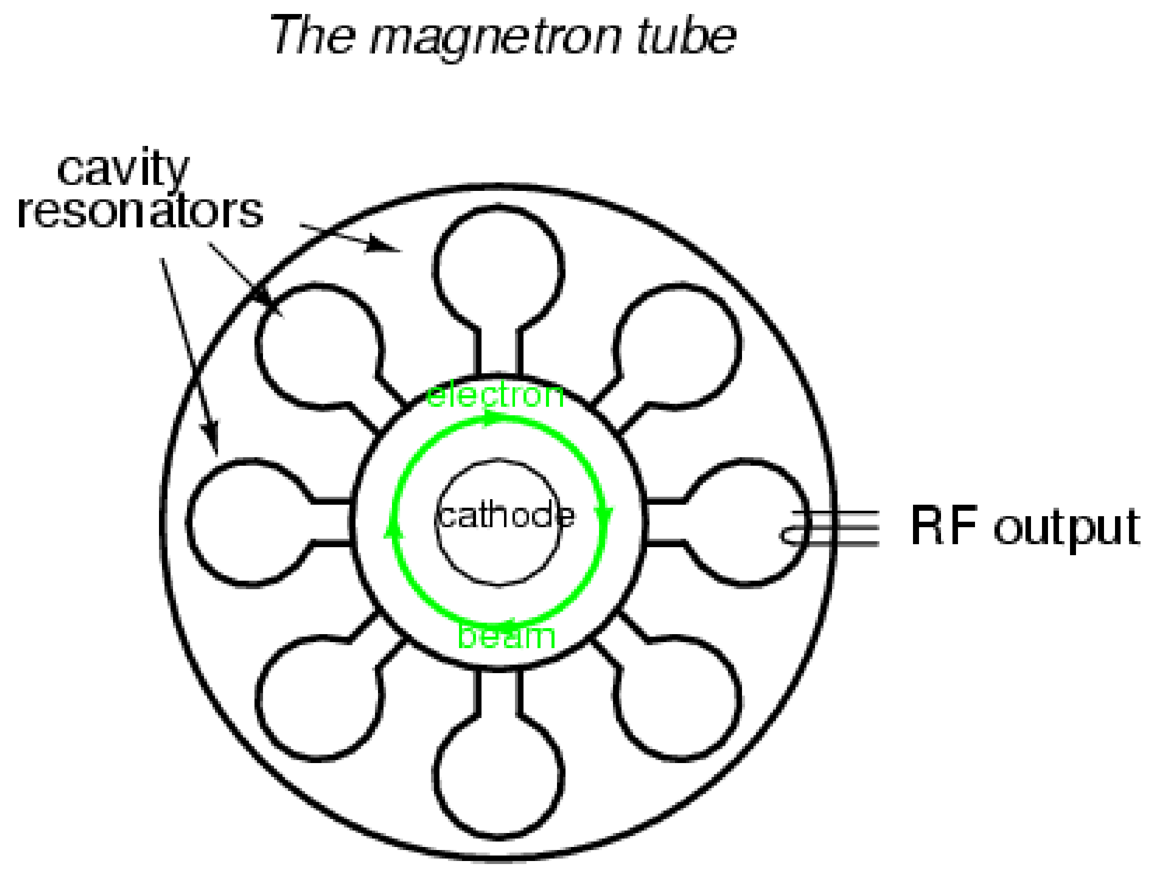
Functional and schematic diagram of a two-cavity klystron.

# Reflex Klystron

- A Reflex Klystron consists of an electron gun, a cavity with a pair of grids and a repeller plate.
- In this klystron, a single pair of grids does the the functions of both the buncher and catcher grids.
- The feedback required to maintain oscillations within the cavity is obtained by reversing the beam and sending it back through the cavity.
- Due to this, they deliver energy to the cavity, the result is the oscillation at the cavity producing RF frequency.



# Magnetron



**Magnetic flux runs perpendicular to the plane of the circular electron path. In other words, from the view of the tube shown in the diagram, you are looking straight at one of the magnetic poles.**

# Magnetron

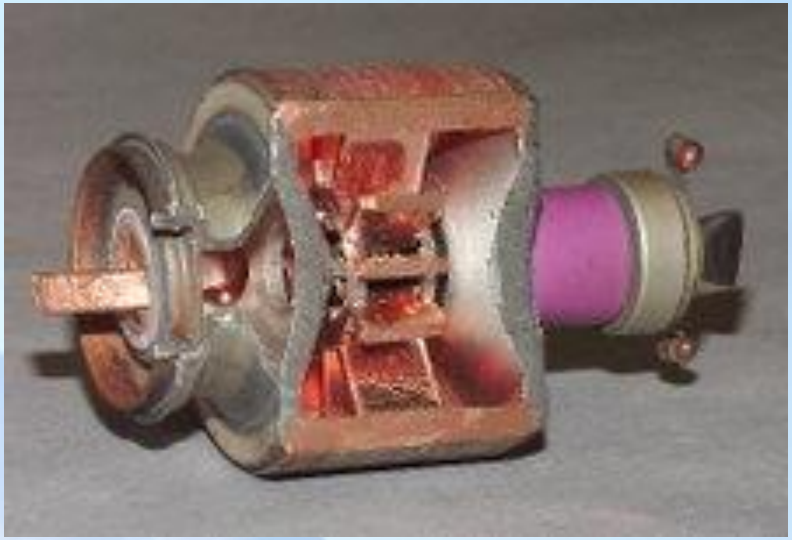
Cavity resonators are used as microwave-frequency "tank circuits," extracting energy from the passing electron beam inductively.

Like all microwave-frequency devices using a cavity resonator, at least one of the resonator cavities is tapped with a *coupling loop*:

A loop of wire magnetically coupling the coaxial cable to the resonant structure of the cavity, allowing RF power to be directed out of the tube to a load.

# Magnetron

Magnetron with magnet in its mounting box. The horizontal plates form a Heatsink, cooled by airflow from a fan



Magnetron with section removed (magnet is not shown)

# Electromagnetic Waves

Mechanical waves require the presence of a medium.

Electromagnetic waves can propagate through empty space.

Maxwell’s equations form the theoretical basis of all electromagnetic waves that propagate through space at the speed of light.

Hertz confirmed Maxwell’s prediction when he generated and detected electromagnetic waves in 1887.

Electromagnetic waves are generated by oscillating electric charges.

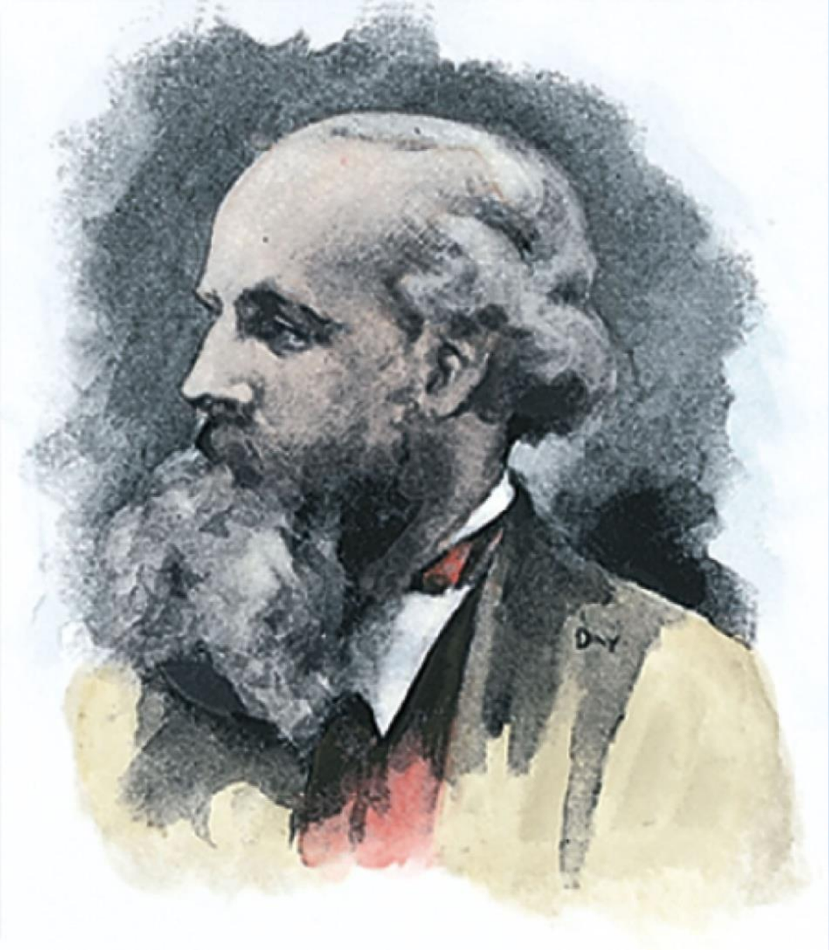
The waves radiated from the oscillating charges can be detected at great distances.

Electromagnetic waves carry energy and momentum.

Electromagnetic waves cover many frequencies.

# James Clerk Maxwell

- 1831 – 1879
- Scottish theoretical physicist
- Developed the electromagnetic theory of light
- His successful interpretation of the electromagnetic field resulted in the field equations that bear his name.
- Also developed and explained
    - Kinetic theory of gases
    - Nature of Saturn’s rings
    - Color vision



# Maxwell's Equations

**In his unified theory of electromagnetism, Maxwell showed that electromagnetic waves are a natural consequence of the fundamental laws expressed in these four equations:**

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{q}{\varepsilon_o} \qquad \oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} = 0$$

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}} = -\frac{d\Phi_B}{dt} \qquad \oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{s}} = \mu_o I + \mu_o \varepsilon_o \frac{d\Phi_E}{dt}$$

# Maxwell’s Equation 1 – Gauss’ Law

The total electric flux through any closed surface equals the net charge inside that surface divided by $\varepsilon_o$

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{q}{\varepsilon_o}$$

This relates an electric field to the charge distribution that creates it.

# Maxwell’s Equation 2 – Gauss’ Law in Magnetism

The net magnetic flux through a closed surface is zero.

$$\oint \vec{B} \cdot d\vec{A} = 0$$

The number of magnetic field lines that enter a closed volume must equal the number that leave that volume.

If this weren’t true, there would be magnetic monopoles found in nature.

- There haven’t been any found

# Maxwell’s Equation 3 – Faraday’s Law of Induction

Describes the creation of an electric field by a time-varying magnetic field.

The emf, which is the line integral of the electric field around any closed path, equals the rate of change of the magnetic flux through any surface bounded by that path.

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}} = -\frac{d\Phi_B}{dt}$$

One consequence is the current induced in a conducting loop placed in a time-varying magnetic field.

# Maxwell’s Equation 4 – Ampère-Maxwell Law

**Describes the creation of a magnetic field by a changing electric field and by electric current.**

**The line integral of the magnetic field around any closed path is the sum of $\mu_o$ times the net current through that path and $\varepsilon_o\mu_o$ times the rate of change of electric flux through any surface bounded by that path.**

$$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{s}} = \mu_o I + \varepsilon_o \mu_o \frac{d\Phi_E}{dt}$$

# Speed of Electromagnetic Waves

**In empty space, $q$ = 0 and $I$ = 0**

**The last two equations can be solved to show that the speed at which electromagnetic waves travel is the speed of light.**

**This result led Maxwell to predict that light waves were a form of electromagnetic radiation.**

# Atmospheric Propagation of Radio Waves

## Sub and Super Refraction

Refraction is a process of bending of electro-magnetic radiation while travelling between two media of different refractive index. The angle of bending is given by Snell’s Law

Refractive index = (Sin i)/ (Sin r)

Where i and r represent the incident and refracted angles of the beam with vertical to the surface of contact between the two media.

**If the radar waves are not bent downwards as much as usual or under more extreme conditions they are bent upwards towards the sky from the anticipated path of the beam for a particular elevation it is called sub-refraction. This will reduce the normal radar range of detection. Similarly if the bending of wave is downward towards the earth more than the anticipated path of the beam for a particular elevation it is called super-refraction. Super-refraction is generally noticed during winters when temperature inversion occurs.**

**In radars the coast line is seen with greater reflectivity recorded even beyond the normal radar range. Under extreme conditions of refraction the radar waves can be trapped in the layers of atmosphere which is called ducting. In cases of ducting the radio waves travels thousands of kilometers along with the surface of the earth.**

The echoes produced due to severe super/ sub-refractions are due to anomalies in the atmospheric propagation of electromagnetic radiation and they are known as AP ECHOES or Anomalous propagation echoes.

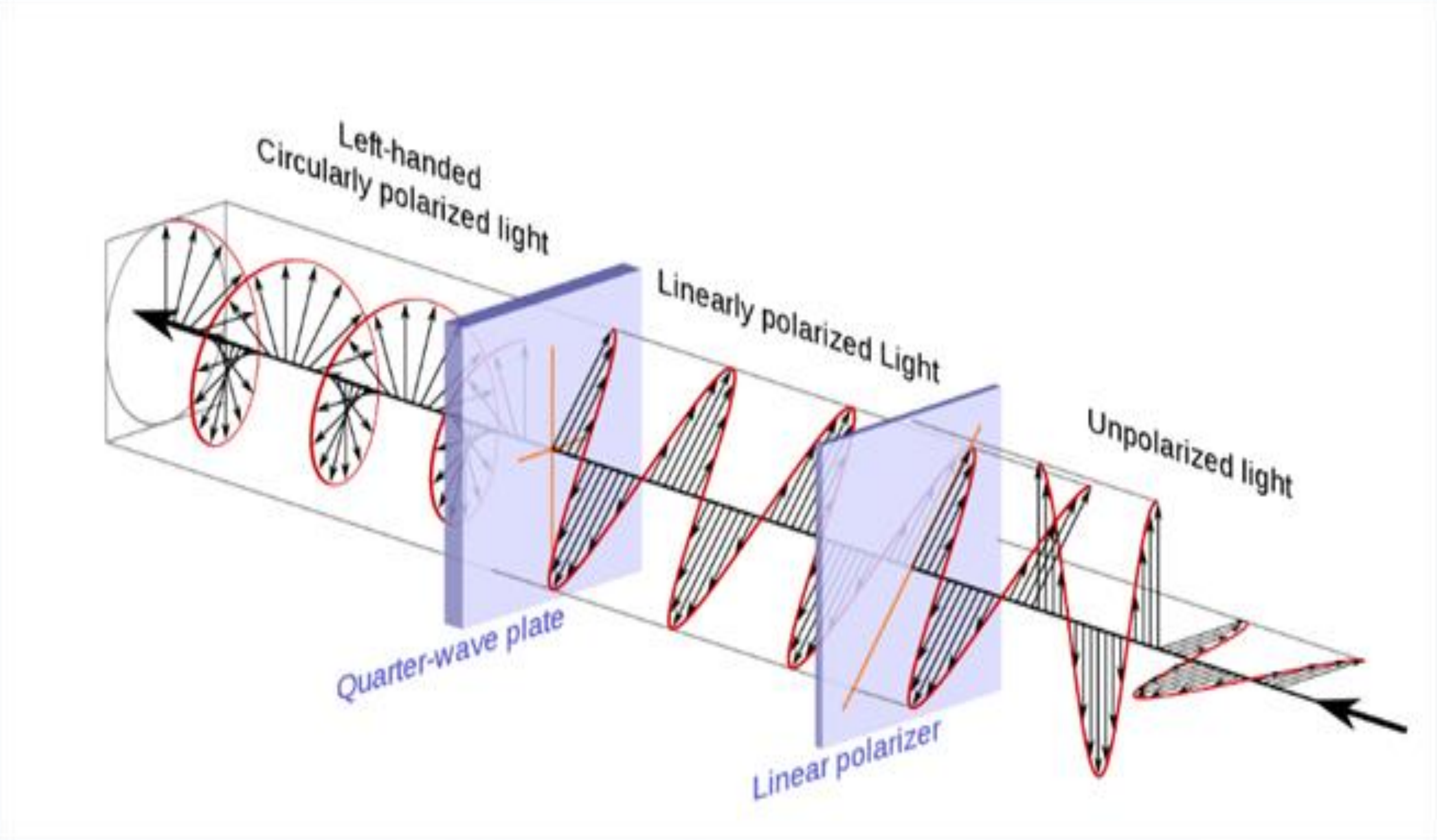
# Wave Polarization

Types of Polarization

Following are the three types of polarization depending on the transverse and longitudinal wave motion.

- Linear polarization
- Circular polarization
- Elliptical polarization

*Unpolarized light is composed of incoherent light waves with random polarization angles.


Left-handed
Circularly polarized light
Linearly polarized Light
Unpolarized light
Quarter-wave plate
Linear polarizer

# Linear Polarization

In linear polarization, the electric field of light is limited to a single plane along the direction of propagation.

# Circular Polarization

**There are two linear components in the electric field of light that are perpendicular to each other such that their amplitudes are equal, but the phase difference is π/2. The propagation of the occurring electric field will be in a circular motion.**

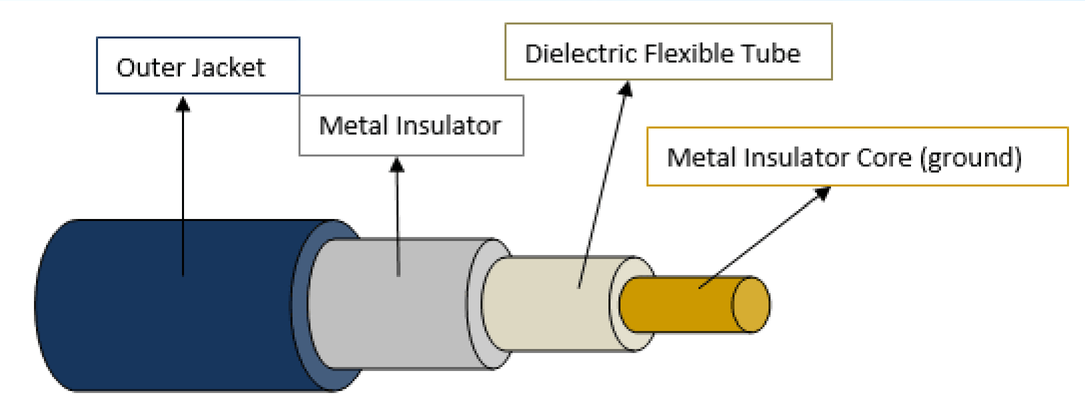
# Elliptical Polarization

The electric field of light follows an elliptical propagation. The amplitude and phase difference between the two linear components are not equal.

# Transmission Media

Both waveguide and coaxial line is used to carry electromagnetic waves of different frequencies.

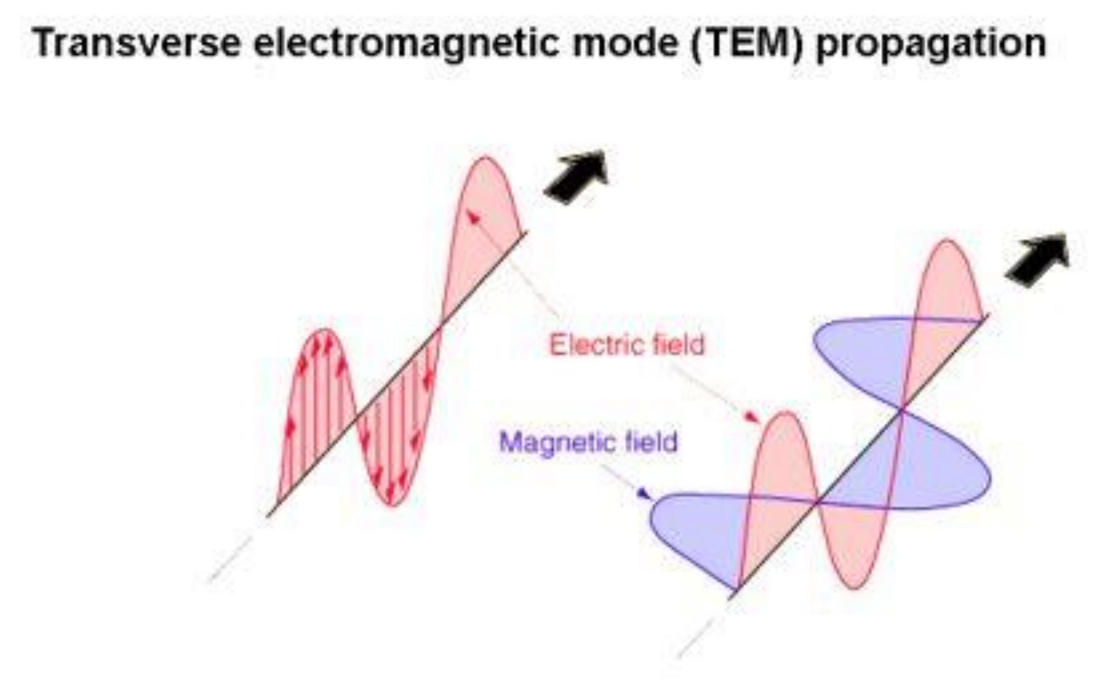
# Coaxial Cables



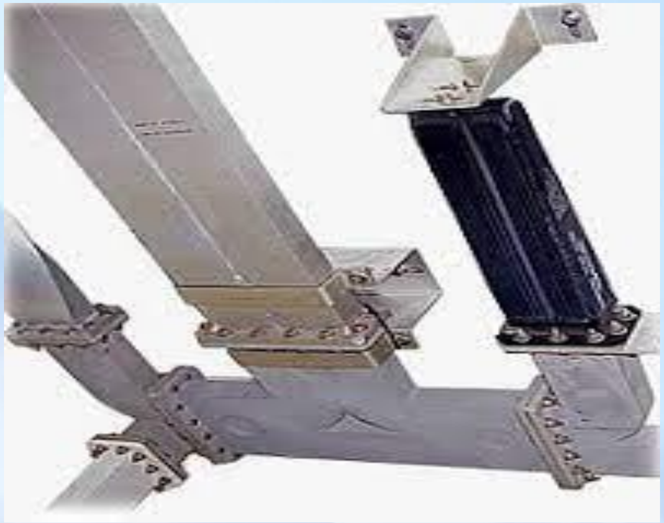
# Coaxial Cables

The fundamental or dominant mode wave in a coaxial line is TEM. So there is no concept of cutoff frequency in the coaxial line cable. But as the frequency increases, the wavelength will become comparable to the dimensions of the coaxial. As a result, higher order non TEM mode starts propagating. These waves are not desired as they cause larger attenuation. They also share power of the dominant mode.

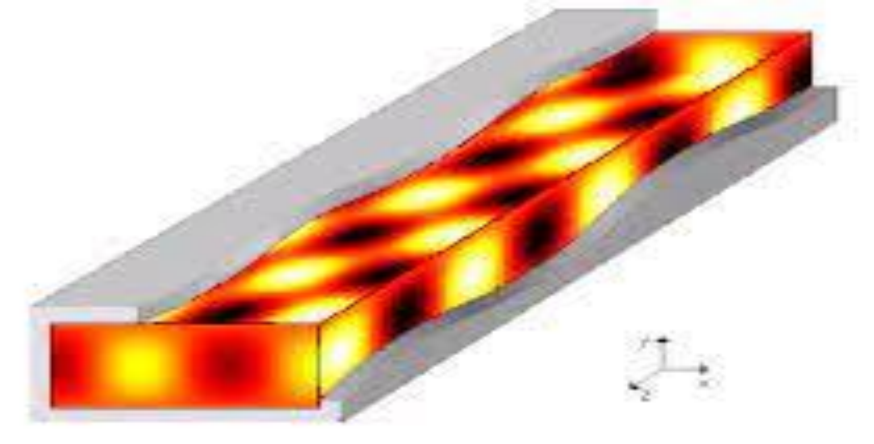
# TEM Mode in Coaxial Cables



# Waveguides



# Waveguides



# Waveguides

There are two types of structures used in the waveguide circular and rectangular. As depicted, waveguide consists of single metallic walls acting as conductor. There is no center conductor in the waveguide. Hence TEM wave can not propagate via it. As a result there is no conduction current. In waveguide, energy transfer takes place using TE or TM modes. Refer TE vs TM mode to understand difference between TE and TM waves. One can also refer TEM mode vs Quasi TEM mode for basics of TEM and quasi TEM modes.

# Waveguides

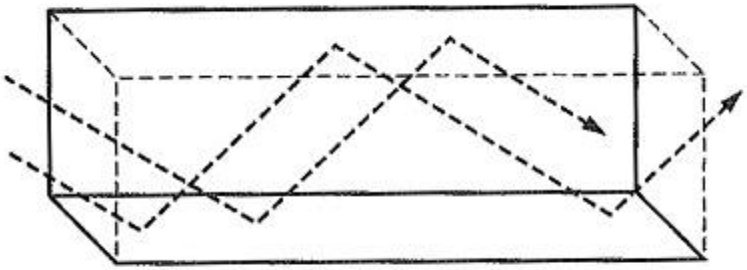
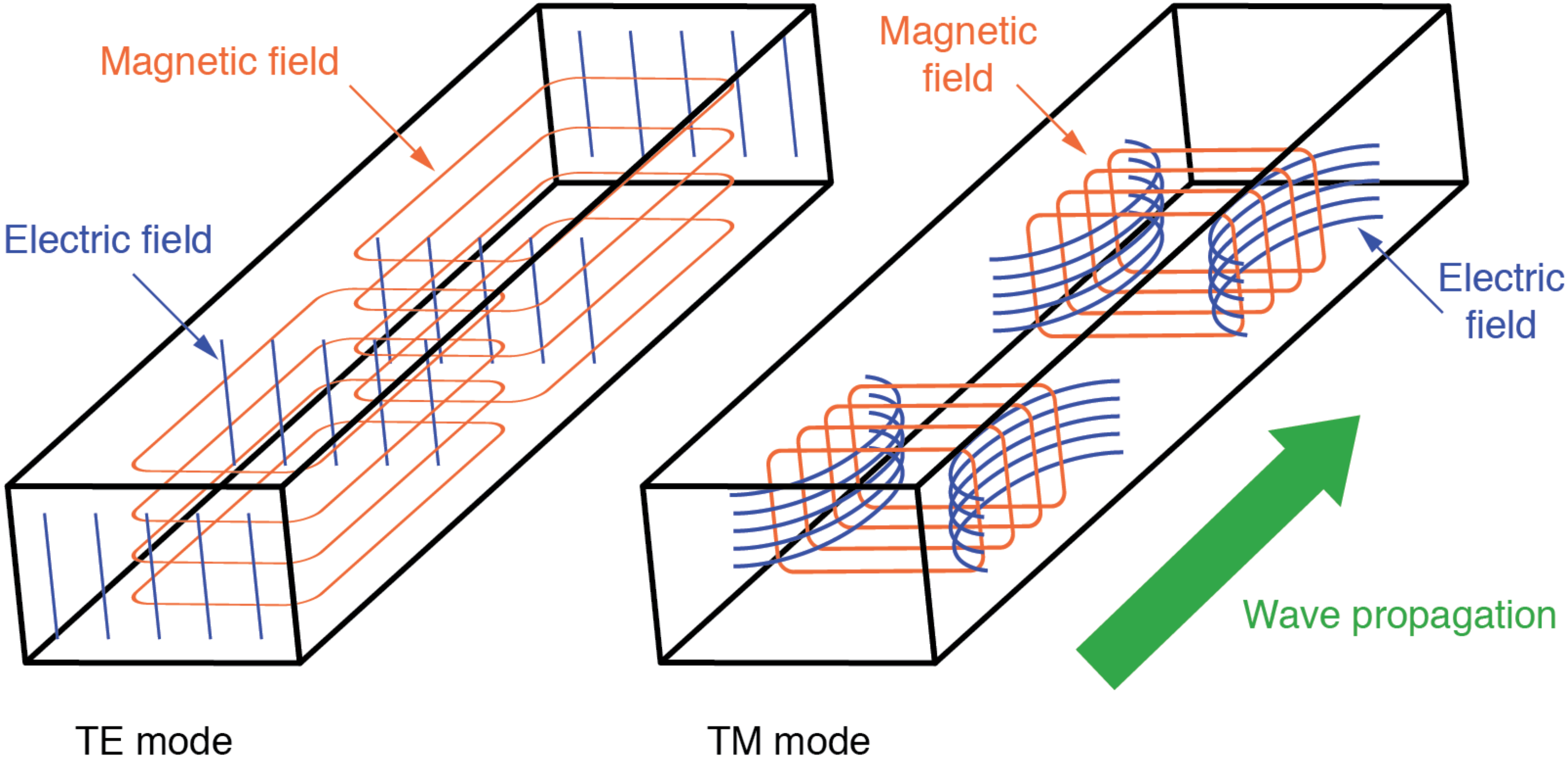


FIGURE 10-3 Method of wave propagation in a waveguide.

# Wave Travel in Waveguides



*Magnetic flux lines appear as continuous loops*

*Electric flux lines appear with beginning and end points*

# Coaxial Vs. Waveguide

Following are the major **difference between waveguide and coaxial line**:

- In case of the waveguide as there is no central or inner conductor and usually it is air filled. Hence it is easy to manufacture.

- As waveguide is air filled there will be less loss compare to coaxial line. In waveguide, no power is lost through radiation and even dielectric loss is negligible.

- Waveguide can handle higher power compared to coaxial cable. This is because inner portion in the waveguide is filled with air as dielectric and air has breakdown voltage of 30 KV/cm. This increases power handling capacity of the waveguide.

- As the outer wall of the waveguide is metallic, it is bulky,heavy and expensive also. While coaxial line is smaller in size and lighter in the weight. Hence coaxial is in use for many microwave applications.

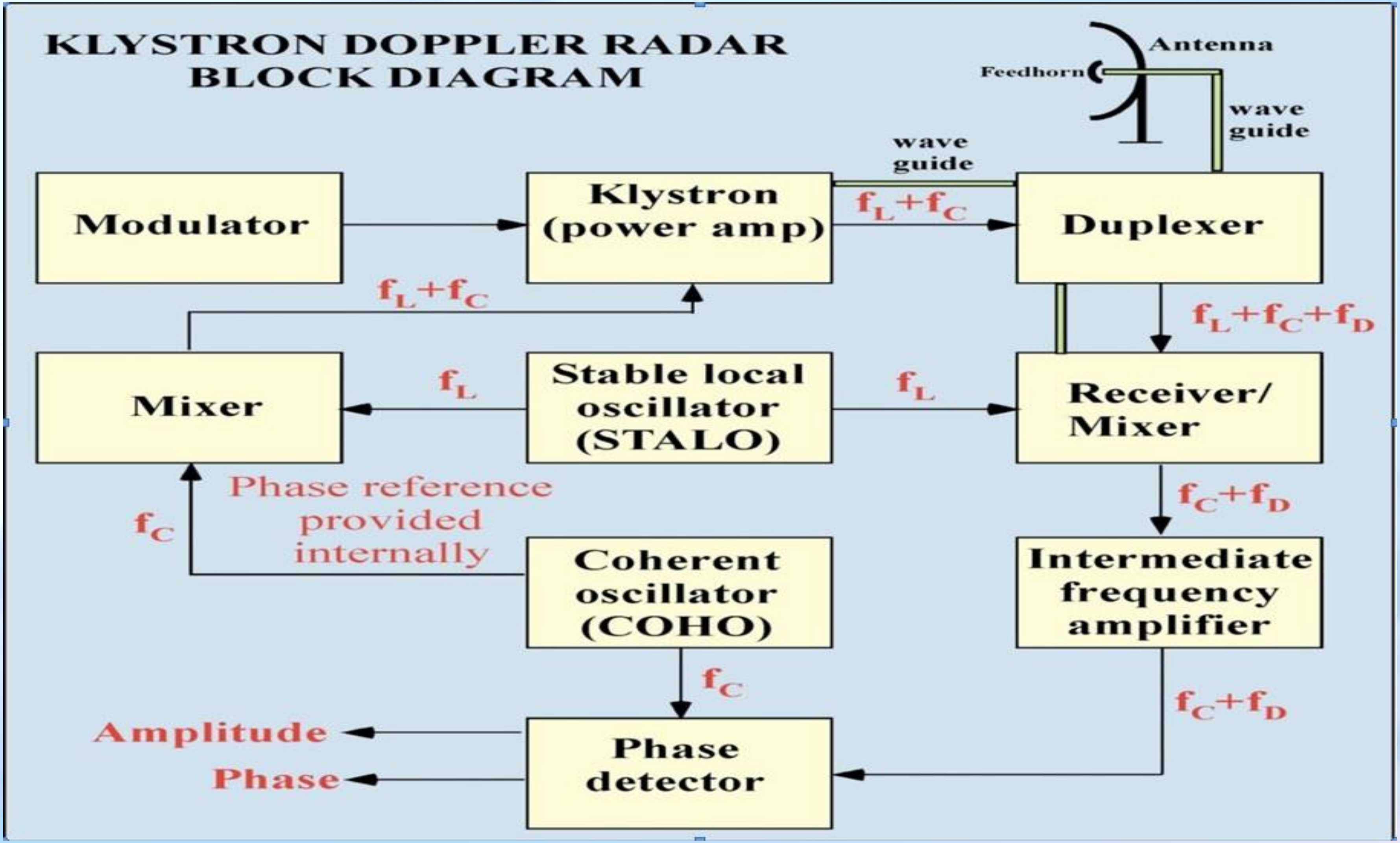
# Coaxial Vs. Waveguide

- In the waveguide uniform cross section need to be maintained which is not the case in coaxial line. This is because, if the dimension changes then mode conversion will take place or higher order mode may also get generated in the waveguide.

- In the waveguide wall is not perfectly conducting, so some power loss as heat will occur in the wall of the waveguide.

- The bandwidth of waveguide is smaller while the coaxial line is used for broadband application.

# Radar Block Diagram



# Working of a Pulsed Doppler Weather Radar

A Doppler Weather Radar (DWR) consists of a RF transmitter that generate high power microwave radiation in pulses, an antenna to send the signal out to space and to receive scattered energy (echoes) from targets around, a servo system to move the antenna in a planned schedule scan, a receiver to detect and process the received echo signals and a display unit to graphically present the signal in user understandable form. Magnetrons, klystrons and travelling wave tubes still continue to be the main RF oscillators of most radar transmitters.

# Transmitter

The transmitter generates the RF energy either in oscillator mode, or in Amplifier mode from a stable RF Source (STALO). Klystrons are used for this purpose most of the time in DWRs for the purpose of coherence to detect the phase differences in the transmitted and received frequencies. RF Power transmitters of the order of 500 KW are common, where as transmitter with 1000 KW power is also used in a IMD radar. Though general working voltages are of the order of 1KV, some transmitters use high voltages too.

# RF Oscillator Tubes

**Magnetrons, Klystron, Thyratron are the popularly used tubes in weather radars. Magnetrons are mostly used in conventional non Doppler radars. After improved technology Magnetrons are also being used in DWRs .Klystrons are used in DWRs particularly to achieve high coherence between the transmitted and received pulses.**

# Wave guides

RF power is transmitted to the antenna using wave guides which are also known as travelling wave tubes. Wave guides are hollow metal tubes with rectangular cross section, made from aluminum or gun metal. In the waveguide chain where ever bends are required L-bends and U-bends are used. Flexible wave guides are also used where-ever links are to be negotiated slightly, during installation.

# Antenna and duplexers

A Radar antenna is generally a parabolic dish antenna that is very sensitive with high gain. It is generally designed to generate beam of about 1 degree beam-width for generating high resolution data sets. The same antenna is used for transmitting and receiving the RF Signals. The switching is done by duplexers. Duplexers allow the receiver to be cut-off from antenna during transmission to safe guard the receiver. Circulators are one type of duplexers and when ferrite materials are used as core of these circulators, they are known as ferrite circulators.

# Receivers

**Receivers are divided into two types basically. RF Front end amplifiers are RF booster amplifiers that increase the signal strength of received energy. Mixer-amplifier actually mixes the Received energy with STALO frequencies and the generated Intermediate Frequency IF is used for further processing. In general 10 MHz or 30 MHz are the IF frequencies. Some radars use two-stage IF mixing.**

# Signal Processors

**Signal processing is the most complicated of all radar hardware. It involves deriving the echo properties/radar base parameters from the received signals. Algorithms like Pulse pair and Fast Fourier Transformation (FFT) techniques are used for this. The basic output of the Receiver consists of information on Amplitude and Phase of the received signal. From amplitude information we deduce the intensity of the back-scattered signal and from Phase information we deduce the radial velocity of the moving targets.**

# Servo System

**The Servo system is the hard ware part of remote control of antenna. It consists of antenna gear assembly, motor systems, position encoders, servo controllers and a control console. Modern servo systems are operated based on computer programs/scan schedule stored in workstation of radar controller.**

# Radar Controllers

A modern DWR needs coordinated operation between transmitter, receiver, servo, antenna, data collection, signal processing and display systems.  This needs a central monitoring and control of all the operations flawlessly.  A Radar controller is a programme that takes care of all these operations, based on the inputs from the operator either in manual (immediate) mode or in automatic (pre-programmed) mode.  Most of the modern radars are generally operated in fully automatic mode that takes care of the operation, calibration, data acquisition, product generation and data dissemination.

# Dual Polarization or Polarimetric Radar

A radio wave is a series of oscillating electric and magnetic fields. The electric and magnetic fields are oriented at 90 degree angles to each other. The direction of propagation is normal to both the electric and magnetic fields. The polarization of the radio wave is defined as the direction of orientation of the electric field wave crest. If the electric field is in the horizontal/vertical direction it is called horizontally/vertically polarized wave.

# Dual Polarization or Polarimetric Radar

**Most weather radars transmit and receive radio waves with a single, horizontal polarization. Polarimetric radars, on the other hand, transmit and receive both horizontal *and* vertical polarizations. There are many different ways to mix the horizontal and vertical pulses together into a transmission scheme; the common methods are either alternate polarization or simultaneous polarization.**

# Dual Polarization or Polarimetric Radar

**In alternate polarization, the radar transmits both horizontal and vertical polarized pulses alternately where as in simultaneous polarization both of these are transmitted simultaneously. In simultaneous polarization, however, the transmitted power is halved in each channel.**

# Dual Polarization or Polarimetric Radar

**Polarimetric Doppler radar differs from conventional Doppler radar by producing both a horizontally polarized beam and a vertically polarized beam. A horizontally polarized beam has its electric field oriented in the horizontal plane, while a vertically polarized beam has its electric field oriented in the vertical plane. This allows the radar to provide information on the shape and orientation of the hydrometeors and non-meteorological scatterers that it detect.**

# Dual Polarization or Polarimetric Radar

**To do this, the return power from the horizontally polarized beam is compared with the return power of the vertically polarized beam. Looking at the different power returns reveals the characteristics of a particle’s horizontal and vertical axes as well as the orientation of individual particles and groups of particles. For instance, large raindrops become oblate as they fall, giving them a longer horizontal axis than vertical axis, while small raindrops are more or less spherical.**

# Dual Polarization or Polarimetric Radar

**Several useful parameters can be calculated using the return power from both the horizontal and vertical polarizations. These parameters are very useful for determining the type of hydrometeor or non-meteorological scatterers sampled by the radar. Classifying different hydrometeors and non-meteorological scatterers is one of the advantages of polarimetric radar over traditional radar. Classification schemes filter out ground clutter, improve rainfall estimations, and track the evolution of storm cells.**

# Antenna Fundamentals

**Beam width ($\theta$, $\Phi$): The average angular width of the radar beam between two half power points on either side of the axis of the beam. The angular width of the radar beam may be different in horizontal ($\theta$)and vertical direction ($\Phi$).This is generally one degree in DWRs.**

**Antenna Aperture ($A_e$): The physical area of the antenna exposed to the RF radiation is called antenna aperture. For a given beam width, larger antenna area is required for longer wave length. Thus, 10-cm radar will have a larger antenna than 3-cm radar.**

# Reflector Antennas

cc

# Parabolic Reflector With Front Feed

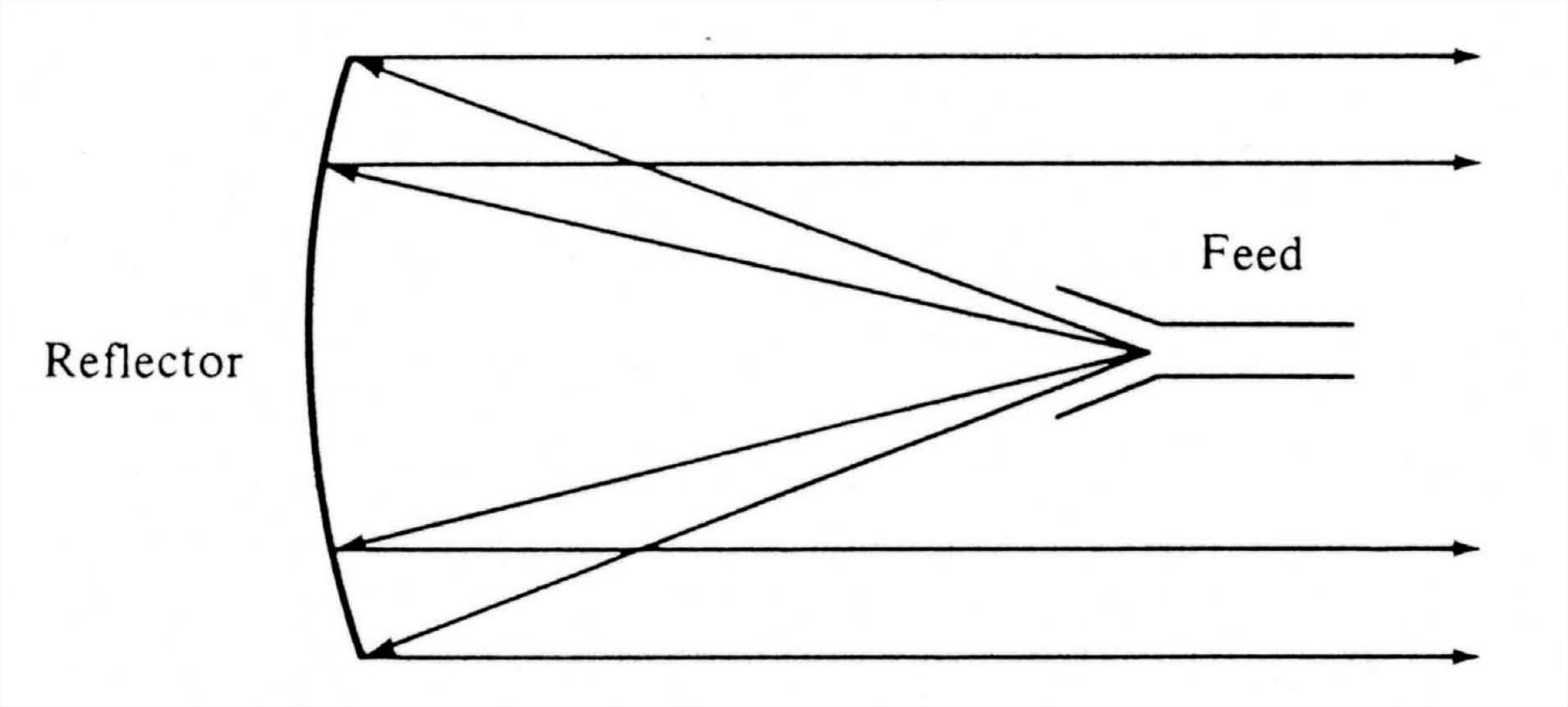


**Fig. 1.7(a)**

# Parabolic Reflector With Cassegrain Feed

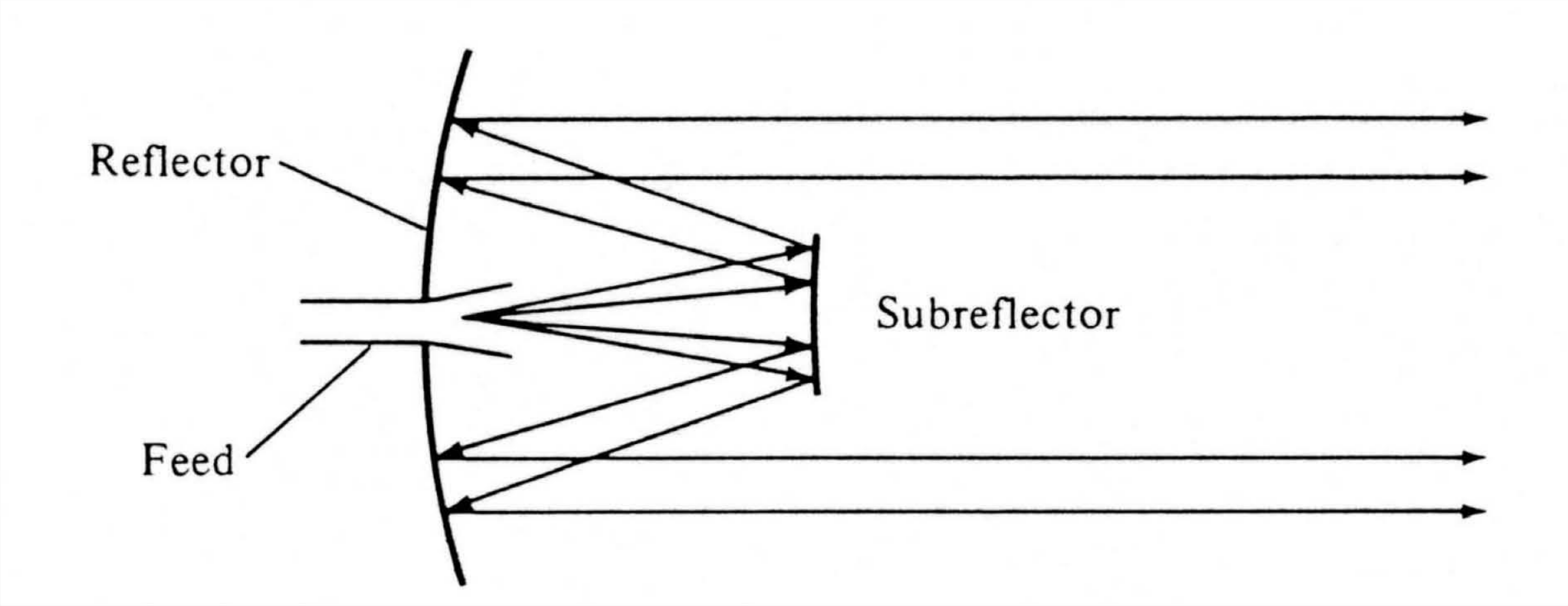


**Fig. 1.7(b)**

# Coordinate System

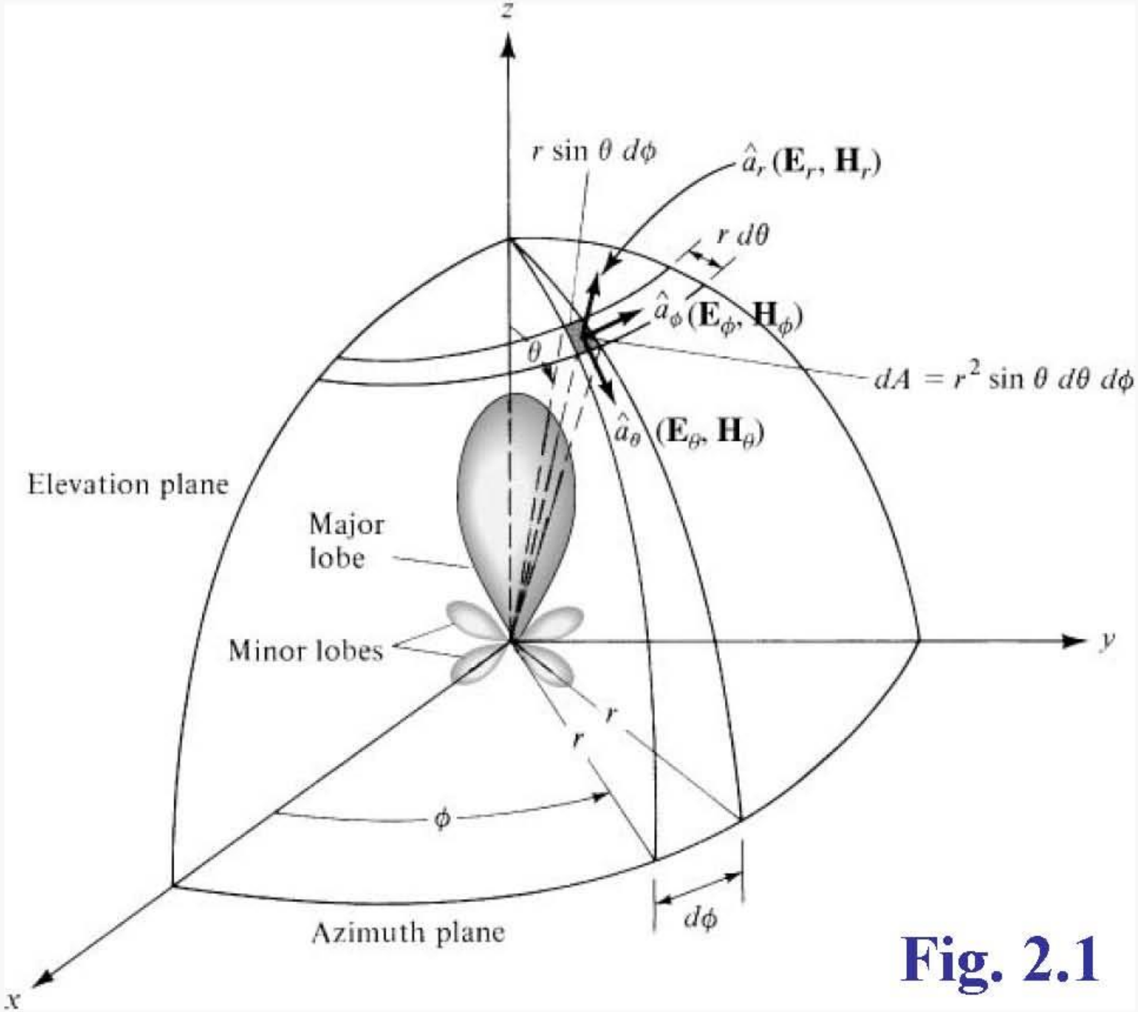


**Fig. 2.1**

# Radiation Pattern

A mathematical and/or graphical representation of the radiation properties of an antenna, such as the:

- amplitude
- phase
- polarization, etc.

as a function of the angular space coordinates $\theta, \phi$.

# Amplitude Radiation Pattern

- Field Pattern:

  A plot of the field (either electric $|\underline{E}|$ or magnetic $|\underline{H}|$) on a *linear* scale

- Power Pattern:

  A plot of the power (proportional to either the electric $|\underline{E}|^2$ or magnetic $|\underline{H}|^2$ fields) on a *linear* or *decibel (dB)* scale.

# 2-D Normalized *Field* $|\underline{E}_n|$ Pattern of a Linear Array

Linear Scale

$N = 10$ elements

$d = \lambda/4$ spacing

HPBW = 38.64°

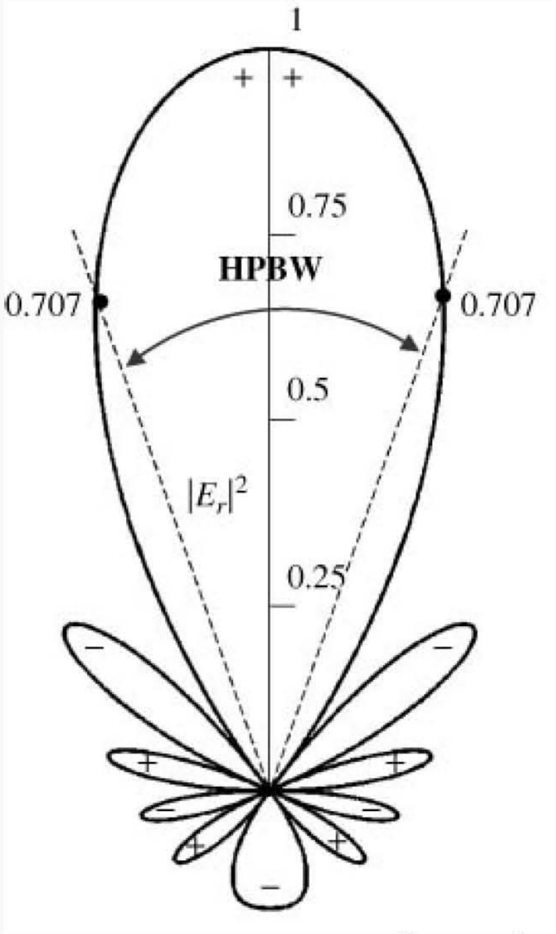
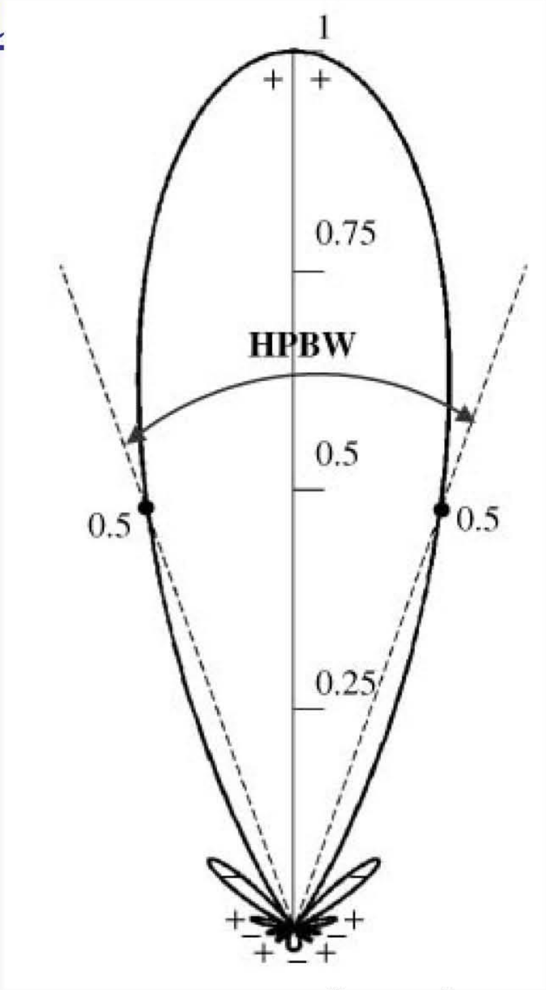


**Fig. 2.2(a)**

# 2-D Normalized *Power* $|\underline{E}_n|^2$ Pattern of a Linear Arra



## Linear Scale

$N$ = 10 elements

$d = \lambda/4$ spacing

HPBW = 38.64°

**Fig. 2.2(b)**

# Polar Pattern

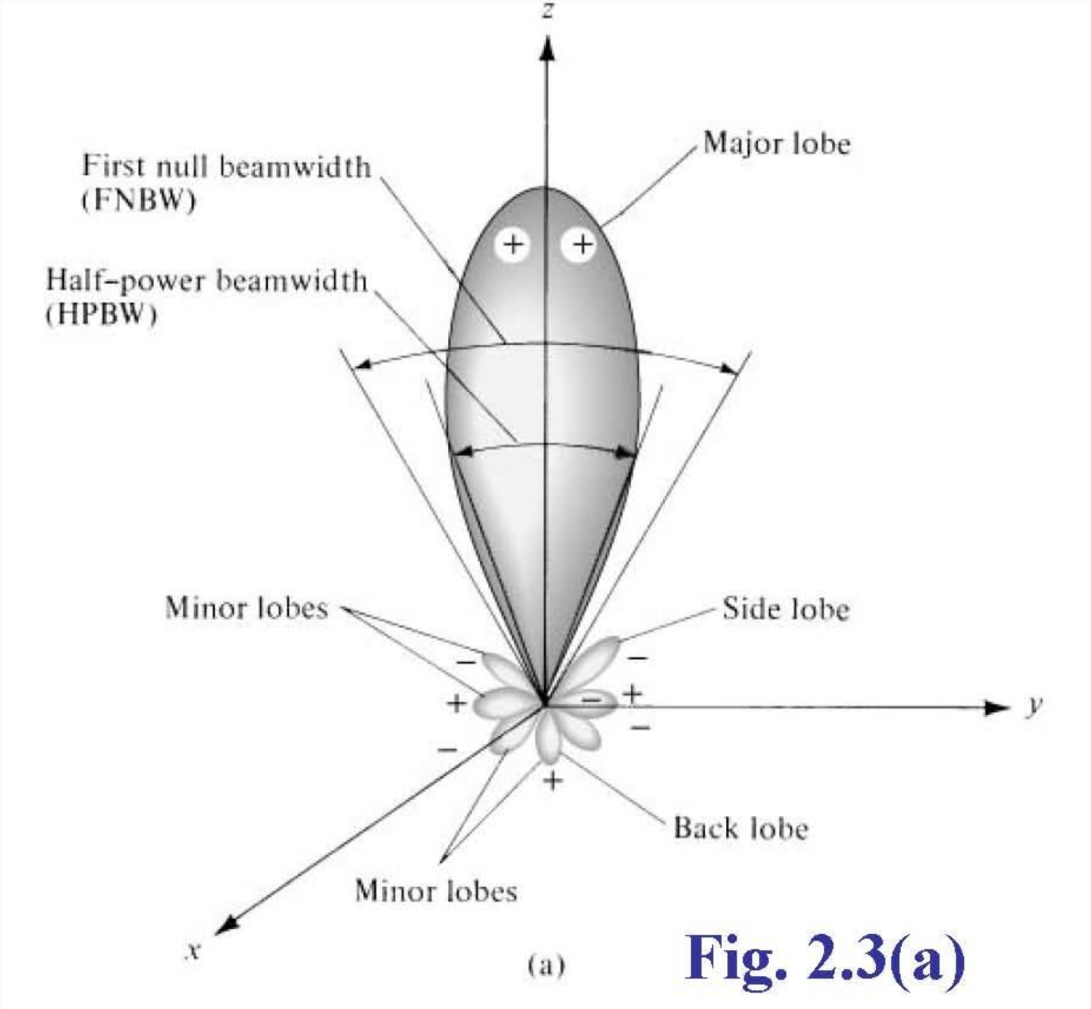


**Fig. 2.3(a)**

# Paraboloid

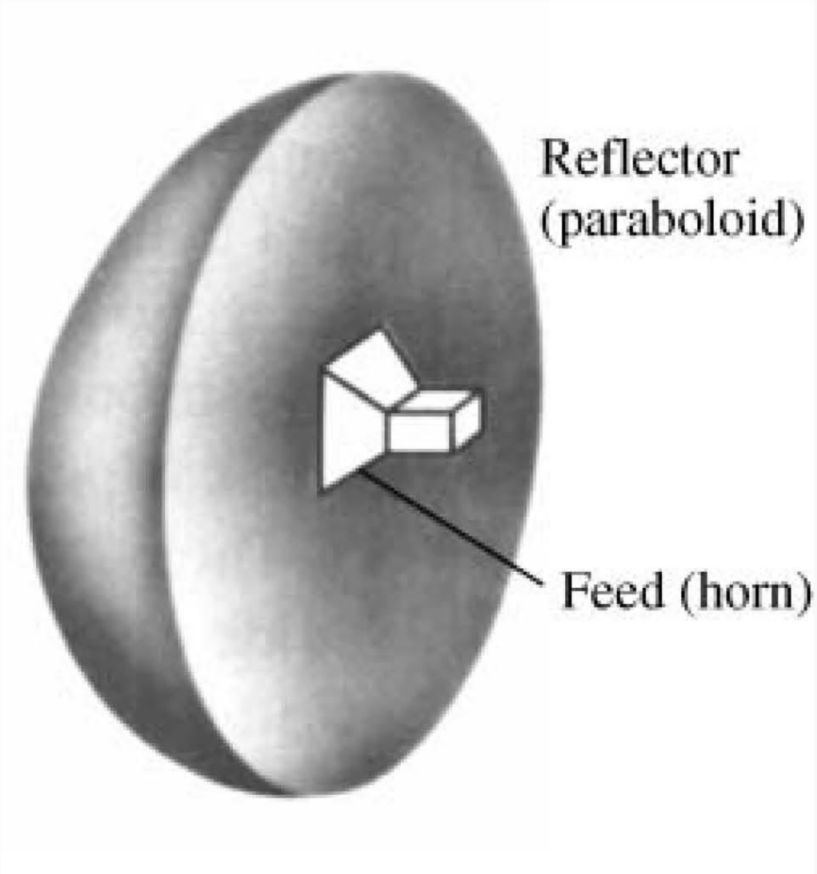


**Fig. 15.8(b)**

# Directional Pattern of a Horn

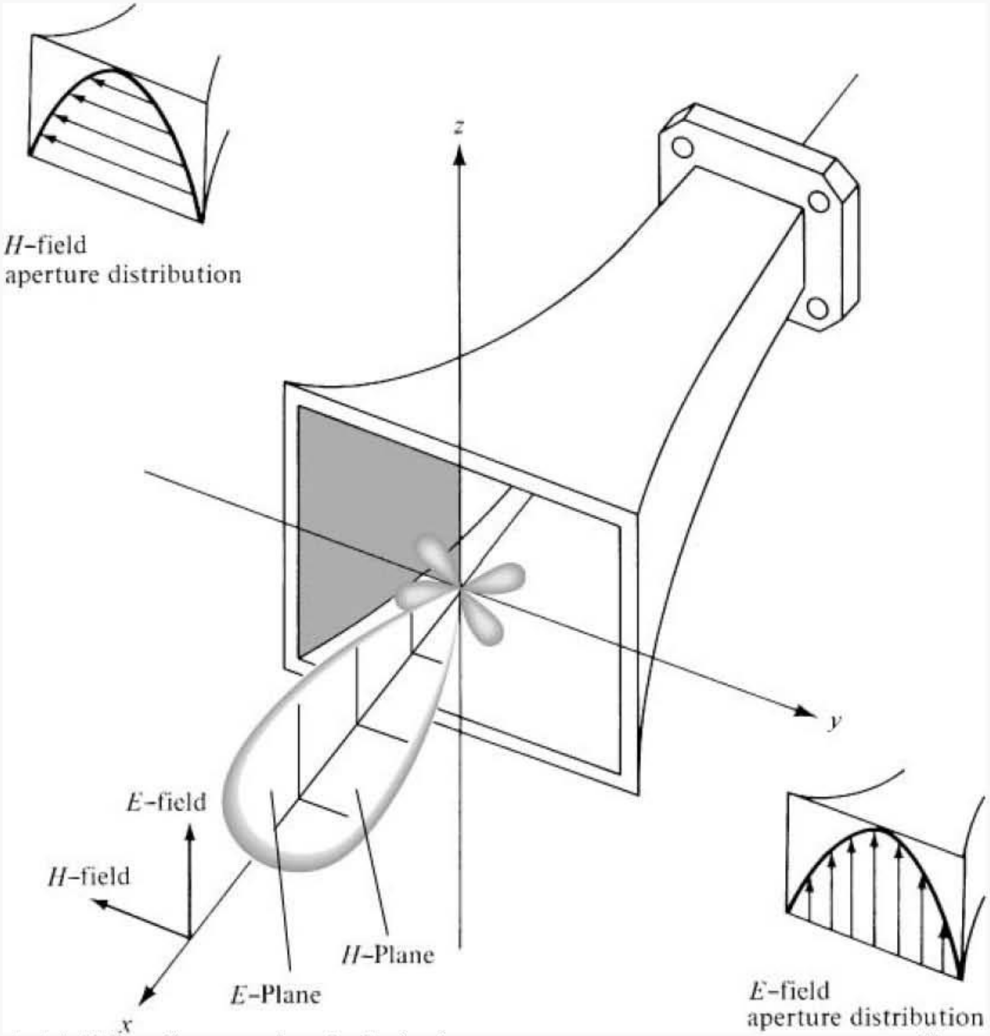
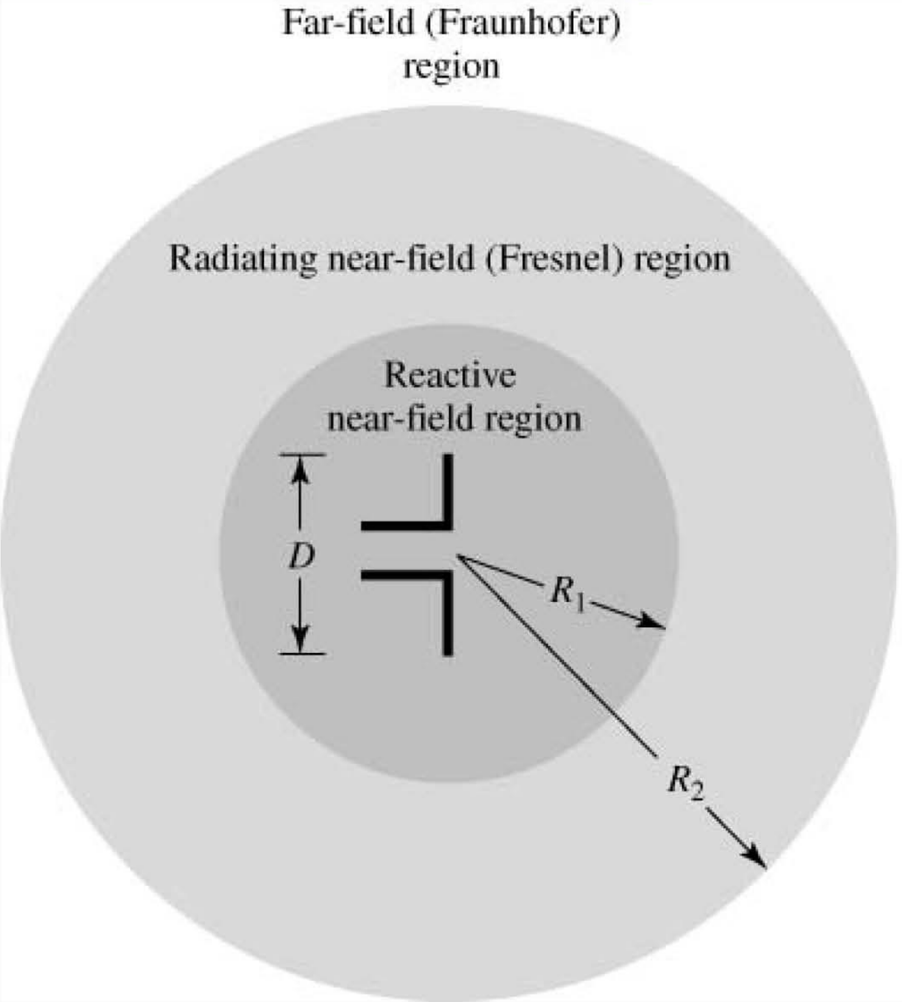


**Fig. 2.5**

# Field Regions



$$R_1 = 0.62\sqrt{D^3/\lambda}$$

$$R_2 = 2D^2/\lambda$$

**Fig. 2.7**

## I. Reactive Near-Field

- A. Phases of electric & magnetic fields are often near quadrature; thus
  - 1. Highly reactive wave impedance
  - 2. High content of non-propagating stored energy near the antenna

## II. Radiating Near-Field

- A. Fields are predominantly in phase
- B. Fields do not yet display a spherical wavefront; thus pattern varies with distance
- C. Region where near-field measurements are made

# III. Far-Field

A. Fields exhibit spherical wavefront ($e^{-jkr}/r$); thus the pattern, ideally, does not vary with distance

B. Electric & magnetic fields are in-phase

C. Wave impedance is, ideally, real

D. Power predominantly real; propagating energy

**Antenna gain (G)** is the ratio of the co-axial radiance measured in the direction of antenna (beam) compared to the radiance for the same power with an isotropic antenna (known as isotropic radiance). Antenna gain increases with smaller beam width; this in turn needs larger antenna sizes.

**Antenna efficiency:**

Target Aperture ($A_\sigma$): The area of the target intercepted by radar beam is the target aperture. Though this appears like physical area, it depends on the nature of the target, antenna surface and its diameter compared to the wave length of the RF transmitted, dielectric properties of the target etc.

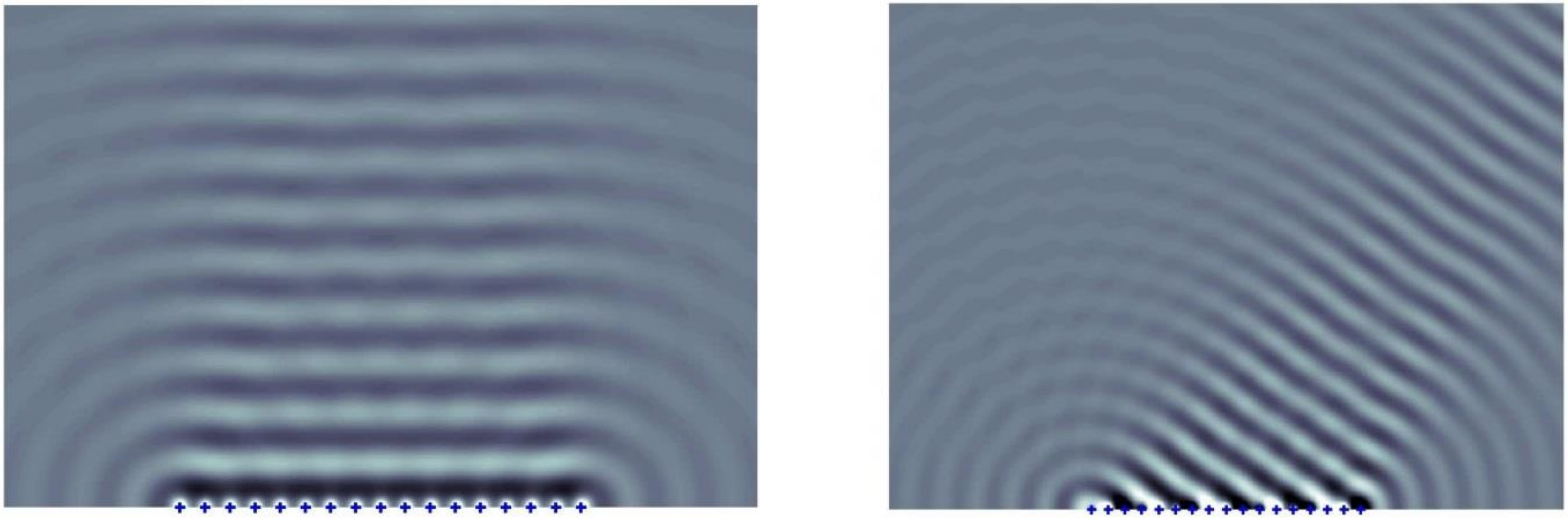
**Back Scattering Cross section Area (σ):** The back scattering cross sectional area is a function of size, shape, material of the target and the wavelength of the radar viewing it. When the target is large compared to the wavelength of the radiation, it is the same as its geometrical area.  In case the size of target is smaller than the wavelength, it appears differently from this(for a radar wave).

# Phased Array Antennas/Radars

## What is a Phased Array?

A phased array is a group of antennas whose effective (summed) radiation pattern can be altered by phasing the signals of the individual elements. - By varying the phasing of the different elements, the radiation pattern can be modified to be maximized / suppressed in given directions, within limits determined by (a) the radiation pattern of the elements, (b) the size of the array, and (c) the configuration of the array

# Phased Array, λ/2 spacing



# Benefits of Phased array

- Does not require moving a large structure around the sky for pointing. (Less infrastructure)
- Fast steering. (Pulse-to-pulse)
- Distributed, solid-state transmitters as opposed to single RF sources. (Less warm-up time, no need for complex feed system, elimination of single-point failures)

# Benefits of Phased array

These features allow for:

- Remote operations
- Graceful degradation / continual operations