MICROWAVE AND RADAR ENGINEERING

BY ANJU

MICROWAVE

- Microwaves are a form of electromagnetic radiation with frequencies ranging from roughly 300 megahertz (MHz) to 300 gigahertz (GHz), falling between conventional radio waves and infrared light in the electromagnetic spectrum.

Applications

- **Communication:** Used extensively in mobile phone networks, Wi-Fi, Bluetooth, point-to-point communication links, and satellite communications .
- **Radar:** Used in weather forecasting, air traffic control, and vehicle speed detection, as their short wavelengths allow for precise detection of objects and their movement .
- **Cooking/Heating:** The most common household application is the microwave oven, which uses microwave radiation to heat food efficiently .
- **Industrial:** Used in various industrial processes for heating, drying, and material processing .

Frequency Bands

Microwave frequency bands

Letter Designation	Frequency range
L band	1 to 2 GHz
S band	2 to 4 GHz
C band	4 to 8 GHz
X band	8 to 12 GHz
K_u band	12 to 18 GHz
K band	18 to 26.5 GHz
K_a band	26.5 to 40 GHz
Q band	33 to 50 GHz
U band	40 to 60 GHz
V band	50 to 75 GHz
E band	60 to 90 GHz
W band	75 to 110 GHz
F band	90 to 140 GHz
D band	110 to 170 GHz

Reflex klystron

- A reflex klystron is a microwave oscillator made of a glass tube with an electron gun, a single re-entrant cavity, and a repeller plate. It operates by using a repeller to send a velocity-modulated electron beam back through the cavity, where it bunches up and transfers energy to the cavity to sustain oscillations. Key applications include use in radar receivers, local oscillators, and signal sources.

Reflex klystron

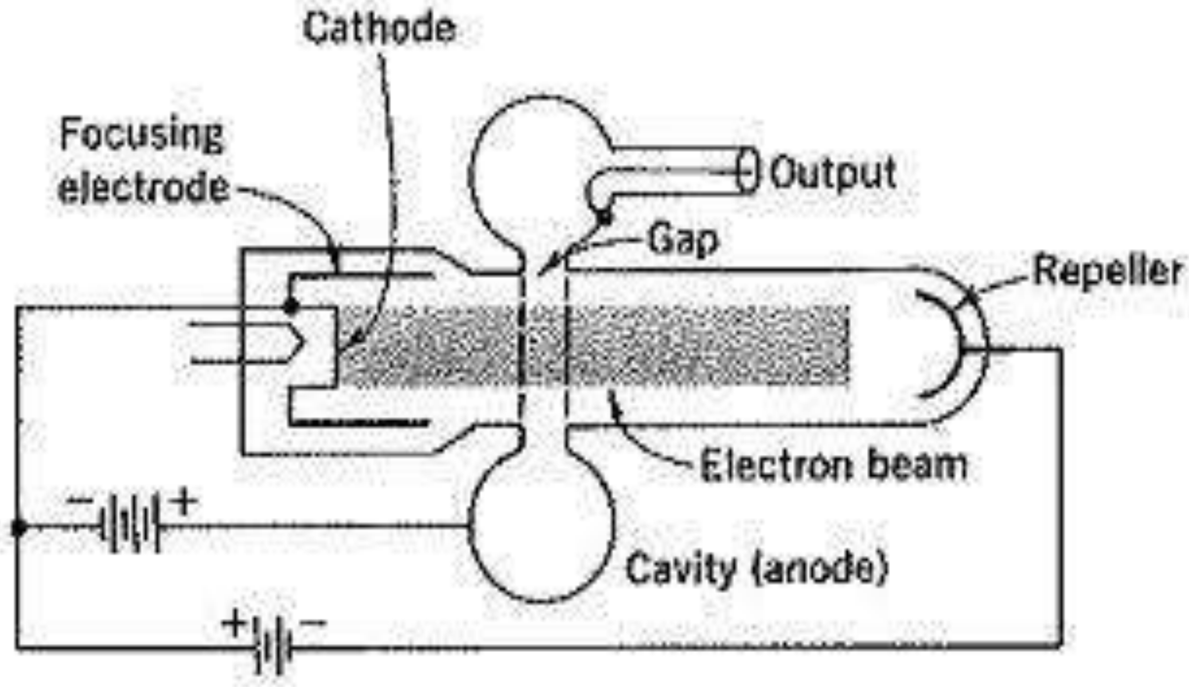


FIGURE 11-8 Reflex klystron schematic.

Construction

- **Glass Tube Housing:** Provides a vacuum-sealed enclosure for the components.
- **Electron Gun:** Consists of a cathode and focusing anode. The cathode emits a focused electron beam when a positive voltage is applied.

Cont.

- **Single Re-entrant Cavity:** A resonant cavity that both accelerates the electrons and extracts power. It acts as a "buncher" on the forward path and a "catcher" on the return path.
- **Repeller Plate:** A negatively charged electrode positioned opposite the electron gun. It repels the electron beam, sending it back through the cavity.
- **RF Output:** A coaxial cable connection to the cavity to extract the microwave signal.

Operating Principles

- **Electron Emission and Acceleration:** The electron gun generates a continuous electron beam, which is accelerated towards the repeller through the cavity.
- **Velocity Modulation:** As the electron beam passes through the cavity gap, the varying RF field imparts a range of velocities to the electrons.
  - Electrons passing during a positive voltage cycle are accelerated.
  - Electrons passing during a negative voltage cycle are decelerated.

Cont.

- **Bunching:** The velocity-modulated electrons then travel into the "repeller space" between the cavity and the repeller plate.
  - Electrons that were accelerated will travel further into the negative repeller field.
  - Electrons that were decelerated will be repelled sooner.
  - Over time, the faster electrons catch up to the slower ones, causing the electrons to "bunch" together.
- **Energy Transfer:** The electron bunches return to the cavity gap and pass through it when the RF field is in a phase to decelerate them, transferring their kinetic energy to the cavity and sustaining the oscillations.

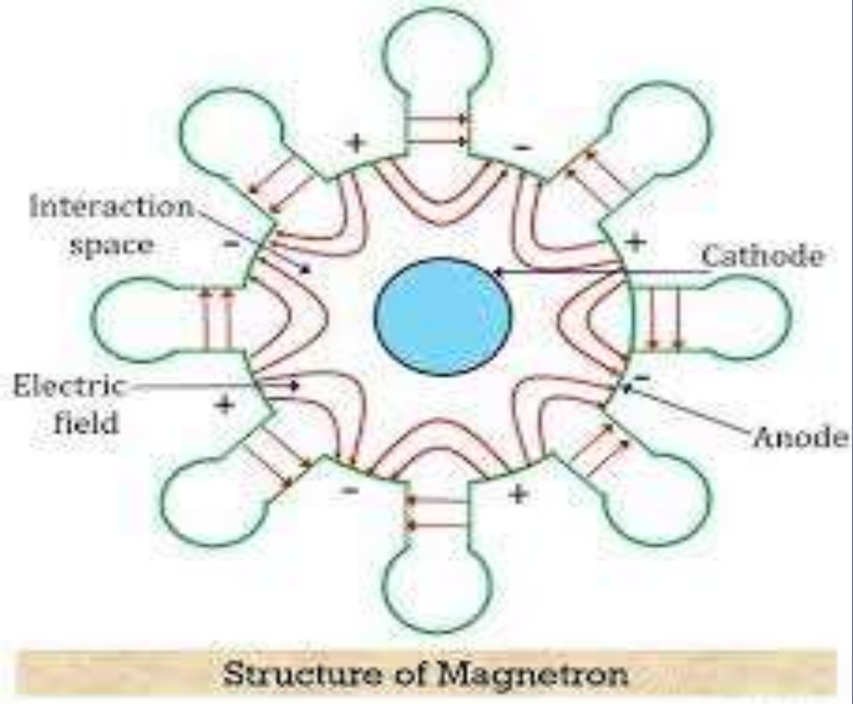
Applications

- **Radar receivers:** Used as local oscillators for frequency conversion.
- **Signal generators:** Serve as a source for generating microwave signals.
- **Local oscillators:** Used in microwave communication systems.
- **Parametric amplifiers:** Can be used as part of the system.

Magnetron

- A magnetron is a high-powered vacuum tube that functions as a self-excited **microwave oscillator**, converting electrical power into microwave radiation using crossed electric and magnetic fields. It is widely used in applications where high power is needed but precise frequency control is not critical.

Magnetron



Interaction space
Cathode
Electric field
Anode
Structure of Magnetron

Construction

- The basic structure of a cavity magnetron includes the following key components:
- **Anode Block**: A large, solid copper cylinder that acts as the anode (positive potential). It contains several (typically an even number, like 8 or 12) built-in resonant cavities around its inner circumference. These cavities function as parallel LC resonant circuits, determining the operating frequency based on their physical dimensions.

Cont.

- **Cathode**: A heated, negatively charged filament made of high-emission material, located at the center of the anode block. It emits electrons via thermionic emission when heated.
- **Interaction Space**: The vacuum-filled space between the central cathode and the inner surface of the anode block where electrons travel and interact with the fields.

Cont.

- **Magnetic Field System**: A strong, permanent magnet (or electromagnet in some high-power designs) is placed around the tube to produce a magnetic field that runs parallel to the cathode axis and perpendicular to the radial electric field. This arrangement gives rise to the term "crossed-field device".
- .

Cont.

- **Output Mechanism**: A coupling loop or a slot/aperture connected to a waveguide extracts the generated microwave energy from one of the resonant cavities and directs it to the load.
- **Strapping (Optional)**: To ensure stable oscillation in the desired "pi-mode", strapping rings may be used to connect alternate anode segments, forcing a 180-degree phase difference between adjacent cavities.

Operating Principles

- The operation involves the interaction of electrons with both static (DC) and alternating (RF) fields:
- **Electron Emission**: The heated cathode emits electrons into the interaction space.
- **Crossed Fields**: A radial electric field (from anode to cathode) and an axial magnetic field (parallel to the cathode axis) are present, causing the electrons to follow a curved, spiral path towards the anode due to the Lorentz force.

Cont.

- **Velocity Modulation & Bunching**: As electrons pass the gaps of the resonant cavities, they interact with the initial, low-power RF fields (transient oscillations). "Favored" electrons moving against the AC field are slowed down and give up energy to the field, while "unfavored" electrons are accelerated and quickly return to the cathode. This process causes the favored electrons to form "bunches" or "spokes" of charge (a "space-charge wheel") that rotate around the cathode.
-

Cont.

- **Sustained Oscillation**: These rotating electron spokes deliver energy to the cavities as they pass, similar to blowing air over a bottle opening to produce a tone. This continuous transfer of kinetic energy from the electrons to the RF field sustains and amplifies the oscillations within the resonant cavities.
- **Energy Extraction**: The high-power microwave energy is extracted from one of the cavities using a coupling loop or aperture and channeled via a waveguide to the intended application.

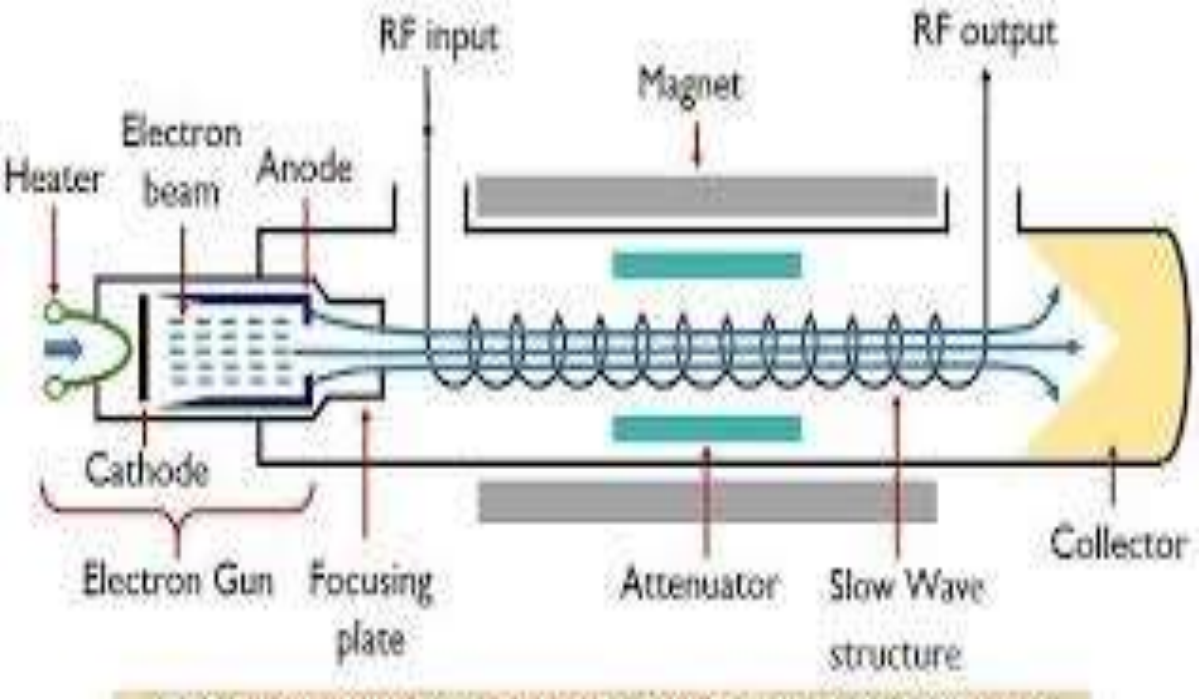
Applications

- **Microwave Ovens**: The most common application, where magnetrons generate microwaves (typically at 2.45 GHz) for heating food.
- **Radar Systems**: Historically a primary application (especially in WWII for compact, high-power systems), magnetrons are still used in many marine and aviation weather avoidance radars where frequency stability is less critical than power and cost.
- **Industrial Heating and Processing**: Used for drying, curing materials (like wood), and processing materials in various industrial settings.

Traveling Wave Tube

- A **Traveling Wave Tube (TWT)** is a specialized vacuum tube used for high-frequency, high-power **microwave signal amplification**, noted for its wide bandwidth and high gain. The amplification is achieved through continuous interaction between an electron beam and a traveling electromagnetic wave.

Traveling Wave Tube



Constructional Structure of Travelling Wave Tube

Construction

- A TWT is an elongated vacuum tube containing several key components arranged linearly.
- **Electron Gun:** A heated cathode at one end emits a narrow, constant-velocity electron beam.
- **Focusing Mechanism:** An external axial magnetic field, often provided by permanent magnets or solenoids, is used to guide and focus the electron beam, preventing it from scattering or diverging.

Cont.

- **Slow-Wave Structure:** A crucial element, typically a wire helix, is wrapped around the path of the electron beam. This structure slows down the axial velocity of the RF signal to a speed comparable to that of the electron beam (a fraction of the speed of light).
- **RF Input/Output Couplers:** The signal to be amplified is fed into the helix near the electron gun end via an input coupler, and the amplified signal is extracted at the other end via an output coupler.

Cont.

- **Attenuator:** A lossy material or circuit is placed along the helix (usually near the center) to absorb any reflected waves, preventing oscillations or self-oscillation within the tube.
- **Collector:** Positioned at the far end of the tube, the collector is kept at a positive potential to capture the spent electrons from the beam.

Operating Principles

- The operation relies on continuous interaction between the electron beam and the RF field.
- **Electron Beam Generation:** The electron gun generates a constant-velocity electron beam, which is focused by a magnetic field and directed down the center of the tube.
- **RF Wave Slowing:** The input RF signal is fed onto the helix, which acts as a slow-wave structure, reducing the wave's axial velocity to approximately match that of the electron beam.

Cont.

- **Continuous Interaction and Velocity Modulation:** As the electron beam travels along the helix, it interacts with the axial electric field of the RF wave. Electrons passing through the accelerating phase of the field speed up, while those in the decelerating phase slow down. This process, called velocity modulation, causes the electrons to bunch together.

Cont.

- **Energy Transfer and Amplification:** The electron bunches travel in synchronism with the RF wave, transferring their kinetic energy to the wave on the helix. This continuous interaction results in an exponential growth (amplification) of the RF signal along the length of the tube.
- **Signal Output:** The greatly amplified signal is extracted from the output coupler at the end of the helix, near the collector.

Applications

- **Satellite Communications:** Due to their high reliability (long life of over 15 years) and efficiency, TWTs are widely used as power output amplifiers in communication satellites and spacecraft transponders, including probes like New Horizons and the James Webb Space Telescope.
- **Radar Systems:** They are used extensively in high-power pulsed and continuous wave (CW) radar systems, particularly in airborne fire-control and ground-based radars.

Impatt diode

- An IMPATT diode is a semiconductor device that operates on avalanche breakdown and transit time effects to produce microwave frequencies. Its construction includes a p+-i-n+ or p+-n-n+ structure with heavily doped p+ and n+ regions and an intrinsic or lightly doped drift region

Impatt diode

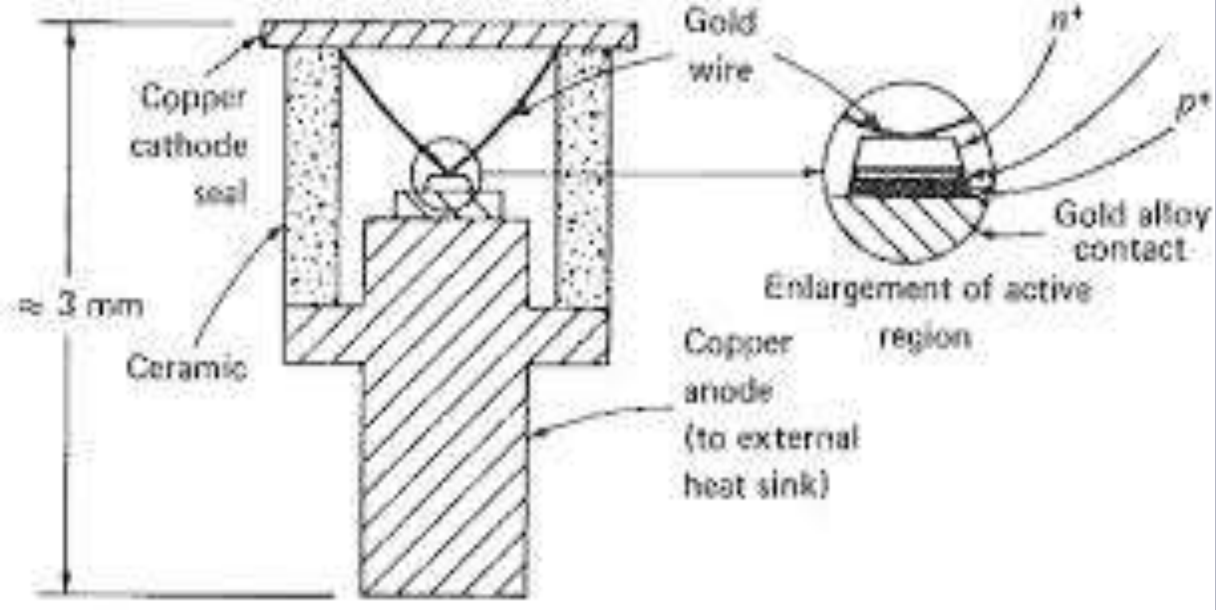


FIGURE 12-30 Typical IMPATT diode.

Construction

- **Slow-Wave Structure:** A crucial element, typically a wire helix, is wrapped around the path of the electron beam. This structure slows down the axial velocity of the RF signal to a speed comparable to that of the electron beam (a fraction of the speed of light).
- **RF Input/Output Couplers:** The signal to be amplified is fed into the helix near the electron gun end via an input coupler, and the amplified signal is extracted at the other end via an output coupler.

Cont.

- **Regions**:
  - **Avalanche region**: A highly doped p+ or n+ region where impact ionization and avalanche multiplication occur.
  - **Drift region**: A lightly doped or intrinsic (i) region where the generated carriers drift to the other side. **Contacts and packaging**: Metal contacts (anode and cathode) are applied to the p+ and n+ sides, respectively. A heat sink is often integrated for heat dissipation, and the entire structure is packaged for protection and easy circuit integration.

Operating Principles

- **Reverse bias**: The diode is operated under a high reverse bias, beyond its breakdown voltage.
- **Avalanche breakdown**: The high electric field in the avalanche region (p+ or n+ region) causes minority carriers to gain high energy. These carriers then collide with the lattice, creating new electron-hole pairs through impact ionization, leading to an avalanche of carriers.

Cont.

- **Transit time**: The generated carriers drift through the intrinsic drift region to the other side. The transit time of these carriers is a critical factor that determines the oscillation frequency, which is dependent on the thickness of the drift region.
- **Negative resistance**: The phase difference between the current and voltage due to the avalanche multiplication and carrier drift creates a negative resistance characteristic at microwave frequencies. This property is what allows the diode to act as an oscillator or amplifier.

Applications

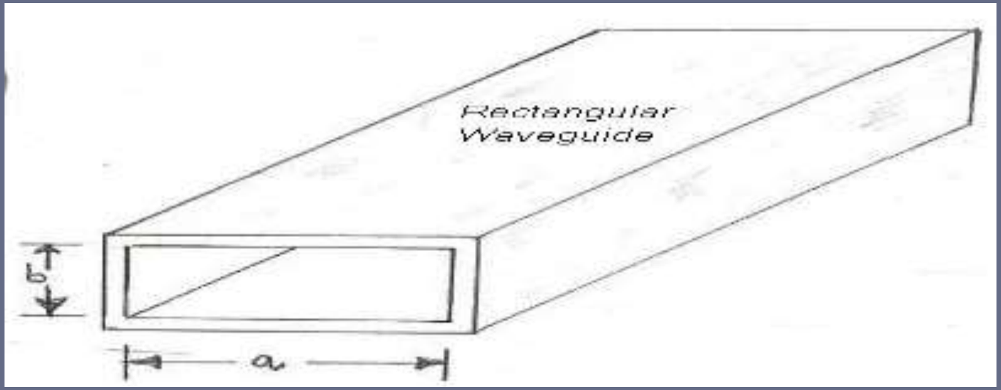
- **Microwave oscillators**: Used as a source of RF power for microwave frequencies.
- **Microwave amplifiers**: Amplifies microwave signals.
- **Radar systems**: Used in low-power radar applications.
- **Alarm systems**: Employed in certain types of alarm systems.
- **Microwave links**: Used in communication systems for microwave links.
- **Parametric devices**: Can be used in certain parametric devices.

What is a Waveguide?

- • A hollow metallic structure that carries electromagnetic waves
- • Operates at microwave frequencies
- • Guides waves by internal reflections
- • Low loss and high power handling

Rectangular Waveguide – Structure

- • Cross-section is rectangular
- • Common dimensions: a × b (a > b)
- • Modes: TE and TM (TE10 is dominant)



Rectangular Waveguide – Working

- • EM waves propagate by reflection from walls
- • Cutoff frequency depends on dimensions
- • TE10 mode has lowest loss and simplest field pattern

Rectangular Waveguide – Advantages

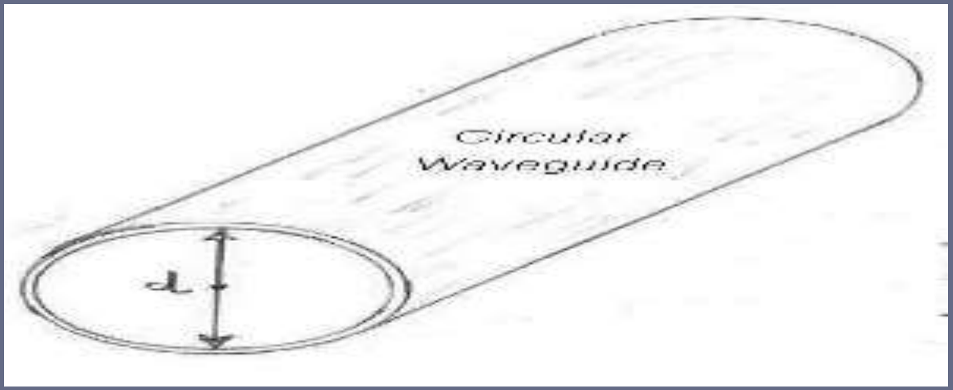
- • High power handling
- • Lower attenuation
- • Easy to manufacture

Rectangular Waveguide – Applications

- • RADAR systems
- • Satellite communication
- • Microwave ovens
- • Test and measurement equipment

Circular Waveguide – Structure

- • Circular cross-section
- • Supports TE, TM, and hybrid modes
- • TE11 is dominant mode



Circular Waveguide – Working

- • Suitable for rotating joints
- • Symmetry allows polarization flexibility
- • Cutoff frequency depends on diameter

Circular Waveguide – Advantages

- • Ideal for rotary couplings
- • Lower sensitivity to misalignment
- • Good mechanical strength

Circular Waveguide – Applications

- • Satellite antenna feeds
- • Gyroscopes and rotary joints
- • High-frequency communication links

Types of Modes

- • TE (Transverse Electric): Electric field has no component along the direction of propagation.
- • TM (Transverse Magnetic): Magnetic field has no component along the direction of propagation.
- • TEM (Transverse Electromagnetic): Both E and H have no longitudinal components — not supported in hollow rectangular waveguides.

TE Modes (Transverse Electric)

- • No electric field along the direction of propagation (Ez = 0)
- • Magnetic field has all components
- • Most commonly used
- • Example: TE10 (dominant mode in rectangular waveguides)

TM Modes (Transverse Magnetic)

- • No magnetic field along propagation direction (Hz = 0)
- • Electric field has all components including Ez
- • Harder to excite compared to TE modes
- • Used in resonators and filters

TEM Mode (Transverse Electromagnetic)

- • Both Ez and Hz = 0
- • Requires two conductors (like coax cable)
- • Not supported in hollow waveguides
- • Only TE and TM modes exist in rectangular/circular waveguides

TE,TM & TEM Modes

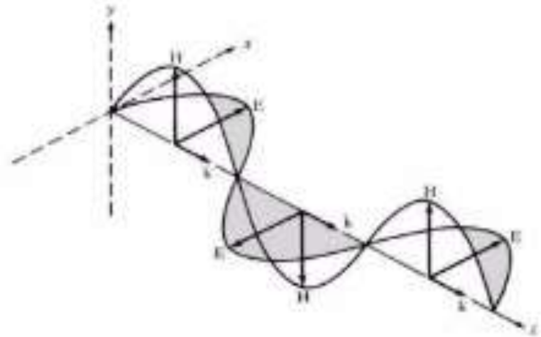
TE,TM & TEM MODES

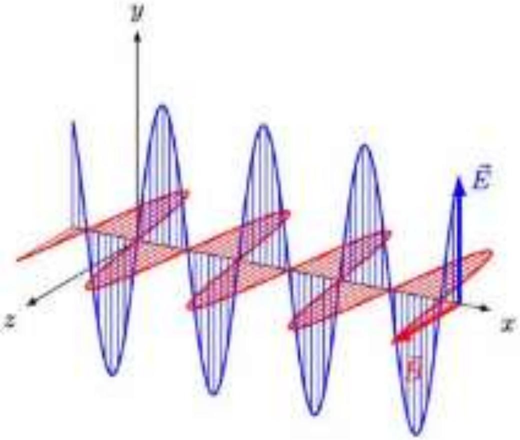
Transverse Electric mode (TE): Electric field is perpendicular to the direction of propagation, **(Ez = 0),** but a corresponding component of the magnetic **field H in the direction of propagation(Z).**

Transverse Magnetic (TM) mode: A component of **E field is in the direction of propagation(Z), but Hz=0.**

Modes with mode numbers; TEm and TMm

Transverse Electro Magnetic (TEM) : Total field lies in the transverse plane **both Ez and Hz are zero.**





Cutoff Wavelength

- • Each mode has a cutoff wavelength (λc).
- • If the free-space wavelength λo is larger than λc ($\lambda o > \lambda c$), that mode cannot propagate — it becomes evanescent and rapidly decays.
- • If $\lambda o < \lambda c$, the mode can propagate along the guide with some phase progression.
- • Engineering implication: choose guide size so desired signals have $\lambda o < \lambda c$ for the desired mode and $\lambda o > \lambda c$ for unwanted modes.

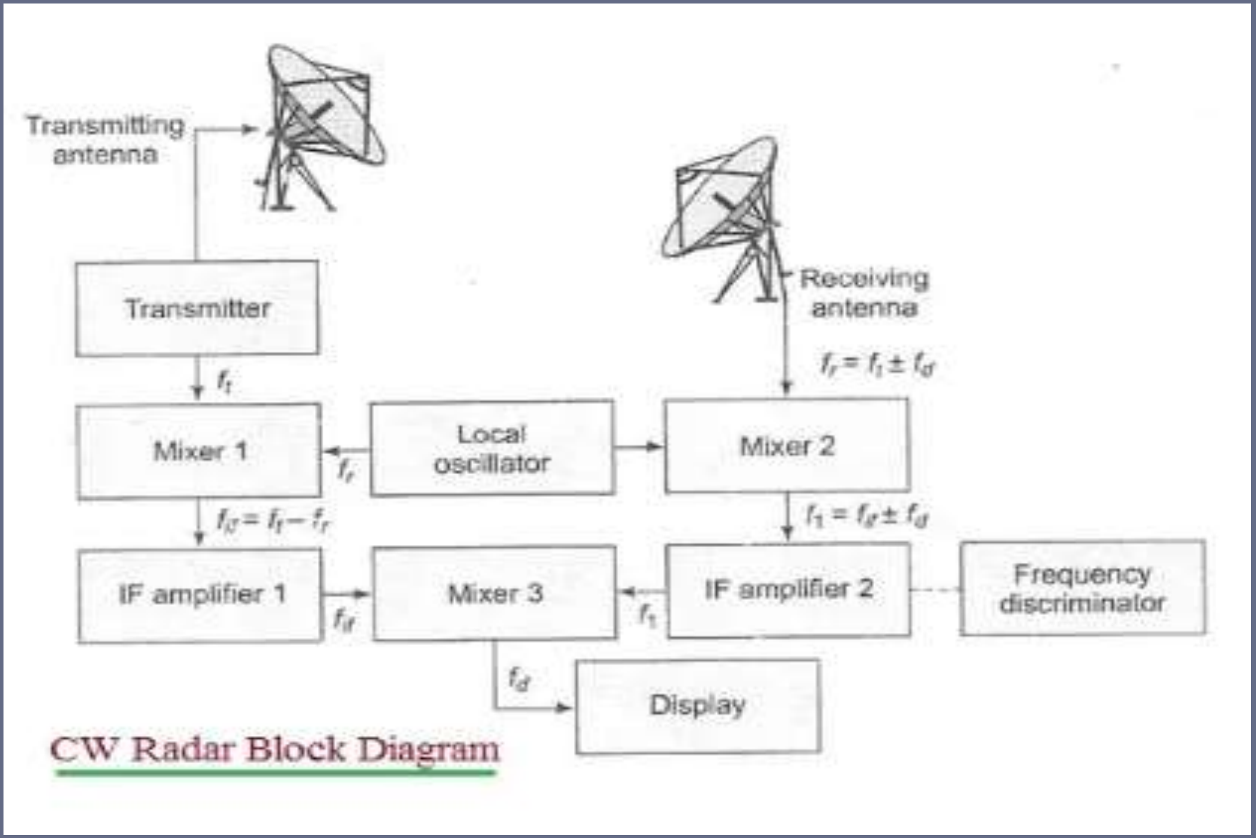
Guide Wavelength

- • Guide wavelength (λg) is the effective wavelength of the wave inside the waveguide measured along the direction of travel.
- • It differs from free-space wavelength because the fields are constrained by the waveguide boundaries.
- • λg governs standing-wave patterns, resonances inside cavities, and phase advance between points along the guide.

CW Radar

- The radar which works based on the use of continuous waveforms to determine target velocity is known as CW radar.
- It works as follows: The frequency of the radar return wave (i.e., echo) remains at the center frequency (f_0) from a stationary target, while it shifts by an amount equal to the Doppler frequency from a moving target.
- By measuring the frequency difference, the target's relative velocity can be measured using CW radar.
- The figure below depicts a block diagram of the CW radar with transmitter and receiver parts.

CW Radar Block Diagram



Advantages of CW Radar

- It is used for relative velocity measurement.
- It is used for a wide variety of applications as listed above.
- It transmits power with a lower value and hence does not interfere with other wireless devices.
- It is simple in construction.
- The performance of CW radar is not affected by stationary targets.

Disadvantages of CW Radar

- It does not measure the range or distance of the target.
- It becomes difficult to make a decision when there are a large number of targets. In this situation, the CW radar system gets confused.

Introduction of MTI Radar

- MTI radar detects moving targets by rejecting stationary clutter.
- Works by comparing successive echo pulses.
- Uses coherent detection to preserve phase.
- Core mechanism: Delay-line Canceller (T = 1/PRF).
-

Block Diagram of MTI Radar

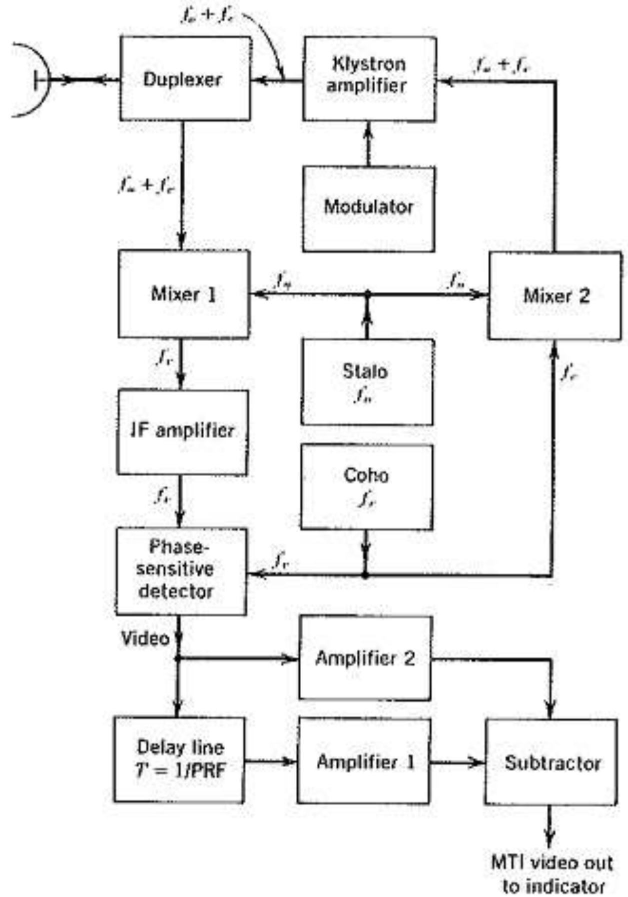


FIGURE 16-12 Block diagram of MTI radar using power amplifier output.

Block Diagram of MTI Radar

- Main Sections:
- Transmitter Chain
- Receiver Chain
- Coherent Reference Oscillators (STALO, COHO)
- MTI Canceller (Delay + Subtractor)

Antenna & Duplexer

- **Antenna**
- Radiates high-power RF pulses.
- Receives weak echoes from targets.
- **Duplexer**
- Acts as a switch between Transmit and Receive modes.
- Protects receiver from high-power transmit pulses.
- Routes received echoes to the receiver chain.

Klystron Amplifier & Modulator

- **Klystron Amplifier**
- High-power microwave amplifier.
- Boosts RF pulse to transmitter power levels.
- **Modulator**
- Controls pulse width and PRF.
- Provides high-voltage pulses to klystron.
- PRF determines delay time $T = 1/PRF$ for cancelling.

Mixer 2 (Transmitter Sampling)

- Samples a fraction of the transmitted pulse.
- Provides a coherent reference for comparison with the received signal.
- Helps cancel system phase variations.
- Essential for coherent MTI operation.

Local Oscillators

- **STALO (Stable Local Oscillator)**
- Provides frequency-stable LO for mixing.
- Minimizes frequency drift.
- **COHO (Coherent Oscillator)**
- Phase-locked to the transmitter.
- Ensures same phase reference for every pulse.
- Makes Doppler/phase changes measurable.

Mixer 1 & IF Amplifier

- Mixer 1
- Mixes received RF echo with LO to produce IF.
- Down converts signal for easier processing.
- IF Amplifier
- Amplifies IF signal.
- Provides filtering to isolate Doppler components.
- Must maintain phase integrity

Phase-Sensitive Detector

- Converts IF signal into video (baseband).
- Extracts both amplitude + phase.
- Phase difference between pulses indicates target motion.
- Output → MTI Canceller.

Applications of MTI Radar

- Air surveillance radars
- Airport surface movement radars
- Marine radars (ship detection)
- Ground-surveillance radars
- Battlefield surveillance
- Speed monitoring radars