ICT 3101
Microwave Engineering

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Microwaves

- **Microwaves** are electromagnetic (EM) waves with frequencies ranging from 300 MHz to 300 GHz, corresponding to wavelengths from 1 meter to 1 millimeter.
- They lie between radio waves **and** infrared in the electromagnetic spectrum.

Characteristics of Microwaves

- **Line-of-sight propagation**: They travel straight unless reflected or refracted.
- **High frequency** → allows for:
  - Small antennas
  - High bandwidth (used in high-speed communications)
- **Short wavelength** → enables:
  - Directional antennas (e.g., parabolic dishes)
  - Precise resolution in radar and imaging systems

Common Applications

Application	Description
Radar	Detection and ranging of objects using reflected microwave signals
Satellite Communication	High-frequency bands allow global data transmission
Wi-Fi & Bluetooth	Operate in microwave spectrum (2.4 GHz, 5 GHz, etc.)
Microwave Ovens	Use 2.45 GHz to heat food by agitating water molecules
Mobile Networks (5G)	Use microwave and millimeter wave bands for high-speed data

Transmission Lines at Microwave Frequencies:

At microwave frequencies, conventional wires become **inefficient** due to:

- High radiation losses
- Skin effect (current flows near the surface)
- Increased parasitic inductance/capacitance

Alternative transmission structures:

- **Coaxial cables**
- **Waveguides** (hollow metal tubes that guide waves)
- **Microstrip lines** (used in PCBs and RF circuits)

Microwave Components

Component	Function
Waveguide	Transmits microwaves with low loss
Circulator/Isolator	Controls direction of signal flow
Coupler	Splits or combines microwave signals
Filter	Allows specific frequencies to pass
Antenna	Converts electrical signals to EM waves (and vice versa)
Mixer	Converts frequency using nonlinear components
Oscillator	Generates microwave signals (e.g., Gunn diode oscillator)

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Important Microwave Parameters

Parameter	Description
Wavelength (λ)	$\lambda = cf$, where $c = 3\times10^8$ m/s
Frequency (f)	How many cycles per second (Hz)
VSWR (Voltage Standing Wave Ratio)	Indicates how well transmission line is matched
S-parameters	Describe signal reflection/transmission (scattering parameters)
Impedance (Z_0)	Characteristic impedance, typically 50 Ω

Microwave Measurement Tools

- **Vector Network Analyzer (VNA)**: Measures S-parameters
- **Spectrum Analyzer**: Displays signal spectrum
- **Power Meter**: Measures microwave power
- **Signal Generator**: Produces test microwave signals

Microwave Spectrum Bands

The microwave spectrum spans frequencies from approximately 1 GHz to 300 GHz. It is commonly divided into bands (L, S, C, X, etc.) for convenience in design, communication, radar, and scientific use.

These bands are defined by organizations like the **IEEE** and **ITU**, and each has specific applications based on propagation characteristics, penetration, and bandwidth availability.

Microwave Frequency Bands, Ranges, and Applications

Band Name	Frequency Range	Wavelength Range	Major Application
L-band	1 – 2 GHz	30 – 15 cm	GPS, mobile communication, satellite navigation
S-band	2 – 4 GHz	15 – 7.5 cm	Weather radar, Wi-Fi (2.4 GHz), airport surveillance radar
C-band	4 – 8 GHz	7.5 – 3.75 cm	Satellite communication, radar, 5G backhaul
X-band	8 – 12 GHz	3.75 – 2.5 cm	Military radar, weather radar, marine radar
Ku-band	12 – 18 GHz	2.5 – 1.67 cm	Satellite TV broadcasting, satellite internet
K-band	18 – 27 GHz	1.67 – 1.11 cm	High-resolution radar, police speed radar
Ka-band	27 – 40 GHz	1.11 – 0.75 cm	High-throughput satellites (HTS), 5G, space communication
V-band	40 – 75 GHz	0.75 – 0.4 cm	Millimeter-wave communication, radar, high-speed wireless links
W-band	75 – 110 GHz	0.4 – 0.27 cm	Imaging radar, automotive radar, security scanners
mmWave (general)	30 – 300 GHz	10 – 1 mm	5G, short-range high-speed wireless, sensing

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Applications

- **L and S bands**: Suitable for long-range communication due to low atmospheric attenuation.
- **C and X bands**: Balance between range and resolution; popular in radar and satellite systems.
- **Ku and Ka bands**: Higher frequencies allow more bandwidth but are more affected by rain fade.
- **V and W bands**: Used in emerging **millimeter-wave** applications like **5G**, **high-speed point-to-point links**, and **radar imaging**.

Microwave Transmission Line

Definition

A **microwave transmission line** is a physical structure used to guide electromagnetic waves (microwaves) from one point to another efficiently. Unlike low-frequency signals that can use simple wires, microwaves require special transmission mediums due to:

- Short wavelengths
- High signal attenuation in regular wires
- Radiation and reflection issues

Types of Microwave Transmission Lines

1. Coaxial Line

- **Structure**: Inner conductor, dielectric insulator, outer conductor (shield).
- **Frequency Range**: Up to ~18 GHz (some types up to 40+ GHz with special design).
- **Characteristic Impedance**: Typically 50 or 75 ohms.

Advantages:

- Shielded (less susceptible to external interference).
- Simple to connect.

Disadvantages:

- High losses at very high frequencies due to skin effect and dielectric loss.
- Not suitable for very high-power or very high-frequency transmission.

Applications:

- Signal distribution, lab testing, interconnects, cable TV, RF/microwave devices.

2. Rectangular Waveguide

- **Structure**: Hollow metallic rectangular tube.
- **Mode of Propagation**: Supports **TE** and **TM** modes, no TEM.
- **Frequency Range**: ~3 GHz to 100+ GHz depending on dimensions.

Advantages:

- Low loss.
- High power handling.
- Very low dispersion.

Disadvantages:

- Bulky and rigid.
- Complex to fabricate and assemble.

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Applications:

- High-power radar, satellite systems, microwave links, test systems.

3. Circular Waveguide

- **Structure**: Hollow cylindrical tube.
- **Supports**: TE and TM modes (not TEM).
- **Used less frequently** due to mode degeneracy and mode-mixing issues.

Applications:

- High-power systems, some satellite communication systems.

4. Microstrip Line

- **Structure**: A conducting strip on a dielectric substrate with a ground plane on the opposite side.
- **Mode**: Quasi-TEM.
- **Frequency Range**: Up to ~100 GHz (depends on substrate and design).

Advantages:

- Compact and lightweight.
- Easy integration with active and passive components (ICs).
- Low cost, suitable for PCB fabrication.

Disadvantages:

- Radiation losses.
- Dispersive at high frequencies.
- Sensitive to substrate properties.

Applications:

- RF circuits, antennas, MMICs, 5G systems, microwave PCBs.

5. Stripline

- **Structure**: Center conductor sandwiched between two ground planes and dielectric layers.
- **Mode**: Pure TEM.
- **Better shielding** than microstrip.

Advantages:

- Low radiation loss.
- Better isolation and impedance control.

Disadvantages:

- More complex fabrication than microstrip.
- Less compact.

Applications:

- High-performance RF/microwave PCBs, filters, couplers.

6. Coplanar Waveguide (CPW)

- **Structure**: Central strip conductor with ground planes on the same dielectric plane.

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- **Mode**: Quasi-TEM.

Advantages:

- Easy component mounting.
- Good for integration with active devices.
- Less radiation than microstrip in some cases.

Disadvantages:

- More difficult to design accurately.

Applications:

- MMICs, RF modules, sensors.

Comparison Table

Type	Mode	Power Handling	Loss	Size	Frequency Range	Applications
Coaxial Line	TEM	Low to medium	Medium	Compact	Up to ~40 GHz	RF interconnects, lab measurements
Rectangular Waveguide	TE/TM	Very high	Very low	Bulky	3 – 100+ GHz	Radar, satellites, test systems
Circular Waveguide	TE/TM	High	Low	Bulky	3 – 100+ GHz	Satellite and military comms
Microstrip Line	Quasi-TEM	Low	Medium	Very compact	DC – 100 GHz	PCBs, antennas, RF modules
Stripline	TEM	Medium	Low	Compact	DC – 40+ GHz	High-performance microwave PCBs
Coplanar Waveguide	Quasi-TEM	Low to medium	Medium	Compact	DC – 100 GHz	MMICs, RFICs, sensor circuits

Microwave Transmission Lines Equations

Step 1: Transmission Line Model

A microwave transmission line is modeled using distributed elements per unit length:

- RRR: Resistance (Ω/m)
- LLL: Inductance (H/m)
- GGG: Conductance (S/m)
- CCC: Capacitance (F/m)

The line carries time-harmonic signals, so we assume e^{jwt} time dependence (phasor domain).

Step 2: Telegrapher's Equations

From the distributed model, the differential voltage and current equations are:

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$$\frac{dV(z)}{dz} = -(R + j\omega L)I(z) \quad (1)$$

$$\frac{dI(z)}{dz} = -(G + j\omega C)V(z) \quad (2)$$

Step 3: Derive the Wave Equations

Differentiating Eq. (1):

$$\frac{d^2V}{dz^2} = -(R + j\omega L)\frac{dI}{dz}$$

Substitute $\frac{dI}{dz}$ from Eq. (2):

$$\frac{d^2V}{dz^2} = (R + j\omega L)(G + j\omega C)V(z)$$

Let:

$$\gamma^2 = (R + j\omega L)(G + j\omega C) \Rightarrow \boxed{\frac{d^2V}{dz^2} = \gamma^2 V(z)}$$

Similarly:

$$\frac{d^2I}{dz^2} = \gamma^2 I(z)$$

Step 4: General Solutions

These are second-order linear differential equations. General solutions are:

Voltage:

$$\boxed{V(z) = V^+e^{-\gamma z} + V^-e^{\gamma z}}$$

Current:

$$\boxed{I(z) = \frac{V^+}{Z_0}e^{-\gamma z} - \frac{V^-}{Z_0}e^{\gamma z}}$$

Where:

- V^+: amplitude of forward (positive z) wave
- V^-: amplitude of backward (negative z) wave
- Z_0: characteristic impedance
- γ: propagation constant

Step 5: Define Key Parameters

Propagation Constant:

$$\boxed{\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}}$$

- α: attenuation constant (Np/m)
- β: phase constant (rad/m)

Characteristic Impedance:

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$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

Assignment1. on Modes of Propagation in a Rectangular Waveguide

Hints:

A rectangular waveguide supports multiple electromagnetic modes of propagation, which depend on the field configurations within the guide. These modes describe how electric (E) and magnetic (H) fields distribute and propagate inside the waveguide.

Types of Modes in Rectangular Waveguides

1. *TE (Transverse Electric) Modes*
2. *TM (Transverse Magnetic) Mode*
3. *TEM (Transverse Electromagnetic) Modes*

Microwave Coupler

A **microwave coupler** (also called a directional coupler) is typically a 4-port device that allows a known fraction of power to be extracted from the main transmission line without disturbing the signal significantly.

Typical Port Configuration

Port	Function
Port 1	Input (main line)
Port 2	Output (main line)
Port 3	Coupled (samples signal)
Port 4	Isolated (ideally receives no signal)

Working Principle

When a signal is applied at **Port 1**, most of it travels to **Port 2**, but a small fraction (coupling factor) is **"coupled"** to **Port 3**. Ideally, **Port 4** (isolated port) receives **no signal** in this direction of operation.

The coupling works based on:

- **Electromagnetic field interaction**
- **Proximity of transmission lines or waveguides**
- **Phase and amplitude matching**

Directional Coupler

A directional coupler is a four-port microwave passive device used to sample or split power from a transmission line in a specific direction without disturbing the main signal path significantly.

It allows power flowing in one direction to be coupled (extracted) to a specific port, while isolating it in the opposite direction.

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Ports in a Directional Coupler

Port	Description
Port 1	Input (main line)
Port 2	Output (main line)
Port 3	Coupled port (samples power traveling from port 1 → 2)
Port 4	Isolated port (ideally receives no power when input is at port 1)

Working Principle

- When a microwave signal is applied to **Port 1**, most of the power flows to **Port 2**.
- A **small fraction** (determined by the coupling factor) is extracted and delivered to **Port 3** (the **coupled port**).
- Ideally, **Port 4** (the **isolated port**) receives **no power**.

Key Concepts:

- **Coupling Factor (C):**

  $$C = 10\log_{10}\left(\frac{P_1}{P_3}\right) \text{ (in dB)}$$

  Describes how much power is coupled from input to coupled port.

- **Directivity (D):**

  $$D = 10\log_{10}\left(\frac{P_3}{P_4}\right) \text{ (in dB)}$$

  Measures how well the coupler isolates power in the unwanted direction.

- **Isolation (I):**

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

Diagram of a Directional Coupler

Types of Directional Couplers

- Waveguide directional coupler
- Stripline or microstrip coupler
- Hybrid couplers (e.g., 3 dB coupler)
- Multihole or Bethe-hole couplers

Applications of Directional Couplers

1. Power Monitoring

- Used to measure forward and reflected power without interrupting the main signal path.

2. VSWR / Return Loss Measurement

- Coupled port samples reflected wave to calculate Voltage Standing Wave Ratio (VSWR) or return loss.

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3. Signal Sampling

- Extracts a small portion of the signal for **testing, analysis, or monitoring**.

4. Isolating Devices in Transmit/Receive Chains

- Helps in building **circulators, isolators**, and **duplexers**.

Feature	Value
Type	4-port passive device
Main function	Samples signal power in a specific direction
Coupling factor	How much power is tapped
Directivity	How well the device distinguishes forward vs reverse waves
Key ports	Input, output, coupled, isolated
Dominant direction	Port 1 → 2, with coupling to Port 3

Klystron:

A klystron is a specialized vacuum tube used to amplify high-frequency microwave signals, typically in the GHz range. It operates based on the principle of velocity modulation of an electron beam.

Basic Purpose

- Converts **DC power** into **microwave RF power**
- Used for **high-power microwave amplification** in:
  - Radar systems
  - Satellite communication
  - TV broadcasting
  - Particle accelerators

Types of Klystrons

Type	Description
Two-Cavity Klystron	Basic amplifier with input and output cavities
Multicavity Klystron	Higher gain and bandwidth
Reflex Klystron	Used as an oscillator, not amplifier

Key Components:

1. **Electron Gun** – Emits a focused electron beam
2. **Buncher Cavity** – Modulates electron velocity (velocity modulation)
3. **Drift Space** – Electrons bunch together due to velocity differences
4. **Catcher Cavity** – Extracts RF power as bunched electrons induce current
5. **Collector** – Absorbs remaining beam energy
6. **Magnetic Field (optional)** – Used to focus the beam

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Microwave Reflex Klystron Oscillator

A Reflex Klystron is a microwave oscillator that generates microwaves using the principle of velocity modulation of an electron beam. It is commonly used in radar systems, signal generators, and microwave communication systems.

The main parts of a reflex klystron are:

Part	Description
Electron Gun	Emits electrons using a heated cathode and accelerates them toward the resonator.
Resonant Cavity	A metallic cavity that resonates at microwave frequencies; it modulates the velocity of electrons.
Repeller (Reflector) Electrode	A negatively charged electrode that reflects the electrons back through the cavity.
Drift Space	The region between the cavity and repeller where velocity modulation converts to density modulation (bunching).
Output Coupling	Extracts the generated microwave power via a probe or loop connected to a waveguide or coaxial line.

Working Principle: Velocity Modulation and Bunching

The reflex klystron operates based on velocity modulation and electron bunching, as described below:

Step-by-Step Working:

1. **Electron Emission**:
   - Electrons are emitted by the cathode and accelerated toward the resonator cavity by an anode voltage.
2. **Velocity Modulation**:
   - As electrons pass through the gap of the resonator, they experience an alternating electric field.
   - Depending on the instant of entry, electrons may be accelerated, decelerated, or unaffected, causing velocity modulation.
3. **Drift and Bunching**:
   - After passing through the cavity, electrons enter the drift space toward the negatively charged repeller.
   - Faster electrons move deeper into the repeller space before being turned back, while slower ones are reflected earlier.
   - As they return, they bunch together (density modulation), forming groups of electrons.
4. **Energy Transfer and Oscillation**:
   - These bunched electrons pass through the cavity gap again.
   - If the bunches arrive in the decelerating phase of the RF field, they give up energy to the cavity.
   - This sustains microwave oscillations in the cavity.
5. **Microwave Extraction**:
   - The oscillating energy is extracted via a coupling loop or probe and sent to the external circuit.

Key Concepts

Velocity Modulation:

- Electrons are modulated in speed due to varying electric field in the resonator.

Bunching:

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- Velocity-modulated electrons regroup into "bunches" due to their different travel times in the repeller field.

Microwave Generation:

- Bunched electrons transfer energy back to the cavity during their return path, sustaining oscillations.

Advantages of Reflex Klystron

- Simple construction
- Compact and lightweight
- Tunable over a small frequency range

Limitations

- Low efficiency (10–20%)
- Limited power output
- Poor frequency stability compared to modern oscillators

Applications

- Radar transmitters
- Microwave signal generators
- Local oscillators in receivers
- Educational labs for microwave principles

Microwave Antenna

A microwave antenna is a transducer that converts electrical microwave signals (typically from 1 GHz to 300 GHz) into electromagnetic waves and vice versa. These antennas are specially designed to operate efficiently at high frequencies and short wavelengths.

Key Characteristics of Microwave Antennas

Property	Description
Frequency Range	Typically 1 GHz – 300 GHz
High Directionality	Focused beams with narrow beamwidths
Gain	High gain (often >20 dBi) due to directive patterns
Compact Size	Small size due to short wavelengths
Polarization	Linear, circular, or elliptical depending on design

Types of Microwave Antennas

1. Horn Antenna

- Flared waveguide
- High gain, wide bandwidth
- Used in test ranges, satellite communication, radar

2. Parabolic Reflector Antenna

- Uses a **parabolic dish** to focus energy
- Very high gain and narrow beamwidth
- Common in satellite dishes, radio telescopes, radar

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3. Microstrip Patch Antenna

- Printed on PCB
- Compact and low-profile
- Used in mobile devices, GPS, IoT, aerospace

4. Slot Antenna

- Slot cut in a metal surface
- Can be integrated into waveguides
- Often used in aircraft and missile systems

5. Helical Antenna

- Wire wound in helix shape
- Circular polarization
- Used in satellite communication and space telemetry

6. Dielectric Lens Antenna

- Uses dielectric materials to focus EM waves
- Compact and high-directivity designs

Important Parameters

Parameter	Description
Gain (dBi)	Measure of how much power is radiated in a particular direction
Beamwidth	Angular width of the main lobe (typically in degrees)
Bandwidth	Range of frequencies over which antenna performs effectively
Polarization	Orientation of electric field (linear, circular, etc.)
VSWR	Should be close to 1:1 for good impedance matching

Radiation Pattern

- **Directional antennas** focus energy in a specific direction (e.g., horn, parabolic)
- **Omnidirectional antennas** radiate uniformly in one plane (e.g., some helical or monopoles)

Applications of Microwave Antennas

Field	Use
Radar	Detection, tracking, and imaging
Satellite Communication	Uplink/downlink of data via parabolic or patch antennas
Aerospace & Defense	Missile guidance, telemetry, EW systems
Wireless Communication	5G, Wi-Fi, microwave backhaul
Medical	Microwave imaging and treatment (e.g., cancer therapy)
Radio Astronomy	Deep space observation using large dish antennas

Advantages of Microwave Antennas

- High resolution and narrow beam (useful for targeting and tracking)

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- Small size at higher frequencies
- High bandwidth capabilities
- Precise control over radiation pattern

Horn Antenna

A **horn antenna** is a type of antenna that consists of a flaring metal waveguide shaped like a **horn** (e.g., conical or pyramidal). It is widely used in **microwave frequency** ranges (typically above 1 GHz) and serves as an efficient radiating element or feed for larger antennas like parabolic reflectors.

How Does a Horn Antenna Work?

1. **Microwave energy** is fed into the **narrow end** (throat) of the horn through a waveguide.
2. The energy **travels through the horn**, which gradually widens (flares).
3. This **flare allows the wave to transition smoothly** from the waveguide to free space, reducing reflections and increasing directivity.
4. The horn shape also helps to **match impedance** and to **focus the radiation** in a specific direction.

Types of Horn Antennas

Type	Description
Pyramidal Horn	Rectangular waveguide flare in both E-plane and H-plane; most common type.
Conical Horn	Flare from a circular waveguide into a cone; produces circularly symmetric beam.
Sectoral Horn	Flared in only one plane (E-plane or H-plane). - E-plane Sectoral: Flare in electric field direction. - H-plane Sectoral: Flare in magnetic field direction.
Corrugated Horn	Lined with grooves to improve beam symmetry and reduce cross-polarization. Used in high-performance systems.
Exponential Horn	Has an exponential flare profile for better impedance matching and broader bandwidth.

Advantages of Horn Antennas

- **High Gain and Directivity**: Narrow beam and focused radiation.
- **Wide Bandwidth**: Suitable for broad frequency ranges.
- **Low VSWR (Voltage Standing Wave Ratio)**: Good impedance matching with waveguides.
- **Simple Construction**: Mechanically robust and easy to fabricate.
- **Low Side Lobes**: Reduces interference from unwanted directions.
- **Efficient Radiation**: Low loss transition from waveguide to space.

Common Applications of Horn Antennas

Application	Purpose
Microwave Communication Links	Used for point-to-point high-frequency communication.
Radar Systems	Acts as a feed for parabolic reflectors in radar antennas.
Antenna Testing Ranges	Used as a reference antenna due to its predictable radiation pattern.

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Application	Purpose
Satellite Communication	As a feed horn for satellite dishes.
EMC (Electromagnetic Compatibility) Testing	Radiates or receives test signals for compliance measurements.
Scientific and Space Research	Used in radio astronomy and deep space communication.

Radar

RADAR stands for RAdio Detection and Ranging. It is a system that uses radio waves to detect, locate, and track objects at a distance. Radar systems are widely used in various applications such as aviation, marine navigation, weather monitoring, military surveillance, and traffic control.

Basic Principle of Radar

The basic working principle of radar involves the following steps:

1. **Transmission**: A radar system transmits a short pulse of radio waves through an antenna.
2. **Propagation**: These waves travel through the atmosphere until they hit an object (target).
3. **Reflection**: The waves bounce off the target and return to the radar antenna as an echo.
4. **Reception**: The radar receiver captures the reflected waves.
5. **Processing**: The system analyzes the time delay between transmission and reception to calculate:
   - **Distance (range)** of the object
   - **Direction** (angle) from which the echo returned
   - **Speed** (using the Doppler effect)
   - **Size or shape** (in advanced systems)

Main Components of Radar System

Component	Description
Transmitter	Generates high-frequency radio signals (pulses).
Antenna	Radiates transmitted signals into space and receives echoes from objects.
Duplexer	Switches the antenna between transmitting and receiving mode.
Receiver	Amplifies and processes the returned echo signals.
Signal Processor	Analyzes the received signals to extract useful information (like range, speed, etc.).
Display (e.g., CRT or digital screen)	Shows the processed data visually to the user.

Types of Radar Systems (Based on Application/Functionality)

Radar Type	Description
Pulse Radar	Uses short-duration pulses. Ideal for long-range detection and is common in air traffic control and military applications.
Continuous Wave (CW) Radar	Transmits continuously and detects moving targets using the Doppler effect. Used in speed detection (e.g., police radars).
Doppler Radar	Measures the velocity of moving objects using the frequency shift of the reflected wave. Used in weather radar and traffic monitoring.

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Radar Type	Description
Phased Array Radar	Uses multiple antennas to steer the beam electronically. Allows fast tracking of multiple targets. Used in missile guidance and advanced military radar.
Synthetic Aperture Radar (SAR)	Mounted on moving platforms (e.g., satellites). Creates high-resolution images of the Earth's surface. Used in remote sensing and mapping.
Weather Radar	Detects precipitation, wind speed, and storm structure. Commonly uses Doppler principles.
Monopulse Radar	Measures direction more accurately in a single pulse. Common in fire control and tracking systems.
Over-the-Horizon Radar (OTH)	Detects targets beyond the line of sight by reflecting signals off the ionosphere. Used in early-warning military systems.
Ground Penetrating Radar (GPR)	Sends signals into the ground to detect buried objects. Used in archaeology, mining, and utility detection.

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