Microwave Engineering & Radar System (315342)

Model Question Paper — Set B · Model Answers

Q.1

a) Phase velocity and group velocity. 2 M

Phase velocity (v_p): the velocity with which a point of constant phase of the wave travels along the guide. $v_p = \omega/\beta = c/\sqrt{(1 - (f_c/f)^2)}$; in a waveguide it is greater than c.

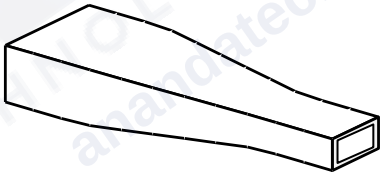
Group velocity (v_g): the velocity with which the energy (signal / envelope) travels along the guide. $v_g = d\omega/d\beta = c\sqrt{(1 - (f_c/f)^2)}$; it is less than c.

Relation (air-filled guide): $v_p \times v_g = c^2$

(Each definition 1 M)

b) Twist and taper. 2 M

Twist: rotates the plane of polarisation (here by 90°) gradually



Taper: gradual change of cross-section to match two different guides

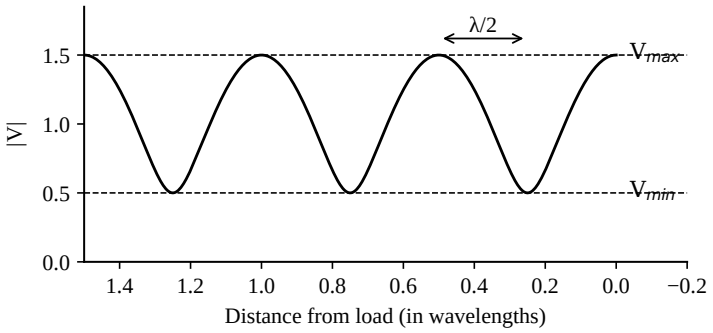
(Each sketch 1 M)

c) VSWR and reflection coefficient. 2 M

Reflection coefficient (Γ): ratio of reflected voltage to incident voltage at the load: $\Gamma = V_r/V_i = (Z_L - Z_0)/(Z_L + Z_0)$; $0 \le |\Gamma| \le 1$.

VSWR: ratio of maximum to minimum voltage of the standing wave on the line: $VSWR = V_{max}/V_{min}$; $1 \le VSWR \le \infty$.

$$VSWR = (1 + |\Gamma|) / (1 - |\Gamma|) \quad |\Gamma| = (VSWR - 1)/(VSWR + 1)$$



Standing-wave pattern on a mismatched line ($|\Gamma| = 0.5$, VSWR = 3)

(Definitions 1 M, relation 1 M)

d) Applications of cavity resonators. 2 M

1. Tank (tuned) circuits of microwave oscillators and tubes — klystron, magnetron.
2. Cavity wavemeter for measuring frequency.
3. Microwave filters (band-pass) and duplexers.
4. Measurement of dielectric constant / Q of materials; frequency stabilisation of oscillators.

(Any four, ½ M each)

e) Doppler effect. 2 M

Doppler effect: the apparent change in frequency of a wave received from (or reflected by) a source/target which is moving relative to the observer. Frequency increases when the target approaches and decreases when it moves away.

$$f_d = 2\, v_r / \lambda = 2\, v_r\, f_0 / c$$

v_r = radial (relative) velocity of target, λ = wavelength, f_0 = transmitted frequency. (Factor 2 because the wave travels to the target and back.)

(Definition 1 M, expression 1 M)

f) RADAR applications in automobiles / daily life. 2 M

1. Vehicle speed detection by traffic police (Doppler speed gun).
2. Adaptive cruise control and collision warning / automatic emergency braking (77 GHz radar).
3. Parking assistance and blind-spot detection.
4. Self-driving (autonomous) cars — obstacle detection with radar + camera + lidar.
5. Weather forecasting radar, air traffic control at airports.

(Any four, ½ M each)

g) IEEE frequency ranges of L, S, C, X bands. 2 M

Band	Frequency range
L	1 – 2 GHz
S	2 – 4 GHz
C	4 – 8 GHz
X	8 – 12 GHz

(½ M each)

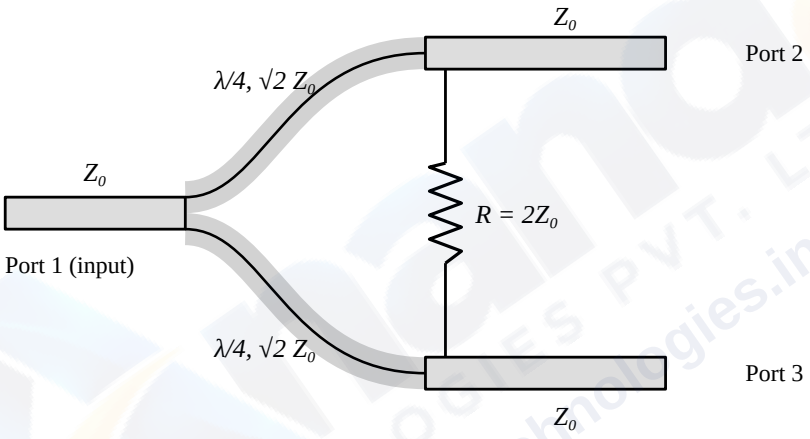
Q.2

a) Rectangular waveguide vs coaxial line. 4 M

Parameter	Rectangular waveguide	Coaxial transmission line
Construction	Single hollow rectangular metal pipe (a × b); no inner conductor.	Two concentric conductors (inner and outer) separated by a dielectric.
Mode of propagation	TE and TM modes only (dominant TE_{10}); TEM not possible.	TEM mode (dominant).
Cut-off frequency	Has a cut-off ($f_{c10} = c/2a$); acts as a high-pass filter.	No cut-off for TEM; works from dc.
Power handling	Very high (air dielectric, large size, no inner conductor).	Lower — limited by dielectric breakdown and heating of the thin inner conductor.

(Each point 1 M)

b) Wilkinson power divider. 4 M



Wilkinson power divider (microstrip, equal split)

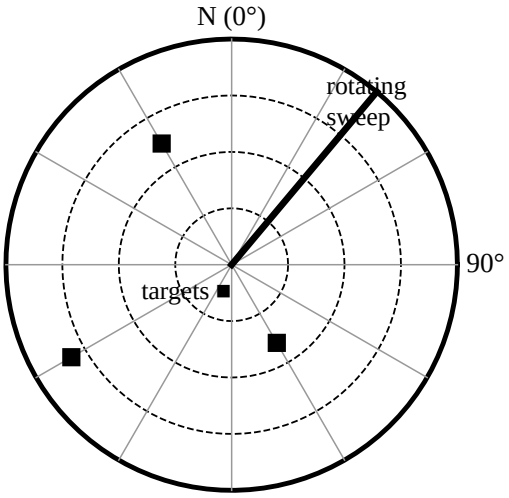
Construction: The input line (Z_0) splits into two quarter-wave (λ/4) transmission lines of impedance $\sqrt{2}\, Z_0$, ending at output ports 2 and 3 (Z_0 each). A lumped isolation resistor $R = 2Z_0$ is connected between the two output ports. Usually made in microstrip/stripline.

Working: Each output load Z_0 is transformed by the λ/4 line to $(\sqrt{2}Z_0)^2/Z_0 = 2Z_0$; two such in parallel give Z_0, so port 1 is matched. Power entering port 1 divides **equally and in phase** (−3 dB each). As ports 2 and 3 are at equal potential, no current flows in R and no power is lost. A signal reflected or entering at port 2 reaches port 3 by two paths (through R and through the two λ/4 lines) which cancel, so **outputs are isolated** and all ports are matched.

Applications: Power splitting/combining in antenna array feeds, power-amplifier combiners, local-oscillator distribution in receivers, test setups.

(Diagram 1 M, construction 1 M, working 1 M, applications 1 M)

c) PPI display. 4 M



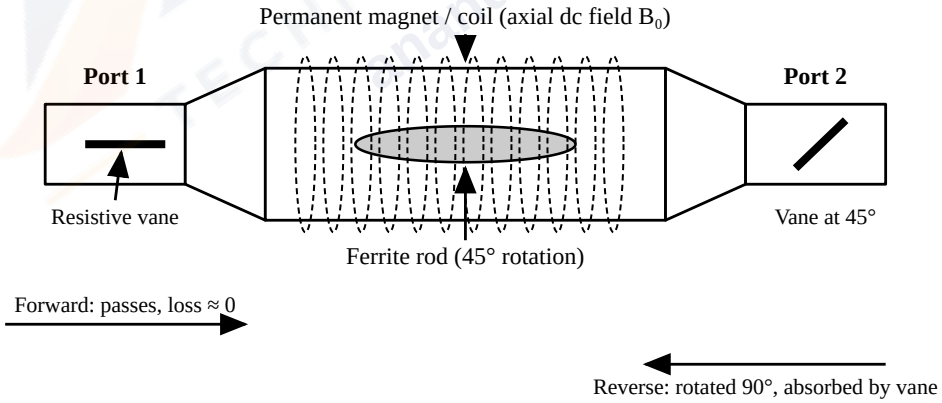
PPI (Plan Position Indicator): range and azimuth (map-like view)

Working principle: The PPI (Plan Position Indicator) is an intensity-modulated display. The electron beam sweeps **radially** from the centre (RADAR position) to the edge; the sweep starts with each transmitted pulse, so distance from the centre is proportional to **range**. The radial sweep line rotates in synchronism with the antenna, so its angle gives the **azimuth (bearing)**. Echoes brighten the trace (intensity modulation) and appear as bright spots. Thus the display is a polar map of the area around the RADAR showing range and bearing of all targets. Long-persistence phosphor (or digital memory) keeps targets visible between rotations; range rings and bearing lines help in reading.

Used in: search/surveillance RADAR, air-traffic control, ship navigation (marine) RADAR, weather RADAR.

(Sketch 1 M, working 2 M, uses 1 M)

d) Faraday-rotation isolator. 4 M



Faraday-rotation isolator

Construction: A rectangular guide (TE_{10}) is converted by a transition to a circular guide (TE_{11}) containing a pencil-shaped ferrite rod magnetised axially by a permanent magnet. The plane of polarisation is rotated by 45° in the ferrite (Faraday rotation). The output rectangular guide is

twisted by 45° with respect to the input. Resistive vanes are placed parallel to the broad walls at both ends.

Working: Forward: the TE_{10} wave entering port 1 has E perpendicular to the input vane, so it is not absorbed; the ferrite rotates it by 45°, so it matches the 45° output guide and leaves port 2 with very little loss. **Reverse:** a wave entering port 2 is rotated by a further 45° in the **same** sense (Faraday rotation is non-reciprocal), so it reaches the input with E rotated by 90°, i.e. parallel to the resistive vane, and is absorbed. Thus power passes only from port 1 to port 2.

Typical: insertion loss ≈ 1 dB, isolation 20 – 30 dB. Used to protect sources (klystron, magnetron) from reflected power.

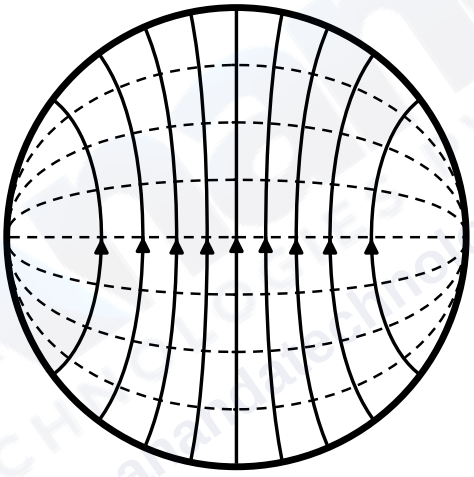
(Diagram 2 M, working 2 M)

Q.3

a) TE and TM modes; TE_{11} in circular waveguide; applications. 4 M

TE (transverse electric) mode: the electric field is entirely transverse to the direction of propagation ($E_z = 0$); a magnetic field component H_z exists along the direction of propagation.

TM (transverse magnetic) mode: the magnetic field is entirely transverse ($H_z = 0$); an electric field component E_z exists along the direction of propagation.



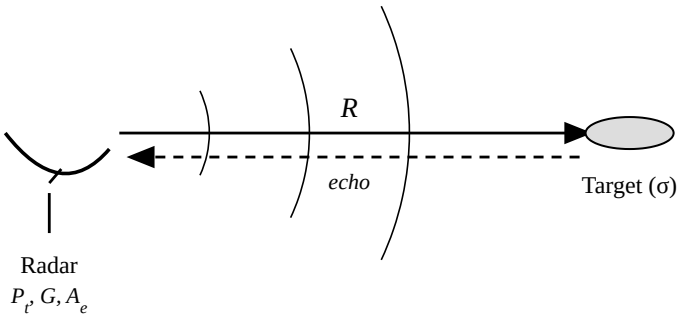
TE_{11} mode in circular waveguide (dominant mode): solid = E, dashed = H

TE_{11} is the dominant mode of circular waveguide: $f_c = 1.841\ c / (2\pi\ r)$ ($\lambda_c = 3.41\ r$).

Applications of circular waveguide: rotary joints of RADAR antennas (rotating feed), Faraday-rotation ferrite devices (isolator, gyrator), circular-polarisation feeds; low-loss long runs using TE_{01} mode.

(Definitions 1 M, sketch 2 M, applications 1 M)

b) Derivation of RADAR range equation. 4 M



Radar range equation — geometry

1. If P_t is radiated by an isotropic antenna, power density at distance R = $P_t/(4\pi R^2)$. With antenna gain G: $\mathbf{P_d = P_tG/(4\pi R^2)}$ W/m².
2. The target intercepts and re-radiates power equal to $P_d \times \sigma$ (σ = RADAR cross-section): reflected power = $P_tG\sigma/(4\pi R^2)$.
3. This power spreads uniformly back towards the RADAR; density at the RADAR = $P_tG\sigma/[(4\pi R^2)(4\pi R^2)]$.
4. Power received by an antenna of effective aperture A_e: $\mathbf{P_r = P_tGA_e\sigma/[(4\pi)^2R^4]}$.
5. Maximum range is reached when P_r falls to the minimum detectable signal S_{min}: $S_{min} = P_tGA_e\sigma/[(4\pi)^2R_{max}^4]$

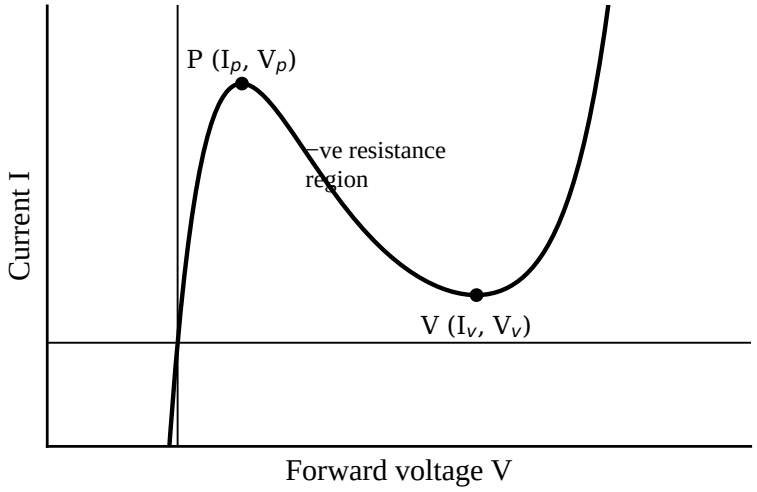
$$\therefore R_{max} = [\ P_t\ G\ A_e\ \sigma\ /\ ((4\pi)^2\ S_{min})\ ]^{1/4}$$

Using $G = 4\pi A_e/\lambda^2$ (same antenna for Tx and Rx): $R_{max} = [P_tA_e^2\sigma/(4\pi\lambda^2S_{min})]^{1/4} = [P_tG^2\lambda^2\sigma/((4\pi)^3S_{min})]^{1/4}$. Range is proportional to the fourth root of transmitted power.

(Steps 3 M, final equation 1 M)

c) Tunnel diode. 4 M

Symbol of tunnel diode



Tunnel diode V–I characteristic (computed model): negative resistance between peak and valley

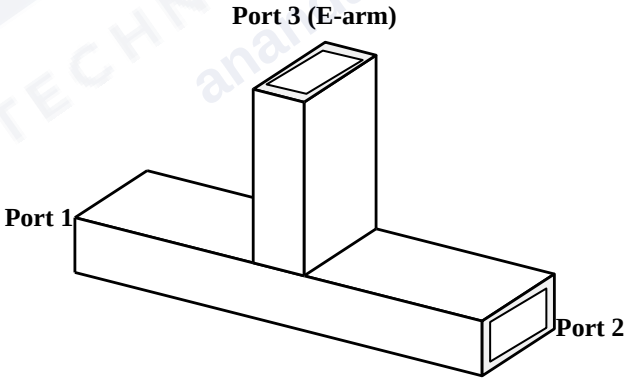
Working: A tunnel diode is a p-n junction with very heavy doping (≈ 10^{19}–10^{20} cm^{-3}) on both sides, so the depletion layer is extremely thin (≈ 10 nm). Electrons can then **tunnel** through the barrier (quantum-mechanical tunnelling) at almost the speed of light.

- Small forward bias: filled states on the n side face empty states on the p side → tunnelling current rises to the **peak current I_p** at V_p.
- Further increase in bias: the bands move out of alignment, tunnelling decreases → current falls to the **valley current I_v** at V_v. This region P–V is the **negative resistance region**.
- Beyond V_v: normal diode (injection) current flows and current rises again.

Applications: microwave oscillators and amplifiers (up to ~100 GHz), very fast switching / logic and pulse circuits, relaxation oscillators.

(Symbol & characteristic 1 M, working 2 M, applications 1 M)

d) E-plane tee. 4 M



E-plane tee (series tee)

An E-plane tee is formed by attaching a waveguide arm (port 3) to the **broad wall** of the main guide, so the arm axis is parallel to the E field of the main guide.

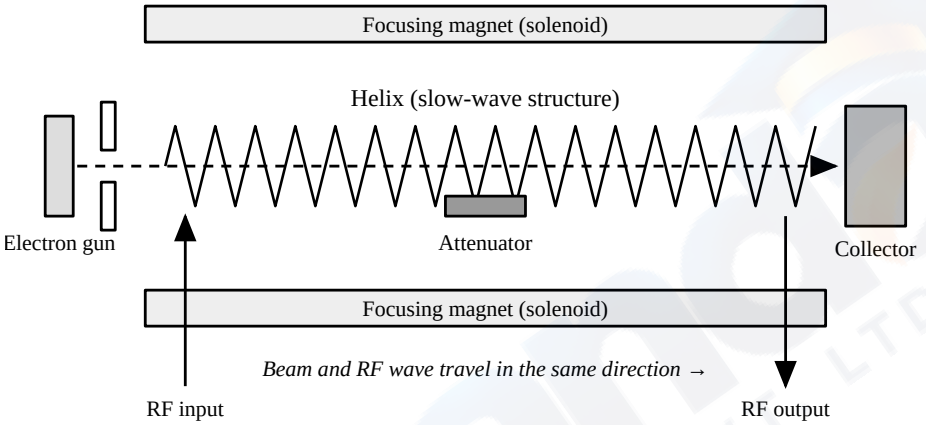
Why series tee: the E-arm interrupts the current flowing on the broad wall, so the arm is effectively in **series** with the main line; the voltages at ports 1 and 2 add/subtract as in a series junction.

Power fed at the E-arm (port 3): it divides equally between ports 1 and 2, but the two outputs are **180° out of phase** (equal magnitude, opposite phase). Conversely, if equal in-phase signals are fed at ports 1 and 2, they cancel at port 3 (no output); if they are out of phase, the outputs add at port 3.

(Sketch 1 M, series tee 1 M, behaviour 2 M)

Q.4

a) Helix travelling wave tube. 4 M



Helix travelling wave tube (TWT) — schematic

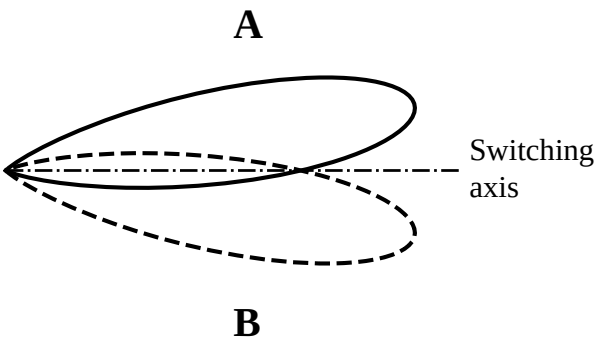
Construction: An electron gun produces a beam that travels along the axis of a long **helix** (slow-wave structure) to a collector. An axial magnetic field from a solenoid / periodic permanent magnet focuses the beam. RF input is coupled at the gun end and output at the collector end. A lossy attenuator near the middle prevents oscillations caused by reflections.

Working: The helix slows the axial phase velocity of the RF wave to about c × (pitch / circumference), i.e. close to the beam velocity (beam is made slightly faster). The axial E field of the wave velocity-modulates the electrons; they bunch in the retarding-field regions and, being slightly faster, they continuously give energy to the wave as both travel together. So the RF signal grows exponentially along the tube (continuous interaction, no resonant cavity).

Features: very wide bandwidth (octave), high gain (30–60 dB), low noise. Used in satellite transponders, RADAR and broadband amplifiers.

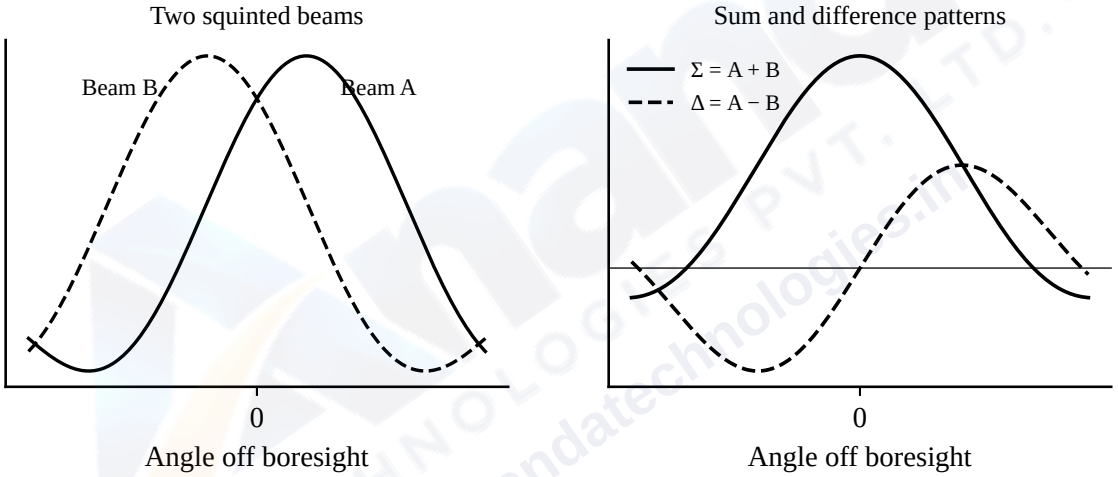
(Diagram 2 M, working 2 M)

b) Sequential lobing and monopulse tracking. 4 M



Sequential lobing: beam switched between two positions A and B

Sequential lobing (lobe switching): the antenna beam is switched alternately between two squinted positions A and B on either side of the switching axis. If the target is on the axis, echoes in both positions are equal. If it is off-axis, the echo in one position is stronger; the difference gives the magnitude and the sign gives the direction of the angular error, which drives the servo. Four positions (up/down/left/right) are used for both azimuth and elevation.

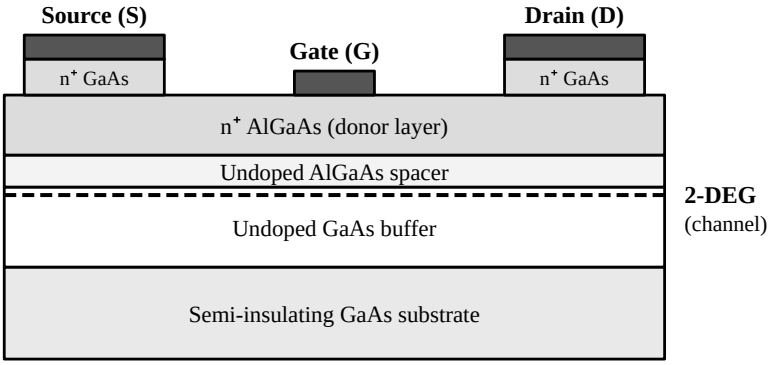


Amplitude-comparison monopulse: two simultaneous beams, sum (Σ) and difference (Δ) patterns (computed)

Monopulse tracking: four (or two per plane) feeds produce several squinted beams **simultaneously**. A comparator (hybrid junctions) forms the sum Σ = A + B and difference Δ = A − B signals from **a single pulse**. Δ/Σ gives the angle error (sign from phase); Σ is used for range and detection. Since the error is found from one pulse, amplitude fluctuations of the echo do not cause errors — high accuracy, used in precision tracking RADARs.

(Each method with sketch 2 M)

c) HEMT. 4 M



Schottky gate controls 2-DEG density → drain current

HEMT (AlGaAs/GaAs MODFET) — layer structure with 2-DEG channel

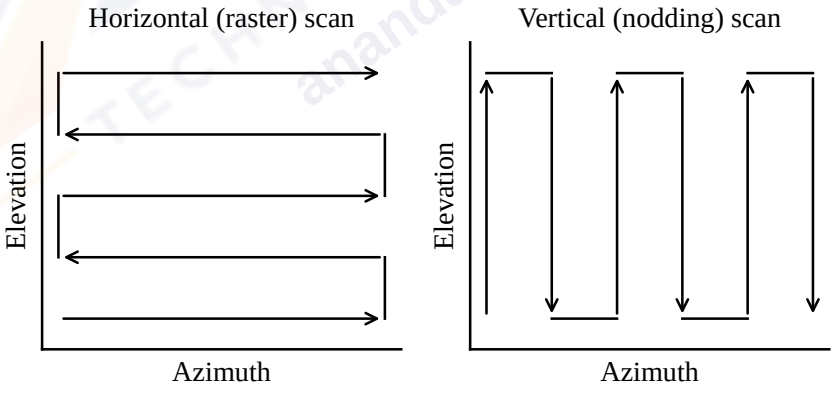
Construction: A HEMT (High Electron Mobility Transistor, MODFET) is a heterojunction FET. A heavily doped n^+ AlGaAs (wide band-gap) layer is grown over undoped GaAs (narrow band-gap), with a thin undoped AlGaAs spacer between them, on a semi-insulating substrate. Source and drain are ohmic contacts; the gate is a Schottky metal contact.

Working: Electrons from the donors in AlGaAs move into the lower-energy conduction band of the undoped GaAs and are confined in a very thin layer at the heterojunction — a **two-dimensional electron gas (2-DEG)**. As the channel is undoped, there is no impurity scattering and electron mobility is very high. The gate voltage changes the 2-DEG density and controls the drain current, as in a MESFET but much faster.

Applications: low-noise amplifiers in satellite receivers / DTH LNBs, radio astronomy, mobile base stations, mm-wave amplifiers and RADAR (up to 100+ GHz).

(Diagram 1 M, construction 1 M, working 1 M, applications 1 M)

d) Horizontal and vertical scanning. 4 M



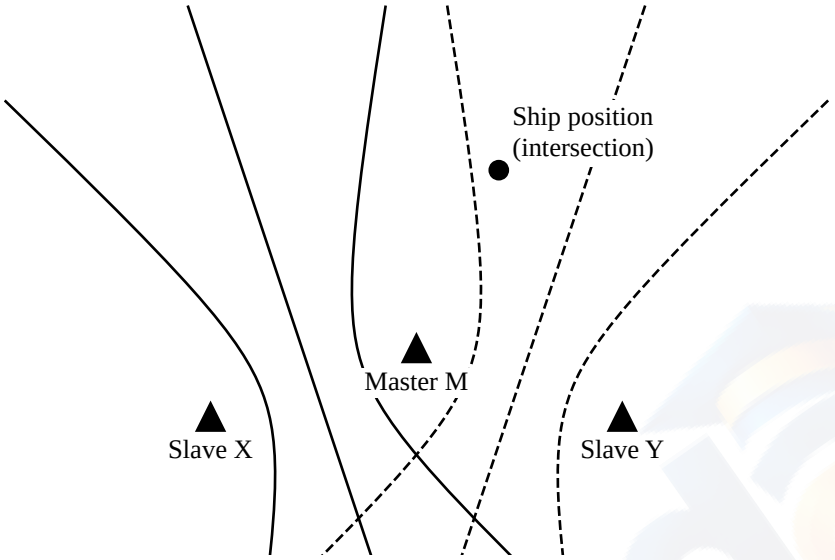
Radar antenna scanning patterns

Horizontal (raster) scanning: the antenna (pencil beam) is swept in azimuth over the required sector; at the end of each sweep the elevation is changed by one beamwidth and the beam sweeps back. The area is covered line by line like a TV raster. Used in fire-control / search RADARs covering a rectangular sector.

Vertical (nodding) scanning: the antenna nods up and down in elevation rapidly while it is slowly moved in azimuth. Used in height-finding RADARs, with the RHI display, to find the elevation (height) of aircraft in a sector.

(Each method with sketch 2 M)

e) LORAN. 4 M



LORAN: lines of constant time difference are hyperbolas; two pairs give a position fix

LORAN (LOng RAnge Navigation) is a **hyperbolic** navigation system. A **master** station and two or more **slave (secondary)** stations, several hundred km apart, transmit synchronised pulses (LORAN-C: 100 kHz).

- The ship/aircraft receiver measures the **time difference** between arrival of master and slave pulses.
- All points with a constant time difference (i.e. constant difference of distances) from two stations lie on a **hyperbola** (line of position).
- A second master–slave pair gives another hyperbola; the **intersection** of the two gives the position (fix), read from LORAN charts or computed.
- Range ≈ 1000–2000 km over sea (ground wave); accuracy of a few hundred metres.

(Sketch 2 M, explanation 2 M)

Q.5

a) Propagating modes in a = 4 cm, b = 2.5 cm guide at 10 GHz. 6 M

Given: a = 4 cm, b = 2.5 cm, air filled (v = c = 3×10^8 m/s), f = 10 GHz.

$$f_{c(mn)} = (c/2)\sqrt{[(m/a)^2 + (n/b)^2]}$$

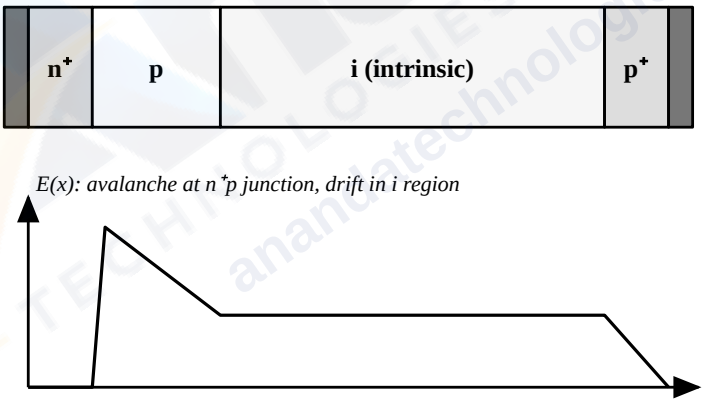
A mode propagates only if its cut-off frequency is **less than** the operating frequency. (TM_{m0} and TM_{0n} do not exist.)

m, n	Mode	f_c (GHz)	Propagates at 10 GHz?
1, 0	TE_{10}	3.750	**Yes**
0, 1	TE_{01}	6.000	**Yes**
1, 1	TE_{11} and TM_{11}	7.075	**Yes**
2, 0	TE_{20}	7.500	**Yes**
2, 1	TE_{21} and TM_{21}	9.605	**Yes**
3, 0	TE_{30}	11.250	No
0, 2	TE_{02}	12.000	No
1, 2	TE_{12} and TM_{12}	12.572	No
3, 1	TE_{31} and TM_{31}	12.750	No
2, 2	TE_{22} and TM_{22}	14.151	No
4, 0	TE_{40}	15.000	No

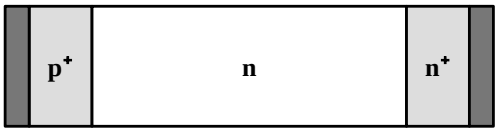
Modes that propagate at 10 GHz: TE_{10}, TE_{01}, TE_{11} and TM_{11}, TE_{20}, TE_{21} and TM_{21}. The dominant mode is TE_{10} (lowest cut-off).

(Formula 1 M, cut-off calculations 4 M, conclusion 1 M)

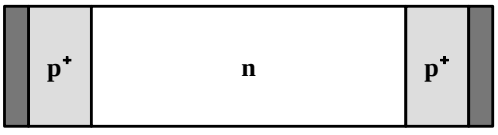
b) IMPATT, TRAPATT and BARITT comparison with structures. 6 M



IMPATT (Read) diode $n^+ p\ i\ p^+$ structure and electric-field profile



TRAPATT diode $p^+ n\ n^+$ structure

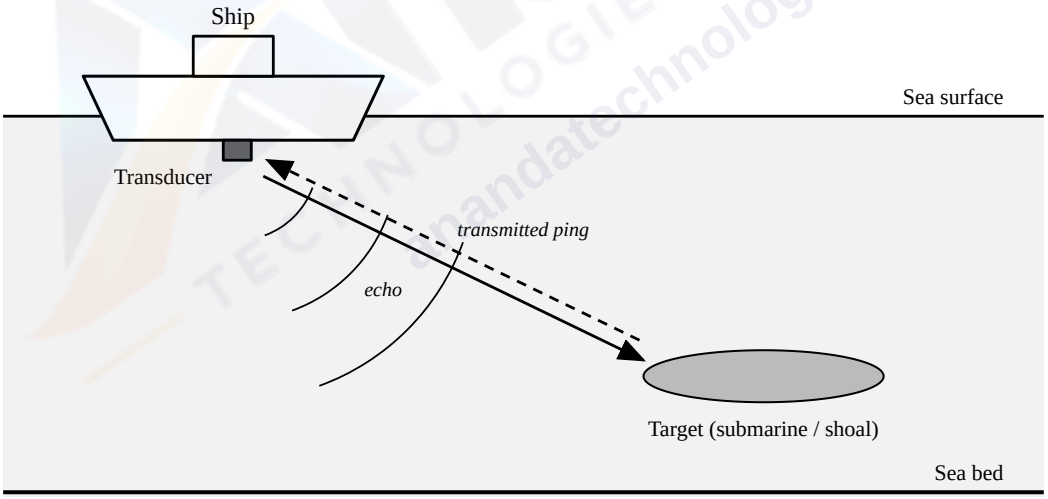


BARITT diode $p^+ n\ p^+$ structure (punch-through)

Parameter	IMPATT	TRAPATT	BARITT
Full form	IMPact ionisation Avalanche Transit-Time	TRApped Plasma Avalanche Triggered Transit	BARrier Injection Transit-Time
Structure	n^+ p i p^+ (Read) / p^+ n n^+	p^+ n n^+ (or n^+ p p^+)	p^+ n p^+ / metal–semiconductor–metal
Principle	Avalanche multiplication + transit-time delay → 180° phase shift (negative resistance)	Trapped electron–hole plasma formed by avalanche shock front, then extracted	Minority carrier injection over forward-biased junction (punch-through) + transit time
Operating frequency	0.5 – 100 GHz	1 – 10 GHz	4 – 8 GHz
Output power	High CW (up to ~ 10 W at X-band)	Very high pulsed power (hundreds of W)	Low (mW)
Efficiency	5 – 15 %	20 – 60 %	2 – 5 %
Noise	High (avalanche noise)	High	Low
Applications	Microwave oscillators, RADAR transmitters, intrusion alarms	Pulsed RADAR transmitters, phased-array RADAR, altimeters	Local oscillators, low-noise mixers, Doppler detectors

(Sketches 1½ M, six points 4½ M)

c) SONAR — principle, types, applications. 6 M



SONAR: transducer sends sound pulse; echo from target measured (R = v t / 2)

Principle: SONAR (SOund NAvigation And Ranging) works on the **echo principle**. A transducer sends a short pulse of sound/ultrasonic energy into the water. The pulse is reflected by an object and the echo is received. The time t between transmission and reception gives the distance: **R = v t / 2**, where v ≈ 1500 m/s is the speed of sound in sea water. Direction is found from the transducer beam direction and the target speed from the Doppler shift. Sound is used because EM waves are rapidly absorbed in sea water.

Types:

- **Active SONAR:** transmits its own sound pulse (ping) and listens for echoes — gives range and bearing; but reveals its own position.
- **Passive SONAR:** only listens to sound radiated by targets (engines, propellers) using hydrophone arrays — gives bearing and classification; it is silent and cannot be detected.

Applications: (1) submarine and mine detection by navy, (2) echo sounding — depth of sea and sea-bed mapping, (3) fish finding, (4) underwater navigation, search & rescue and locating ship wrecks.

(Diagram 2 M, principle 2 M, types 1 M, applications 1 M)

Q.6

a) RADAR range, unambiguous range, duty cycle, average power. 6 M

i) Maximum range

Given: $P_t = 4 \times 10^5$ W, G = 1800, $A_e = 2.5$ m², $\sigma = 8$ m², $S_{min} = 5.00 \times 10^{-13}$ W.

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

Numerator = $4 \times 10^5 \times 1800 \times 2.5 \times 8 = 1.440 \times 10^{10}$

Denominator = $(4\pi)^2 \times 5.00 \times 10^{-13} = 157.91 \times 5.00 \times 10^{-13} = 7.896 \times 10^{-11}$

$R_{max} = (1.824 \times 10^{20})^{1/4} = 1.1621 \times 10^5$ m ≈ **116.21 km**

ii) Maximum unambiguous range $R_{un} = c/(2\ PRF) = 3 \times 10^8/(2 \times 800)$ = **187.5 km**

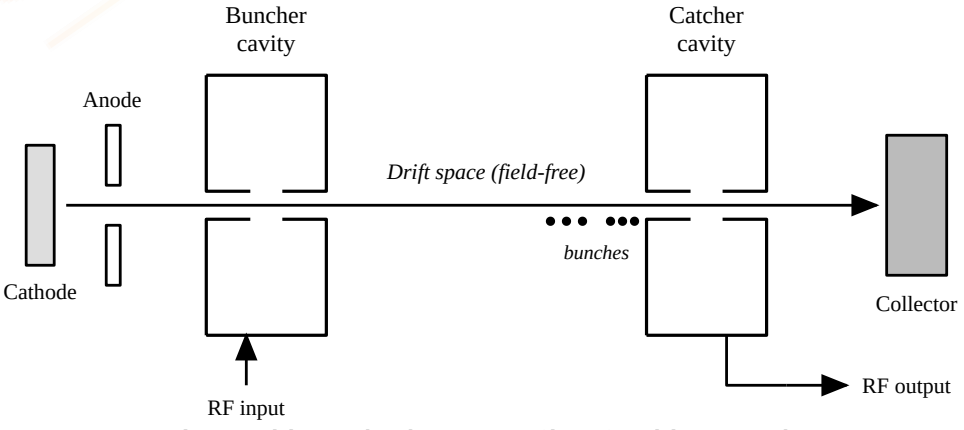
Duty cycle = $\tau \times PRF = 1.5 \times 10^{-6} \times 800$ = **0.0012**

Average power $P_{av} = P_t \times$ duty cycle = 400000 × 0.0012 = **480 W**

Since R_{max} (116.2 km) < R_{un} (187.5 km), all detectable targets are displayed without range ambiguity.

(R_{max} 3 M, R_{un} 1 M, duty cycle 1 M, average power 1 M)

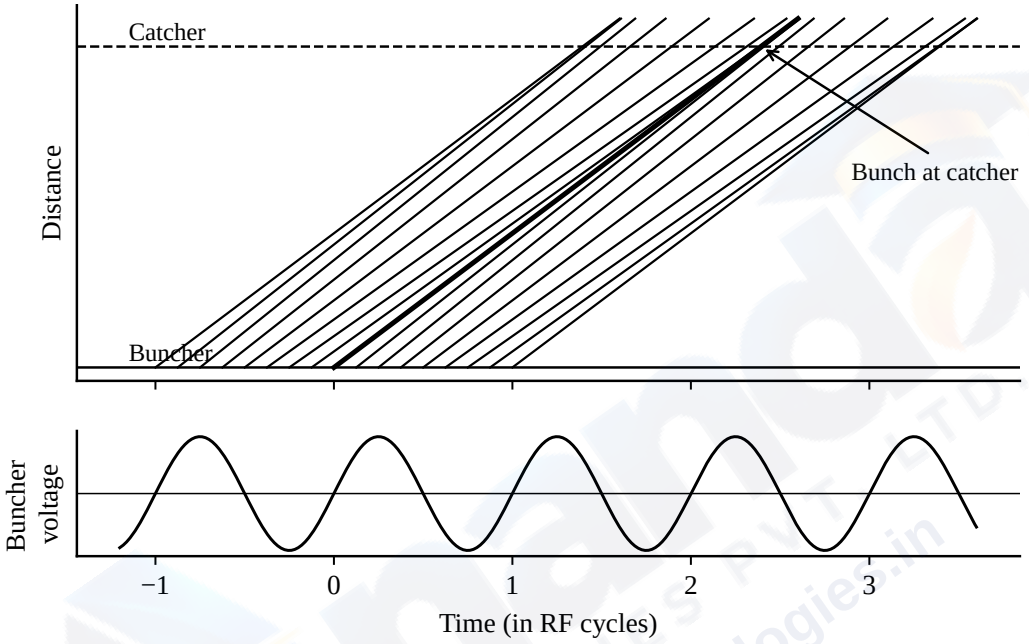
b) Two-cavity klystron with Applegate diagram. 6 M



Two-cavity klystron amplifier — schematic

Construction: An electron gun (cathode, focusing electrode, anode) produces a high-velocity beam which passes through the grids of two re-entrant cavities — the **buncher** (input) and the **catcher** (output) — separated by a field-free **drift space**, and is finally collected by the collector.

Bunching process: The RF input produces an alternating voltage $V_1 \sin \omega t$ across the buncher gap. Electrons crossing the gap during the positive half-cycle are accelerated, those in the negative half-cycle are retarded, and those at zero crossing pass with unchanged velocity v_0 (**velocity modulation**). In the drift space the faster electrons catch up with the slower electrons that left earlier, so electrons gather into **bunches** around the electron that crossed when the voltage changed from retarding to accelerating. Velocity modulation is thus converted into **current (density) modulation**.



Applegate diagram of two-cavity klystron (computed)

The Applegate diagram (distance vs time) shows the lines of faster electrons (steeper) converging with slower ones at the catcher. The catcher is placed where bunching is maximum; the bunches induce a large RF current in the catcher cavity and give energy to the RF field, which is taken out as amplified output.

Applications: high-power amplifiers in UHF TV transmitters, RADAR transmitters, satellite uplinks, particle accelerators.

(Diagram 2 M, bunching 2 M, Applegate 1 M, applications 1 M)

c) Pulse vs CW Doppler vs MTI RADAR. 6 M

Parameter	Pulse RADAR	CW Doppler RADAR	MTI RADAR
Principle	Echo time delay of short pulses	Doppler shift of continuous wave	Pulse RADAR + Doppler phase change between successive pulses
Transmitted signal	High-power pulses (low duty cycle)	Continuous unmodulated wave	Coherent pulses (STALO + COHO)
Range measurement	Yes (R = ct/2)	No	Yes
Velocity measurement	No (not directly)	Yes ($f_d = 2v_r/\lambda$)	Detects moving targets; velocity only coarsely
Fixed targets / clutter	Displayed together with moving targets	Rejected (zero Doppler)	Rejected by delay-line canceller
Antenna	One antenna + duplexer	Usually two antennas	One antenna + duplexer
Complexity	Moderate	Simple	Complex (stable oscillators, canceller)
Applications	Surveillance, navigation, weather	Speed guns, proximity fuzes	ATC and air-defence RADAR in clutter

(Any six points, 1 M each)

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