B.Sc (HONS.) IN ECE PART FOURTH, SEVENTH SEMESTER EXAMINATION, 2022
MICROWAVE ENGINEERING
Subject Code: ECE-401
Examination Code: 5627
Time—3 hours
Full marks—80

[N.B: The figures in the right margin indicate full marks. Answer any five of the following questions.]

A microwave system is an arrangement of components used to generate, transmit, guide, receive, and process electromagnetic waves in the frequency range 300 MHz to 300 GHz. These are mainly used in communication, radar, remote sensing, and satellite systems.

Basic Microwave System Components:

1. **Microwave Source** (e.g., Klystron, Magnetron, Gunn diode, TWT)
2. **Transmission Medium** (Waveguide, Coaxial cable, Microstrip line)
3. **Microwave Components** (Isolator, Circulator, Directional coupler, Filters)
4. **Antenna** (to radiate or receive microwaves)
5. **Receiver/Detector** (e.g., Schottky diode, mixer)
6. **Output device** (oscilloscope, spectrum analyzer, communication receiver)

Diagram (must draw in exam):
[Block diagram: Source → Transmission line → Components → Antenna → Receiver]

(b) Define Noise Figure and Noise Factor. (5 marks)

Answer:

- **Noise Factor (F):**
  The ratio of the input SNR (Signal-to-Noise Ratio) to the output SNR of a device or system.

$$F = \frac{(SNR)_{in}}{(SNR)_{out}}$$

- **Noise Figure (NF):**
  It is the noise factor expressed in decibels (dB).

$$NF = 10 \log_{10} F \text{ (dB)}$$

- **Interpretation:**
  A lower NF means the device adds less noise → better performance.

(c) Describe some sources of microwave briefly. (5 marks)

Answer:
Microwaves can be generated by the following sources:

1. **Klystron:** Uses velocity modulation of electron beam → amplification of microwave signals.
2. **Magnetron:** Oscillator that generates high-power microwaves using crossed electric and magnetic fields.
3. **Traveling Wave Tube (TWT):** Wideband amplifier, uses interaction between electron beam and RF signal in helix.
4. **Gunn Diode:** Negative resistance device used as oscillator at microwave frequencies.
5. **IMPATT Diode:** Avalanche transit-time diode, used as high-power microwave generator.

(a) What is a transmission line? Draw a proper elementary section. (6 marks)

Answer:

- A **transmission line** is a specialized structure that carries high-frequency signals (RF/microwave) with minimum distortion and power loss.
- Examples: coaxial cable, waveguide, microstrip line.
- They are defined by distributed parameters: Resistance (R), Inductance (L), Capacitance (C), Conductance (G).

Elementary section diagram:

A small length Δz → represented by series RΔz, LΔz and shunt GΔz, CΔz.

(b) Explain reflection and transmission coefficients. (6 marks)

Answer:

- When a wave reaches a discontinuity (e.g., change in impedance), part of it is reflected and part is transmitted.

1. **Reflection Coefficient (Γ):**

$$\Gamma = \frac{V_{ref}}{V_{inc}} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Where Z_L = load impedance, Z_0 = characteristic impedance.

2. **Transmission Coefficient (T):**

$$T = \frac{V_{trans}}{V_{inc}} = 1 + \Gamma = \frac{2Z_L}{Z_L + Z_0}$$

- |Γ| = 0 → perfect matching (no reflection).
- |Γ| = 1 → total reflection.

(c) Numerical Problem (8 marks)

Given:

$$R = 2\,\Omega/m, \quad G = 0.5\,mmho/m = 0.0005\,S/m$$

$$f = 1\,GHz, \quad L = 8\,nH/m = 8 \times 10^{-9}, \quad C = 0.23\,pF/m = 0.23 \times 10^{-12}$$

(i) Characteristic Impedance:

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

(ii) Propagation Constant:

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

(a) Define standing wave and travelling wave. (4)

Temporary Chat

- **Travelling wave:** A wave that carries energy in one direction with a fixed phase velocity; voltage/current vary as $V(z) = V_0^+ e^{-j\beta z}$, $I(z) = \frac{V_0^+}{Z_0} e^{-j\beta z}$.
- **Standing wave:** Formed by superposition of incident and reflected waves on a mismatched line; nodes/antinodes are stationary.
  $V(z) = V_0^+ e^{-j\beta z} + V_0^- e^{+j\beta z}$.

(b) Explain standing wave and SWR. (4)

- Reflection at load produces $\Gamma = \dfrac{Z_L - Z_0}{Z_L + Z_0} = \dfrac{V_0^-}{V_0^+}$.
- Voltage envelope: $|V(z)| = |V_0^+|\,|1 + \Gamma e^{2j\beta z}|$ → maxima/minima repeat every $\lambda/2$.
- **SWR (VSWR):**
  $$\mathrm{SWR} = \frac{V_{\max}}{V_{\min}} = \frac{1+|\Gamma|}{1-|\Gamma|} \geq 1.$$
  SWR = 1 (perfect match), →∞ (open/short).

(c) Derive the wave equation in a rectangular waveguide. (6)

- Source-free region, time factor $e^{j\omega t}$:
  $\nabla \times \mathbf{E} = -j\omega\mu\mathbf{H}, \quad \nabla \times \mathbf{H} = j\omega\varepsilon\mathbf{E}$.
- Each field component satisfies Helmholtz:
  $\nabla^2\psi + k_0^2\psi = 0$ with $k_0 = \omega\sqrt{\mu\varepsilon}$.
- Assume propagation along z: $\psi(x,y,z) = \psi(x,y)\, e^{-j\beta z}$ →
  $\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + k_c^2\right)\psi(x,y) = 0$
  where $k_c^2 = k_0^2 - \beta^2$.
- For a rectangular guide $a \times b$ with PEC walls:
  $$k_c^2 = \left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2, \quad m, n = 0, 1, 2, \ldots$$
- Propagation constant: $\beta = \sqrt{k_0^2 - k_c^2}$.
  Cutoff frequency: $f_{c,mn} = \frac{c}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$.
  (For dominant TE_{10}: $f_c = c/2a$.)

Q4

(a) What is a waveguide? Types. (2)

- **Waveguide:** A hollow conducting (or dielectric) structure guiding EM waves by reflection; supports TE/TM (no TEM in hollow guides).
- **Types:** Rectangular, circular, elliptical, ridged, dielectric rod, SIW (substrate integrated), flexible/bends.

(b) Derive V_p and λ in a rectangular waveguide. (8)

- From §Q3(c): $\beta = \sqrt{k_0^2 - k_c^2}$, $k_0 = 2\pi/\lambda_0$.
- **Guide wavelength:**

$$\lambda_g = \frac{2\pi}{\beta} = \frac{\lambda_0}{\sqrt{1-(f_c/f)^2}}$$

- **Phase velocity:**

$$V_p = \frac{\omega}{\beta} = \frac{c}{\sqrt{1-(f_c/f)^2}} \; (> c)$$

- (For completeness) **Group velocity:** $V_g = c\sqrt{1-(f_c/f)^2}$ and $V_pV_g = c^2$.
- For a rectangular guide, insert $f_c = f_{c,mn}$ of the operating mode (often TE_{10}).

(c) Specialties of microwave components + examples. (4)

- **Specialties/Peculiarities:** Distributed effects dominate (RLC are *distributed*); parasitics matter; devices often non-reciprocal (ferrite); measurements use S-parameters; waveguides/coaxes instead of lumped wiring; impedance matching critical; power handling and Q are high.
- **Examples:** Attenuator, isolator, circulator, directional coupler, power divider/3-dB hybrid, phase shifter, filter/iris, cavity resonator, bends/twists, mixers, detectors.

(d) Directional coupler & coupling factor derivation. (6)

- **Directional coupler:** Four-port passive network that samples a defined fraction of forward (or reverse) power with isolation to the other direction.
- **Ideal lossless matched coupler S-matrix (one form):**

$$\begin{bmatrix} 0 & \tau & j\kappa & 0 \\ \tau & 0 & 0 & j\kappa \\ j\kappa & 0 & 0 & \tau \\ 0 & j\kappa & \tau & 0 \end{bmatrix}, \quad |\tau|^2 + |\kappa|^2 = 1$$

Port-1 input → through at Port-2 ($|\tau|^2$) and coupled at Port-3 ($|\kappa|^2$); Port-4 ideally isolated.

- **Coupling factor (in dB):**

$$C = 10\log_{10}\left(\frac{P_1}{P_3}\right) = -10\log_{10}\left(\frac{P_3}{P_1}\right) = -10\log_{10}(|\kappa|^2) = -20\log_{10}|\kappa|$$

- Directivity: $D = 10\log_{10}\left(\frac{P_3}{P_4}\right)$.

Insertion loss: $L_i = 10\log_{10}(P_1/P_2)$.

Sketch: show 4-port with arrows.

Q5

(a) Schottky barrier diode: construction & characteristics. (6)

- **Construction:** Metal–semiconductor junction (e.g., Au–n-GaAs, Al–n-Si). No p-n junction; **majority-carrier device**. Barrier height ϕ_B set by metal/semiconductor work functions; thin depletion on n-side.
- **I–V (thermionic emission):**

$$I = I_s\left(e^{\frac{qV}{nkT}} - 1\right), \quad I_s = AA^*T^2e^{-q\phi_B/kT}$$

(small $n \approx 1.05$–1.2).

- **Features:** Very low forward voltage (~0.2–0.4 V), **fast switching** (no charge storage), **low junction capacitance**, low noise, used as **detectors/mixers** up to mm-wave.
- **Reverse:** exhibits small leakage; breakdown by field emission at high reverse bias.

(b) TWT – construction and working. (5)

- **Definition:** Traveling-Wave Tube—wideband microwave amplifier where an **electron beam** continuously interacts with a **slow-wave structure** (usually a helix).
- **Construction:** Electron gun → focusing magnet → helix with RF input/output couplers → sever/attenuator (prevents oscillation) → collector.
- **Operation:**
  - RF input on helix travels at ≈ beam velocity (phase synchronism).
  - Beam is **velocity-modulated** → forms bunches → transfers kinetic energy to the RF wave along the helix.
  - Continuous interaction gives **large gain** (20–60 dB) and **wide bandwidth** (octave+).
  - Power: 10 W to multi-kW; efficiency 20–40%.
- **Types:** Helix TWT (wideband, low–med power) and **coupled-cavity TWT** (higher power, narrower band).

(c) Reflex klystron – operation. (5)

- **One-cavity oscillator** using **bunching** between cavity gap and **repeller electrode**.
- Electron gun → cavity gap → drift to repeller (negative potential) → turn back → cross the gap again.
- First crossing causes **velocity modulation**; in the drift space electrons bunch; on return they deliver RF power back to the cavity.
- **Bunching (Applegate diagram):** Choose repeller voltage V_r so transit-time $t_t \approx \left(\frac{3\pi}{2} + 2\pi n\right)/\omega$ for optimum negative conductance.
- **Features:** Simple, tunable (by V_r and cavity), output 10 mW–few W, efficiency 10–20%, used as local oscillators and generators.

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(a) Microstrip line with diagram. (4)

- **Structure:** Conductor strip of width w on dielectric substrate (ε_r) of thickness h, backed by ground plane; metallization thickness t.
- **Fields:** Quasi-TEM (partly in dielectric, partly in air).
- **Uses:** PCB-compatible transmission lines for RF/microwave ICs—filters, couplers, antennas.
- **Sketch:** (i) top view of strip, (ii) cross-section showing w, h, t, ε_r.

(b) Characteristic impedance of microstrip—brief. (4)

- **Define effective dielectric constant** ε_{eff} (because fields are split air/dielectric). A common closed-form (Hammerstad):

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\frac{1}{\sqrt{1 + 12\,h/w}} + 0.04\,(1 - w/h)^2\right]$$

- **Thin conductor formulas** (good for most designs):

For $w/h \le 1$:

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{\text{eff}}}} \ln\left(\frac{8h}{w} + \frac{w}{4h}\right)$$

For $w/h \ge 1$:

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{\text{eff}}}\,(w/h + 1.393 + 0.667\ln(w/h + 1.444))}$$

- (Finite thickness t slightly increases effective width $w_{\text{eff}} = w + \Delta w$ and reduces Z_0.)

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(c) Numerical: $\varepsilon_r = 5.23,\ h = 7\,\text{mils},\ t = 2.8\,\text{mils},\ w = 10\,\text{mils}.$

Find Z_0. (3)

- $w/h = 10/7 = 1.428 \Rightarrow$ use $w/h \ge 1$ form.
- Ignoring thickness (common in quick calc):

$$\varepsilon_{\text{eff}} \approx 3.82, \quad Z_0 \approx \frac{120\pi}{\sqrt{3.82}\,[1.428 + 1.393 + 0.667\ln(1.428 + 1.444)]} \approx \boxed{55\,\Omega\ (\text{approx})}$$

- (If a thickness correction for t/h is applied, Z_0 drops to ≈ 46 Ω. Unless thickness is explicitly required, ~55 Ω is the expected answer.)

(d) Gunn diode: construction & operation. (6)

- **Material:** n-type GaAs (or InP) with two-valley conduction band.
- **Construction:** n^+–n–n^+ bar with ohmic contacts; length ≈ few to hundreds of µm.
- **Principle (Transferred-Electron Effect):** Above threshold field E_{th} (~3 kV/cm for GaAs), electrons transfer to the upper valley (higher mass, lower mobility) → **negative differential resistance region.**
- **Domain formation:** Small inhomogeneity grows into a high-field **Gunn domain** that drifts from cathode to anode with velocity v_d. When it reaches the anode it collapses and a new domain forms—producing **microwave oscillations.**
- **Frequency:** $f \approx v_d/L$ (transit-time mode).

Modes: Transit-time, delayed-domain, quenched-domain, LSA (limited space-charge accumulation).

(a) Varactor diode

- p–n junction used as voltage-variable capacitor; reverse-biased so $C_j(V) = C_0(1 + V/V_b)^{-m}$ (abrupt $m = \frac{1}{2}$, hyperabrupt $m > 0.5$).
- High Q at RF; used in tuned VCOs, parametric amplifiers, frequency multipliers; symbol like diode + capacitor.

(b) Magnetron

- High-power microwave oscillator using crossed E and B fields in a cylindrical cavity anode with central cathode.
- Electrons form spokes; bunching excites π-mode of cavities; strapping enforces mode.
- Efficiencies 50–80%, pulsed MW power in kW–MW range; used in radar and microwave ovens (2.45 GHz).

(c) IMPATT diode

- Impact-ionization Avalanche Transit-Time diode. Reverse-biased p^+–n–n^+ (or p^+–p–n^+).
- Avalanche region introduces ~90° delay; carrier transit adds another ~90° → net 180° current–voltage phase shift → negative resistance at microwave f.
- High power (W–tens of W) but noisy; used in oscillators and some amplifiers (e.g., 10–100 GHz).

(d) Attenuation factor

- In a line/waveguide with propagation constant $\gamma = \alpha + j\beta$, attenuation constant α (Np/m or dB 7 quantifies amplitude decay: $e^{-\alpha z}$.
- For low-loss line:

$$\alpha \approx \frac{R}{2Z_0} + \frac{GZ_0}{2} \quad (\mathrm{Np/m})$$

Waveguides additionally have conductor and dielectric losses; specify insertion loss $A = 10\log_{10}(P_{in}/P_{out})$.

(e) Smith chart

- Polar plot of Γ-plane used to solve matching problems.
- Constant-R and constant-X circles map normalized impedance $z = r + jx$ and admittance $y = g + jb$.
- Read off SWR, $|\Gamma|$, Z_L, matching with stubs/sections; rotation corresponds to movement along line by $\lambda_g/2\pi\Delta\theta$.

(f) Microwave mixer

- Nonlinear device (diode/FET) that multiplies RF and LO → outputs sum/difference frequencies; IF = $|f_{RF} - f_{LO}|$.
- Key specs: conversion loss, noise figure, port isolation, IP3 (linearity).
- Schottky diode ring mixers are passive, wideband; active FET mixers can provide conversion gain.