EE3-18
EE9-AO12

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2014-15

MSc and EEE PART III/IV: MEng, BEng and ACGI

MICROWAVE TECHNOLOGY

Corrected Copy

Thursday, 11 December 9:00 am

Time allowed: 3:00 hours

There are SIX questions on this paper.

Answer FOUR questions.

All questions carry equal marks

Any special instructions for invigilators and information for candidates are on page 1.

Examiners responsible First Marker(s) : S. Lucyszyn
Second Marker(s) : O. Sydoruk

Special instructions for invigilators

This is a closed book examination.

Special instructions for students

Permeability of free space, $\mu_o = 4\pi \times 10^{-7}\ [H/m]$

Permittivity of free space, $\varepsilon_o \approx 8.854\ [pF/m]$

The Questions

1.

a) The constitutive terms for a material can be represented as a quad chart:

i) Draw the quad chart, clearly labelling the axes and the regions in terms of the constitutive terms being greater and less than zero.

[2]

ii) In each quadrant, indicate if the refractive index in real or imaginary and positive or negative.

[2]

iii) In each quadrant, indicate if the electromagnetic wave within the material is evanescent or propagating. With the latter, in which direction.

[2]

iv) In each quadrant, indicate the type of material that best represents that quadrant.

[2]

b) If a material has permittivity and permeability values of minus unity, draw a ray tracing diagram that illustrates how a perfect lens can be made.

[2]

c) Give one example of how a unit cell can be constructed that result in negative permittivity and permeability values. Sketch the typical resonant frequency response for each element within the cell and comment on their size.

[4]

d) From first principles, and assuming Drude modelling to represent frequency dispersion, derive a simple expression that shows how a non-magnetic metal has a negative permittivity below its plasma frequency. Given a bulk conductivity at DC of 4.1×10^7 S/m and phenomenological scattering relaxation time of 27.135 fs, calculate the plasma frequency for gold. From its constitutive terms, at microwave frequencies, can gold be considered as a metamaterial?

[6]

2. A 10 kΩ.cm high resistivity silicon (HRS) wafer has a measured dielectric constant of 11.64 and loss tangent of 1×10^{-4} at 100 GHz.

a) Calculate the bulk effective conductivity and quality factor of the wafer.

[5]

b) Using the result from (a), how does the real part of conductivity differ from the original value quoted for the high resistivity silicon?

[3]

c) When a plane electromagnetic wave in free space has normal incidence to the HRS, determine a simple expression for the voltage wave reflection coefficient and from this calculate the reflectivity. *Hint: state any simplifying assumption made for the dielectric property of the HRS.*

[5]

d) If the HRS is heavily doped, such that its surface layer behaves like a good conductor, determine an expression for reflectivity, in terms of surface resistance and intrinsic impedance of free space, given that a plane wave in free space has normal incidence. *Hint: the total magnetic field has both forward and backward travelling waves, represented by the following expression:*

$$H(z) = H(0)e^{-\gamma z} + H(0)e^{+\gamma z} \qquad (2.1)$$

All variables have their usual meaning.

[5]

e) Calculate the reflectivity in (d), given a surface impedance of 0.5 Ω.

[2]

3.

a) Very briefly:

i) Explain why electromagnetic cavity resonators are preferred when compared to lumped-element resonators.

[2]

ii) Explain why spherical cavity resonators are preferred when compared to either rectangular or cylindrical.

[2]

iii) Give at least three examples of where lossy resonances can be found.

[2]

iv) State the use and limitation of perturbation techniques.

[2]

b) Given an air-filled spherical cavity resonator with radius R_a and perfect electrical conducting wall:

i) State the exact dominant mode for this cavity resonator and the associated non-zero field components.

[2]

ii) With the use of a simple sketch that shows the boundary conditions for the electric field distribution, derive a very approximate expression for the ideal resonance frequency for the dominant mode.

[2]

iii) With a 300 μm diameter sphere, calculate the approximate ideal resonance frequency for the dominant mode.

[2]

c) If the conducting wall is made using a real conductor that has loss:

i) Define the eigenfrequency in terms of its damped (or undriven) resonance frequency, napier frequency and undamped (or driven) resonance frequency.

[2]

ii) Give expressions for the unloaded quality factor at the damped and undamped resonance frequencies. In addition, derive an expression that relates both quality factors to each other.

[2]

iii) Sketch the unloaded quality factors at the damped and undamped resonance frequencies of an infinitely thick cavity resonator, as the conductivity decreases from infinity (giving a perfect electrical conducting wall) to zero (giving free space).

[2]

4. You have been given a quartz crystal sphere, having a radius of $R_a = 150\ \mu\text{m}$ and dielectric constant of $\varepsilon_r = 3.8$.

a) If the sphere is plated with a perfect electrical conductor (PEC), the wavenumber β_{I} is given by the following:

$$\beta_{\mathrm{I}} R_a = 2.74370$$

Calculate the ideal resonance frequency f_{I} for the resonator.

[3]

b) Calculate the geometrical factor Γ for a spherical cavity, given the following:

$$\Gamma = \frac{\mu_0}{\xi}\left(\frac{V}{S}\right); \quad \xi \cong 0.90790$$

where V is the internal cavity volume and S is the inner surface area of the wall.

[3]

c) If the PEC is replaced by a real metal having loss, the undamped resonance frequency ω_0 can be found using perturbation theory, by solving the following:

$$X_o(\omega_0) - 2(\omega_{\mathrm{I}} - \omega_0)\Gamma = 0$$

Where $X_o(\omega_0)$ is the classical skin-effect model surface reactance and the other variable have their usual meaning. If the infinitely thick lossy metal wall results in 10% detuning, calculate:

i) The undamped resonance frequency and classical skin-effect model surface reactance.

[3]

ii) The conductivity of the wall material. What material could the wall be made from?

[3]

iii) The unloaded quality factor at the undamped resonance frequency using the extended perturbation theory.

[3]

iv) The complex eigenfrequency.

[3]

v) The unloaded quality factor at the damped resonance frequency.

[2]

5. A simple low frequency microwave FET amplifier can be realised by employing conventional microstrip transmission lines for its interconnects, impedance matching and biasing networks.

a) Describe the main problem with conventional microstrip circuits when trying to ground the source connection of a FET. Give two examples of catastrophic circuit failure. Also, state how a conventional microstrip circuit can be modified to reduce this problem.

[3]

b) Compare and contrast the manufacture of TFMS with conventional microstrip. Use suitable illustrations, showing variables for the main cross-sectional dimensions.

[4]

c) Write simple equations, to a first-order approximation, to justify each of the following claims:

i) The characteristic impedances of a TFMS and conventional microstrip line can be made equal.

[3]

ii) Losses in a TFMS are higher than in a corresponding conventional microstrip line.

[4]

d) Figure 5.1 shows the photograph of a MMIC amplifier, employing TFMS transmission lines. By inspection, draw the equivalent circuit model of this amplifier and state the role of the two longest TFMS transmission lines. What kind of amplifier topology is this?

[6]

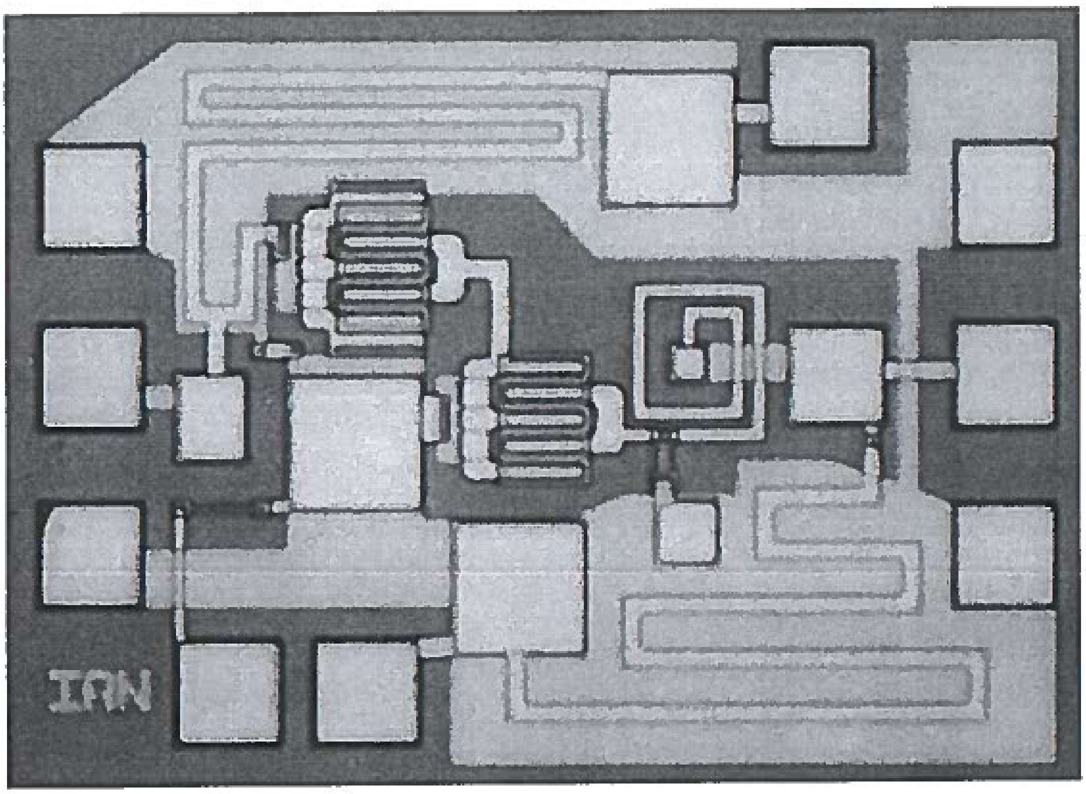

Figure 5.1

6.

a) With conventional ground-penetrating radars (GPRs):

i) With the aid of a diagram, describe the principle of operation.

[5]

ii) Briefly discuss the main problems associated with soil composition.

[5]

iii) If the dynamic range of a GPR is 120 dB and at 10 GHz the attenuation of the sand is 10 dB/m, calculate the maximum depth the radar can detect an ideal target. Comment on the result of this depth if the sand is wet. What assumption has to be made with respect to impedance mismatching?

[5]

iv) Briefly discuss the main problems associated with a non-ideal buried target.

[5]