IMPERIAL COLLEGE LONDON

EE3-18
EE9-AO12

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2017

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

Corrected copy

MICROWAVE TECHNOLOGY

Friday, 8 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

All variables and abbreviations have their usual meaning.

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. Human breast tissue can be modelled as a microwave material. At 850 MHz, the following material properties have been reported:

Normal breast tissue has $\varepsilon_r' = 17.5$ and $\sigma = 0.175\ S/m$
Breast tumour tissue has $\varepsilon_r' = 55$ and $\sigma = 1.1\ S/m$

The above variables have their usual meaning.

a) For both normal and abnormal tissue types, calculate:

i) Intrinsic impedance.

[3]

ii) Propagation constant.

[2]

iii) Skin depth.

[2]

iv) Power attenuation in dB per unit wavelength.

[3]

v) Power flux density given the RMS E-field intensity is 2 V/m.

[2]

b) From the results in 1(a), calculate the voltage-wave reflection coefficient and power reflectance between the normal and abnormal tissues.

[4]

c) Based on the results calculated in 1(a) and 1(b), compare and contrast the different materials and suggest how it may be possible to detect the presence of a tumour using microwave techniques.

[4]

2. An 8 kΩ.cm high resistivity silicon (HRS) wafer has a measured dielectric constant of 12.86 and loss tangent of 6 x 10^{-4} at 300 GHz.

a) From the 300 GHz measurements, determine the effective conductivity.

[5]

b) Using the result from 2(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 H-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 2(d), given a surface impedance of 0.1 Ω.

[2]

3. There is an analogy between the characteristics of electromagnetic waves as they propagate within a homogenous material (for an unbounded plane wave as it travels in one-dimensional space) and down a transmission line (using the telegrapher's equations).

a) For a uniform electromagnetic plane wave travelling at normal incidence to the surface of a semi-infinite half space, derive the general form of the intrinsic impedance η_i for a homogeneous material and the corresponding propagation constant γ, for complex constitutive terms.

Hint: the constitutive terms are the relative magnetic permeability $\mu_r = \mu / \mu_o \equiv \mu_r' - j\mu_r''$; relative electric permittivity due to molecular and atomic resonances, $\varepsilon_r = \varepsilon / \varepsilon_o \equiv \varepsilon_r' - j\varepsilon_r''$; and intrinsic bulk conductivity due to free charge carriers, $\sigma \equiv \sigma' - j\sigma''$.

[2]

b) Give the general form of the characteristic impedance *Zo* and propagation constant γ for a uniform transmission line with infinite length.

[2]

Electromagnetic wave propagation within a homogeneous material can be represented by the textbook equivalent one-dimensional uniform transmission line (or distributed-element) model shown in Figure 3.1, terminated by the secondary line parameter characteristic impedance *Zo*.

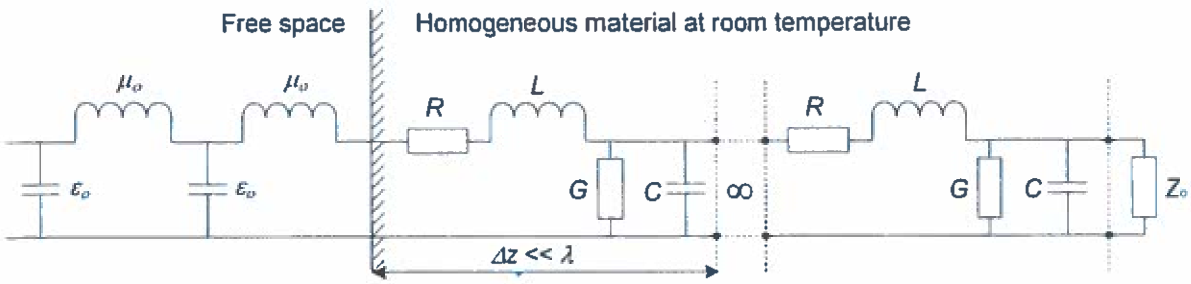

Figure 3.1 Generic equivalent transmission line model for a homogeneous material

c) Using the expressions from 3(a) and 3(b), determine equivalent primary line (i.e. distributed-element) parameters for this generic case. For the elementary lumped-element circuits to be valid, what is the relationship between the distance of propagation Δz and the wavelength λ of the electromagnetic wave within the homogeneous material?

[2]

The intrinsic conductivity of a metal can be expressed by the following equation:

$$\sigma_R = \frac{\sigma_o}{1 + j\omega\tau} \qquad (3.1)$$

where σ_o is the bulk conductivity at dc, the angular frequency $\omega = 2\pi f$, where f is the frequency of the driving electromagnetic fields, and the phenomenological scattering relaxation time for the free electrons is τ.

d) With the over-simplified classical skin-effect model, familiar to microwave engineers, electron scattering relaxation and displacement current terms are ignored (i.e. $\omega\tau \cong 0$ and $\omega\varepsilon_o \cong 0$, respectively).

For normal metals at room temperature, determine the textbook expressions for the:

(i) constitutive parameters [1]

(ii) characteristic impedance [2]

(iii) propagation constant [1]

(iv) distributed-element parameters [1]

Draw the equivalent one-dimensional uniform transmission line model. [2]

What, if any, are the relationships between the distributed-element parameters and the operating temperature and frequency? [1]

e) For gold at room temperature, $\sigma_o = 4.517 \times 10^7$ [S/m]. Calculate the following at a frequency of 1 THz:

(i) characteristic impedance [1]

(ii) surface inductance [1]

(iii) propagation constant [1]

(iv) wavelength [1]

(v) maximum recommended value for the distance of propagation Δz [1]

(vi) elementary lumped-element circuit values using Δz given in 3(e)(v) [1]

4.

a) Define the following terms for waves travelling on a lossless transmission line and in each case comment on their practical importance:

(i) velocity factor

[2]

(ii) characteristic impedance

[2]

(iii) return loss

[2]

(iv) complex reflection coefficient

[2]

(v) phase delay

[2]

b) A lossless coaxial cable has distributed inductance, L [H/m] and distributed capacitance C [F/m]. Give expressions for the characteristic impedance and velocity factor for the line. Calculate the inductance and capacitance of a 1 m length of line if it has an impedance of 50 Ω and velocity factor of 0.6.

[4]

c) Assuming a 50 Ω measurement reference impedance, calculate the complex voltage-wave reflection coefficient and associated return loss at the load impedance of 75 + j 13 Ω terminating a 50 Ω transmission line. Express the complex reflection coefficient in real and imaginary parts, and also as a modulus and phase angle. How does the complex reflection coefficient change as the reference plane at which it is measured moves towards the generator?

[6]

5.

a) Define mathematically the voltage and current at any position z along a uniform length of linear transmission line, and explain how standing waves are formed when this line is terminated by impedance Z_T.

[2]

b) From first principles, derive the equation for the normalised input impedance of a lossless transmission line having a characteristic impedance Z_O, physical length l, and electrical length θ and that is terminated by an impedance Z_T.

[6]

c) From the equation derived in 5(b), determine the solution for the input impedance for the following conditions and give an application for each condition if:

i) $l = \lambda g/2$

[2]

ii) $l = \lambda g/4$

[2]

iii) $Z_T = Zo$

[2]

iv) $Z_T = 0$ and sketch the curve of normalized input impedance against distance from the termination impedance.

[3]

v) $Z_T = \infty$ and sketch the curve of normalized input impedance against distance from the termination impedance.

[3]

6. 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 equal. Hint: use the variables defined in 6(b).

[3]

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

[4]

d) Figure 6.1 shows the photograph of a MMIC amplifier, employing TFMS transmission lines. By inspection, draw the equivalent circuit model for this amplifier and state the role of the two longest TFMS transmission lines. What kind of amplifier topology is this?

[6]

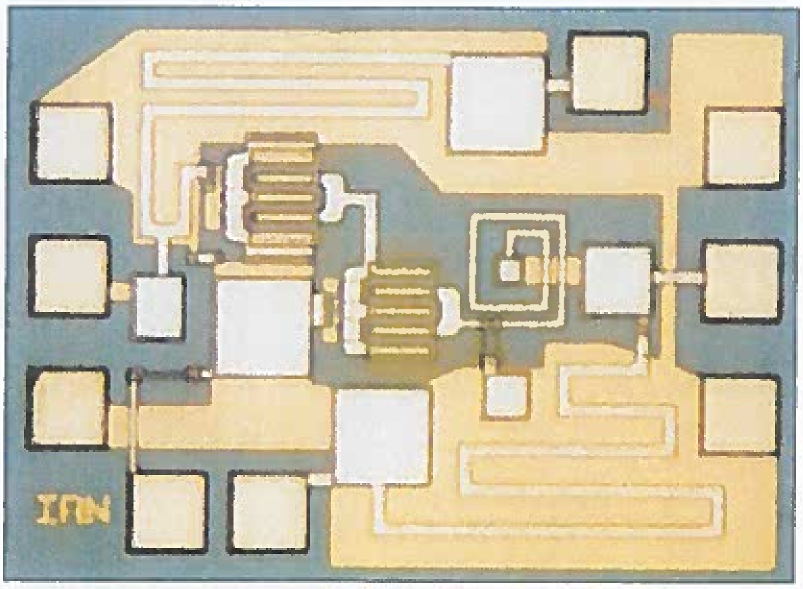

Figure 6.1