EE3-18
EE9-AO12

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2016

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

Corrected copy

MICROWAVE TECHNOLOGY

Friday, 9 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.

The Questions

1.

a) Consider the intrinsic permeability of a material.

i) What is the value of permeability for free space? [1]

ii) With a generic material, the intrinsic relative permeability can be represented by a complex number. Write this simple expression and briefly explain the physical interpretation of each part. [2]

iii) What is the value of relative permeability for aluminium? [1]

iv) What is the value of relative permeability for alumina? [1]

b) Consider the intrinsic permittivity of a material.

i) From the speed of light in free space, derive its value of permittivity. [2]

ii) With a generic material, the intrinsic relative permittivity can be represented by a complex number. Write this simple expression and briefly explain the physical interpretation of each part. [2]

iii) What is the approximate value of relative permittivity for silicon? [1]

c) Consider the intrinsic conductivity of a material.

i) What is the value of conductivity for free space? [1]

ii) With a generic material, the intrinsic conductivity can be represented by a complex number. Write this simple expression. [1]

iii) What is the approximate value of conductivity for copper? [1]

d) Derive an expression for the effective permittivity of a material in terms of its complex intrinsic variables. [2]

e) Derive an expression for the effective conductivity of a material in terms of its complex intrinsic variables. [1]

f) Given the measured values of low frequency dielectric constant of 3 and DC conductivity of 2,000 S/m, derive the following and calculate the values for a frequency of 1 GHz:

iv) Effective relative permittivity. [1]

v) Effective conductivity. [1]

vi) Loss tangent and dielectric quality factor. [2]

2. Consider a FET that has been assembled into a hybrid microwave integrated circuit, as illustrated in Figure 2.1, which employ isolated bond wires of 1 mm length.

a) Draw the equivalent circuit model of this circuit and choose typical values for the associated parasitic components from the following options of:

Bond-wire inductance $L \in [0.8\ \text{fH/mm}, 0.8\ \text{pH/mm}, 0.8\ \text{nH/mm}]$

Fringe capacitance $C \in [30\ \text{fF}, 30\ \text{pF}, 30\ \text{nF}]$

For simplicity, assume all values are equal for a particular type of parasitic component.

[6]

b) From the model drawn in 2(a), what is the general frequency response of the input and output interconnects, between the FET and associated microstrip transmission lines, due to the associated parasitic components? Also, can the microstrip lines be used to supply DC bias voltages to the FET?

[4]

c) From the model drawn in 2(a) and your typical chosen values for the parasitic components, at what frequency will the input and output interconnects, between the FET and associated microstrip transmission lines, behave like an equivalent quarter-wavelength section of transmission line? How does this compare to the -3 dB cut-off frequency? Also, calculate the characteristic impedance of the equivalent quarter-wavelength section of transmission line.

[6]

d) From the model drawn in 2(a), give examples of the potentially adverse effects that the interconnect between the source of the FET and ground can have, if not properly considered in the overall circuit of an amplifier and oscillator operating at 10 GHz.

[4]

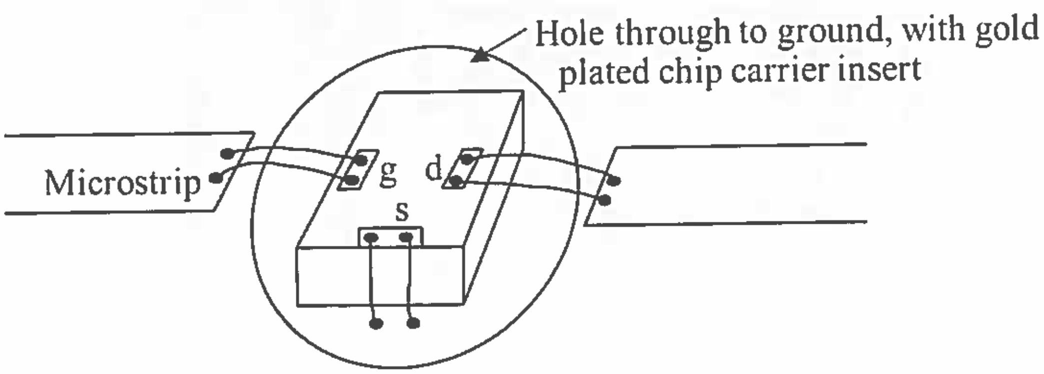

Figure 2.1 Bare-chip FET assembled into a hybrid microwave integrated circuit

3.

a) Draw a microstrip 3 dB rat-race coupler, clearly identifying all electrical lengths and characteristic impedances, relative to that of the system's reference impedance Zo: [2]

b) Briefly compare and contrast this coupler with a Wilkinson coupler. [2]

c) Briefly compare and contrast this coupler with a branch-line coupler. [2]

d) Using the figure drawn in 3(a), assign the output ports for a power divider when its input is the Isolated (or Difference) port. Also, using basic vector notation, express the voltage waves at each output, relative to the input. [2]

e) Using the figure drawn in 3(a), assign the input ports for a power combiner when its outputs are at the Direct and Coupled ports. Also, using basic vector notation, express the voltage waves at the other ports, relative to the input. [2]

f) Figure 3.1 shows the photograph of an MMIC.

i) Briefly describe what this MMIC represents. [1]

ii) Draw the high level block diagram of this circuit. [5]

iii) Using basic vector notation, try to explain the operation of this circuit and highlight any potential anomaly. [4]

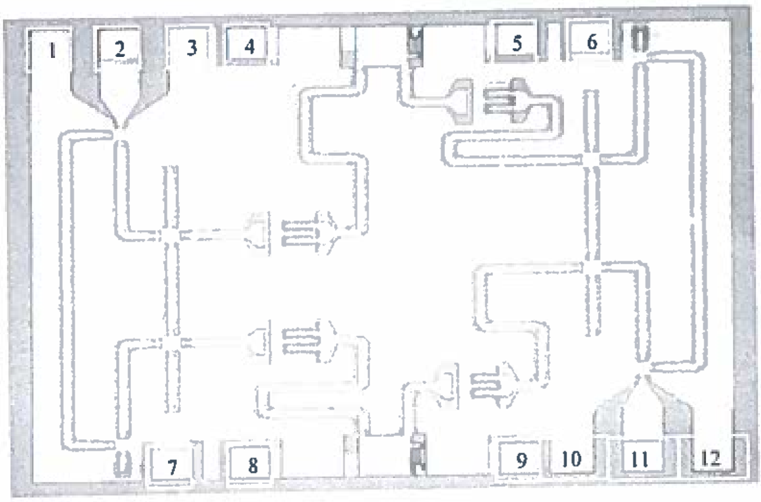

Figure 3.1 Photograph of an MMIC

4. Consider a series RLC "Tank" circuit having an inductance of 10 nH and capacitance of 3 pF.

a) Draw the one-port "Tank" circuit and indicate key voltages and currents.

[1]

b) Using the circuit drawn in 4(a), from first principles (i.e. in terms of energy), derive an expression for the unloaded quality factor in terms of impedances. State any assumptions made.

[6]

c) Calculate the frequency that gives the maximum unloaded quality factor and the associated characteristic impedance.

[4]

d) When the "Tank" is undriven, in how many cycles will it be depleted of energy if the unloaded quality factor is 10π and what will be the value of series resistance?

[4]

e) With the value of series resistance calculated in 4(d), if the ideal lossless inductor and capacitor are now replaced by components having unloaded quality factors of 10 and 50, respectively, calculate the resulting unloaded quality factor at resonance.

[5]

5. Consider an air-filled spherical cavity resonator with internal radius $R_a = 150$ μm and having infinitely thick metal wall. The lowest resonance frequency for an ideal spherical cavity resonator is defined using its phase constant β_1 by the following:

$$\beta_1 R_a = 2.74370 \qquad (5.1)$$

This resonator can be characterized using a series *RLC* equivalent circuit model, having the following generic equations for its *LC* lumped-element components:

$$L(\omega_0) = \mu_d V \left|\tilde{\beta}_0\right|^2 \qquad (5.1)$$

$$C(\omega_0) = \frac{\varepsilon_d}{V} \frac{1}{\left|\tilde{\beta}_0\right|^4} \qquad (5.2)$$

where, the internal cavity volume is given by:

$$V = 4\pi R_a^3/3 \qquad (5.3)$$

a) What is the dominant mode of operation referred to as and, with the use of sketches or otherwise, briefly describe either its electric or magnetic field variations. [2]

b) Calculate the ideal resonance frequency and the associated *RLC* values. [5]

c) With a non-PEC wall (having a DC conductivity of approximately 100 S/m), transient time-domain measurements indicate a damped resonance frequency of 700 GHz and a decay time constant of 5 ps. Calculate the following:

i) Unloaded quality factor at the damped resonance frequency. [2]

ii) Undamped resonance frequency. [2]

iii) Unloaded quality factor at the undamped resonance frequency. [2]

iv) *RLC* values at the undamped resonance frequency. [5]

d) Briefly comment on the frequency dispersive nature of the *RLC* components when wall losses are introduced. [2]

6. A short transmission line is used to transform an arbitrary termination impedance $Z = R + jX$ to the reference impedance Zo. The impedance looking into the transformer is given by the following expression:

$$z_{IN} = \frac{z + jz_{TX} \tan\theta}{z_{TX} + jz \tan\theta} \tag{6.1}$$

where the normalised impedances used have their usual meanings.

a) Using this equation, derive the equations for the characteristic impedance of the transmission line Z_{TX} and the corresponding electrical length θ.

[7]

b) From the expressions derived in 6(a), what are the mathematical limits for the resistive and reactive values of the termination impedance that can be mapped into the input impedance of the short transmission line transformer?

[3]

c) A load termination consisting of a 2 nH inductance in series with a 3 Ω resistance must be matched at 900 MHz to a 50 Ω reference impedance using a short transmission line transformer. Using expressions derived in 6(a) and 6(b), calculate
before exam Z_{TX} and θ for the short transmission line transformer.

[7]

d) Comment on the suitability, or otherwise, of implementing the short transmission line transformer calculated in 6(c) using conventional microstrip and thin-film microstrip technologies.

[3]