E3.18

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2007

EEE PART III/IV: MEng, BEng and ACGI

MICROWAVE TECHNOLOGY

Corrected Copy

Friday, 11 May 10:00 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
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Special instructions to candidates

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 frequency spectrum has limits on performance and low cost exploitation.

i) As frequency decreases below 1 GHz, what affects the signal/noise ratio of a wireless communications system?

[1]

ii) Why is the frequency spectrum between 1 GHz and 10 GHz so convenient for commercial exploitation?

[2]

iii) What justifications are there for choosing 2.45 GHz as a suitable operating frequency for a microwave oven?

[2]

iv) Where in the frequency spectrum are the water and oxygen absorption peaks, between 10 GHz and 200 GHz?

[2]

v) What is significant about the 38 GHz and 94 GHz frequency bands? Give an appropriate application for each band and state the reasons for choosing these applications.

[2]

vi) What is significant about the 60 GHz frequency band? Give two applications for this band and state the reasons for choosing these applications.

[2]

b) Lumped-element components exhibit undesirable frequency behaviour.

i) State the simple relationship between the unloaded Q-factor and frequency for a lumped-element tuned circuit. Define all variables clearly.

[1]

ii) Calculate the transition cut-off frequency for a field-effect transistor having an intrinsic transconductance of $41\ mS$ and gate-source capacitance of $0.2\ pF$.

[1]

iii) What technique can be adopted to increase the Q-factor of a lumped-element tuned circuit using a simple transistor circuit? Give a basic rule-of-thumb, in terms of transition cut-off frequency, for the frequency range that this technique can be applied to.

[2]

c) Distributed-element components exhibit undesirable frequency behaviour.

i) State the simple relationship between the electrical length and frequency for a transmission line operating in a (quasi-)TEM mode. Define all variables clearly.

[2]

ii) Which simple rule-of-thumb relates electrical lengths and physical lengths for integrated circuits that employ transmission lines? What are the practical implications of this as frequency decreases and increases?

[1]

iii) State the simple relationship between the attenuation coefficient and frequency for a transmission line operating in a purely-TEM mode. Define all variables clearly.

[2]

2.

a) Clearly defining all variables and their SI units, state the following (in relation to the differential form of Maxwell's equations) and give a brief description of their physical interpretation:

i) Faraday Law of Electromagnetic Induction and any associated constitutive relationship.

[3]

ii) Ampere's Law of Magnetomotive Force and any associated constitutive relationship.

[3]

iii) Electric form of Gauss's Law.

[2]

iv) Magnetic form Gauss's Law.

[2]

b) From 2(a), derive an expression for the intrinsic impedance of a homogenous and isotropic material, in terms of the propagation constant of a TEM wave propagating though it.

[3]

c) As an extension on 2(b), derive expressions for the skin depth and wavelength.

[2]

d) Using 2(c), calculate the approximate skin depth and wavelength for a TEM wave propagating through distilled water, having dielectric constant of 53 and bulk DC conductivity of 31 S/m, at 15 GHz. State any assumptions made.

[5]

3.

a) Describe the key characteristics, including advantages and disadvantages, of ohmic contact RF MEMS switches.

[4]

b) If an ohmic contact switch has an effective closed-state series resistance of $R_{on} = 1.5\ \Omega$ and an effective open-state isolation capacitance of $C_{off} = 5\ fF$, calculate the resulting performance figure-of-merit.

[4]

c) Describe the key characteristics, including advantages and disadvantages, of capacitive membrane (or switch capacitance) RF MEMS switches.

[4]

d) Write the well-known equation for the capacitance of a parallel-plate capacitor and calculate an approximate value for the down-state capacitance for a capacitive membrane switch, given the following variables:

- Plate Length, $L = 500\ \mu m$
- Plate Width, $W = 300\ \mu m$
- Plate separation distance, $d = 2\ \mu m$
- Separation dielectric constant, $\varepsilon_r = 3.4$

[2]

e) What would the separation distance of the membrane switch specified in 3(d) need to be so that it has the open-state capacitance given in 3(b)? Assume that the $2\ \mu m$ thick separation dielectric can be ignored in the open-state.

[4]

f) In practice, can the separation distance calculated in 3(e) be realised using electrostatic actuation? Which of the variables in 3(d) does the chip designer have any control over?

[2]

4. 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 electric field intensity is 2 V/m. [2]

b) From the results in 4(a), calculate the voltage-wave reflection coefficient and power reflectance between the normal and abnormal tissues. [4]

c) Based on the results calculated in 4(a) and 4(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]

5.

a) Compare and contrast hybrid and monolithic technologies for realising microwave integrated circuits.

[5]

b) Draw the block diagram for a TVRO LNB. For each block, comment on the suitability for their implementation using monolithic technology.

[5]

c) For a GaAs MESFET:

i) Draw the cross-section and briefly describe its operation, indicating the dominant input parasitic components.

[2]

ii) Define the simple well-known equation that relates the transition cut-off frequency (f_T) to the dominant parasitic capacitance.

[1]

iii) How does the MESFET compare with a MOSFET?

[1]

iv) How can the circuit designer achieve higher peak output current swings and how will this effect f_T?

[2]

v) Using 5(c)(ii) as the starting point, and with the help of 5(c)(i), derive a simple equation that relates the transition cut-off frequency (f_T) to the most critical physical dimension of the gate finger. Clearly define all variables used. Hint, $g_{mo} = \varepsilon v_{sat} W_g / d$ and all variables have their usual meaning. How can the foundry/designer increase the transition frequency?

[4]

6.

a) Consider a vertically polarized TEM wave travelling in air and parallel to the flat surface of a normal metal having a finite conductivity:

i) Draw the field vectors and Poynting vectors at the surface of normal metal, for both the TEM wave outside the conductor (travelling parallel to the surface) and the evanescent wave (travelling into the normal metal). Also draw the Cartesian reference axes, to indicate *x, y* and *z* directions.

[4]

ii) Define the average values of the Poynting vectors for both the TEM wave and the evanescent wave, in terms of their field vectors.

[3]

iii) Define the intrinsic impedance experienced by the TEM wave and the evanescent wave, in terms of their field vectors.

[3]

iv) Define the resulting average Poynting vector sum, in terms of the magnetic field and corresponding intrinsic impedances within both the air and normal metal.

[3]

d) From 6(a), it can be found that the average power flow (per unit area) is not parallel to the surface of the normal conductor, but inward with a forward tilt angle of τ.

i) Derive the simple expression for τ, using the result in 6(a)(iv). Hint: use simple geometry.

[4]

ii) Calculate the intrinsic impedance in free space and in copper ($\sigma = 5.8\times10^{7}\ S/m$) at 3 GHz.

[2]

iii) Calculate the forward tilt angle for a vertically polarized 3 GHz wave travelling in air along a sheet of copper.

[1]

13/4/07

The Solutions for E3.18, 2007

Model answer to Q 1(a): Bookwork and Discussions in Class

i) Signal/noise ratio becomes more problematic as frequency decreases below 1 GHz, because of the increase in galactic noise. As a result, more signal power is required to maintain a good signal/noise ratio.

[1]

ii) The frequency between 1 GHz and 10 GHz is convenient for commercial exploitation because both galactic and atmospheric noise are very low. Also, cheap lumped-element passive components and high gain active components can be used in this frequency band.

[2]

iii) For microwave ovens, high power has to be generated at low cost. At higher frequencies it becomes more difficult to generate high power and also increased tolerances increase the cost of manufacturing. Moreover, cooking skin depth decreases and, therefore, it becomes more difficult to cook uniformly. At lower frequencies, the there will be fewer hot-spots, and these will be spaced further apart, again making it difficult to cook uniformly. Moreover, the size and weight of the magnetron would increase.

[2]

iv) The water absorption peaks are found at 22 GHz and 183 GHz; while the oxygen absorption peaks are found at 60 GHz and 119 GHz.

[2]

v) At 38 GHz and 94 GHz there are troughs in the atmospheric attenuation curves. As a result, Line-of-Sight communication links (having wide bandwidths) and directional radar systems (having highly directional antennas) are used in these bands, respectively.

[2]

vi) The 60 GHz band has very high atmospheric attenuation. As a result, it is ideal for indoor wireless local area network applications and inter-satellite communication links. The potential interference to other nearby services operating in the same band can be minimized by the inherent drop in signal strength, as distance increases.

[2]

Model answer to Q 1(b): Bookwork and Discussions in Class

i) Unloaded Q-factor for a tuned circuit can be represented by that of the inductor, by assuming all the loss resistance is effectively lumped into the inductor: $Q = \omega L / R$, where ω = angular frequency; L = inductance and R = equivalent loss resistance.

[1]

ii) The simple transition cut-off frequency for a field-effect transistor is given by: $f_T = \frac{g_{mo}}{2\pi C_{gs}} = 32.6\ GHz$

[1]

iii) With a suitable inductor or capacitor and bias network, a transistor can be configured to create a negative resistance that can cancel out the effective loss resistance in a tuned circuit. This "active resonator" technique is possible as long as the operating frequency is at least an order of magnitude lower in frequency to that of the transition cut-off frequency of the transistor.

[2]

Model answer to Q 1(c): Bookwork and Discussions in Class

i) The simple relationship between electrical length and frequency for a transmission line operating in the (quasi-)TEM mode is: $\theta = \frac{\omega\sqrt{\varepsilon_{r\,effective}}}{c}l$, where c = speed of light in a vacuum, l = physical length and $\varepsilon_{r\,effective}$ = effective relative permittivity.

[2]

ii) Integrated circuits employ transmission lines of fixed electrical length. Therefore, as frequency decreases the lengths of line increase. This can be a problem, as the large size may be prohibitive in terms of space available and/or cost. As frequency increases, sensitivity to the tolerances of open-circuit stubs also increases, but chip package density can increase.

[1]

ii) In general, the attenuation constant of a transmission line is directly proportional to the surface resistance, given by: $Rs = \sqrt{\frac{\omega\mu}{2\sigma_o}}$, where μ = permeability of the metal conductor and σ_o = bulk DC conductivity of the metal conductor.

[2]

Model answer to Q 2(a): Bookwork

i) Faraday Law of Electromagnetic Induction

$$\nabla x\hat{E} = -\frac{\partial \hat{B}}{\partial t} \Rightarrow -j\omega\mu\hat{H} \quad [V/m]$$

$$\textit{where constitutive relationship,} \quad \hat{B}\,[T \text{ or } Wb/m^2] = \mu\,[H/m]\,\hat{H}\,[A/m]$$

i.e. electromotive force induced in a closed circuit is proportional to the rate of change in the magnetic flux density threading the circuit.

[3]

ii) Ampere's Law of Magnetomotive Force

$$\nabla x\hat{H} = \hat{J}c + \hat{J}_D \Rightarrow \sigma_o\hat{E} + \hat{J}_D \quad [A/m^2]$$

$$\textit{where} \quad \hat{J}c\,[A/m^2] = \sigma_o\,[S/m]\,\hat{E}\,[V/m] \Rightarrow 0 \quad \text{with in a perfect indulator}$$

i.e. conduction current creates a closed loop of magnetic field. Note that conduction current is simply a surface current density, where the surface is transverse to the direction of current flow (i.e. *width x depth*). In addition, Maxwell discovered that a magnetic field can also be created by a displacement current. Note that displacement (i.e. electric flux density) is simply a surface charge density.

$$\hat{J}_D = \frac{\partial \hat{D}}{\partial t} = \varepsilon\frac{\partial \hat{E}}{\partial t} \Rightarrow j\omega\varepsilon\hat{E} \quad [A/m^2]$$

$$\textit{where constitutive relationship,} \quad \hat{D}\,[C/m^2] = \varepsilon\,[F/m]\,\hat{E}\,[V/m]$$

For example, when a time-varying conduction current flows through the leads of a parallel-plate capacitor then an equal displacement or "wireless" current must also flow between its plates, thus creating a closed loop of magnetic field between the plates.

[3]

iii) Gauss's Law: Electric form

$$\nabla\cdot\hat{D} = \rho \Rightarrow 0 \quad \text{with no stored charges} \quad [C/m^3]$$

i.e. an E-field is created by a stored electric charge. Note that a volume charge density is used here.

[2]

iv) Gauss's Law: Magnetic form

$$\nabla\cdot\hat{B} = 0 \quad [Wb/m^3]$$

i.e. a H-field is not created by a stored magnetic charge. Therefore, it must exist in a closed loop.

[2]

Model answer to Q 2(b): Bookwork

The electromagnetic wave is periodic in both time (t) and space (z), i.e. $e^{(j\omega t-\gamma z)}$ where γ = jq and q = complex wavenumber.

Therefore:

$$\nabla x\hat{E} = -\frac{\partial \hat{B}}{\partial t} \Rightarrow -jqE = -j\omega\mu H$$

$$\therefore \eta = \frac{E}{H} = \frac{j\omega\mu}{\gamma} = \frac{j\omega\mu}{jq}$$

$$but, q = \frac{2\pi}{\lambda} = \frac{\omega\sqrt{\varepsilon_r}}{c} = \omega\sqrt{\mu\varepsilon_o\varepsilon_r}$$

$$\therefore \eta = \sqrt{\frac{\mu_o\mu_r}{\varepsilon_o\varepsilon_r}}$$

[3]

Model answer to Q 2(c): Bookwork

$$\gamma = \frac{j\omega\mu}{\eta} = \alpha + j\beta$$

$$skin\ depth = \frac{1}{\alpha}$$

$$wavelength = \frac{2\pi}{\beta}$$

[2]

Model answer to Q 2(d): Bookwork

Given $\varepsilon_r' = 53$ and $\sigma_o = 31$ at 15 GHz:

It is assumed that the distilled water is treated as a homogeneous and isotropic material. Also, distilled water is a non-magnetic material and the following first order approximation is assumed:

$$\varepsilon_r'' = \frac{\sigma_o}{\omega\varepsilon_o}.$$

$$\varepsilon_o = \frac{1}{c^2\mu_o} \quad and\ c = 3\times10^8\ m/s \quad and\ \mu_o = 4\pi\times10^{-7}\ H/m$$

$$\therefore \varepsilon_o = 8.842\ pF/m$$

$$\therefore \varepsilon_r'' = 37.2$$

$$\therefore \eta = \frac{377}{\sqrt{53 - j37.2}} = 44.7 + j14.1\,\Omega$$

$$\therefore \gamma = \frac{j\omega\mu}{\eta} = 762 + j2411 \quad \therefore \delta = 1.31\,mm \quad and \quad \lambda = 2.61\,mm$$

[5]

Model answer to Q 3(a): Bookwork

Ohmic contact switch has:

* high open-state isolation
* low closed-state insertion loss
* considerable force is required to create a good contact
* microscopic bonding of the metal surfaces
* highly susceptible to corrosion and stiction

[4]

Model answer to Q 3(b): Computed Example

Performance figure-of-merit, $fc = 1/(2\pi R_{on} C_{off}) = 21Thz$

[4]

Model answer to Q 3(c): Bookwork

Switched capacitance switch has:

* compromise is made between insertion loss and isolation
* insertion loss is independent of the contact force
* electrode separation need to be maximised
* higher lifetime (typically several orders of magnitude)

[4]

Model answer to Q 3(d): Computed Example

Capacitance $\approx C_{fringe} + \varepsilon_o \varepsilon_r \times (L \times W)/d \sim \varepsilon_o \varepsilon_r \times (L \times W)/d = 2.25 pF$

[2]

Model answer to Q 3(e): Computed Example

(e) Separation distance needs to be, $d \sim \varepsilon_o \varepsilon_r \times (L \times W)/5fF = 902 \mu m$

[4]

Model answer to Q 3(f): Bookwork

The separation distance calculated in 3(e) is way too big for conventional electrostatic actuation. The chips designer only has control over L and W.

[2]

Model answer to Q 4(a): Computed Example (normal/abnormal)

i) Intrinsic impedance.

$$\varepsilon_r'' = \frac{\sigma}{\omega\varepsilon_o} = 3.706/23.234$$

$$\eta = \frac{377}{\sqrt{\varepsilon_r' - j\varepsilon_r''}} = 88.65 + j9.28\Omega / 47.80 + j9.71\Omega$$

[3]

ii) Propagation constant.

$$\gamma = \frac{j\omega\mu_o}{\eta} = 7.84 + j74.88/27.38 + j134.83$$

[2]

iii) Skin depth.

$$\delta = \frac{1}{\mathrm{Re}(\gamma)} = 128mm/36.5mm$$

[2]

iv) Power attenuation in dB per unit wavelength.

$$\alpha = 7.84/27.38$$

$$\beta = 74.88/134.83$$

$$\lambda = \frac{2\pi}{\beta} = 83.9mm/46.6mm$$

$$Power\ Attenuation = e^{-2\alpha\lambda}\ Np/\lambda$$

$$Power\ Attenuation = 8.686\alpha\lambda\ dB/\lambda = 5.715/11.083 dB/\lambda$$

[3]

v) Power flux density given a RMS electric field intensity is 2 V/m.

$$P_D = \frac{|E|^2}{\mathrm{Re}(\eta)} = 45/84 mW/m^2$$

[2]

Model answer to Q 4(b): Computed Example

$$\rho = \frac{\eta_{abnormal} - \eta_{normal}}{\eta_{abnormal} + \eta_{normal}} = 0.5447 + j0.0525$$

$$\Gamma = |\rho|^2 = 0.299$$

[4]

Model answer to Q 4(c): Deductive Reasoning

It can be seen from the results in 4(a) that the two different tissue types have very different microwave properties. The tumour is almost twice as effective at attenuating/absorbing microwave power, when compared to normal tissue. Therefore, it may be possible to detect the tumour by transmitting microwave pulsed energy into the breast and observing the transmission and reflected properties. With transmission measurements, high levels of attenuation and longer delays will be found with large tumours. With reflection measurements, large reflected waves will be observed at the interface between the different tissue types.

[4]

Model answer to Q 5(a): Bookwork

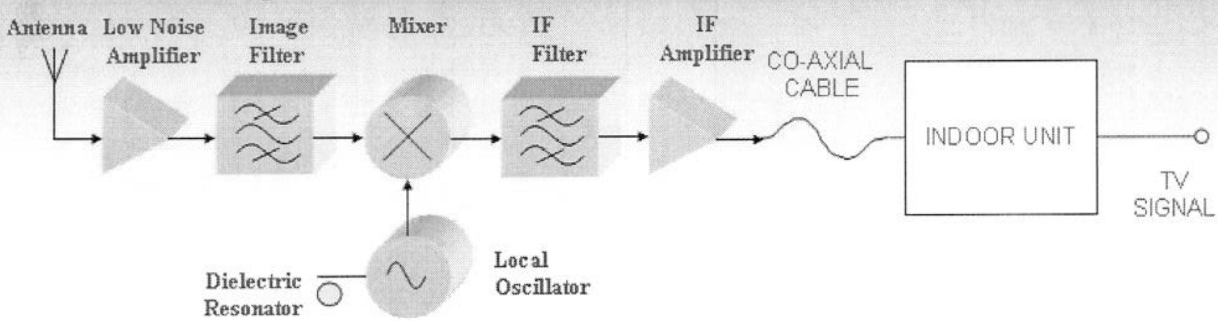
The Advantages/disadvantages of MMICs when compared with hybrid MICs are given in the Table below.

MMICs	*Hybrid MICs*
Cheap in large quantities; especially economical with many transistors	Large passive circuits can be cheaper; automatic assembly is possible
Very good reproducibility	Poor reproducibility due to device placement errors and bond-wires
Small and light	Compact multilayer substrates with embedded passives now available
Reliable	Hybrids are mostly 'glued' together and so reliability suffers
Less parasitics – more bandwidth and higher frequencies	Poor interconnects can kill the performance of individual components
Space is at a premium; the circuit must be made as small as possible	Substrate is cheap, which allows microstrip to be used abundantly
Very limited choice of component	A vast selection of passive components is available and the best transistors are always available for LNAs and PAs
Long turn around time (3 months)	Can be very fast (1 week), making multiple iterations possible
Very expensive to start up	Very little capital equipment is required

[5]

Model answer to Q 5(b): Bookwork

Consider the simplified block diagram of a satellite TV receiver's LNB

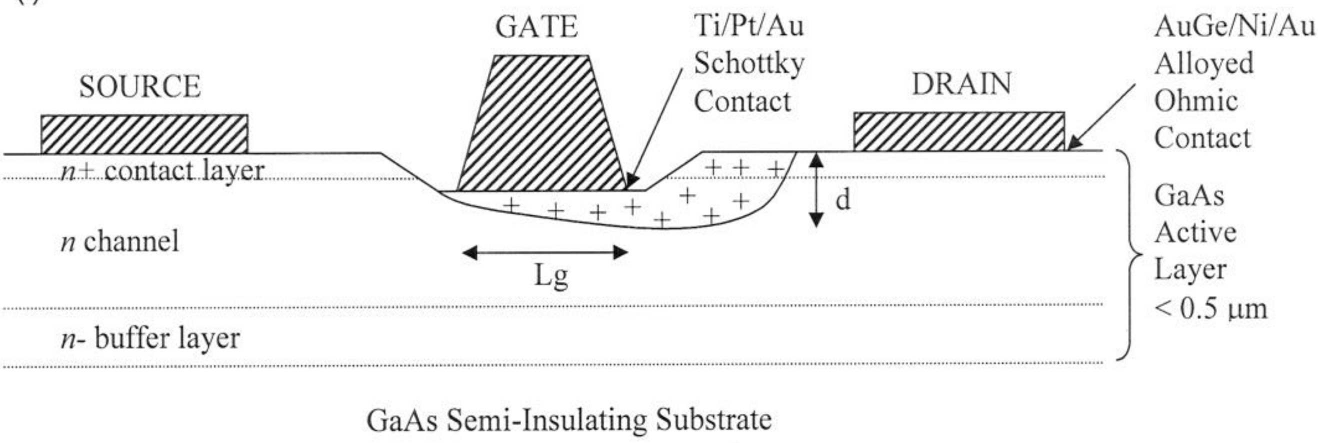


- *LNA (NF < 1 dB):* low noise transistors are not standard & matching circuits are lossy
- *RF Filter (50 dB Image Rejection):* poor Q-factors, ∴poor selectivity & rejection
- *Mixer:* double-balanced mixers can be large, ∴ expensive
- *Oscillator:* high-Q off-chip resonator is required for stability/low phase noise
- *IF Filter:* low frequency components are very large, ∴ expensive
- *IF Amplifier:* cheaper to implement in silicon technology

[5]

Model answer to Q 5(c): Bookwork

(i)



- The Schottky contact's built-in barrier potential, $\phi(0)$, creates a region below the gate which is depleted of its majority carrier electrons. With an additional gate-source bias voltage applied, Ids can be modulated.

[2]

(ii) $f_T = \frac{gmo}{2\pi Cgs}$

[1]

(iii) Compared to the metal-oxide semiconductor field-effect transistor (MOSFET), the omission of the oxide layer results in a very low Cgs and, therefore, provides a high transition (or cut-off) frequency.

[1]

(iv) To achieve higher output powers requires larger peak-to-peak current and/or voltage swings. Increasing the doping concentration of the channel will increase Idss (and, therefore, the peak-to-peak current), but reduce the avalanche breakdown voltage (and, therefore, the peak-to-peak voltage). Thus, the designer is forced to increase the gate's periphery in order to achieve large current swings, but this is at the expense of a lower f_T.

[2]

(v)

$$f_T = \frac{g_{mo}}{2\pi Cgs}$$

$$g_{mo} = \frac{\varepsilon v_{sat} W_g}{d}$$

$$but, Cgs = \frac{\varepsilon W_g Lg}{d}$$

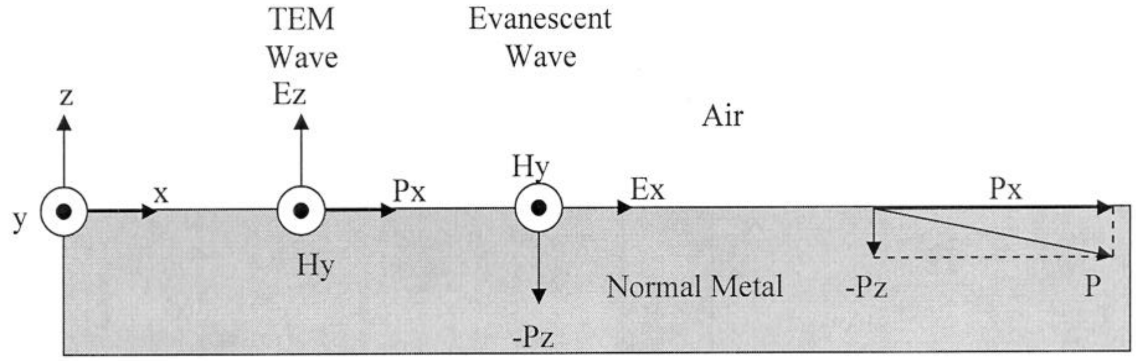
$$\therefore f_T = \frac{v_{SAT}}{2\pi Lg}$$

To increase the transition cut-off frequency, either the saturation velocity has to increase (i.e. using a different fabrication technology) or the designer/foundry has to control the gate length, Lg (if possible).

[4]

Model answer to Q 6(a): Extended Bookwork

(i)



[4]

(ii) For the TEM wave: Px = Re{Ez Hy*}
For the evanescent wave: –Pz = Re{Ex Hy*}

[3]

(iii) For the TEM wave: Zair = Ez / Hy
For the evanescent wave: Zmetal = Ex / Hy

[3]

(iv) For air: Px = $|Hy|^2$ Re{Zair}
For metal: -Pz = $|Hy|^2$ Re{Zmetal}

Therefore, $\underline{P}$ = ($|Hy|^2$ Re{Zair}) $\underline{x}$ + $|Hy|^2$ Re{Zmetal} $\underline{y}$

[3]

Model answer to Q 6(b): Extended Bookwork and Computed Example

(i) Forward tilt angle = $\tan^{-1}$(-Pz/Px) = $\tan^{-1}$(Re{Zmetal}/Re{Zair})

[4]

(ii)

$$\mathrm{Re}\{Zair\} = \sqrt{\frac{\mu_o}{\varepsilon_o}} = 377$$

$$\mathrm{Re}\{Zmetal\} = \sqrt{\frac{\omega\mu_o}{2\sigma}} = 14.4m\Omega$$

[2]

(iii) Forward tilt angle = $\tan^{-1}$(0.0144 / 377) = 0.0022°

[1]