IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2016

EEE PART III/IV: MEng, BEng and ACGI

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OPTOELECTRONICS

Wednesday, 7 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) : R.R.A. Syms
                         Second Marker(s) : O. Sydoruk

Fundamental constants

$e = 1.6 \times 10^{-19}$ C

$m_e = 9.1 \times 10^{-31}$ kg

$\varepsilon_0 = 8.85 \times 10^{-12}$ F/m

$\mu_0 = 4\pi \times 10^{-7}$ m kg/C^2

$c = 3 \times 10^8$ m/s

$h = 6.62 \times 10^{-34}$ Js

Maxwell's equations – integral form

$\iint_A \underline{\mathbf{D}} \cdot d\underline{a} = \iiint_V \rho \, dv$

$\iint_A \underline{\mathbf{B}} \cdot d\underline{a} = 0$

$\int_L \underline{\mathbf{E}} \cdot d\underline{L} = - \iint_A \partial\underline{\mathbf{B}}/\partial t \cdot d\underline{a}$

$\int_L \underline{\mathbf{H}} \cdot d\underline{L} = \iint_A [\underline{\mathbf{J}} + \partial\underline{\mathbf{D}}/\partial t] \cdot d\underline{a}$

Maxwell's equations – differential form

$\mathrm{div}(\underline{\mathbf{D}}) = \rho$

$\mathrm{div}(\underline{\mathbf{B}}) = 0$

$\mathrm{curl}(\underline{\mathbf{E}}) = -\partial\underline{\mathbf{B}}/\partial t$

$\mathrm{curl}(\underline{\mathbf{H}}) = \underline{\mathbf{J}} + \partial\underline{\mathbf{D}}/\partial t$

Material equations

$\underline{\mathbf{J}} = \sigma \underline{\mathbf{E}}$

$\underline{\mathbf{D}} = \varepsilon \underline{\mathbf{E}}$

$\underline{\mathbf{B}} = \mu \underline{\mathbf{H}}$

Vector calculus (Cartesian co-ordinates)

$\mathrm{grad}(\phi) = \partial\phi/\partial x \, \underline{i} + \partial\phi/\partial y \, \underline{j} + \partial\phi/\partial z \, \underline{k}$

$\mathrm{div}(\underline{\mathbf{F}}) = \partial F_x/\partial x + \partial F_y/\partial y + \partial F_z/\partial z$

$\mathrm{curl}(\underline{\mathbf{F}}) = \underline{i} \, \{\partial F_z/\partial y - \partial F_y/\partial z\} + \underline{j} \, \{\partial F_x/\partial z - \partial F_z/\partial x\} + \underline{k} \, \{\partial F_y/\partial x - \partial F_x/\partial y\}$

$\mathrm{curl} \, \{\mathrm{curl}(\underline{\mathbf{F}})\} = \mathrm{grad} \, \{\mathrm{div}(\underline{\mathbf{F}})\} - \nabla^2\underline{\mathbf{F}}$

$\iint_A \underline{\mathbf{F}} \cdot d\underline{a} = \iiint_V \mathrm{div}(\underline{\mathbf{F}}) \, dv$

$\int_L \underline{\mathbf{F}} \cdot d\underline{L} = \iint_A \mathrm{curl}(\underline{\mathbf{F}}) \cdot d\underline{a}$

1. Electromagnetic waves are propagating in dielectric media at angular frequency ω and are polarised in the y-direction.

a) Write down Faraday's law for time-independent fields. Assuming that the time independent electric field can be written as $\underline{E} = E_y \underline{j}$, what are the corresponding components of the magnetic field? If there is an interface between two different media along $x = 0$, what field components must match at this boundary?

[7]

b) A y-polarized plane wave is propagating in the z-direction in a medium with propagation constant k. Write down an expression for the time-independent electric field, find the magnetic field, and hence calculate the impedance of the medium.

[6]

c) Define the irradiance $\underline{S}$, and calculate the irradiance for the plane wave in part b). Define the time-averaged power P passing through an area A. Calculate the power carried by the wave in free space, if it has electric field amplitude 1 V/m, and the area concerned is a 1 m^2 aperture arranged either perpendicular or parallel to the z-axis.

[7]

2. a) Sketch a three-layer asymmetric slab dielectric waveguide on the x-z plane, and identify the conditions needed for wave guidance. Explain what is meant by 'cutoff'.

[5]

b) Assuming TE polarization, write down the wave equations for the three layers. Explain what is meant by a modal solution, and derive the corresponding waveguide equations. Explain what types of solutions can exist.

[5]

c) Assuming the waveguide is now symmetric, sketch the transverse fields of the two lowest order modes. Describe the boundary matching conditions that must be satisfied, and explain how these can be seen in your sketches.

[4]

d) The eigenvalue equation for the waveguide in part a) is:

$$\tan(\kappa h) = \kappa[\gamma + \delta] / [\kappa^2 - \gamma\delta]$$

What are κ, γ and δ? Show how the equation can be rewritten if the waveguide is symmetric. Determine the cutoff conditions for all the modes.

[6]

3. a) Figure 3.1 shows a radiative star. Explain its construction and operation, and its advantages over a non-radiative star. Show that the amplitude at port q can be related to the amplitude at port p by:

$$A_q = (A_p/\sqrt{N}) \exp\{-j\beta R(1 - pq\Delta\theta^2)\} \text{ where } N = 2M + 1$$

[8]

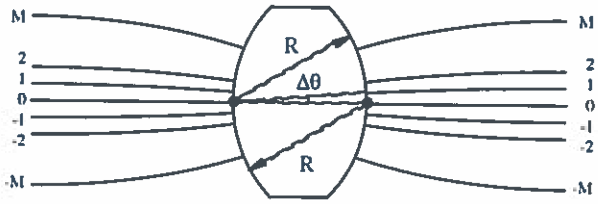

Figure 3.1

b) Describe and sketch the physical arrangement of an arrayed waveguide grating multiplexer (AWG MUX). Explain its operation, and its advantages over other types of filter. (NB: there is no need to derive its transfer function).

[6]

c) Using an equivalent block representation, describe and sketch the operation of an AWG MUX in its main modes. Using this, show how AWG MUX components can be combined with other components to form an ADD-DROP MUX.

[6]

4 a) Using suitable band diagrams, contrast the processes of optical absorption in photoconductive detectors and pn-junction photodiodes, and hence indicate which should be preferred for optical telecommunications.

[8]

b) Explain the factors limiting the quantum efficiency in photodiodes. Using suitable band diagrams once again, explain how these are overcome in homostructure and heterostructure pin photodiodes.

[7]

c) Derive the responsivity of a photodiode. An InGaAs photodiode has a responsivity of 1 mA/mW at 1.55 μm wavelength. What is its quantum efficiency?

[5]

5. a) Using suitable diagrams, explain how the density of occupied states is determined in a semiconductor. By considering this function, explain the spectral distribution of light generated through recombination. Why does this characteristic render light emitting diodes (LEDs) unsuitable for long-distance optical communications?

[9]

b) Describe the two most common methods for generating white light using LEDs. How must LEDs be further adapted for use in lighting?

[6]

c) Compare the economic advantages and disadvantages of LEDs and conventional sources for lighting.

[5]

6. The rate equations for a semiconductor laser diode can be written in the form:

$$d\phi/dt = \beta n/\tau_{rr} + G\phi(n - n_0) - \phi/\tau_p$$

$$dn/dt = I/ev - n/\tau_e - G\phi(n - n_0)$$

a) Explain the meaning of each of the five different blocks of terms on the right-hand sides of the equations. How do these equations differ from the corresponding equations for a LED? Why is there no rate equation for holes?

[8]

b) Explaining your assumptions, find an approximate steady-state solution for the optical power output, valid below threshold. Identify and describe two terms in your result that relate to efficiency.

[5]

c) Find the corresponding solution above threshold. What is the electron density at transparency, and during laser operation? What is the threshold current? Sketch the complete variations of the electron density and the optical power with drive current.

[7]