IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2014-15

EEE PART III/IV: MEng, BEng and ACGI

Corrected Copy

OPTOELECTRONICS

Tuesday, 9 December 2:00 pm

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

$\int \int_A \underline{\mathbf{D}} \cdot d\underline{a} = \int \int \int_V \rho \, dv$

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

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

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

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)

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

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

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

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

$\int \int_A \underline{\mathbf{F}} \cdot d\underline{a} = \int \int \int_V \mathrm{div}(\underline{\mathbf{F}}) \, dv$

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

1. Propagation of TE polarized electromagnetic waves in the (x, z) plane may be described by the scalar wave equation:

$$\partial^2E_y/\partial x^2 + \partial^2E_y/\partial z^2 + n^2k_0{}^2E_y = 0$$

Here E_y is the amplitude of the (y-polarised) electric field, n is the refractive index, and $k_0 = 2\pi/\lambda$ where λ is the free-space wavelength.

a) Show that the field $E_y(x, z) = E_0 \exp\{-jnk_0[x \sin(\theta) + z \cos(\theta)]\}$ is a solution. What does it represent? Assuming that $\theta \approx 30^\circ$, sketch lines of constant phase.

[6]

b) Show that the field $E_y(x, z) = E_0 \exp(\gamma x) \exp(-j\beta z)$ can also be a solution. What does this solution represent? Sketch lines of constant amplitude and constant phase. How realistic is the solution, if its amplitude becomes very large as x rises?

[8]

c) Assuming a modal solution in the form $E_y = E(x) \exp(-j\beta z)$, derive the waveguide equation for z-propagating modes. Show that the transverse field $E(x) = E_0 \exp(\gamma x)$ may be a solution. What other solutions are possible, and when?

[6]

2. a) Sketch the spectral variation of attenuation in silica fibre, and outline the major physical mechanisms contributing to loss. Explain how this variation drives the choice of operating wavelength for long-distance optical fibre communication systems.

[6]

b) Sketch the corresponding spectral variation of refractive index. Explain how this variation drives the choice of wavelength for high bit-rate fibre communications. Is this conclusion in conflict with part a)? If so, what can be done to resolve the situation?

[6]

c) The broadening of a pulse of bandwidth $\Delta\omega$ as it propagates through a distance L is $\Delta T = L\, d(1/v_g)/d\omega\ \Delta\omega$, where $v_g = d\omega/dk$ is the group velocity. Show that this is equivalent to $\Delta T = -L(\lambda_0/c)\, d^2n/d\lambda_0^2\ \Delta\lambda_0$, where n is the refractive index of the medium, λ_0 is the free-space wavelength and $\Delta\lambda_0$ is the equivalent spectral range.

[8]

3. a) Sketch the layout and briefly describe the operation of an electro-optic directional coupler switch, explaining what is meant by the 'bar' and 'cross' states.

[6]

b) Draw the schematic of a 4 x 4 non-blocking switch array and sketch the physical arrangement of a coupler-based array. How many couplers are required in a general N x N non-blocking array?

[4]

c) The coupled mode equations of an asynchronous directional coupler are:

$$dA_1/dz + j\kappa\, A_2 \exp(-j\Delta\beta z) = 0$$

$$dA_2/dz + j\kappa\, A_1 \exp(+j\Delta\beta z) = 0$$

Here A_1 and A_2 are the amplitudes of the modes in the two guides, κ is the coupling coefficient and $\Delta\beta$ is the dephasing parameter. Without solving the equations, show that they conserve power.

[5]

d) Assuming that the device is synchronous, solve the equations for the boundary conditions $A_1 = 1$, $A_2 = 0$ on $z = 0$. Show that the solutions also conserve power.

[5]

4. a) Explain the operation of a photodiode. Why is a photodiode more efficient than a photoconductive detector?

[7]

b) Sketch and explain the distribution of electrons near the valence and conduction band edges at room temperature in a semiconductor. What does this distribution imply about the relative likelihood of absorption of photons whose energies are i) only just greater and ii) much greater than the band-gap?

[7]

c) Draw the physical arrangement of a surface entry photodiode. How does the result in b) above affect its performance? Sketch the spectral variation in responsivity you would expect.

[6]

5. a) Explain the difference between direct- and indirect-gap materials. Which type of material is required in optoelectronics?

[6]

b) Explain the difference between spontaneous emission and stimulated emission. Which phenomenon is exploited in LEDs and lasers?

[6]

c) Explain why the external efficiency of an LED is so low. Assuming the refractive index of GaAs is 3.5, estimate the external efficiency of a GaAs LED.

[8]

6. A semiconductor laser designed for operation at 1.5 μm wavelength is based on a waveguide with effective index $n_{eff} = 3.5$ and gain coefficient $g = 2355\ m^{-1}$ when lasing.

a) Determine the conditions for round trip resonance, and show how this leads to separate conditions for phase and gain.

[8]

b) Estimate the length of the laser and the spectral separation $\Delta\lambda$ between adjacent longitudinal modes.

[6]

c) A new laser is fabricated, with a different cavity length, and it is noted that its spectral separation $\Delta\lambda$ has double the value found in b). Estimate the gain coefficient now needed for lasing. Comment on the tradeoff between spectral separation and gain.

[6]