EE4-06
EE9-AO9
EE9-SO9

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2015

MSc and EEE/EIE PART IV: MEng and ACGI

Corrected Copy

OPTICAL COMMUNICATION

Tuesday, 5 May 2:30 pm

Time allowed: 3:00 hours

There are SIX questions on this paper.

Answer Question ONE, and ANY THREE of Questions 2 to 6

All questions carry equal marks.

Any special instructions for invigilators and information for candidates are on page 1.

Examiners responsible First Marker(s) : E.M. Yeatman, E.M. Yeatman
Second Marker(s) : A.S. Holmes, A.S. Holmes

Special instructions for invigilators: None.

Information for Candidates:

Numbers in brackets in the right margin (e.g. [5]) indicate maximum marks for each section of each question.

The following constants may be used:

electron charge :	$e = 1.6 \times 10^{-19}$ C
permittivity of free space :	$\varepsilon_0 = 8.85 \times 10^{-12}$ F/m
relative permittivity of silicon :	$\varepsilon_r = 12$
Planck's constant :	$h = 6.63 \times 10^{-34}$ J s
Boltzmann's constant :	$k = 1.38 \times 10^{-23}$ J/K
speed of light :	$c = 3.0 \times 10^{8}$ m/s

The eigenvalue equations for TE modes in a symmetric slab waveguide of thickness d are

$\kappa = k_{1x}\tan(k_{1x}d/2)$ and $\kappa = -k_{1x}\cot(k_{1x}d/2)$

1. You should attempt all parts of this question. Short answers only are required; there is no need to re-state the questions in your answer book, but you should show any calculations you use to arrive at your answers, state any assumptions or approximations made, and give a brief (one or two lines) explanation where appropriate. All parts have equal value. [20]

a) Approximately how long does it take for an optical pulse to travel down 200 km of silica-based optical fibre?

b) A step-index highly multi-mode silica fibre has a numerical aperture NA = 0.30. Estimate the maximum angle away from the axial direction that light can propagate and still be guided by total internal reflection at the core-cladding boundary.

c) A photodiode produces 10.4 nA of photocurrent for an incident optical power of 15 nW at a nominal wavelength λ_o = 980 nm. Calculate the quantum efficiency η of the diode.

d) A certain symmetric slab waveguide of thickness d = 4 μm supports exactly 3 TE modes for λ_o = 850 nm. Calculate the range of possible values of NA of this waveguide.

e) Briefly explain why the wavelength of zero dispersion in silica fibre is different from that of bulk silica glass.

f) The drift velocity of charge carriers in a semiconductor for low values of applied electric field E equals the product of E and what other quantity? For which type of carrier does this quantity usually have a higher value, electrons or holes?

g) An optical detector receives a steady signal of 10^{11} photons per second at λ_o = 1550 nm. Give the power level of the optical signal in both nW and dBm.

h) If the refractive index of a material has an imaginary component, what does this imply about a wave propagating in that material?

i) What is the main advantage of graded index over step-index multi-mode fibre?

j) A certain glass absorbs an optical wave propagating in it such that over a distance of 100 m the intensity is reduced by 5%. Calculate the corresponding attenuation coefficient in dB/km.

2.

a) Consider a symmetric slab waveguide as shown in Fig. 2.1, operating at a certain nominal wavelength λ_o. For the lowest order TE mode (m=0), the electric field amplitude at the core boundary is found to be half that at the centre, i.e. $E(x=d/2) = 0.5E(x=0)$. Calculate the value of $X = k_{1x}d/2$ for this mode. [4]

b) Calculate the number of TE modes supported by the waveguide of part (a). Plot a diagram of Y vs X (with $Y = Kd/2$), showing the supported modes. [4]

c) Show that for the m=0 mode described in (a), the effective index n' satisfies the relation:

$$n'^2 = \frac{n_1^2 + n_2^2}{2} \quad \times \quad n'^2 = \frac{3n_1^2 + n_2^2}{4}$$

[6]

d) If the m=o mode has unit electric field amplitude (in V/m) at x=0, find the amplitude at $x = 2d$. [6]

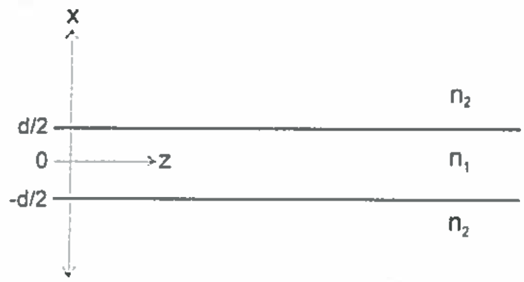

Figure 2.1 Slab waveguide

3. a) Sketch a plot of the typical relation between input current and output optical power for a semiconductor laser diode. Explain what is meant by each of the threshold current I_{th} and the slope efficiency S, and indicate these on your plot. [4]

b) A certain semiconductor laser diode operating at a nominal wavelength $\lambda_o \approx 1300$ nm has a quantum efficiency $\eta = 0.85$. If the output power is 2.3 mW for an input current of 26 mA, calculate the threshold current I_{th}. [4]

c) Because of a change in temperature, the threshold current of the laser in (b) now drops by 2 mA. Calculate the change in output optical power. [4]

d) The laser in (b) above is a Fabry-Perot laser, and is found to have longitudinal modes in its output separated by $\Delta\lambda \approx 0.2$ nm (in terms of the free-space wavelengths). The effective index of the guided modes $n' \cong 3.40$. Calculate the approximate cavity length L of the laser. [4]

e) Describe a way in which the laser described in (d) could be modified so that it outputs only a single longitudinal mode. [4]

4. a) Two optical links are constructed over the same length. Link A uses a receiver with noise equivalent power (NEP) of 10.0 pW/√Hz, and fibre with loss 0.35 dB/km. Link B uses a receiver with NEP of 8.0 pW/√Hz, and fibre with loss 0.36 dB/km. The transmitted power and bit rate are the same for both systems. The link capacity (maximum bit rate) is found to be limited by receiver noise, and to be the same, in both systems. Calculate the link length L, stating any approximations or assumptions made [6]

b) Estimate the bit rate in the links of part (a). Hence, show that for these links the shot noise will be significantly less than the receiver noise, assuming that the optical SNR equals 12 when considering receiver noise only. [6]

c) Show that for an optical receiver with quantum efficiency $\eta = 1$, the shot noise and receiver noise will be equal if twice the received optical power equals the noise equivalent power squared divided by the photon energy. [4]

d) Show that if an optical link is limited by shot noise, the number of electrons per bit in the photocurrent is simply equal to the square of the optical signal-to-noise ratio. State any assumptions or approximations made. [4]

5. A certain glass has an index of refraction n given by:

$$n(\lambda_o) = n_o + a(\lambda_o - \lambda_c)$$

where λ_o is the free space wavelength, λ_c is a constant reference wavelength, n_o is the index of refraction at λ_c, and a is a constant coefficient.

a) Explain why there is no material dispersion in this glass. [4]

b) Derive an expression for the group delay τ_g for a propagation length L in this glass. [6]

c) Using a definition for group velocity in a guided mode, derive an expression showing that the pulse broadening due to chromatic dispersion is proportional to $d^2n'/d\lambda^2$, where n' is the mode effective index. [6]

d) Give an approximate equation indicating the maximum dispersion that can be included in a fibre link analysis as a power budget penalty, in terms of D, L, σ_λ and the bit rate B. Briefly explain why this is valid. [4]

6. A silicon p-i-n photodiode has *p*, *i* and *n* doping levels respectively of $N_A^+ = 5\times10^{20}\ m^{-3}$, $N_D^- = 10^{19}\ m^{-3}$ and $N_D^+ = 10^{20}\ m^{-3}$. The distances from the diode surface to the top and bottom of the intrinsic layer are $X_1 = 1.5$ μm and $X_2 = 6.5$ μm respectively.

a) Find the minimum applied voltage needed to fully deplete the intrinsic layer. On a single sketch, show the shape of the electric field E(x) at this voltage, and at voltages somewhat above and somewhat below this level. Label and dimension your sketch as appropriate. [4]

b) Assume that the electron and hole mobilities are 1400 and 450 $cm^2V^{-1}s^{-1}$ respectively, and that the saturation drift velocity for both electrons and holes is $v_D = 5\times10^4$ m/s. Calculate the minimum applied voltage such that the electrons are at v_D throughout the intrinsic region. Determine for which portion of the intrinsic region, if any, the holes are also at v_D for this voltage. [4]

c) If the photodiode is biased at the level specified in (a) above, estimate the fractional change in the diode capacitance per percent increase in applied voltage above this level. For what reasons is the diode capacitance significant? [8]

d) Discuss why it may be disadvantageous for the intrinsic layer in a p-i-n photodiode to be lightly p-doped rather than n-doped. [4]