EE4-06
EE9-AO9
EE9-SO9

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2016

MSc and EEE/EIE PART IV: MEng and ACGI

Corrected copy

OPTICAL COMMUNICATION

Thursday, 28 April 10:00 am

Time allowed: 3:00 hours

There are FIVE questions on this paper.

Answer Question ONE, and ANY THREE of Questions 2 to 5

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
Second Marker(s) : 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) What is the relationship between the refractive index and the permittivity of a dielectric material?

b) If at some instant in time a 1 km length of optical fibre contains 5000 bits of propagating information, what is the bit rate of this signal?

c) A certain step-index optical fibre supports two modes, m=0 and m=1. For which of these two modes is a larger proportion of the propagating signal contained within the fibre core?

d) A certain laser diode transmits a signal of average power 6 dBm at a nominal wavelength λ_o = 1330 nm. Calculate the average number of photons per second transmitted.

e) Calculate the slope efficiency of a laser diode operating at λ_o = 1510 nm if the quantum efficiency is 0.85.

f) Give an expression for the electrical power per unit bandwidth of thermal noise in an optical detector.

g) If thermal noise and shot noise are equal in a certain optical fibre link, and then the fibre length is decreased by 50%, which of these noise sources will now be greatest at the detector?

h) Briefly explain why silicon is a poor semiconductor for constructing optical sources.

i) A silica optical fibre has a numerical aperture of 0.28. Estimate the refractive index difference Δn.

j) Estimate the spectral width in nm of an LED operating at a nominal wavelength of 490 nm.

2. A symmetric slab waveguide as shown in Fig. 2.1 has a core thickness d, and a numerical aperture NA = 0.19.

a) Find the value d/λ_0, where λ_0 is the free space wavelength, for which the m=0 TE mode of this guide has an electric field distribution E(x) such that $E(d/2) = E(0)/\sqrt{2}$. [10]

b) Does the guide that satisfies the condition in (a) support any additional TE modes, and if so how many? [5]

c) If the guide that satisfies the condition in (a) has a core thickness $d = 4.5$ µm, at what distance Δx beyond the boundary at x = $d/2$ does the electric field amplitude drop to ½E(0)? [5]

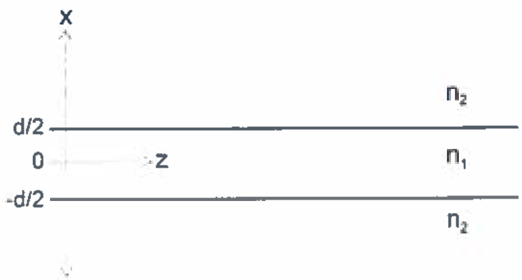

Figure 2.1

3. a) Give expressions for the optical SNR of a fibre link for each of the two cases: (i) when dominated by shot noise; (ii) when dominated by receiver thermal noise. Define all terms used. [6]

b) A certain optical receiver has a noise equivalent power (NEP) of 8 pW/√Hz, and is used in a link with an operating (free space) wavelength $\lambda_0 = 1.53$ µm. Find the received optical power Φ_r for which the noise contributions of shot noise and receiver noise are equal. [6]

c) For the case given in (b), if the required SNR is 12, what will be the maximum bit rate B that can be supported? Indicate any assumptions or approximations made. Is this a realistic bit rate, and if not why not? [8]

4. a) How are group and phase velocity each defined for a propagating electromagnetic wave? What is the main physical significance of group velocity? [6]

b) In the wavelength range of interest, the refractive index of a sample of silica glass can be approximated by

$$n(\lambda) \cong D_o + D_1 \lambda_o^{-2} - D_2 \lambda_o^2 \qquad (5.1)$$

where $D_o = 1.45$, $D_1 = 0.0028\ \mu m^2$ and $D_2 = 0.0026\ \mu m^{-2}$. Find expressions for the phase and group velocities v_p and v_g in this material, as functions of D_o, D_1, D_2, and λ_o and c. Hence show that v_g is always $< v_p$ in this case. [8]

c) For the glass described above, find the wavelength of zero material dispersion. [6]

5. a) A silicon p-i-n photodiode has intrinsic layer thickness $w_i = 8\ \mu m$, and p and n doping levels respectively of $N_A^+ = 2\times10^{21}\ m^{-3}$ and $N_D^+ = 10^{21}\ m^{-3}$. The intrinsic layer doping level is labelled as N_D^-. The electron and hole velocities can be approximated as linearly proportional to applied field, with mobilities (drift velocity per unit electric field) of $0.125\ m^2/Vs$ and $0.05\ m^2/Vs$ respectively, up to a saturation velocity of 10^5 m/s (for both electrons and holes). Find the applied electric field amplitude at which the electrons reach their saturation velocity. Hence, find the value of N_D^- such that the electron velocity reaches the saturation value at the p-i junction, and drops 10% below this value across the intrinsic region. Calculate also the corresponding applied voltage needed to reach this condition. [10]

b) For the structure and conditions of part (a), find the maximum time for a carrier pair to be swept out of the depletion region for a photon absorbed in the intrinsic region (you may neglect the propagation in the depleted parts of the n^+ and p^+ regions). You may find the following integral useful:

$$\int \frac{dx}{C+ax} = \frac{1}{a}\ln(C+ax)$$

[5]

c) Explain why the photodiode is a superior detector to the simple photoconductor for optical communications. [5]