EE4-06
EE9-AO9
EE9-SO9

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2019

MSc and EEE/EIE PART IV: MEng and ACGI

Cc **Corrected Copy** 1

OPTICAL COMMUNICATION

Thursday, 2 May 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) :	R.R.A. Syms

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 :	$\varepsilon_o = 8.85 \times 10^{-12}$ 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) An optical signal arrives at the end of a 50 km length of fibre with 1% of the intensity launched at the transmitter end. Calculate the fibre loss coefficient in dB/km.

b) A certain slab waveguide supports two TE modes, m=0 and m=1. For the m=1 mode, is the optical intensity higher at the centre of the guide, or at the core-cladding boundary? Give a brief explanation.

c) A certain slab waveguide supports 20 TE modes at a nominal wavelength $\lambda_o = 780$ nm. For an increased wavelength of $\lambda_o = 1350$ nm, would you expect the guide to support fewer, more or the same number of TE modes? Give a brief explanation.

d) If at some instant in time a 600 m length of optical fibre contains 3750 bits of propagating information, what is the bit rate of this signal?

e) Why is silicon not a suitable material for constructing detectors for optical systems operating at nominal wavelength 1550 nm?

f) Calculate the slope efficiency of a laser diode operating at $\lambda_o = 1330$ nm if the quantum efficiency is 0.88.

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

h) Estimate the spectral width in nm of an LED operating at a nominal wavelength of 580 nm.

i) A silicon p-n photodiode has p and n doping levels of $N_A = N_D = 4 \times 10^{20}$ m^{-3}. Calculate the bias voltage for which the maximum electric field strength will be 10^5 V/m.

j) A certain glass, for a nominal wavelength of $\lambda_o = 600$ nm, has a refractive index of $n = 1.50 + j \cdot 10^{-6}$. Find the attenuation coefficient at this wavelength, in units of m^{-1}.

2. On pg. 1 the eigenvalue equations are given for TE modes in a symmetric slab waveguide as shown in Fig. 2.1 For a slab thickness $d = 4$ μm, a nominal wavelength $\lambda_o = 0.92$ μm, and refractive indices $n_1 = 1.51$ and $n_2 = 1.50$, and considering only TE modes:

a) How many modes does the guide support? [4]

b) On a single plot, labelled appropriately, sketch the cross sectional shape $|E|^2$ vs x for each of the supported modes. [4]

c) Calculate the effective index n' for each of the supported modes to 3 decimal places. [8]

d) For a TE mode of order m=1 in an arbitrary symmetric slab waveguide, derive an expression for the position x_m at which the field intensity $|E|^2$ is maximised, as a function of the effective index n' of the mode, the nominal wavelength, and the core index n_1. [4]

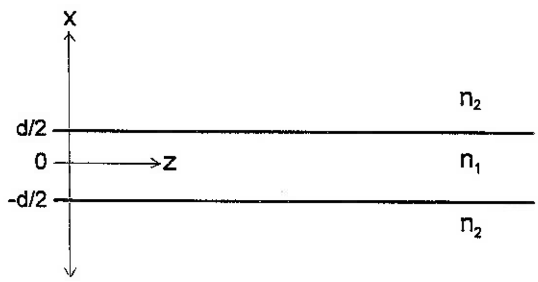

Figure 2.1 Slab waveguide

3. 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

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

where $D_o = 1.45$, $D_1 = 0.003$ μm^2 and $D_2 = 0.0032$ μm^{-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. [6]

c) For the glass described above, find the wavelength of zero material dispersion. [4]

d) For the glass described above, derive an expression for the phase change $\Delta\varphi$ experienced by a wave of nominal wavelength λ_o propagating a distance L. [4]

4. a) Describe and discuss the important attenuation mechanisms in optical fibres, and the influence these have in choice of operating wavelengths. Use diagrams and equations where appropriate. [6]

b) An optical receiver can be implemented as a photodiode in series with a resistor, followed by a voltage amplifier. State the principal noise sources in this case, and draw a noise equivalent circuit for the receiver. [4]

c) A certain optical link has a receiver with noise equivalent power (NEP) of 8.0 pW/√Hz, at the end of 100 km of fibre having attenuation of 0.35 dB/km at the operating wavelength of 1310 nm. The transmitted power is 4 mW and the photodetector quantum efficiency can be approximated as 1.

i) Determine whether shot noise or receiver noise is greater in this case; [4]
ii) Considering only the dominant noise source as determined in (i), find the maximum bit rate for an optical SNR of 12; [4]
iii) For the bit rate determined in (ii), find an approximate value for the maximum dispersion coefficient for this fibre above which the dispersion penalty would exceed 3 dB. Assume a transmitter spectral width σ_λ of 1.0 nm. [2]

5. a) A silicon p-n photodiode (Fig. 6.1) has a depletion layer thickness of w, and p and n doping levels respectively of N_A and N_D, with $N_A = 5N_D = 5\times10^{20}$ m^{-3}. The quantities w_p and w_n are the depleted widths in the p and n regions respectively. A reverse bias voltage V_b is applied. Find an expression for the full depletion width w as a function of V_b, and the value of V_b for which $w = 6$ μm. [8]

b) Neglecting Fresnel reflection, find an expression for the quantum efficiency η of the photodiode of (a) if the total p region thickness $h = 6$ μm, and the absorption coefficient $\alpha = 0.85\times10^5$ m^{-1}. Hence find the value of V_b for which $\eta = 0.80$. [6]

c) Give a typical approximate value for the saturation drift velocity of electrons in a semiconductor. For the photodiode of part (a) and an electron mobility in the silicon of 0.12 m^2/Vs, find the bias voltage for which the electron drift velocity is above this saturation value in half of the depleted region. [6]

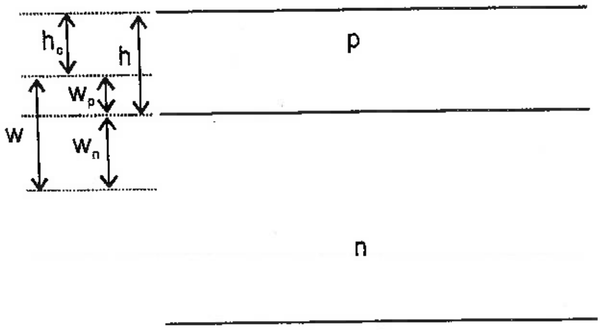

Figure 5.1 p-n photodiode