IMPERIAL COLLEGE LONDON

EE4-06
EE9-AO9
EE9-SO9

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2014

MSc and EEE/EIE PART IV: MEng and ACGI

Corrected Copy

OPTICAL COMMUNICATION

Thursday, 22 May 10:00 am

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) If a laser operating at a nominal wavelength of 1330 nm has a fractional bandwidth of 5%, what is its bandwidth in GHz?

b) An optical point-to-point link has thermal noise and shot noise of similar magnitude. If the fibre length is now increased by 20 km, and the system is otherwise unchanged, which would you expect would now dominate: thermal noise, shot noise, or neither? Give a brief explanation.

c) A lens can be used to increase the coupling of light from an LED to a fibre only if what condition is true?

d) An optical pulse associated with a single bit of a communication signal, propagating in glass optical fibre, is 40 cm long. Estimate the signal bit rate.

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

f) A certain optical fibre supports two modes of effective indices 1.475 and 1.480 respectively. Which of the two modes will experience higher loss due to bending of the fibre? Give a brief explanation.

g) A certain symmetric slab waveguide has core and cladding indices of 1.52 and 1.50. For a nominal operating wavelength of 1300 nm, what is the slab thickness below which it will only support a single TE mode?

h) Give one practical advantage of multi-mode optical fibre compared to single mode fibre.

i) Find the power reflection coefficient for light at normal incidence on a planar boundary between lossless media of refractive indices 1.30 and 1.50 respectively. Does this value depend on which side the light is incident from?

j) Why can the attenuation of an optical signal in free space not be adequately represented by a value in units of dB/km?

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 $\lambda_o = 1.30$ μm, and refractive indices $n_1 = 1.52$ 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. [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]

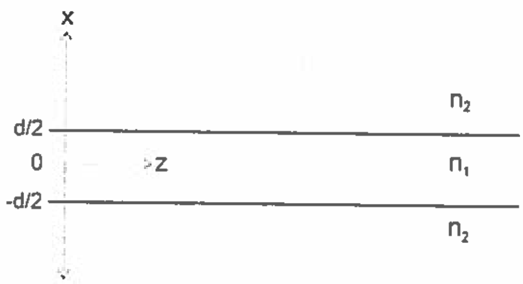

Figure 2.1 Slab waveguide

3. a) Name and briefly describe the two mechanisms that contribute to chromatic dispersion in an optical communications fibre. [4]

b) In the wavelength range of interest, the effective index of the propagating mode in a single mode fibre can be approximated by

$$n'(\lambda_o) \cong D_o + D_1(\lambda_o - \lambda_{oc}) \qquad (3.1)$$

where λ_o is the free space (nominal) wavelength, λ_{oc} is a reference wavelength, and D_o and D_1 are constants. Show that the group velocity v_g can be expressed as:

$$v_g = \frac{c}{D_o - D_1\lambda_{oc}}$$

in this case. [8]

c) Hence, find the group delay τ_g in this case for a fibre of length L. [4]

d) What can you conclude about the chromatic dispersion in this case? [4]

4. A laser of peak output power 10 dBm, with nominal wavelength $\lambda_o = 1510$ nm, emits into a fibre with an attenuation of 0.25 dB/km. It is modulated with an on-off keying format at a bit rate B = 1 Gbit/s. The receiver has quantum efficiency $\eta = 0.85$ and input resistance R = 10 kΩ.

a) Assume that the SNR is dominated by thermal noise in the receiver. Hence, find the maximum fibre length L for which the optical SNR will be 12 or greater. Neglect dispersion, and state any other approximations or assumptions made. [6]

b) Assume that the SNR is dominated by shot noise in the receiver. Hence, find the maximum fibre length ΔL for which the optical SNR will be 12 or greater. Neglect dispersion, and state any other approximations or assumptions made. [6]

c) Considering only thermal noise and only shot noise respectively, as in (a) and (b) above, find in each case the additional fibre length L which reduces the maximum bit rate to 0.5 GBit/s for an optical SNR of 12. [6]

d) For lengths significantly less than those determined in (a) and (b) above, what other factors might limit the maximum bit rate besides signal-to-noise ratio? [2]

5. a) Sketch a typical optical power vs. input current curve for a laser diode, indicating key features. Describe qualitatively the reasons for the existence of a threshold current, and the factors that contribute to it, and briefly discuss its practical implications. [4]

b) A certain Fabry-Perot laser diode has a threshold current of 3.0 mA. Hence, calculate the input current required to reach an output optical power of 6 dBm, assuming a free space operating wavelength of 1.51 μm and a quantum efficiency $\eta = 0.8$. [6]

c) Show that the frequency spacing of the longitudinal modes of a laser diode is just the reciprocal of the round-trip time in the cavity. [4]

d) Explain what is meant by internal and external quantum efficiency for an optical source. What are the key factors affecting the quantum efficiencies for (i) light emitting diodes; and (ii) laser diodes. [6]

6. 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 $N_A = 5N_D = 5\times10^{20}\ \mathrm{m}^{-3}$. 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 $w = 5\ \mu\mathrm{m}$. [8]

b) Neglecting Fresnel reflection, find an expression for the quantum efficiency η of the photodiode of (a) if the total p region thickness $h = 8\ \mu\mathrm{m}$, and the absorption coefficient $\alpha = 0.8\times10^5\ \mathrm{m}^{-1}$. Hence find the value of V_b for which $\eta = 0.80$. [6]

c) For an electron mobility in the silicon of $0.12\ \mathrm{m}^2/\mathrm{Vs}$, find the bias voltage for which the peak electron drift velocity in this device reaches 6×10^4 m/s. [6]

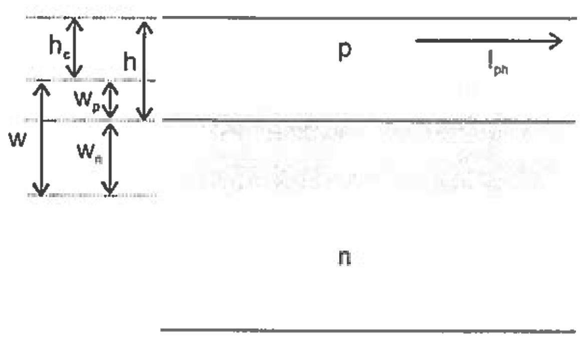

Figure 6.1 p-n photodiode