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IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2008

MSc and EEE/ISE PART IV: MEng and ACGI

Corrected Copy

OPTICAL COMMUNICATION

Wednesday, 21 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
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 :	$\varepsilon_o = 8.85 \times 10^{-12}$ 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

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

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) A slab waveguide supports 3 TE modes, m = 0, 1 and 2. Which of these has the highest phase velocity, and why?

b) A transmitter launches 3 mW of optical power into a fibre 150 km long, and the optical power at the far end of the fibre is 100 nW. Calculate the propagation loss in dB/km.

c) An optical fibre is constructed having a silica core and an air cladding. Estimate its numerical aperture.

d) An optical link is running at 2.5 Gbit/s. Estimate the thermal electrical noise assuming the receiver operates at room temperature.

e) Briefly describe one way in which a heterostructure can be used to increase the performance of a p-i-n photodiode.

f) If a particular semiconductor has an indirect bandgap, does this prevent, or significantly impede, its use to construct an optical detector?

g) A photodetector operating at a nominal wavelength of 1.53 μm has a responsivity of 1.022 A/W. Calculate the quantum efficiency.

h) Two Fabry-Perot laser diodes have cavity lengths of 400 and 450 μm respectively. Which will have the closest spacing of longitudinal modes?

i) Briefly describe the difference between homodyne and heterodyne coherent receivers.

j) Many silica fibres have a peak in attenuation between the 1.3 and 1.5 μm communications wavelength bands. What is the cause of this peak?

2. On pg. 1 the eigenvalue equations are given for TE modes in a symmetric slab waveguide as shown in Fig. 2.1.

a) Consider two such slab waveguides, for use at a free-space wavelength of 1.530 μm. Guide *A* has $n_1 = 1.470$ and $n_2 = 1.450$. Guide *B* has $n_1 = 1.465$ and $n_2 = 1.460$. For each of these guides, determine the maximum thickness *d* for which only a single TE mode is supported. [6]

b) For each of guide *A* and *B*, with the thickness *d* chosen as calculated in (a), determine the effective index of the m=0 mode, to 4 significant figures. Show your work. [10]

c) Discuss the factors and trade-offs involved in choosing the core diameter and refractive index difference for a single mode optical fibre. [4]

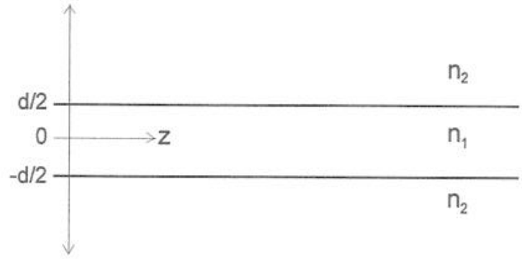

Figure 2.1 Slab waveguide

3. a) To construct a certain optical link, two receivers are available. Receiver A has a detector quantum efficiency η of 0.8 and a noise equivalent power (NEP) of 12 pW/√Hz, while receiver B has η = 0.7 and NEP = 9 pW/√Hz. Assuming the link capacity (maximum bit rate) is limited by receiver noise, which receiver will provide the highest link capacity? Show your reasoning. [4]

b) For the two receivers described in (a), which will provide the highest capacity if shot noise is the limiting factor? [4]

c) Show that for an optical receiver with quantum efficiency η = 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) For a certain optical link whose maximum bit rate of 1.5 Gbit/s is limited by shot noise, if we increase the required electrical SNR by 3 dB, what will the maximum bit rate now be? [2]

e) Show that if an optical link is limited by receiver noise, the maximum bit-rate×length product B×L will be obtained for a length L=1/2α, with α the attenuation coefficient. Calculate a corresponding bit rate, taking reasonable values for the relevant parameters. Explain why such a bit rate cannot be exploited in practice. [6]

4. a) A light emitting diode (LED) has a horizontal active region located 4 μm from the flat, horizontal semiconductor-air interface. Calculate the maximum angle from the vertical, θ_m, for which emitted photons are able to cross the semiconductor-air interface, and find the fraction of photons which are emitted within this angular range. Assume that the active region emits photons equally in all directions. The refractive index of the semiconductor is 3.6. [6]

b) For the photons emitted within the angular range θ_m determined above, estimate the fraction absorbed between the active region and the surface. Assume an attenuation coefficient of 2×10^3 cm^{-1}. State any assumptions or approximations made. [4]

c) A uniform plastic layer of thickness 5 μm and refractive index 1.48 is now added to the semiconductor surface. Find the maximum emission angle θ_m which is now required for emitted photons to cross the semiconductor-plastic interface. For the photons crossing this interface, and neglecting absorption and Fresnel reflection at the interfaces, find the fraction which escape into the air. Briefly discuss the effect of this added layer on the overall external quantum efficiency η_{ext}. [6]

d) A domed plastic layer placed on the semiconductor surface can be used to increase η_{ext}. Why is such a structure unlikely to increase the amount of light that can be coupled from the LED into a single mode optical fibre? [4]

5. a) Describe the structure and operating principles of erbium doped fibre amplifiers. Use diagrams where appropriate. Indicate the main performance criteria, and give typical values for these. Include a definition of amplified spontaneous emission (ASE) and discuss its significance. [8]

b) The ASE noise spectral density can be approximated as:

$$(I_A^*)^2 = 4\frac{e^2\lambda}{hc}G(G-1)\Phi_o \qquad (5.1)$$

where G and Φ_o are the gain and input optical power respectively. Show that if a high gain amplifier is placed before the receiver, the resulting optical SNR is worse by a factor of $\sqrt{2}$ than without the amplifier, if the latter case is dominated by shot noise. State any assumptions or approximations used. Hence, deduce the rate at which SNR degrades with number of amplifiers in a particular link.

Describe the most general conditions under which an optical amplifier will improve the SNR. [12]

6. A silicon avalanche photodiode (Fig. 6.1) has intrinsic and avalanche layer thicknesses of w_i and w_A respectively, acceptor doping levels N_{A+}, N_{Ai} and N_{AA} in the p^+, intrinsic and avalanche layers respectively, and donor doping level N_D in the n layer.

a) Assuming that a sufficient bias voltage has been applied to fully deplete both the intrinsic and avalanche regions, derive expressions for the difference in electric field strength ΔE_i across the intrinsic region, and the difference in electric field strength ΔE_A across the avalanche region, in terms of the doping levels and layer thicknesses. Hence, derive an expression for the minimum bias voltage, V_{min}, required to fully deplete these two layers. [8]

b) Calculate V_{min} as derived in (a) for the following parameter values:

$w_i = 8\ \mu m$, $w_A = 3\ \mu m$

$N_{A+} = 10^{21}\ m^{-3}$, $N_{AA} = 4\times10^{21}\ m^{-3}$, $N_{Ai} = 10^{20}\ m^{-3}$ and $N_D = 6\times10^{21}\ m^{-3}$

Plot and dimension the electric field profile E(x) for this case where the bias voltage equals V_{min}. On the same graph, sketch additional field distributions for bias voltages higher than and lower than this value. [8]

c) Discuss the necessary and the desirable properties of the electric field distribution for such a device, and some factors limiting the optimisation of the field distribution. [4]

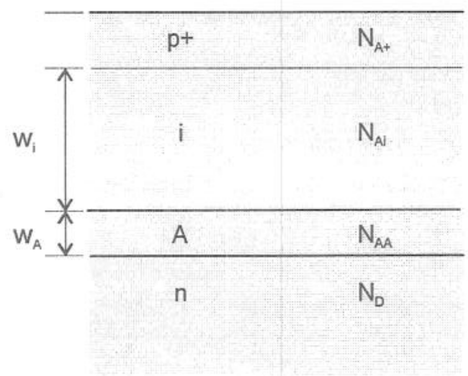

Figure 6.1