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IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2003

MSc and EEE/ISE PART IV: M.Eng. and ACGI

OPTICAL COMMUNICATION

Tuesday, 20 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.

Corrected Copy

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

Examiners responsible First Marker(s) : E.M. Yeatman
Second Marker(s) : K.D. Leaver

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, and give a brief (one or two lines) explanation where appropriate. All parts have equal value. [20]

a) A step index silica fibre has a core diameter of 6 μm and the cutoff wavelength for single mode operation is 1.520 μm. Estimate the index difference of the fibre.

b) Raising the refractive index difference has what effect (if any) on the number of supported modes in step index multi-mode fibre?

c) What loss mechanism dominates in silica-based fibre at wavelengths in the range 1600 – 2000 nm?

d) Estimate the spread in wavelengths, $\Delta\lambda$, emitted by a light emitting diode at room temperature with a nominal operating wavelength of 1310 nm.

e) Why is silicon not a suitable material for photodetectors for long-haul optical communication systems?

f) Which of the following is currently the highest bit rate in commercial optical transmitters – 10 Mbit/s, 400 Mbit/s, 1 Gbit/s, or 40 Gbit/s? What is the main factor limiting this value?

g) Briefly explain the main performance advantage for optical communications of distributed feedback lasers over Fabry-Perot lasers.

h) What is the maximum possible slope efficiency of a semiconductor laser operating at a nominal wavelength of 780 nm?

i) Briefly describe the main considerations in choosing suitable wavelengths for pump lasers in erbium-doped fibre amplifiers.

j) A passive 4-port coupler with negligible excess losses has an input of –10 dBm at one port, no signal at the other input port, and –20 dBm is emitted at one output port. What is the output power in dBm at the other output port and why?

2. a) A symmetric slab waveguide has a core thickness of 6 μm. For a certain transverse electric (TE) mode, the transverse wavevector component in the core is $k_{1x} = 1.19 \times 10^6 \text{ m}^{-1}$. Find the order m of this mode, and determine the total number of TE modes supported by this guide. You may find it helpful to sketch a graph of the eigenvalue equations. [8]

b) For the waveguide and mode of part (a), with a free-space wavelength of 1.50 μm, the phase velocity is found to be 2.027×10^8 m/s. Find the refractive index of the core, n_c, to 4 significant decimal places. [6]

c) For the waveguide and wavelength described in (a) and (b), estimate the effective index n', to 4 significant digits, of the lowest order (m=0) TE mode. [6]

3. a) Show that, at the wavelength λ where $d^2n/d\lambda^2 = 0$, the spread in pulse length due to material dispersion in a fibre is proportional to the third derivative of refractive index with respect to wavelength, i.e. $d^3n/d\lambda^3$. Derive an expression for the pulse broadening $\Delta\tau_g$ in this case. Note that the group delay $\tau_g = (L/c)(n - \lambda dn/d\lambda)$, where L is the fibre length. [6]

b) If the spread in wavelength of a signal is dominated by the inherent source width $\sigma_{\lambda S}$, derive an expression for the received pulse width in the time domain σ_R as a function of the transmitted pulse width σ_o, the fibre length L, and the dispersion coefficient D. Derive an expression for the minimum of σ_o as a function of $\sigma_{\lambda S}$ for which the relative pulse spreading $\sigma_R/\sigma_o < 1.25$. [6]

c) In a certain system the optical signal's spectral width is dominated by the input signal spectrum, and the inherent source width $\sigma_{\lambda S}$ is negligible. The input pulses are transform limited Gaussian, with variance σ_o. Show that for a certain fibre dispersion D·L there is a minimum received pulse width σ_R. Find an expression for the input pulse width σ_o at which this is obtained, and for the corresponding pulse spreading ratio σ_R/σ_o. [8]

4. a) A certain light emitting diode (LED) has radiative and non-radiative recombination lifetimes, τ_{rr} and τ_{nr} respectively, in the ratio $\tau_{nr}/\tau_{rr} = 5$. Calculate the internal quantum efficiency for this device. [2]

b) Describe four factors that may limit the external quantum efficiency in an LED, and for each of these indicate a technique that can reduce the effect of this factor. [8]

c) An LED is emitting into a step index, silica-based multi-mode fibre as shown in Fig. 4.1. The numerical aperture of the fibre is 0.10. Find the maximum emission angle θ from the LED active region for which light can be guided in the fibre, and the fraction of emitted power falling within this angle if the generated photons have a uniform directional distribution. [6]

d) For the fibre described in (c), derive an expression for the limit on bit rate imposed by multi-mode dispersion, and sketch this as a function of fibre length. [4]

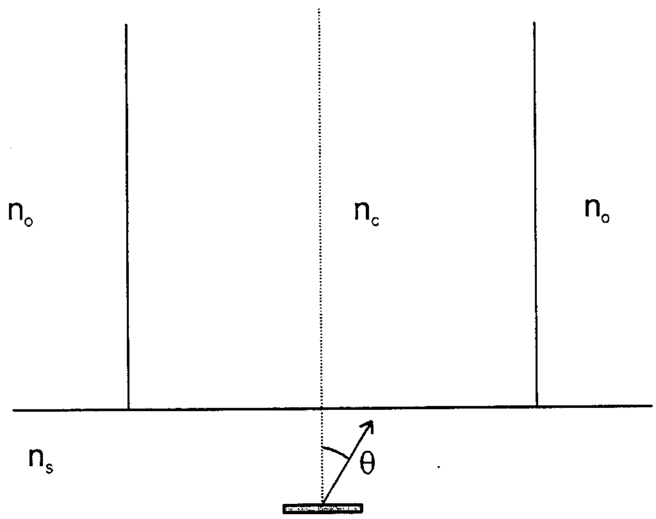

Figure 4.1

5. a) A certain receiver has unit quantum efficiency, and a noise equivalent power (NEP) of 5 pW/√Hz. Find the received optical power for which the shot noise and receiver noise are equal. [4]

b) The receiver in (a) is used in a system with transmitted power of 10 mW, and fibre attenuation of 0.43 dB/km. On-off keying is used, the signal bandwidth is at the Nyquist limit, and the minimum optical SNR is 10 dB.

Find an expression for the maximum bit rate B as a function of fibre length L, and simplify this expression for the two cases where shot noise or receiver noise dominate respectively. Using these approximations, sketch log(B) vs. L over a practical range of fibre lengths. [8]

c) The system described in part (a) is extended by adding an optical amplifier at a suitable point along the fibre. The amplifier has 20 dB gain and a noise figures of 4 dB. Modify your expressions from (b) for maximum bit rate, and sketch log(B) vs. L. [8]

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 $N_A = 5N_D = 10^{20}$ 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 = 10 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 = 10 μm, and the absorption coefficient $\alpha = 10^5$ m^{-1}. Hence find the value of V_b for which η = 0.9. [6]

c) Assume that the resistance R encountered by the photocurrent I_{ph} is dominated by the resistance of the undepleted part of the p region, as the current flows laterally through it as shown in Fig. 6.1. If this resistance is in turn is inversely proportional to the thickness h_c of this region, find the value of h_c in terms of h for which the time constant RC of the diode is minimised. [6]

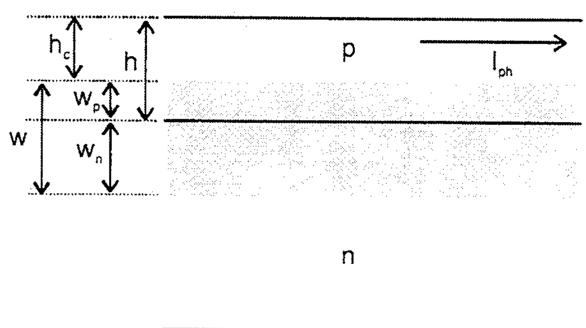

Figure 6.1