EE4-06
EE9-AO9
EE9-SO9

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2018

MSc and EEE/EIE PART IV: MEng and ACGI

Corrected copy

OPTICAL COMMUNICATION

Thursday, 3 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

© Imperial College London

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) Visible light passes through a sheet of transparent window glass at normal incidence. Estimate the attenuation experienced in dB.

b) A silica-based optical step-index fibre has an index difference Δn of 0.5%. Estimate the numerical aperture NA of the fibre.

c) Give one advantage and one disadvantage of plastic optical fibre for communications compared to glass optical fibre.

d) A p-i-n photodiode of refractive index ns = 3.61 is used to detect light of free space wavelength λ_o = 780 nm propagating in the air. Calculate the optimum thickness and refractive index of an anti-reflection coating for this application.

e) A 20 km long optical fibre with attenuation 0.4 dB/km has a power reflection coefficient R = 0.1 at the receiver end. If the transmitted power is 5 mW, calculate the power level of the reflected signal arriving at the transmitter.

f) An optical link using a p-i-n photodiode has an optical SNR of 10, dominated by shot noise, for a bit rate of B = 2.0 Gbit/s. calculate the photocurrent I_{ph}.

g) A certain dopant element is used in a 3-level optical fibre amplifier to give gain for optical signals having λ_o = 1300 nm. Estimate the energy difference ΔE in eV between the metastable and ground states for this element.

h) A silicon p-n photodiode has p and n doping levels of $N_A = 4 \times 10^{20}$ m^{-3} and $N_D = 1 \times 10^{20}$ m^{-3} respectively. Calculate the bias voltage for which the total depletion layer width will be 2.0 μm.

i) A certain optical fibre supports three modes of effective indices 1.473, 1.481 and 1.487 respectively. Which of these modes will experience higher loss due to bending of the fibre? Give a brief explanation.

j) What is the principal attenuation mechanism in high purity silica optical fibre at nominal wavelengths greater than 1.7 μm?

2\. a) A symmetric slab waveguide as shown in Fig. 2.1 has a core thickness d = 5.0 μm, and refractive indices n_1 = 1.480 and n_2 = 1.470. Find the minimum and maximum free space wavelengths, $\lambda_{o\text{-}min}$ and $\lambda_{o\text{-}max}$, for which this guide supports exactly two TE modes. [6]

b) Sketch a plot of κ vs. k_{1x} for a symmetric slab waveguide which illustrates the two examples above. Derive an expression for the effective index n′ of modes that are just at the cut-off condition, and hence show that they have $n' \cong n_2$. Explain why this should be so, with reference to the mode shape. [8]

c) For the waveguide of part (a), for the wavelength $\lambda_{o\text{-}max}$, calculate the effective index n′ for the m=0 TE mode to 3 decimal places. [6]

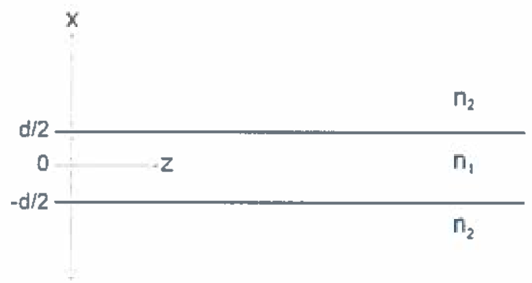

Figure 2.1

3\. a) Two optical links are constructed over the same length. Link A uses a receiver with noise equivalent power (NEP) of 9.0 pW/√Hz, and fibre with loss 0.32 dB/km. Link B uses a receiver with NEP of 6.5 pW/√Hz, and fibre with loss 0.33 dB/km. The transmitted power and bit rate are the same for both links. The link capacity (maximum bit rate) is found to be limited by receiver noise, and to be the same, in both systems. Calculate the link length L, stating any approximations or assumptions made. [6]

b) For Link A of part (a), find the length L for which the shot noise and receiver noise are of the same magnitude. You may assume that the quantum efficiency of the receiver $\eta = 1$, the operating wavelength λ_o = 1300 nm, and the transmitted optical power is 10 mW. [6]

c) Give an approximate equation indicating the maximum dispersion that can be included in a fibre link analysis as a power budget penalty, in terms of D, L, σ_λ and the bit rate B. For Link A above, find the bit rate B for which this limit is reached for the length L determined in (b). Assume that the transmitter spectral width σ_λ = 2.0 nm and the fibre dispersion coefficient D = 10 ps/nm·km. [4]

d) Show that if an optical link is limited by shot noise, the number of electrons per bit in the photocurrent is simply equal to the square of the optical signal-to-noise ratio. State any assumptions or approximations made. [4]

4. a) A certain Fabry-Perot laser diode has a cavity length of 450 μm and an effective index for the cavity modes of 3.80. The output spectrum has peaks separated in free space by $\Delta\lambda_o = 0.3$ nm. Estimate the centre wavelength λ_o of the device. [4]

b) For the laser in (a), estimate the number of longitudinal modes in the spectrum. [4]

c) The laser is then modified by adding distributed Bragg reflectors. Calculate a suitable period Λ for these. What is the main advantage of such structures? [4]

d) Sketch the output optical power vs input current for a typical laser diode, indicating key features. Illustrate how you would expect this to alter with changes in temperature. [4]

e) Derive an expression for the slope efficiency of a laser diode, explaining your assumptions and reasoning. [4]

5. A silicon p-i-n photodiode has *p*, *i* and *n* doping levels respectively of N_A, $N_D^- = 10^{19}\ m^{-3}$ and N_D^+. The distances from the diode surface to the top and bottom of the intrinsic layer are $X_1 = 2.0$ μm and $X_2 = 7.0$ μm respectively.

a) Find the optical attenuation coefficient α, in units of m^{-1}, which maximises the fraction of incident photons which are absorbed in the intrinsic layer of this device. [4]

b) Find the value of N_D^+ which allows the peak electric field magnitude to be only 20% greater than the magnitude at the bottom of the intrinsic layer, while only depleting 1.0 μm of the *n* layer. Then, find the value of N_A which allows these conditions to be achieved while only depleting 0.5 μm of the *p* layer. [8]

c) Find the applied bias voltage V such that the conditions in (b) are achieved and the peak electric field magnitude is 2×10^6 V/m. [4]

d) Calculate the junction capacitance per unit area of the photodiode, for the conditions given in (b). [4]

 © Imperial College London