**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 × 10-19 C

permittivity of free space : o = 8.85 × 10-12 F/m

relative permittivity of silicon : r = 12

Planck’s constant : h = 6.63 × 10-34 J s

Boltzmann’s constant : k = 1.38 × 10-23 J/K

speed of light : c = 3.0 ×108 m/s

The eigenvalue equations for TE modes in a symmetric slab waveguide of thickness d are

 = k1xtan(k1xd/2) and  =  k1x cot(k1xd/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.

Most people got the power reflection coefficient = 0.04, but wrongly converted this to dB by taking 10log(0.04). Correct answer is 10log(Pout/Pin) i.e. 10log(0.96). Also many people forgot to double this for the two surfaces passed through.

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

Many people took this to mean Δn = 0.005, but % means % of the index, so should be Δn = 0.005n.

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

Some people talked about plastic fibre having lower index (true) but without explaining well why this is good, or bad (it isn’t really either).

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

Most people got the index nAR being the geometric mean of 3.6 and 1, and that the thickness is /4, but for  used o, or used o/ns, whereas it should be o/nAR.

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.

The reflected signal is proportional to the power reflection coefficient R – many people incorrectly used (R-1). Generally people worked out the attenuation along the fibre, either by taking 8 dB off 5 mW converted to dBm, or by converting dB to  in km-1. But many forgot to add a further 8 dB loss for the return path.

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 Iph.

Most people got this without errors.

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

Here there was confusion between ΔE meaning the energy difference between the two states, and ΔE referring to a spread of energies as in an LED emission spectrum. This question is a straightforward calculation of the photon energy at the given wavelength. There was a tendency to give the answer to a very large number of decimal places, which suggests a precision that isn’t real.

h) A silicon p-n photodiode has p and n doping levels of NA = 4 ×1020 m-3 and ND = 1 × 1020 m-3 respectively. Calculate the bias voltage for which the total depletion layer width will be 2.0 µm.

Generally handled fine, no common errors or misconceptions.

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.

Generally handled fine, no common errors or misconceptions.

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

Many people identified this correctly as IR absorption, but many added no explanation of what IR absorption is caused by, without which it’s just a name.

2. a) A symmetric slab waveguide as shown in Fig. 2.1 has a core thickness *d* = 5.0 µm, and refractive indices n1 = 1.480 and n2 = 1.470. Find the minimum and maximum free space wavelengths, o-min and o-max, for which this guide supports exactly two TE modes. [6]

This one generally done well.

b) Sketch a plot of  vs. k1x 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´ ≅ n2. Explain why this should be so, with reference to the mode shape. [8]

Some people didn’t show the 2 limiting cases (as 2 circular arcs) on their plot. Some people mixed up the K-kix version of the graph (cut-offs at /d etc) with the Y-X version (cut-offs at /2 etc). Many calculated that n´ ≅ n2 for the specific cases, but didn’t find a general proof. (Noting that Y=0 at cut-off is a simple way). Some sketched the mode shape near cut-off, but no-one managed to show how the mode stretches out into the cladding.

c) For the waveguide of part (a), for the wavelength o-max, calculate the effective index n´ for the m=0 TE mode to 3 decimal places. [6]

Many calculated R, rather than just noting that it must be = /2 in this case. Otherwise fine.

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]

Just need to note that Link A needs 9/6.5x as much power, and find the length where that is so. Must either convert ratio 9/6.5 to dB, or convert the attenuation coefficients from dB to km-1. Some people forgot. Some solutions very long-winded/complicated, which is fine if correct but increases the chance of calculation error.

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  = 1, the operating wavelength o = 1300 nm, and the transmitted optical power is 10 mW. [6]

Most got the need to compare the SNRs for each case. Key point is that one is in optical power units, the other in photocurrent, need to use responsivity to convert one.

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*,  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  = 2.0 nm and the fibre dispersion coefficient *D* = 10 ps/nm·km. [4]

Typical error is to forget that max pulse spreading is ¼ bit (=1/4B), not just 1/B.

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]

Some didn’t provide full explanation, e.g. just solving SNR^2 = Iph/eB without explaining that Iph/e is electrons/sec and B is bits/sec.

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

A common mistake was to confuse Δλo meaning the spacing between modes, as stated in the question, and Δλo to mean the total range of wavelengths (the spectral width), which can be related to the spread in Energy approximated by 2kT. The latter is relevant in part (b), not here.

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

A number of people simply calculated the value of m. But the only values of m for which a mode exists are those giving a wavelength within the emission spectrum.

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

Oddly, a number of people got the right value of  but gave the units in s (or ns) rather than m (or nm). The period is in space – the grating is a physical structure.

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]

Generally fine.

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

Some people neglected to mention the basic principle leading to the equation – that exactly one additional photon is emitted for each additional electron input (if  = 1).

5. A silicon p-i-n photodiode has *p*, *i* and *n* doping levels respectively of *NA, ND = 1019 m-3* and *ND+*. The distances from the diode surface to the top and bottom of the intrinsic layer are X1 = 2.0 m and X2 = 7.0 m 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]

Important to state the units for α.

b) Find the value of *ND+* 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 m of the *n* layer. Then, find the value of *NA* which allows these conditions to be achieved while only depleting 0.5 m of the *p* layer. [8]

If E at the top and bottom of the intrinsic layer are labelled E1 and E2, then this question clearly states E1=1.2E2. This is not the same as E2=0.8E1! Many people made this error.

c) Find the applied bias voltage V such that the conditions in (b) are achieved and the peak electric field magnitude is 2 ×106 V/m. [4]

This part of the question is flawed (sorry!). If all the conditions of (b) are met, then Emax is fixed, and not at 2 ×106 V/m. Only one person noticed, but I marked this part extra generously anyway.

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

Some people tried to do this using C=Q/V. This doesn’t work because of the way the charge is distributed.