Imperial College London

BSc/MSci EXAMINATION May 2012

This paper is also taken for the relevant Examination for the Associateship

OPTICAL COMMUNICATIONS PHYSICS

For Third- and Fourth-Year Physics Students

Thursday, 31st May 2012: 10:00 to 12:00

Answer ALL parts of Section A, ONE question from Section B and ONE question from Section C.
Marks shown on this paper are indicative of those the Examiners anticipate assigning.

General Instructions

Complete the front cover of each of the FOUR answer books provided.

If an electronic calculator is used, write its serial number at the top of the front cover of each answer book.

USE ONE ANSWER BOOK FOR EACH QUESTION.

Enter the number of each question attempted in the box on the front cover of its corresponding answer book.

Hand in FOUR answer books even if they have not all been used.

You are reminded that Examiners attach great importance to legibility, accuracy and clarity of expression.

SECTION A: Compulsory questions

1. (i) (a) Explain the term Information Entropy, giving one example of a lossless compression technique to illustrate its importance. [1 mark]

(b) Explain the term Contitional Entropy, giving one example of a lossless compression technique to illustrate its importance. [2 marks]

(c) Explain the term perceptual coding, giving one example of a lossy compression technique to illustrate its importance. [2 marks]

(ii) A binary data stream is to be transmitted over a non-return to zero optical fibre link at B = 10Gbit/s.

(a) For the data as an electrical signal write down an expression for the simplest sinusoidal form needed to transmit the most unfavourable signal when the data stream consists of alternating ones and zeros? [1 mark]

(b) The electrical signal is used to modulate the intensity of a laser transmitter at a wavelength of λ = 1550nm. Determine an expression for the optical signal in frequency space. [2 marks]

(c) Sketch the amplitude spectrum of the transmitted optical signal, concentrating on only positive frequency components and hence determine its bandwidth [2 marks]

[Total 10 marks]

2. (i) A step index multimode optical fibre is constructed with a diameter of 50 μm, a core index of n_1 = 1.5 and a cladding index of n_2 = 1.45.

(a) In the ray picture, write down an expression for the range of allowed angles (θ) that enable the ray to guide along the fibre, and calculate the critical angle (θ_c). [2 marks]

(b) If the fibre is 1 km long estimate how many reflections take place in the path of a ray propagating at the critical angle, θ_c. [1 mark]

(c) The total fibre loss is 5dB/km. Estimate the loss in dB and percent at each reflection at the core/cladding interface for the critical ray assuming that this is the major source of loss in the fibre. [2 marks]

(ii) A semiconductor p-i-n diode uses a ternary of Al(x)Ga(1-x)As material (with a bandgap of 1.8 eV) for the p- and n-regions and a binary GaAs material (with a bandgap of 1.424 eV) for the intrinsic region. The substrate material is GaAs.

(a) What structural considerations should be considered when selecting materials for use in heterostructure devices? [1 mark]

(b) Under forward bias operation, the spectral width of the light emission from the structure is found to increase as the forward bias injection is increased. Briefly explain why this is expected? [2 marks]

(c) The internal quantum efficiency (i.e. electron-to-photon generation) in the device is very high and around 90%. Explain why the measured external quantum efficiency (found to be around 2%) is far lower? [2 marks]

[Total 10 marks]

SECTION B: Optional Questions - choose ONE

3. A message consisting of the string of 10 symbols ABBCBADDAB is to be transmitted over a binary physical channel.

(i) In order to make the transmitted bit string as short as possible, derive a Huffman code for the symbols {A,B,C,D} and hence determine a string of coded bits with which the message could be transmitted. [4 marks]

(ii) Calculate efficiency of the produced binary code. [3 marks]

The binary message is transmitted down the physical channel with a small bit error rate of $p_e = 0.001$.

(iii) Show that the probability that there is an undetected error in the transmitted message is given approximately by Np_e, where N is the number of bits in the message. [2 marks]

It is decided to add error detection to the message in the form of parity check bits by splitting the message into 3-bit symbols and adding a 4th bit to each to give even parity.

(iv) Write down the new transmitted 4-bit symbols in your message with the included parity bits, padding the final symbol with zeros to make it up to 3 bits if necessary. [1 mark]

(v) Estimate the probability that a given 4-bit symbol is transmitted with an undetected error. [2 marks]

(vi) Hence determine the probability that your whole message is transmitted with an undetected error and compare this to that for the message without error detection. [3 marks]

[Total 15 marks]

You may assume that the probability of k errors in n trials is given by the binomial probability distribution:

$$P(k;n) = \frac{n!}{k!(n-k)!} p_e^k (1-p_e)^{n-k}$$

Where p_e is the probability of an error in a single trial.

4. (i) Shannon's formula for the capacity C of a noisy channel is given by:

$$C = \Delta f \log_2(1 + S/N)$$

(a) Explain what is meant by channel capacity and the other terms Δf, S and N that appear in Shannon's equation. [3 marks]

In the PSTN transmission from the handset to the local exchange occurs over an analog line with bandwidth 4KHz and signal to noise ratio 40dB.

(b) Rewrite Shannon's equation to use a signal to noise ratio expressed in dB, that is valid in this case, and hence calculate the capacity of the analog channel. [2 marks]

(c) Suggest how the signal can be converted to a 64 kbit/s DS0 digital signal at the local exchange, explaining any precautions that should be taken. [3 marks]

(ii) Downstream of the local exchange the telephone call is routed over physical channels with a range of larger capacities including at one point a T2 coaxial cable at 6.32 Mbit/s and at another an OC48 optical fibre at 2.5 Gbit/s.

(a) Explain how this is achieved and in each case estimate how many other telephone calls can share the same connection. [3 marks]

(b) Actually the capacity of the T1 channel is only 96 calls and OC48 carries only 32,256 calls. What explains the difference between your estimate and these actual numbers. [1 mark]

(iii) The PSTN is referred to as a "circuit switched network", while the internet is a "packet switched network". Explain what is meant by each of these terms including examples of what works well and what works badly in each case. [3 marks]

[Total 15 marks]

SECTION C: Optional Questions - choose ONE

5. (i) Optical fibre modes, calculated from a full consideration of Maxwell's equations and the boundary conditions, may be classified into 4 distinct modal types.

(a) Write down the four classifications, noting for each case the dominant field component present along the propagation direction (taken as $z-$direction), also include any conditions on the radial mode number (m). [4 marks]

(b) What is the fundamental mode for a typical step-index fibre system? [1 mark]

(ii) An optical fibre system comprises a step-index fibre with a diameter of 5.5 μm, a core index of n_1 = 1.5 and a cladding index of n_2 = 1.485. A tunable laser diode with a fixed linewidth is to be used as the source, and spans the S-band (1480 – 1530 nm), C-band (1530 – 1565 nm) and L-band (1565 – 1625 nm) spectral windows.

(a) Verify that fibre system is sufficient to guarantee single mode operation for both the C- and L-spectral bands. (The first zero of the zero order Bessel function occurs for an argument of 2.405). [2 marks]

(b) Describe and comment on the main sources of dispersion likely to be present for operation over the S-, C- and L-bands. [2 marks]

(c) Justify which of the spectral bands should be used to maximise the achievable bit-rate? (The zero dispersion point of the fibre occurs around 1.3 μm.) [3 marks]

The fibre diameter is now changed to 4 μm to provide single-mode operation from $\lambda \geq 1.1$ μm.

(iii) Comment on how the total dispersion of the fibre is likely to be affected as a result of the change in diameter. Use a sketch of the total dispersion as a function of wavelength to justify your answer. [3 marks]

[Total 15 marks]

6. A p-i-n structure semiconductor comprises an active region (intrinsic) region of the quarternary compound InGaAsP, with a bandgap of 0.75 eV and lattice matched to the InP substrate, while the p- and n-regions are InP and have a bandgap 1.35 eV. The absorption coefficient of InGaAsP is $24,000\ \text{cm}^{-1}$ at 1.3 μm and thickness of the intrinsic region is 2 μm.

(i) The structure is designed to operate as a photodiode for 1.3 μm incident radiation.

(a) Sketch the spectral response of the structure, clearly indicating the wavelength range where efficient photogenerated current may be expected. [3 marks]

(b) Briefly list and comment on three key parameters that govern the speed response of a photodiode. [3 marks]

(ii) A general expression relating the resulting photocurrent (I) for a given incident optical power (I_0) may be written as

$$I = P_0 \times \frac{q}{\hbar\omega} \times \eta \times (1 - R) \times (1 - e^{-\alpha D})$$

such that 0.58 mA are generated for 1 mW incident radiation at 1.3 μm, despite the fact that around 30% of the incident radiation is reflected.

(a) How much photocurrent would be expected if 2.5 mW of optical power, at a wavelength of 1.3 μm, falls on the detector? [2 marks]

(b) From the measured responsivity of the device calculate its external quantum efficiency, η_{ext}. [2 marks]

(c) Calculate the internal quantum efficiency η and give one reason why this might not be 100%. [2 marks]

(d) If you were interested in maintaining a fast photodetector and could choose to maximise any one of the limiting terms which one would you choose and why? [3 marks]

[Total 15 marks]