ENGINEERING TRIPOS PART IIA

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26 April 2012 9 to 10.30

Module 3B6

PHOTONIC TECHNOLOGY

*Answer not more than **three** questions.*

All questions carry the same number of marks.

*The **approximate** percentage of marks allocated to each part of a question is indicated in the right margin.*

Attachment: Photonic Technology Data Sheet (2 pages)

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS
Engineering Data Book
CUED approved calculator allowed

You may not start to read the questions printed on the subsequent pages of this question paper until instructed that you may do so by the Invigilator

FINAL version

1 (a) Describe the important criteria for selecting materials for use in light emitting diodes for operation at a required wavelength, explaining why indirect bandgap materials have lower efficiencies than direct bandgap materials. [10%]

(b) Compare and contrast in detail the structures of surface-emitting and edge-emitting light emitting diodes, explaining, for each diode, how their emission efficiency may be maximised. What are the respective advantages and disadvantages of the structures? [30%]

(c) A GaAlAs/GaAs light emitting diode is driven from a voltage source, V, with an internal resistance of 10 Ω. The diode operates at a wavelength of 850 nm, has a parasitic resistance of 2 Ω, and has internal and external quantum efficiencies of 70% and 4% respectively.

(i) What value must V have if the light emitting diode is to generate an output optical power of 0.5 mW? [20%]

(ii) If the radiative lifetime of the light emitting diode is 2 ns, determine the non-radiative lifetime and hence estimate the maximum bit rate of the device, assuming that the bit period must be no less than 1.4 times the minimum rise-time of the device. [20%]

(iii) The light emitting diode is to be used in a system where its spectral linewidth must be less than 35 nm. What is the maximum temperature for such operation? State any assumptions that you make in your calculation. [20%]

2 (a) Describe the structure of a Fabry Perot laser diode, explaining its advantages and disadvantages for general photonic applications. [30%]

(b) By considering the gain and loss encountered by light within a Fabry Perot laser cavity, and explaining any assumptions made, show that the photon lifetime may be written as

$$\tau_p = \frac{\mu}{c}\left\{\alpha + \left(\frac{1}{2L}\right)\ln\left(\frac{1}{R_1R_2}\right)\right\}^{-1}$$

Give a clear definition of all the symbols used in the expression. [30%]

(c) Hence derive an equation for the differential quantum efficiency of the Fabry Perot laser diode. [20%]

(d) A Fabry Perot laser is to be constructed to operate at a wavelength of 1.5 μm, with an effective refractive index of 3.6 and a scattering loss of 20 cm^{-1}. Determine the facet reflectivity required if the mode spacing of the device is to be 1 nm and the differential quantum efficiency is to be 80%. Assume for this part of the question that the facet reflectivities are equal. [20%]

(TURN OVER

3 A deep space probe is being designed to orbit an alien sun. This sun has an unusual irradiance spectrum, which has a constant value between wavelengths of 500 nm and 1100 nm and zero elsewhere.

(a) Describe the operation of a solar cell with the aid of band diagrams. Referring to the irradiated voltage-current characteristic, contrast the different operating regimes of a solar cell and a photodiode. [20%]

(b) Discuss how a photonics engineer might design the bandgap wavelength of a solar cell optimised for the deep space probe application described above. You may assume that the quantum efficiency of the cell does not vary with bandgap wavelength. You do not need to calculate the optimum bandgap wavelength. [25%]

(c) The cell designed by the photonics engineer is tested by illuminating it with 300 mW of incident radiation at a wavelength of 900 nm. It is found to have the following characteristics:

Quantum efficiency	0.85
Ideality factor	1
Operating temperature	75 K
Dark current	2 μA
Shape factor	0.7

(i) Calculate the maximum photocurrent generated by the solar cell under these illumination conditions. [10%]

(ii) Using the diode equation, calculate the open circuit voltage and the short circuit current. [20%]

(iii) Sketch the illuminated and dark I–V curves. Mark the optimum operating point under illumination. [15%]

(iv) Calculate the maximum power that can be generated. [10%]

4 (a) Describe the construction of step and graded index multimode fibre and step index single mode fibre. Explain, giving reasons, what the differences are in performance of these fibre types. In what application scenarios would each be deployed? [20%]

(b) A step index single mode fibre is to be designed in order to maximise the core diameter at an operating wavelength of 1550 nm. Three glasses with refractive indices of 1.51, 1.52 and 1.55 are available. Using the appropriate choice of glasses, design the single mode fibre. Explain why this choice of diameter would not be a good one in practice. [25%]

(c) The step index fibre is manufactured and is found to have an attenuation of 0.6 dB km^{-1} and a chromatic dispersion of 15 ps nm^{-1} km^{-1} at the operating wavelength. The fibre is to be used within an Ethernet link operating at a data rate of 1.25 Gbit s^{-1}. The Fabry Perot laser used in the transmitter has an optical linewidth of 3 nm and launches an optical power of 2 dBm into the fibre. The PIN-TIA receiver has a sensitivity of –30 dBm and the system should have a power margin of at least 3 dB. Calculate the maximum link length that is achievable using the fibre. You may assume that the dispersion limit is reached when a single "one" is broadened to twice its original length. [40%]

(d) Describe the measures whereby the maximum link length using this fibre may be extended:

(i) by a factor of 2;

(ii) by a factor of 10. [15%]

END OF PAPER

3B6 PHOTONIC TECHNOLOGY 2012

This data sheet is designed to provide an *aide-memoire* on certain physical and device-orientated aspects of optoelectronics. It will be issued for the 3B6 exam.

Note: e = charge of an electron, e = exponential

Wave-particle view of light (photons)	$E = hf = hc/\lambda$
Photon-electron interaction	$eV_{band\text{-}gap} = hf$
Diode equation	$I = I_0(\mathrm{e}^{\frac{eV}{nkT}} - 1)$
Quantum efficiency: emission	$P = \eta hfI/e$
Quantum efficiency: detection	$I = \eta(e/hf)P$
Conversion to dBm	Power in dBm = $10\log_{10}[P/1\mathrm{mW}]$
LED linewidth	$\Delta\lambda \sim 2kT\lambda^2/hc$
LED power temperature dependence	$\frac{P(T)}{P(T_1)} = \mathrm{e}^{-\left(\frac{T-T_1}{T_0}\right)}$
LED power time dependence (ageing)	$P(t) = P(0)\,\mathrm{e}^{-\beta t}$ $\beta = \beta_0\,\mathrm{e}^{-\frac{E_a}{kT}}$
Laser: photon rate equation	$\frac{dP}{dt} = g(n - n_o)P + \beta\frac{n}{\tau_s} - \frac{P}{\tau_p}$
Laser: electron rate equation	$\frac{dn}{dt} = -\frac{n}{\tau_s} + \frac{I}{eV} - g(n - n_o)P$

Laser: photon lifetime

$$\tau_p = \left(\frac{\mu}{c}\right)\frac{1}{\alpha + \frac{1}{2L}\ln\frac{1}{R_1R_2}}$$

Laser switch on delay

$$\tau_{delay} = \tau_s \ln\left[\frac{I - I_{bias}}{I - I_{threshold}}\right]$$

Laser threshold temperature dependence

$$J_{th}(T) = J_0\, e^{\frac{T}{T_0}}$$

Laser Ageing

$$t_{lifetime} \propto e^{\frac{E_a}{kT}}$$

Optical fibre: numerical aperture (NA)

$$NA = \sin(\alpha) = (n_{core}^2 - n_{cladding}^2)^{1/2}$$

Optical fibre: normalised frequency (V)

$$V = \frac{2\pi a}{\lambda}(n_{core}^2 - n_{cladding}^2)^{1/2} = \frac{2\pi a}{\lambda}NA$$

Number of modes in step index multimode fibre

$$N \approx V^2/2$$

Dispersion

$$\tau_{out}^2 = \tau_{in}^2 + \tau_{dispersion}^2$$

Shot noise

$$\overline{i_{shot}^2} = 2eIB$$

Shot noise: Poisson distribution

$$P\langle k|N\rangle = \frac{e^{-N}.N^k}{k!}$$

Thermal noise: resistor

$$\overline{i_{thermal}^2} = 4kTB/R\ ;\ \overline{v_{thermal}^2} = 4kTRB$$

APD excess noise factor

$$F = M^x$$

3B6 Photonic Technology

No changes were required for the exam.

Numerical Answers

1. (c) i) 1.61V, ii) 510 MHz, iii) 359 K
2. (d) 8%
3. (c) i) 0.185 A, ii) 0.074 V, 0.185 A, iv) 9.6 mW
4. (b) 6.8 μm, 30.8 km