ENGINEERING TRIPOS PART IIA

Friday 12 May 2006 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	SPECIAL REQUIREMENTS
Single-sided script paper	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

1 (a) Describe important criteria for selecting materials for use in light emitting diodes for operation at a required wavelength, explaining how 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 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 risetime of the device. [20%]

(iii) The light emitting diode is to be used in a system where its spectral linewidth must be less than 40 nm. What is the maximum temperature for such operation? [20%]

2 (a) Explain the operation of a laser diode, describing the role of population inversion and optical feedback. What steps must be taken to ensure efficient lasing performance? What impact on laser performance does an increase in operating temperature have? [20%]

(b) A coated Fabry Perot laser diode operates at a wavelength of 1.5 μm, and has a threshold current of 20 mA at a temperature of 20 °C. It has a length, L, of 1 mm, an internal scattering loss, α, of 5 cm^{-1}, and an overall differential quantum efficiency, η_D, of 60 %.

(i) Determine the drive current required for the laser to generate a total output power of 5 mW. [15%]

(ii) If the laser has a characteristic temperature of 100 K, what is the maximum temperature that the laser can operate at, if the output power is to be maintained at 5 mW and the drive current is not to exceed 40 mA? [20%]

(iii) Derive an equation for the differential quantum efficiency. [20%]

(iv) Hence estimate the reflectivity of the facets of the laser diode. [15%]

(v) Describe the advantages and disadvantages for a laser diode of increasing or decreasing its facet reflectivities. [10%]

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3 (a) Describe the factors that can influence the speed of response of a *p+n* photodiode. [20%]

(b) Describe the construction and operation of a *pin* photodiode and explain what advantage is provided by the intrinsic region. [10%]

(c) The bandgap energy of GaAs is 1.424 eV. Explain why a GaAs photodiode would not be suitable for detecting light at a wavelength of 1300 nm. The substitution of a molar fraction x of Indium for some of the Gallium decreases the bandgap energy (in eV) according to the relation:

$$E_g = 1.424 - 1.50x + 0.4x^2$$

Calculate the minimum molar fraction x that would enable an InGaAs photodiode to detect 1300 nm radiation. [25%]

(d) A receiver is constructed by connecting a photodiode, with a depletion capacitance of 40 pF and a quantum efficiency of 90%, to an amplifier with a voltage gain of 100 used in transimpedance mode with a transimpedance resistance of 200 Ω. The operating wavelength for the receiver is 1.3 μm. The receiver is required to operate in hostile environments at temperatures up to 125 °C.

(i) Calculate the bandwidth of the receiver. [15%]

(ii) Calculate the worst case sensitivity of the receiver in units of dBm assuming that the following circuitry requires a signal to noise ratio of 22 dB to operate correctly. You may assume that thermal noise is the limiting noise process in the receiver. [30%]

4 (a) The majority of optical communications systems are guided systems, employing optical fibres. Explain, with reasons, why this is so. [20%]

(b) Describe the key dispersion processes that occur in optical fibres. What can be done to minimise the effects of dispersion in high bandwidth, long haul optical communications systems? [15%]

(c) An optical communications system is designed to operate at a data rate of 2.5 Gb/s at a wavelength of 1.55 μm over a fibre length of 100 km. The laser source employed launches an average power of +3 dBm into the single mode optical fibre used in the link. The fibre has a dispersion of 16 ps nm^{-1} km^{-1} and an attenuation of 0.3 dB km^{-1}. The receiver has a sensitivity of –20 dBm. A splicing loss of 0.5 dB is suffered where the laser and receiver pigtails are spliced to the transmission fibre. The system designer has specified a 3 dB margin.

(i) Calculate the maximum value of the spectral linewidth of the source which would allow the design length to be achieved. You may assume that the dispersion limit is achieved when a single "one" is broadened to 1.4 times the bit period. [25%]

(ii) Using the spectral linewidth calculated in (i), determine whether the link is dispersion or attenuation limited. [25%]

(iii) Explain how it is possible to extend the link to transoceanic (i.e. 1000s km) distances and detail the technologies involved. [15%]

END OF PAPER

3B6 PHOTONIC TECHNOLOGY 2006

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 $\frac{dn}{dt} = -\frac{n}{\tau_s} + \frac{I}{eV} - g(n - n_o)P$

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Laser: photon lifetime

$$\tau_p = \left(\frac{\mu}{c}\right)\frac{1}{\alpha + \frac{1}{2L}\ln\frac{1}{R_1 R_2}}$$

Laser switch on delay

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

Laser threshold temperature dependence

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

Laser Ageing

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

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

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

Thermal noise: resistor

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

APD excess noise figure

$$F = M^x$$

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Numerical Answers

Q.1 (c) (i) 1.6 V, (ii) 510 MHz, (iii) 399 K
Q.2 (b) (i) 30 mA, (ii) 333 K, (iv) 47 %
Q.3 (c) 0.345, (d) (i) 2.0 GHz, (ii) -22 dBm
Q.4 (c) (i) 0.245 nm, (ii) 63.3 km (attenuation limited)