ENGINEERING TRIPOS PART IIA

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24 April 2009 2.30 pm to

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) Explain in detail the main processes involved in the interaction between photons and electrons, and hence describe the principle of operation of the Light Emitting Diode (LED). In your answer, review the main features of the LED and how these make the device suitable for a range of applications. [25%]

(b) Describe in detail the structure of the Surface Emitting LED and the Edge Emitting LED, indicating how their structures affect certain performance characteristics of the devices. Briefly explain the relative advantages and disadvantages of the two devices. [30%]

(c) An LED is to be formed for use as a source in a short range optical link.

(i) The device is to use a semiconductor active region with a bandgap energy of 0.95 eV. What wavelength should the device operate at? [10%]

(ii) If the radiative and non-radiative carrier recombination times are 2 ns and 3 ns respectively, and the external quantum efficiency of the device is 4%, what is the overall quantum efficiency of the LED? [15%]

(iii) If the LED is to generate an output power of 1 mW, determine the drive current at which it should operate. [10%]

(iv) What is the overall carrier response time of the LED, and how will this limit the overall bit rate of the link? [10%]

2 (a) The operation of a Fabry-Perot laser diode may be represented by the following rate equations:

$$dP/dt = g(n - n_o)P - P/\tau_p + \beta n/\tau_s$$

$$dn/dt = I/(eV) - n/\tau_s - g(n - n_o)P$$

Describe in detail the physical meanings of the terms in the equations, explaining any assumptions. [20%]

(b) Assuming that β is negligible, derive equations for the carrier concentration, n, both below and above threshold under steady-state conditions. Hence, derive equations for the threshold carrier concentration and threshold current. [30%]

(c) By considering the basic structure of the Fabry-Perot laser diode, show that the photon lifetime, τ_p, can be written as $(n_r/c)/(\alpha+(1/L)\ln(1/R))$, where n_r is the refractive index, c is the speed of light, α is the scattering loss, L is the cavity length, and R is the reflectivity of each facet. [30%]

(d) Derive an expression for the differential quantum efficiency of the Fabry-Perot laser diode. [20%]

3 (a) Describe in detail the operation of *pin* and avalanche photodiodes, explaining how their structures are designed for optimum performance. Describe the relative advantages and disadvantages of the two devices, and give an example of their typical applications. [25%]

(b) Describe the main sources of noise in optical receivers using *pin* and avalanche photodiodes, indicating their physical origin. [20%]

(c) An optical receiver able to operate at a wavelength of 1.5 μm is to be formed using a *pin* photodiode with a quantum efficiency of 90% and a dark current of 1 nA. Within the receiver, the photodiode is connected to an electrical amplifier with a 1 kΩ input impedance and 1 GHz bandwidth. The receiver is to be used in a specific sensing application, operating at a temperature of 20°C. Estimate the minimum sensitivity of the sensor receiver, defined in this case when the signal-to-noise ratio is unity. [25%]

(d) It is decided that it is necessary to enhance the sensitivity of the receiver described in section (c). To do this, it is proposed that an avalanche photodiode replace the *pin* photodiode. The avalanche photodiode operates at an avalanche gain $M = 7$, and has a quantum efficiency of 90%, a dark current of 1 nA and an excess noise factor of $M^{0.5}$. Determine the new receiver sensitivity. [30%]

4 (a) Describe in detail the major classes of optical fibre explaining their preferred applications. [25%]

(b) Explain the causes of dispersion in optical fibre, and how this can be minimised in long distance single-mode fibre links. [20%]

(c) An optical communication system is to be constructed for transmitting signals at a data rate of 2.5 Gbit s^{-1}, using a source which operates at a wavelength of 1.5 μm.

The link is to use a single-mode optical fibre.

(i) If the fibre is to have a numerical aperture of 0.1 and the cladding material of the fibre has a refractive index of 1.49, what should the core refractive index be? [10%]

(ii) What should the maximum diameter of the core of the optical fibre then be, for single-mode operation to be ensured? [10%]

(iii) If the dispersion of the fibre is 18 ps nm^{-1} km^{-1}, what is the maximum dispersion-limited length of the link if the source has an optical bandwidth of 0.1 nm and the receiver circuitry is unable to detect error-free signals once the pulse broadening due to the dispersion of the fibre exceeds one quarter of the bit period? [20%]

(iv) If the output power from the source is 1 mW, the insertion loss is 4 dB, and the fibre has an attenuation of 0.3 dB km^{-1}, what is the worst-case receiver sensitivity which would mean that the link length was dispersion limited? [15%]

END OF PAPER

3B6 PHOTONIC TECHNOLOGY 2009

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	$P\langle k \mid N\rangle = \frac{e^{-N}.N^k}{k!}$
Thermal noise: resistor	$\overline{i_{thermal}^2} = 4kTB/R\ ;\ \overline{v_{thermal}^2} = 4kTRB$
APD excess noise factor	$F = M^x$

Numerical Answers

Q.1 (c) (i) 1.31 μm, (ii) 2.4 %, (iii) 44 mA, (iv) 1.2 ns
Q.3 (c) 0.12 μW, (d) 16 nW
Q.4 (c) (i) 1.493, (ii) 11.4 μm, (iii) 167 km, (iv) -54 dBm