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EGT2
ENGINEERING TRIPOS PART IIA

Friday 25 April 2014 9.30 to 11

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.*

*Write your candidate number **not** your name on the cover sheet.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Attachment: 3B6 Photonic Technology Data Sheet (2 pages)
Engineering Data Book

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

1 (a) Describe in detail the structure and operation of a *Surface Emitting Light Emitting Diode* (SELED), explaining techniques used to maximise device efficiency and minimise adverse thermal effects. [30%] 6

(b) A SELED operating at a wavelength of 850 nm is driven directly by a 2 V voltage source with an internal resistive impedance of 10 Ω. At an operating temperature of 20 °C, the internal impedance of the SELED is 1 Ω, and it has a radiative recombination time of 2 ns.

(i) What overall *quantum efficiency* should the device have if it is to generate an output power of 5 mW? [30%] 6

(ii) If the external quantum efficiency of the SELED is 10%, what overall *risetime* can be expected? [10%] 2

(iii) If the SELED has a characteristic temperature of 80 K, what will be the change in output power if the device operating temperature is increased to 85 °C? [10%] 2

(iv) What *activation energy* does the SELED have if its lifetime, defined as the operational time before the power of the SELED has fallen to half its original value, is 6 times greater at 20 °C than it is at 85 °C? [20%] 4

2 (a) (i) Briefly describe the physical processes and basic device structure required for a *Fabry Perot* laser diode. [15%] 3

(ii) On this basis, explain how the operational properties affect the choice of materials that can be used in a laser diode. [5%] 1

(b) The rate equations describing the operation of a laser diode may be written as

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

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

(i) Explain the processes represented by the different terms in each equation, making clear any assumptions made. [10%] 2

(ii) Hence derive equations for the *threshold current* and *slope efficiency* of the laser diode. [20%] 4

(iii) Sketch graphs for photon density versus current and carrier concentration versus current. [10%] 2

(c) A Fabry Perot laser diode operating at 1.5 μm wavelength uses an active region with a *gain constant* of 3 x 10^{-7} $\text{cm}^3\ \text{s}^{-1}$, *spontaneous lifetime* of 3 ns, *refractive index* of 3.6, *transparency density* of 1.0 x 10^{18} cm^{-3} and *scattering loss* of 30 cm^{-1}. If the laser has a *facet reflectivity* of 0.32 and has an active region of width 3 μm and depth of 0.25 μm, what should the length of the laser be if the threshold current is to be 50 mA? [20%] 4

(d) What would the resulting wavelength spacing be between the Fabry Perot modes of the cavity? [20%] 4

3 (a) Explain why it is difficult to use a conventional photodiode to detect radiation in the mid-IR range (wavelengths of 2-10 μm) and how a photoconductor overcomes this problem. [15%]

(b) The expression for current in a semiconductor sample is given below

$$I = VA(nq\mu_n + pq\mu_p)/L$$

V is the voltage across the sample, and *A* and *L* are its area and length respectively.

(i) Explain what is the physical significance of the terms in the bracket, giving the meaning of each of the individual terms. [10%]

(ii) Hence derive an expression for photoconductive gain in the photoconductor. [25%]

(c) A 10 Gbit s^{-1} optical communications systems has been designed to operate at a wavelength of 1.55 μm. The receiver consists of a photodetector connected to a *transimpedance amplifier*, which has a feedback impedance of 1 kΩ and a bandwidth of 7.5 GHz. The operating temperature of the receiver is 35 °C.

(i) Discuss the advantages and disadvantages of a *pin* photodiode and an *avalanche photodiode* (APD) for use in the above receiver. In particular, discuss the noise processes that will occur in the receiver in each case. [10%]

(ii) The *pin* photodiode has a *quantum efficiency* of 0.9. Calculate the *sensitivity* of the *pin* photodiode receiver circuit. Express your answer in units of dBm. You may assume that a minimum *signal to noise ratio* (SNR) of 20 dB is required and thermal noise is the dominant noise component under low incident optical power. [20%]

(iii) The APD has a dark current of 10 nA, an *avalanche gain* of 30, a quantum efficiency of 0.9 and an *excess noise factor* $x = 0.5$, with all other system parameters remaining the same. What is the SNR of the APD receiver circuit for the input power calculated in (ii). Hence state which photodiode circuit will result in the most sensitive receiver. [20%]

4 (a) Plastic *optical fibre* is becoming popular for certain applications. Describe an application where it is often deployed and why plastic fibre is preferred over glass fibre for this. Explain why glass fibre is preferred for long distance, high data rate communication systems and describe the best fibre design for this application. Give reasons for your choice. [15%]

(b) The *numerical aperture* of a *step index* optical fibre is given by the expression

$$NA = \sqrt{{n_1}^2 - {n_2}^2}$$

where n_1 and n_2 are the *core* and *cladding refractive indices* respectively. Derive this expression from first principles. (Initially derive the expression for the fibre's *critical angle* from *Snell's Law*). [25%]

(c) A *step index* fibre is to be constructed from two glasses of refractive index 1.44 and 1.45.

(i) Calculate the maximum fibre core diameter for which the fibre remains *single mode* at an operating wavelength of 1.55 μm. [10%]

(ii) Calculate the *coupling efficiency* from a *Lambertian emitter*, such as an LED, into the fibre. [10%]

(d) The fibre described in part (c) is found to have an *attenuation* of 0.3 dB km^{-1} and a *chromatic dispersion* of 15 ps nm^{-1} km^{-1} at the operating wavelength and is to be used in a 2.5 Gbit s^{-1} system.

(i) What is the maximum dispersion limited length of the link if the source used has an *optical linewidth* of 0.2 nm and the receiver is able to detect pulses with a broadening of 50% of the *bit period*. [20%]

(ii) If the source output power is 2 mW, the *coupling loss* is 2 dB and the *link margin* is 3 dB, what is the worst case receiver *sensitivity* which would result in the link being dispersion limited? [20%]

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3B6 PHOTONIC TECHNOLOGY 2014

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	$\dfrac{P(T)}{P(T_1)} = \mathrm{e}^{-\left(\frac{T-T_1}{T_0}\right)}$
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	$\dfrac{dP}{dt} = g(n - n_o)P + \beta\dfrac{n}{\tau_s} - \dfrac{P}{\tau_p}$
Laser: electron rate equation	$\dfrac{dn}{dt} = -\dfrac{n}{\tau_s} + \dfrac{I}{eV} - g(n - n_o)P$

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Laser: photon lifetime	$\tau_p = \left(\frac{\mu}{c}\right)\frac{1}{\alpha + \frac{1}{2L}\ln\frac{1}{R_1R_2}}$
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	$F = M^x$

ENGINEERING TRIPOS PART IIA 2014
MODULE 3B6: PHOTONIC TECHNOLOGY
NUMERICAL SOLUTIONS

Q.1 (b) (i) 0.07, (ii) 1.4 ns, (iii) 2.8 mW, (d) 0.25 eV
Q.2 (c) 508 µm, (d) 0.62 nm
Q.3 (c) (ii) – 25.0 dBm, (iii) 268 (or 24.3 dB), APD
Q.4 (c) 7.0 µm, 2.9%, (d) (i) 149 km, -46.7 dBm