EGT2
ENGINEERING TRIPOS PART IIA

Monday 30 April 2018 9.30 to 11.10

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

10 minutes reading time is allowed for this paper.

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 major processes involving the interaction of photons and electrons, and explain how these relate to the principles of operation of photodiodes, light emitting diodes and laser diodes. Explain the impact of using indirect or direct bandgap materials in each of these devices. [25%]

(b) A Light Emitting Diode (LED) is to generate light at a wavelength of 850 nm.

(i) The device is to be driven from a 5 V voltage source with an internal resistance of 1 Ω in series with a resistance of value *R* Ω. Assuming that at a temperature of 20 ^{o}C, the radiative lifetime of the LED is 2 ns, the non-radiative lifetime is 3 ns, and the external quantum efficiency is 4%, what value should *R* be if the LED is to emit an optical power of 5 mW? [25%]

(ii) What should the characteristic temperature of the device be if it is to emit an optical power of 2.5 mW at a temperature of 80 ^{o}C? [20%]

(iii) If the activation energy is 0.6 eV, what is the ratio of the lifetime of the LED at 80 ^{o}C versus that at 20 ^{o}C? [15%]

(c) Describe briefly how doping can be used to improve the efficiency of an LED. [15%]

2 (a) Describe the structures of ridge laser diodes and buried heterostructure laser diodes, explaining their relative merits in respect of key performance parameters. [30%]

(b) The electron and photon rate equations for a laser diode may be written respectively as:

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

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

Describe in detail the parameters used, the assumptions made in relation to the equations, and the physical phenomena represented by the different terms. [20%]

(c) If the spontaneous coupling coefficient is assumed to be negligible, derive expressions for n and P as a function of current, both below and above threshold. [20%]

(d) By considering the round trip gain required for lasing or otherwise, derive an expression for the total output power of the laser from both facets, if the laser has a length L, scattering loss α, and each facet has a reflectivity R. [30%]

3 (a) Describe the phenomenon of *photoconductivity* and explain why a photoconductor, rather than a photodiode, is often used to detect radiation in the mid-infrared range (wavelengths of 2-10 μm). [15%]

(b) The expression for current I in a semiconductor sample to be used in a photoconductor is given below. V is the voltage across the sample, A and L are its area and length, respectively, and σ_n and σ_p are the electron and hole conductivities.

$$I = VA(\sigma_n + \sigma_p)/L$$

(i) Using this expression, derive an expression for photoconductive gain in the photoconductor. [25%]

(ii) If the electron and hole transit times are 1 μs and 3 μs, respectively, and the electron and hole recombination times are 0.4 s and 0.2 s, respectively, calculate the value of the photoconductive gain. [10%]

(c) An engineer wishes to design the front end of a sensitive low light imaging sensor operating in the near infra-red at a wavelength of 1179 nm using a *pin* photodiode array. Each individual *pin* photodiode has its own amplifier circuit, and has a quantum efficiency of 0.9 at the operating wavelength and a dark current of 4.7 nA under the design operating conditions, which include a temperature of operation of 30 °C. Each photodiode is connected to an electrical amplifier with an input impedance of 67 kΩ and a bandwidth of 10 kHz. Calculate the sensitivity of the individual photodiode circuit, assuming that a signal to noise ratio of 7 dB is sufficient and stating any assumptions that you make. [35%]

(d) Experiments show that the sensitivity needs to be improved upon the value calculated in (c).

(i) Explain how the operating conditions of the circuit could be changed to improve the sensitivity. [5%]

(ii) Describe another type of photodiode that could improve the sensitivity still further. Explain qualitatively how the sensitivity could be optimised using the new photodiode. [10%]

4 (a) Describe how the three main types of optical fibre are constructed and explain the differences in performance that result. Using a table, show the main wavelength operating regimes for the three fibre types and describe, with reasons, the main applications for which each fibre is normally deployed. [20%]

(b) A step index multimode fibre is to be constructed. Three different glasses, which have refractive indices 1.50, 1.52 and 1.53, respectively, are available. Determine the optimum choice of core and cladding glass in each case for the requirements below:

(i) to maximise the coupling efficiency from a Lambertian source, such as an LED, calculating the value of the coupling efficiency in this case; [15%]

(ii) to minimise the fibre dispersion, calculating its value in this case. [15%]

(c) An engineer decides to employ the fibre design in (b)(ii) in a fibre communications link. It is found to have an attenuation of 1.3 dB km^{-1} at the operating wavelength of 850 nm. The optical source is a 1 mW LED with a 5 nm linewidth which is operated at a data rate of 100 Mbit s^{-1}. The LED is butt coupled to the optical fibre. The fibre link includes two connectors, each with a loss of 0.5 dB. The customer requires a power margin of at least 3 dB.

(i) What is the maximum dispersion limited length of the link if the receiver is able to detect pulses with a broadening of 30% of the bit period? [20%]

(ii) What is the worst case receiver sensitivity which would mean that the link was dispersion limited? [20%]

(iii) Assuming the customer wishes to use multimode fibre, though not necessarily the design used above, what changes to the system could be made to enable it to operate at a data rate of 1 Gbit s^{-1} over a length of 1 km? [10%]

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ENGINEERING TRIPOS PART IIA

3B6 PHOTONIC TECHNOLOGY 2018

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

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

Laser switch on delay

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

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

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

Thermal noise: resistor

$$\overline{i^2_{thermal}} = 4kTB / R \; ; \; \overline{v^2_{thermal}} = 4kTRB$$

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