Version QC/5

EGT2
ENGINEERING TRIPOS PART IIA

Tuesday 29th April 2025   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 at the start of the exam.

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

You may not remove any stationery from the Examination Room.

1 (a) Explain in detail the processes involving the interaction of photons and electrons in a semiconductor, and hence describe the main principles of operation of an LED. In answering review the main features of an LED and hence what applications these make LEDs suitable for. [20%]

(b) Describe the structure of both a Surface Emitting LED and a Edge Emitting LED, indicating how the structure affects device performance. Briefly explain the relative advantages and disadvantages of these two device structures. [15%]

(c) An LED is to be used as the optical source for a short range optical communications link.

(i) The device has an active region with a bandgap energy of 1.05 eV at room temperature of 20 °C. Calculate the centre operating wavelength of the LED along with the spectral linewidth. [15%]

(ii) The radiative and non-radiative carrier lifetimes are 1 ns and 3 ns, respectively, and the external quantum efficiency is 7%. Calculate the overall quantum efficiency of the LED. [10%]

(iii) The LED has a parasitic series resistance of 2 Ω and is driven from a voltage source with an internal resistance of 15 Ω. Calculate the voltage needed for the LED to generate an output power of 1 mW. [15%]

(iv) If the LED has a characteristic temperature of 100 K, calculate the output power if the device temperature is raised to 70 °C. [10%]

(v) Calculate the overall carrier response time of the LED and indicate how this might limit the overall bit rate of the optical link. How might the bandwidth of the LED be increased? Describe any trade off in performance associated with your suggested approach. [15%]

2 (a) Detail the requirements for lasing operation and explain how these are achieved in a laser diode. [15%]

(b) The operation of a Fabry Perot diode laser can be described by the rate equations:

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

(i) Describe in detail the physical meaning of each of the terms of the two equations, and explain any assumptions that have been made. [15%]

(ii) Explaining why you may assume the term containing β to be negligible, derive expressions for the carrier concentration, n, both below and above the lasing threshold under steady state conditions. [20%]

(iii) Hence derive expressions for the threshold carrier concentration and the threshold current. [15%]

(c) A Fabry Perot laser has a cavity length, L, of 500 µm, facet reflectivity, R, of 0.3, an effective refractive index, μ, of 3.3, a waveguide scattering loss, α, of 10 cm^{-1}, and an operating wavelength of 1550 nm.

(i) Calculate the wavelength mode spacing of the laser. [10%]

(ii) By considering the round trip gain required for lasing, calculate the optical gain per unit length required for the laser to operate above threshold. Derive an equation for the differential quantum efficiency and calculate its value. [15%]

(d) Describe how confinement of carriers and photons affects the operation of Fabry Perot lasers. [10%]

3 (a) Describe the key difference between a p^+n and an MSM photodiode. [10%]

(b) For a *pin* photodiode, explain why a reverse bias is needed and how increasing the reverse bias changes its responsivity and bandwidth, giving an explanation for these changes. [20%]

(c) Explain what an Avalanche photodiode is and describe its principle of operation. [10%]

(d) A 25 Gbit s^{-1} optical link is 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 20 GHz. The operating temperature is 300 K.

(i) An engineer is first designing a *pin* photodiode for the link. It has a quantum efficiency of 0.9. The link is required to have a minimum signal to noise ratio of 23 dB. Calculate the link sensitivity. Express your answer in units of dBm. Assume that thermal noise is dominant under low incident optical power. [10%]

(ii) If an APD is also considered to be used with the same power launched to the photodiode as calculated in part (d) (i). The APD has a dark current of 10 nA, an avalanche gain of 50, a quantum efficiency of 0.9 and an excess noise factor x of 0.5. Which photodiode is more sensitive? [25%]

(iii) The avalanche gain M is dependent upon the applied voltage. Calculate the largest M that keeps the APD more sensitive compared to the *pin* photodiode. You can assume that the excess noise factor x remains at 0.5 and you may apply a numerical approximation to find an integer solution of M. [25%]

4 (a) Explain if there is a cut-off wavelength in a step-index single mode fibre. [10%]

(b) What are the ways in which signal quality is degraded in single mode fibres? Explain how these effects influence how optical fibre transmission systems are operated. [10%]

(c) A step index optical fibre is to be manufactured with a core refractive index of 1.52 and a cladding refractive index of 1.51.

(i) Calculate the minimum core diameter for the fibre to be multi-mode at a wavelength of 850 nm. [10%]

(ii) Describe how the optical fibre can be manufactured. [10%]

(iii) Detail how to increase the fibre collection efficiency. [10%]

(d) The fibre of part (c) is used to build a multi-mode fibre link and is found to have attenuation of 1 dB km^{-1}. An optical source with an optical linewidth of 0.2 nm is used. The power penalty of the linewidth broadening in this link can be assumed as:

$P = 10log(t_{out}/t_{in})$.

(i) The optical source has a launched optical power of 0 dBm and is modulated at 10 Gbps. A *pin* photodetector with a sensitivity of -20 dBm is used in the link. There is a 3 dB coupling loss in total, 3 dB incomplete modulation penalty, and the link specification requires a power margin of at least 3 dB. Calculate the maximum fibre transmission length. You may apply a numerical approximation to find an integer solution. [25%]

(ii) If the fibre transmission length is the same as calculated in part (d) (i), but a faster modulation speed at 25 Gbps is required, what is the sensitivity needed for the photodetector? Assume that the incomplete modulation penalty is now 4 dB. [25%]

END OF PAPER

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3B6 PHOTONIC TECHNOLOGY

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 = $10\log_{10}[P/1\text{mW}]$
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

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

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 factor

$$F = M^x$$