EGT2
ENGINEERING TRIPOS PART IIA

Tuesday 28 April 2026 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) Describe in detail the structure and operation of a Surface Emitting Light Emitting Diode (SELED). [20%]

(b) Describe the engineering techniques used to maximise overall device efficiency and to minimise undesirable thermal effects. [10%]

(c) Explain what properties the active material of the SELED should have for efficient LED operation and what appropriate materials would be for SELEDs operating in each of the blue, red and near infra-red wavelength regimes. [15%]

(d) A SELED is to be designed to operate at a wavelength of 633 nm at 20°C using an active material that has a radiative recombination time of 1 ns and a non-radiative recombination time of 2.5 ns. The SELED is required to have an overall quantum efficiency of 6%.

(i) What is the minimum value of external quantum efficiency that will meet the overall quantum efficiency requirement. [10%]

(ii) Assuming the radiative recombination process has been optimised and cannot be improved further, what measures might be taken to improve the non-radiative processes to improve the overall quantum efficiency. [10%]

(iii) The SELED is driven from a 3.5 V electrical supply with an internal resistance of 1.5 Ω. If the SELED has an internal resistance of 2 Ω, what series resistance must be used in the circuit so that the SELED is to generate an output power of 2.3 mW. [10%]

(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) The non-radiative processes within the device have been improved so that an enhanced SELED has an overall carrier lifetime of 5 ns. Assuming the radiative lifetime remains at 1 ns, calculate the enhanced value of non-radiative lifetime. Assuming the external quantum efficiency also remains unchanged, determine the value of circuit series resistance that is now required to maintain the output optical power of 2.3 mW. [15%]

2 (a) Detail the operation of a laser diode, in particular describing the role of population inversion and optical feedback. [15%]

(b) Outline the design features of an edge emitting laser diode that ensure efficient operation. [15%]

(c) A Fabry-Perot laser operates at a wavelength of 1.55 μm and has a threshold current of 18 mA at an operating temperature of 20 °C. It has a cavity length, L, of 800 μm, an effective refractive index, μ, of 3.3, a waveguide scattering loss, α, of 7 cm^{-1}, and an overall quantum efficiency, η_d , of 63%.

- (i) Determine the drive current required for the laser to generate a total output power of 7 mW. [10%]
- (ii) The laser is measured to have a characteristic temperature of 90 K. What is the maximum temperature that the laser can operate at whilst maintaining the output power at 7 mW, assuming the drive circuit cannot deliver more than 60 mA. [15%]
- (iii) Derive the equation for the differential quantum efficiency. [15%]
- (iv) Hence calculate the facet reflectivity of the laser diode. [10%]
- (v) Calculate the wavelength mode spacing of the laser. [10%]

(d) Describe the effects on the operation of the Fabry-Perot laser diode of increasing or decreasing the two facet reflectivities. [10%]

3 (a) A photonic detector is required for a free-space spectroscopic system operating at a wavelength of 1.9 μm, with the additional requirement that it must operate reliably up to 120 °C.

(i) Determine the maximum allowable semiconductor bandgap energy for this application. [10%]

(ii) Identify a suitable semiconductor material system, and explain why this material is appropriate both optically and thermally. [10%]

(b) Describe the operation of a photoconductive detector, clearly identifying the roles of carrier lifetime, mobility, and applied electric field. [15%]

(c) The photoconductive detector has a quantum efficiency of 0.75, carrier lifetime of 4 ns, bias voltage of 12 V, device length of 20 μm, electron mobility of 6000 $cm^2 V^{-1} s^{-1}$, dark current of 15 nA, and incident optical power of 2 μW.

(i) Calculate the photoconductive gain of the detector. [10%]

(ii) Hence determine the photocurrent generated. [15%]

(iii) By considering the dark current, estimate the signal-to-noise ratio, assuming shot-noise-limited operation. [15%]

(d) At elevated temperatures the detector exhibits both reduced responsivity and increased noise.

(i) Explain the physical mechanisms responsible for both effects. [10%]

(ii) Discuss two design or material modifications that could improve high-temperature performance, explaining the physical principles involved. [15%]

4 (a) Explain the physical origins of material dispersion and waveguide dispersion in optical fibres. Describe how the total chromatic dispersion may be engineered to approach zero at a chosen wavelength. [10%]

(b) A step-index optical fibre is to be designed for operation at 1550 nm using two glasses with refractive indices 1.47 and 1.50.

(i) Determine which glass should be used for the core and which for the cladding, explaining your reasoning. [10%]

(ii) Calculate the maximum core radius for which the fibre remains single-mode. [10%]

(iii) Explain qualitatively why operating close to this maximum radius is undesirable in practice. [10%]

(c) The fibre is used in a digital optical link operating at 25 Gb s^{-1}. The receiver consists of a PIN photodiode followed by a transimpedance amplifier. The photodiode has a depletion capacitance of 6 pF and a quantum efficiency of 0.85. The transimpedance resistor is 200 Ω and has a stray capacitance of 0.15 pF.

(i) Estimate the receiver bandwidth, clearly stating all assumptions. [10%]

(ii) Identify the dominant noise source and justify your answer quantitatively. [10%]

(iii) Determine the minimum detectable optical power, assuming a required SNR of 15 dB. [10%]

(d) The optical transmitter launches an average power of +2 dBm into the fibre. The fibre attenuation is 0.22 dB km^{-1}, and the chromatic dispersion is 16 ps nm^{-1} km^{-1}. The laser has a spectral linewidth of 0.3 nm, and the receiver can tolerate pulse broadening of 25% of the bit period. A system margin of 3 dB is required.

(i) Determine whether the link is dispersion-limited or attenuation-limited, clearly showing your reasoning. [10%]

(ii) Calculate the maximum achievable transmission distance. [10%]

(iii) Briefly discuss one system-level modification that could extend this distance without changing the fibre type. [10%]

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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

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

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

$$\tau_{\mathrm{p}} = \left(\frac{\mu}{\mathrm{c}}\right)\frac{1}{\alpha + \frac{1}{2L}\ln\frac{1}{R_1R_2}}$$

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

$$F = M^x$$