EGT2
ENGINEERING TRIPOS PART IIA

Monday 1 May 2023 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 the operation of a Surface Emitting Light Emitting Diode (SELED), including in your description the interaction processes between electrons and photons in such a device. Using a diagram, explain how the structure of the device can be optimised to maximise the efficiency of converting current into light emitted from the SELED. [20%]

(b) Explain how the generation of light by a SELED is affected by its temperature and how heating effects can be reduced in the device. [15%]

(c) A SELED, operating at a temperature of 20 °C and at a centre wavelength of 850 nm, is to be driven from a voltage source with an internal resistance of 2 Ω. The device has radiative and non-radiative carrier lifetimes of 3 ns and 8 ns respectively, an external quantum efficiency of 4%, and an internal resistance of 0.5 Ω.

(i) Calculate the internal quantum efficiency and response time of the SELED. [15%]

(ii) Determine the required voltage and current generated by the source to deliver an output power of 1 mW from the SELED. Calculate the overall efficiency in converting electrical to optical power. [15%]

(iii) The characteristic temperature for the SELED is measured to be 90 K. Determine the voltage required from the source to generate 1 mW output power when the device temperature increases to 85 °C. [15%]

(iv) Calculate the spectral linewidth of the SELED at both original and elevated temperatures. [20%]

2 (a) Explain why optical feedback, alongside optical gain, is necessary for laser operation. [15%]

(b) Describe in detail the operation and structure of a Fabry Perot ridge laser diode and explain how the structure affects the wavelength or wavelengths at which it functions. [15%]

(c) A Fabry Perot laser has a cavity length, L, of 400 μm, an effective refractive index, μ, of 3.3, a waveguide scattering loss, α, of 15 cm^{-1}, a facet reflectivity of 0.32 and an operating wavelength, λ, of 1.3 μm.

(i) Derive an equation for the wavelength mode spacing of a Fabry Perot laser. [10%]

(ii) Calculate this mode spacing for the laser described above. [10%]

(iii) By considering the round trip gain required for lasing, calculate the optical gain per unit length required for the laser to operate. Assume that both facets have the same reflectivity. [25%]

(d) By considering the laser cavity, show that the photon lifetime in the laser can be written as

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

where c is the free space speed of light and R_1 and R_2 are the facet reflectivities. Explain how the value of the photon lifetime can affect the laser performance and calculate the value for the device described in part (c). [25%]

3 (a) Describe the difference between a photodiode and a solar cell. Explain the operation of both types of device with the aid of band diagrams. [15%]

(b) Sketch the graph for the spectral irradiance of solar radiation against wavelength and discuss the choice of solar cell bandgap in terms of efficiency. [15%]

(c) Two different materials are being considered for a solar cell: Materials #1 and #2 have a bandgap wavelength of 1000 nm and 1500 nm, respectively, and both have a similar quantum efficiency of 0.8. Given the graph sketched in part (b), state with reasons which material is the best to use in the solar cell. [20%]

(d) In a test, a 2 m^2 solar cell constructed from the material chosen in part (c) is illuminated with light at its bandgap wavelength at an intensity of 1.2 kW m^{-2}. The solar cell is found to have an ideality factor of 1.1, a dark current of 10 μA, and an operating temperature of 300 K.

(i) Find the maximum photocurrent generated by the solar cell. [20%]

(ii) Calculate the maximum power that can be generated. Assume the shape factor is 0.7. [20%]

(e) Discuss possible ways to increase the generated solar power. [10%]

4 (a) A step-index optical fibre has core and cladding refractive indices of n_1 and n_2, respectively. Derive the numerical aperture of the fibre from first principles and explain its significance. [15%]

(b) A step-index single mode fibre is to be designed in order to maximise the fibre collection efficiency at a wavelength of 1550 nm. Three glasses with refractive indices of 1.51, 1.52 and 1.55 are available. Determine the optimum choice of core and cladding glass and calculate the collection efficiency for this design. [15%]

(c) A transimpedance amplifier (TIA) receiver is to be constructed using a p-i-n photodiode. The photodiode has a depletion capacitance of 10 pF and a quantum efficiency of 0.8. The TIA has a voltage gain of 100 and a 100 Ω transimpedance resistor, which has a stray capacitance of 0.1 pF. The receiver circuit needs to operate with a signal to noise ratio of at least 20 dB and at a temperature of 300 K. The input wavelength to the photodiode is 1550 nm.

(i) Calculate the receiver bandwidth. [20%]

(ii) Calculate the receiver sensitivity. Assume it is thermal noise limited. [20%]

(d) The step-index fibre designed in part (b) is found to have an attenuation of 0.25 dB km^{-1} and a chromatic dispersion of 17 ps nm^{-1} km^{-1}. The fibre is to be used within an Ethernet link with the TIA receiver described in part (c) at a data rate of 10 Gb s^{-1}. The laser transmitter has a spectral linewidth of 0.15 nm and an output power of 0 dBm. Assume the coupling efficiency is the fibre collection efficiency you have calculated in part (b) and there is no coupling loss at the receiver end. There is also a 2dB incomplete modulation penalty and a 2 dB margin specified by the customer. The receiver is able to detect pulses with a broadening of 25% of the bit period.

(i) Is the link dispersion limited or attenuation limited? [20%]

(ii) What is the maximum fibre transmission distance? [10%]

END OF PAPER

Answers
Q.1 b)i) 2.18ns, 0.73, ii) 1.52V, 2.8% iii) 1.59V iv) 29.4 nm, 35.9 nm
Q.2 b)ii) 0.63nm c) 43.5 cm-1 d) 2.53ps
Q.3 c) material #1, d)i) 1546 A, (ii) 580 W
Q.4 b) 1.55, 1.51, 12.2% c)i) 7,96 GHz, ii) -19.4 dBm, d)i) attenuation limited, ii) 25.1 km

THIS PAGE IS BLANK

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

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

Thermal noise: resistor

$$\overline{i_{thermal}^2} = 4kTB/R \; ; \; \overline{v_{thermal}^2} = 4kTRB$$

APD excess noise factor

$$F = M^x$$