EGT2
ENGINEERING TRIPOS PART IIA

Monday 3 May 2021 9.00 to 10.40

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
Write on single-sided paper.

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed.
Attachment: 3B6 Photonic Technology Data Sheet (2 pages).
You are allowed access to the electronic version of the Engineering Data Books.

10 minutes reading time is allowed for this paper at the start of the exam.

The time taken for scanning/uploading answers is 15 minutes.

Your script is to be uploaded as a single consolidated pdf containing all answers.

1 (a) Describe the three main processes by which photons and charge interact in semiconductors and give examples of how each process is used in common photonic components. [20%]

(b) An SELED with a direct bandgap energy of 1.40 eV is to be used to generate light.

(i) Describe the basic SELED structure and explain what processes that arise from the structure lead to a poor overall device efficiency. Describe how these can be mitigated by optimising the device structure. Sketch the construction of the optimised device. [20%]

(ii) Calculate the emission wavelength and spectral linewidth at room temperature (20 °C). [10%]

(iii) At this temperature, the radiative and non-radiative lifetimes are found to be 1.5 ns and 2.5 ns respectively. If the overall quantum efficiency of the device is 3%, calculate its external quantum efficiency. [15%]

(iv) The SELED is measured to have a parasitic series resistance of 2 Ω. It is driven directly by a voltage source with an internal series resistance of 10 Ω. Determine the voltage of the source if the SELED is to emit an optical power of 10 mW? [20%]

(v) If the characteristic temperature of the SELED is 90 K, calculate the increase in voltage that would be required to maintain the 10 mW output power if the ambient temperature is raised to 70 °C. [15%]

2 (a) Describe the operation of a Fabry Perot laser diode, explaining the role of optical feedback and population inversion. [15%]

(b) A Fabry Perot laser operates at a wavelength of 1.3 μm. It has an effective refractive index of 3.6, a waveguide scattering loss of 20 cm^{-1} and a length of 250 μm.

(i) Determine the longitudinal mode spacing of the laser. [15%]

(ii) By considering the round trip gain required for lasing, calculate the facet reflectivity required for the laser to exhibit a differential quantum efficiency of 60%. You should assume that both facets have the same reflectivity. [35%]

(iii) The laser has a characteristic temperature of 90 K and an activation energy of 0.7 times the bandgap energy. At an operating temperature of 20 °C, the laser exhibits a threshold current of 30 mA and a lifetime of 25 years. Determine the threshold current and lifetime if the operating temperature is increased to 50 °C. [25%]

(c) Explain qualitatively how the laser device structure may be designed to maximise efficiency. [10%]

3 (a) The bandgap energy of GaAs is 1.424 eV.

(i) Explain why GaAs would not be able to detect light at a wavelength of 1320 nm. [10%]

(ii) If some of the Gallium is replaced by Indium with a molar fraction x, the bandgap energy (in eV) of the resulting InGaAs varies according the expression:

$$E_g = 1.424 - 1.52x + 0.39x^2$$

Calculate the minimum molar fraction that would enable the InGaAs to detect 1320nm light [15%]

(b) The above material is to be used in a solar cell on a satellite.

(i) Describe the operation of a solar cell with the aid of band diagrams. [15%]

(ii) Sketch the graph of the spectral irradiance of solar radiation against wavelength. Using this, discuss the choice of optimum bandgap wavelength for a solar cell to maximise its efficiency. State, with reasons, whether the above material would be a good choice for a solar cell deployed on the satellite. [25%]

(c) The solar cell has the following characteristics when illuminated with 1W incident light at a wavelength of 1150 nm in a test cell.

Operating Temperature, T:	400 K
Quantum efficiency, η:	0.9
Ideality factor, n:	0.95
Dark current, I_0:	1.3 μA
Shape factor, A:	0.6

(i) Calculate the open circuit voltage and the short circuit current. [15%]

(ii) Sketch the dark and the illuminated I-V curves. Indicate the power generation region on the illuminated curve and the optimum operating point. Calculate the maximum generated power. [20%]

4 (a) Describe how the three main fibre types differ, both in terms of construction and performance. [20%]

(b) A step index multimode optical fibre is to be designed to operate at a wavelength of 850 nm. Four different glasses are available, with the refractive indices of glasses 1 to 4 being 1.500, 1.520, 1.535 and 1.580 respectively. The core diameter is specified to be 50 μm.

(i) Identify the best glass for each of the core and the cladding of the fibre, assuming that the fibre is to be used for high capacity optical communications. [10%]

(ii) Calculate the numerical aperture and the approximate number of fibre modes for this design. [10%]

(iii) Calculate the intramodal dispersion and the output pulse width after 1 km of the fibre if the input pulse width is 30 ns. [15%]

(c) A long haul communications link is to be designed to operate at a data rate of 10 Gbit s^{-1} over a fibre length of 120 km. The laser source has an average power of +5 dBm launched into the single mode fibre used for the link and suffers from a 2 dB incomplete modulation penalty. The fibre has a chromatic dispersion of 17 ps nm^{-1} km^{-1} and an attenuation of 0.22 dB km^{-1}. The receiver has a sensitivity of -24 dBm. There is a splicing loss of 0.5 dB where the laser and receiver pigtails are spliced to the transmission fibre. The customer has specified a 3 dB margin.

(i) Calculate the maximum value of the spectral linewidth of the laser source which would allow the design length to be achieved. You may assume that the dispersion limit is reached when a single "one" is broadened to 1.3 times the bit period. [15%]

(ii) Using the spectral linewidth calculated in (i), determine whether the link is dispersion or attenuation limited. [20%]

(iii) Explain how it would be possible to extend the link to national (i.e. 100s km) distances and detail the technologies involved. [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	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	$\frac{dn}{dt} = -\frac{n}{\tau_s} + \frac{I}{eV} - g(n - n_o)P$

Version RVP/3

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

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

Thermal noise: resistor

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

APD excess noise factor

$$F = M^x$$