Version RVP/2

EGT2
ENGINEERING TRIPOS PART IIA

Monday 2 May 2022 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 structure and operation of Surface Emitting and Edge Emitting Light Emitting Diodes and how their properties influence the applications that they are used for. [20%]

(b) An SELED is to be used to generate light at a wavelength of 830 nm.

(i) Calculate the bandgap energy in eV of the active region of the LED and give, with reasons, the name of a good candidate compound semiconductor material for this application. [15%]

(ii) At room temperature (20 °C), the radiative and non-radiative lifetimes of the LED are 2 ns and 5 ns respectively. Calculate the internal quantum efficiency and response time of the LED. [15%]

(iii) The LED is to be operated at a current of 60 mA and is designed to generate a power of 1.5 mW at room temperature. Calculate the required external quantum efficiency. [15%]

(iv) The current to the LED is set initially at the operating current of 60 mA and falls instantaneously to 0 mA at time t = 0 ns. Calculate the time taken for the power from the LED to fall to 1 mW. You may assume that the characteristic time for the LED output is the same as the overall carrier response time of the LED. [20%]

(v) If the characteristic temperature of the SELED is 100 K, calculate the increase in current that would be required to maintain the 1.5 mW output power if the ambient temperature is raised to 100 °C. [15%]

2 (a) Describe the underlying physics of a Fabry Perot laser diode. In particular explain how confinement of carriers and photons is important for efficient operation and describe how this can be best achieved. [25%]

(b) A Fabry Perot laser operates at a wavelength of 1.55 μm and has an effective refractive index of 3.5. Determine the length of the laser if it exhibits a longitudinal mode spacing of 0.8 nm. [15%]

(c) The laser rate equations are:

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

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

(i) Describe the assumptions made in deriving these equations, explaining the variables represented by each term. [15%]

(ii) Using the rate equations, derive the equations for the carrier concentration and photon density in the laser cavity as a function of injection current. Sketch the curves, highlighting the key features. [20%]

(iii) The laser described in (b) has an active region width of 2.5 μm and depth of 0.2 μm, facet reflectivities of 30%, a gain constant of 2.4×10^{-7} cm^3 s^{-1}, a transparency carrier density of 1.2×10^{18} cm^{-3}, a spontaneous emission lifetime of 4.5 ns and a scattering loss of 25 cm^{-1}. Calculate the threshold current. [25%]

3 (a) Describe the difference between a photodiode and a photoconductor. Explain why a photoconductor is suitable for detecting radiation in the wavelength range 2-10 μm. [20%]

(b) For a photoconductor sample that has length *L*, area *A* and bias voltage *V*.

(i) Explain what can be done to increase its photoconductive gain *G*. [15%]

(ii) If the electron and hole transit times are 2 μs and 4 μs, respectively, and the electron and hole recombination times are 0.5 s and 0.4 s, respectively, calculate the value of the photoconductive gain. [15%]

(c) The engineer decides to construct a receiver front end by connecting a *pin* photodiode, which has a capacitance of 1 pF, to a transimpedance amplifier. The feedback resistor has a 10 kΩ impedance and the photodiode's quantum efficiency is 0.8. This is to be used in a 40 Gbit s^{-1} communications link.

(i) The receiver is designed to operate with a bandwidth of at least 80% of the data rate. Calculate the minimum amplifier gain that is required. [15%]

(ii) Calculate the thermal noise limited receiver sensitivity. You may assume that the operating wavelength λ = 1.3 μm, the temperature T = 310 K, and that an electrical signal to noise ratio of 23 dB is sufficient. [20%]

(d) If the engineer decides to use an APD instead of a *pin* photodiode, explain qualitatively how the receiver sensitivity can be further improved. [15%]

4 (a) Explain how to shift the dispersion of single mode fibres. [10%]

(b) A multi-mode optical fibre is to be constructed. Both step index and graded index fibres are under consideration.

(i) Explain which type is most suitable for high capacity optical transmission links and sketch the propagation routes of the rays (modes) in both types of fibres. [15%]

(ii) Four different glasses, which have refractive indices 1.50, 1.52, 1.53, and 1.58, respectively, are available to construct the step index fibre. Determine the optimum choice of core and cladding glass to maximise the coupling efficiency from a Lambertian source. [20%]

(c) A long haul communications link is designed to operate at a data rate of 40 Gbit s^{-1} over a single mode fibre. The laser transmitter has a spectral linewidth of 0.01 nm and an output power of +2 dB m. The coupling loss is 2 dB per fibre connection (both from the laser to the fibre and from the fibre to the receiver) and there is 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}. There is also a splicing loss of 0.1 dB. The customer has specified a 3 dB margin.

(i) Using electronic forward error correction technology, the bit error rate of the optical link cannot be greater than 6×10^{-5}. Calculate the quantum limited receiver sensitivity, assuming the photodiode in the receiver has a quantum efficiency of 0.9. State any assumptions you make. [20%]

(ii) What is the worst case receiver sensitivity which would mean that the link was dispersion limited if the receiver is able to detect pulses with a broadening of 30% of the bit period? [25%]

(iii) To increase the transmission capacity with wavelength division multiplexing technology, engineers propose the use of longer wavelength lasers in the L band. Explain why a low phonon energy glass fibre is needed. Assuming the fundamental loss of a low phonon energy glass fibre is 0.22 dB km^{-1} at a wavelength of 1.55 μm, estimate the fundamental loss at a wavelength of 1.85 μm. [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 = $10\log_{10}[P/1\text{mW}]$
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

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

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

$$F = M^x$$