Version QC/5

EGT2
ENGINEERING TRIPOS PART IIA

Friday 26th April 2024   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 processes involving the interaction of photons and charge carriers in a semiconductor, and explain how these relate to the operation of photodiodes, light emitting diodes and laser diodes. Give an explanation for whether direct or indirect bandgap materials may be used in each of these device types. [25%]

(b) A Surface Emitting Light Emitting Diode (SELED), operating at a temperature of 20 °C and at a centre wavelength of 450 nm, is to be driven from a 5 V voltage source with an internal resistance of 2 Ω. At this temperature, the SELED has an external quantum efficiency of 5% and radiative and non-radiative carrier lifetimes of 2 ns and 4 ns, respectively.

(i) Calculate the bandgap of the active material of the SELED in eV and suggest a suitable semiconductor. [10%]

(ii) Calculate the resistance of the SELED if, when driven by the voltage source described above, it emits an output power of 10 mW. Calculate the overall efficiency in converting electrical to optical power. [20%]

(iii) Calculate the characteristic temperature for the SELED if it emits a power of 3 mW when the device temperature increases to 85 °C. [15%]

(iv) If the SELED has an activation energy of 0.5 eV and its lifetime is 500 hours at the elevated temperature of 85 °C, calculate its lifetime at 20 °C. [15%]

(c) Describe briefly how doping of the active material can be used to improve the efficiency and change the rise time of an LED. [15%]

2 (a) Describe in detail the main requirements for the operation of a laser diode. Compare and contrast how lasing performance differs from LED operation. [20%]

(b) A Fabry Perot laser has coated facets. It has a cavity length, L, of 700 µm, an effective refractive index, μ, of 3.3, a waveguide scattering loss, α, of 8 cm^{-1}, an overall differential quantum efficiency, η_d , of 0.5 and a characteristic temperature, T_0, of 90 K. It has an operating wavelength, λ, of 1.3 µm and a threshold current of 24 mA at a temperature of 20 °C.

(i) Determine the drive current required for the laser to generate an overall output power of 4 mW. [15%]

(ii) Derive an equation for the differential quantum efficiency. Calculate the facet reflectivity assuming an equal reflectivity for the two facets. [20%]

(iii) Draw a schematic of the control system that allows the laser output power to be maintained whilst the ambient temperature is allowed to vary. Assuming the laser is required to continue to operate with an output power of 4 mW, calculate the maximum operating temperature assuming the drive current cannot exceed 50 mA. [20%]

(iv) Describe the trade-offs in laser operation if the facet reflectivies can be varied. [10%]

(c) Describe the structure of ridge and buried heterostructure lasers, and explain their relative merits. [15%]

3 (a) List contributions to losses in optical fibres. Can the fibre loss be reduced to zero? [10%]

(b) An optical fibre remains single mode at the wavelength of 1310 nm. Detail the impact on fibre dispersions, when:

(i) It is used to transmit 850 nm signals. [10%]

(ii) It is used to transmit 1550 nm signals. [10%]

(c) Explain what are optical fibre modes? Use a sketch to show optical fibre modes from wave interference. [15%]

(d) Explain why the V parameter for normalised frequency only applies for step-index fibres. From the V-number graph given in Fig.1, explain the condition for a single-mode fibre. [15%]

(e) A step-index optical fibre is constructed with two glasses that have refractive indices of 1.50 and 1.52, respectively. Its core diameter is designed to be 5 μm and its operating wavelength is set at 1550 nm.

(i) Calculate its V parameter and figure out how many linear polarized modes it has. [15%]

(ii) Could a special light coupling technique that only excites the fundamental mode of the fibre reduce the fibre dispersion? If so, why? [10%]

(f) The core diameter of the above step-index fibre is now reduced to 2 μm for a single-mode link. Its dispersion factor can be read from the graph shown in Fig.2 and it has to be maintained within ±10 ps/nm-km. Define the allowed laser wavelength range in this link. [15%]

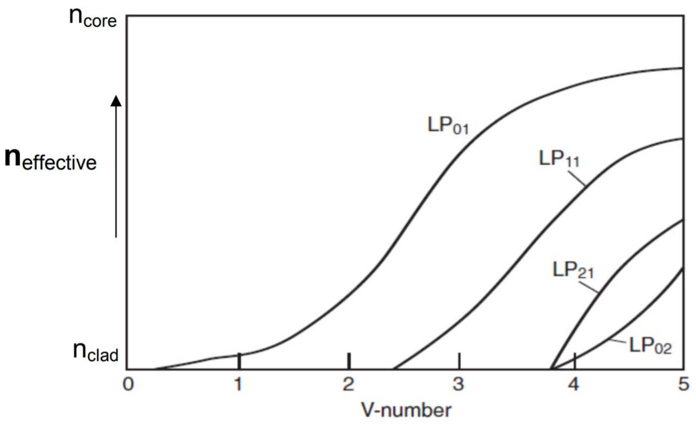
n_core
n_effective
n_clad
LP01
LP11
LP21
LP02
0
1
2
3
4
5
V-number

Fig. 1

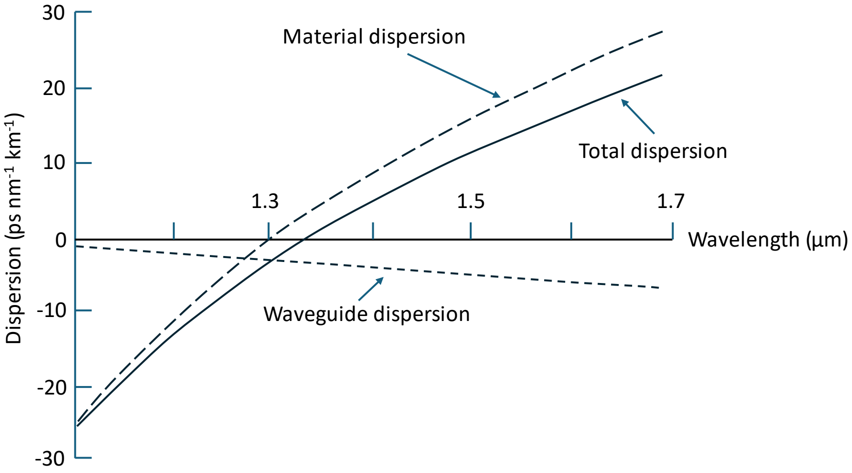
Dispersion (ps nm-1 km-1)
30
20
10
0
-10
-20
-30
1.3
1.5
1.7
Wavelength (µm)
Material dispersion
Total dispersion
Waveguide dispersion

Fig. 2

4 (a) Describe the difference between drift and diffusion for carrier transport, and use the Einstein relationship to explain why diffusion is a very slow process compared with drift. [15%]

(b) Describe the main noise processes in an optical receiver. [10%]

(c) Explain what limits the bandwidth of a *p+n* photodiode and describe how the required high bandwidth design may trade off against its responsivity. Describe how the use of a *pin* photodiode could overcome this problem. [20%]

(d) The expression for current in a semiconductor sample is given as:

$$I = VA(nq\mu_n + pq\mu_p)/L$$

where V is the voltage across the sample, and A and L are its area and length, respectively.

(i) Explain what is the physical significance of the terms in the bracket, giving the meaning of each of the individual terms. [10%]

(ii) Derive the expression for photoconductive gain. [20%]

(e) A 25 Gbit s^{-1} optical link is designed to operate at the wavelength of 1.31 μm. The receiver used in the link has an avalanche photodetector (APD) and a transimpedance amplifier that has a feedback impedance of 1 kΩ and a bandwidth of 20 GHz. The operating temperature is 300 K. The APD has a dark current of 10 nA, an avalanche gain of 100, a quantum efficiency of 0.9 and an excess noise factor x of 0.5.

(i) Quantitatively explain what is the dominant noise source in this link. [15%]

(ii) What is the signal to noise ratio when the optical power is -10 dBm? [10%]

END OF PAPER

Answers

Q.1 (b) (i) 2.75 eV (ii) R = 18.6 Ω, $\eta_i = 0.667$ (iii) 54K (iv) 18,160 hours (2.07 years)

Q.2 (b) (i) I = 32.4 mA (ii) R = 0.571 (iii) $T_{max} = 69.5$ °C

Q.3 (b) (i) Multi-mode fibre with intermodal dispersion (ii) Single-mode fibre but material dispersion will increase (e) (i) V=2.49, 2 LP modes (f) 1284nm to 1490nm

Q.4 (e) (i) Shot noise (ii) 31.7 dB

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)	$\mathrm{E = hf = hc/\lambda}$
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 = 10log$_{10}$[P/1mW]
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	$\tau_{\mathrm{delay}} = \tau_{\mathrm{s}}\ln\left[\frac{I - I_{bias}}{I - I_{threshold}}\right]$
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	$P\langle k\vert N\rangle = \frac{\mathrm{e}^{-N}.N^k}{k!}$
Thermal noise: resistor	$\overline{i_{thermal}^2} = 4kTB/R$; $\overline{v_{thermal}^2} = 4kTRB$
APD excess noise factor	$F = M^x$