UNIVERSITY OF CAMBRIDGE

ENGINEERING TRIPOS PART IIA

Friday 13 May 2005   9 to 10.30

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*

Attachment:
Formulae sheet (2 pages)

You may not start to read the questions printed on the subsequent pages of this question paper until instructed that you may do so by the Invigilator

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1 (a) Describe the three main processes in which charge and photons interact in semiconducting materials, providing examples as to how each is used in common photonic components. [20%]

(b) It is proposed to construct a GaAs surface-emitting light-emitting diode (SELED).

(i) Describe the structure of the SELED. Explain what processes lead to poor device efficiency and how these can be minimised by optimising the device structure. [25%]

(ii) If the bandgap energy of the active region of the SELED is 1.46 eV, estimate the emission wavelength. What would be the spectral linewidth of the device at a temperature of 300 K? [15%]

(iii) Measurements at a temperature of 300 K indicate that the non-radiative and radiative lifetimes of the SELED are 2 ns and 3 ns respectively. If the overall quantum efficiency of the device is 10 %, what is the external efficiency of the device? [15%]

(iv) If the characteristic temperature of the SELED is 80 K, determine the increase in SELED current that would be required to maintain an output power of 2 mW, if the SELED temperature is increased from 300 K to 350 K. [15%]

(c) Explain how an edge-emitting light-emitting diode can be used to provide enhanced beam irradiance when compared with a SELED. What disadvantages however does this device have? [10%]

2 (a) The following electron and photon rate equations are to be used to model the operation of a laser diode:

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

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

(i) Explain the physical origins of the different terms in each equation, indicating any assumptions made. [20%]

(ii) Assuming that $\beta = 0$, derive equations for the threshold current and threshold carrier concentration of the laser under steady state operation. Sketch the *P/I* and *n/I* characteristics of the laser, labelling key points of operation. [20%]

(b) The laser uses a Fabry Perot cavity of length L to achieve optical feedback. If the optical loss per unit length is α and each facet has a reflectivity, R, show that,

$$\tau_p = 1/\,[v_g\,\{\,\alpha + (1/L)\ln(1/R)\,\}]$$

where v_g is the speed of light in the laser cavity. [40%]

(c) Hence derive an expression for the differential quantum efficiency of the laser. What steps can be taken in laser construction to maximise this efficiency? [20%]

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3 A solar cell is constructed from a material with a bandgap wavelength of 1.1 μm.

(a) Describe the operation of solar cells with the aid of band diagrams. [20%]

(b) Sketch a graph showing the spectral irradiance of solar radiation, which has a peak at approximately 0.4 μm, against wavelength. With reference to this, discuss the choice of solar cell bandgap wavelength in terms of efficiency. State, with reasons, whether 1.1 μm is the optimum choice. [25%]

(c) The solar cell has the following characteristics under illumination with 200 mW incident radiation at a wavelength of 1.0 μm.

Quantum efficiency, η :	0.9
Ideality factor, n :	1
Operating temperature, T :	300 K
Dark current, I_0 :	1.0 μA
Shape factor, A :	0.65

(i) Calculate the maximum photocurrent. [10%]

(ii) Using this and the diode equation, calculate the open circuit voltage and the short circuit current. [25%]

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

4 (a) Describe the differences, in terms of both construction and performance, between step-index multimode fibre, graded-index multimode fibre and single-mode fibre. [20%]

(b) An engineer is to design a single-mode fibre for operation at a wavelength of 1.55 μm. The manufacturing process can employ any of three candidate glasses which have refractive indices of 1.44, 1.46 and 1.47 respectively. Calculate the maximum possible diameter of the fibre core and the numerical aperture of this design. [25%]

(c) Upon manufacture, the fibre is found to have a dispersion of 17 ps nm^{-1} km^{-1} and an attenuation of 0.8 dB km^{-1} at the operating wavelength. It is to be used in an optical communications system operating at a data rate of 622 Mbit s^{-1}. The transmitter has an optical bandwidth of 2 nm and launches an average power of 0 dBm into the fibre. The receiver has a sensitivity of −28 dBm and the system is required to have a power margin of at least 2 dB. Calculate the maximum link length that is achievable using the fibre. You may assume that the dispersion limit is reached when a single "one" is broadened to 1.4 times its original length. [40%]

(d) Describe how the maximum link length may be extended. [15%]

END OF PAPER

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3B6 PHOTONIC TECHNOLOGY 2005

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

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Laser: photon lifetime

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

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 figure

$$F = M^x$$