Version RVP/2

EGT2
ENGINEERING TRIPOS PART IIA

Wednesday 22 April 2015 9.30 to 11

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

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

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1 (a) Describe in detail the structure and operation of a *Surface Emitting Light Emitting Diode* (SELED), explaining techniques used to maximise device efficiency and minimise adverse thermal effects. [30%]

(b) Explaining what properties materials should have for efficient LED action, state what materials might be used if LEDs are to operate at 450 nm, 650 nm and 800 nm wavelengths? [20%]

(c) An SELED is to be designed to operate at a wavelength of 650 nm using an emitting material with a *radiative recombination time* of 2 ns and a *non-radiative recombination time* of 4 ns.

(i) If the device must have an overall quantum efficiency of 5%, what *external quantum efficiency* should the device have? [20%]

(ii) The SELED is to be driven from a 3V electrical supply with an internal resistance of 1 q. If the SELED has an internal resistance of 2 q, what series dropping resistance must be used if the SELED is to generate an output optical power of 2mW? [20%]

(iii) An enhanced version of the SELED is to be developed with an overall *carrier lifetime* of 1.5 ns. Assuming that the radiative recombination time of the material used remains at 2 ns, determine what non-radiative lifetime is now required. Assuming that the external quantum efficiency also remains unchanged, determine the circuit dropping resistance to ensure that the SELED continues to generate an optical output power of 2 mW. [10%]

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2 (a) Describe in detail the main interactions between electrons and photons in materials and how these affect the two major properties required for successful laser operation. [25%]

(b) A laser diode is to be constructed using a Fabry Perot cavity. If the cavity has a length of *L*, scattering loss per unit length of Ŭ, refractive index of µ, and if each facet has a reflectivity of *R*, by derivation, show that the *photon lifetime*, Ű$_{p}$, is given as

$$\tau_{\mathrm{p}} = 1/\left\{v_g\left\{\alpha + (1/L)\ln(1/R)\right\}\right\}$$

[20%]

(c) Hence, or otherwise, derive an expression for the *differential quantum efficiency* of the Fabry Perot laser. [25%]

(d) A Fabry Perot laser is to be designed to operate at a wavelength of 850 nm, with a length of 0.5 mm and facet reflectivities of 30%. What scattering loss should the device have if it is to generate a total output power, from both facets, of 10 mW at a current of 10 mA above threshold? [30%]

3 An engineer wishes to design a receiver to form part of a sensitive gas sensor. The gas has an absorption spectrum which has a peak at a wavelength of 1278 nm. The receiver is to incorporate a *p+-n* photodiode.

(a) Calculate the bandgap for a suitable semiconductor for the photodiode. What would be a suitable material from which to construct it? [15%]

(b) *p+-n* photodiodes are usually operated in reverse bias. Explain why that is and how increasing the reverse bias changes important performance characteristics such as responsivity and bandwidth, giving an explanation for these changes. You may assume that the available bias voltage does not cause avalanche operation. [20%]

(c) Sketch the construction of *mesa* and *planar diffused p+-n* photodiodes. [15%]

(d) The sensor is to be operated at a temperature of 100 °C. The photodiode has a *quantum efficiency* of 0.85 at the operating wavelength and a dark current of 10 nA. It is connected to an electrical amplifier with a 17 kΩ input impedance and a bandwidth of 1 kHz. Estimate the *sensitivity* of the receiver, assuming a signal to noise ratio of 3 dB is required. State any assumptions that you make. [35%]

(e) The sensor requires a better sensitivity than you have calculated in part (d). Describe another type of photodiode that could achieve this and explain qualitatively how to optimise the sensitivity assuming that the circuit remains the same apart from the new photodiode. [15%]

4 (a) Describe the differences in construction of the three main types of optical fibre. Explain the reasons for the differences in performance of these fibres. Give the main wavelength operating regimes and construct a table showing which fibre type is used for which wavelength regime, and also for what communications applications each fibre would be deployed. [25%]

(b) A step index multimode optical fibre is to be designed. Four different glasses are available, with the refractive indices of glasses 1 to 4 being 1.510, 1.530, 1.545 and 1.595 respectively.

(i) Determine the optimum choices from the above glasses to use in the construction of the fibre in order to minimise dispersion. [10%]

(ii) Calculate the numerical aperture and the intermodal dispersion of this design. Give your answer to the intermodal dispersion in units of ns km^{-1}. [15%]

(c) A long haul communications link is to operate at a data rate of 10 Gbit s^{-1}. The laser transmitter operates at a wavelength of 1550 nm, has a spectral linewidth of 0.18 nm and an output power of 2 dBm, though there is a 3 dB coupling loss to the transmission fibre. The fibre has a chromatic dispersion of 18 ps nm^{-1} km^{-1} and an attenuation of 0.4 dB km^{-1} and has two fibre splices, each with a loss of 0.25 dB. The receiver has a thermal noise limited sensitivity of -27 dBm and can accommodate a pulse broadening of 50% of the bit period without inducing significant errors. The link specification requires a power margin of at least 3 dB.

(i) Electronic forward error correction technology allows the bit error rate of the optical link to be a maximum of 3×10^{-4}. Calculate the quantum limited receiver sensitivity, assuming the photodiode in the receiver has a quantum efficiency of 0.9. [25%]

(ii) Determine whether the link is dispersion or attenuation limited and calculate the maximum link length. [25%]

END OF PAPER

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3B6 PHOTONIC TECHNOLOGY 2015

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

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

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

$$F = M^x$$

Numerical Answers

Q.1 (c) (i) 7.5 %, (ii) 49 q , (iii) 55 q
Q.2 (d) 11 cm^{-1}
Q3 (a) 0.97 eV, (d) -72.5 dBm
Q4 (c)(i) core 1.545, cladding 1.530, (ii) 0.215, 50.4 ns/km, (c)(i) -52.8 dBm, (ii) 34.5km (dispersion limited)