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EGT2
ENGINEERING TRIPOS PART IIA

Monday 8 May 2017 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

10 minutes reading time is allowed for this paper.

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

1 (a) Describe in detail the structure, operation and properties of an Edge Emitting Light Emitting Diode. Explain what its advantages and disadvantages are in comparison with a Surface Emitting Light Emitting Diode. [30%]

(b) A Light Emitting Diode (LED) is to generate light at a wavelength of 850 nm.

(i) What should be the bandgap energy of the active material of the LED, and which compound semiconductor material would be a good candidate for this application? [10%]

(ii) At a temperature of 20 ^{o}C, the radiative lifetime of the LED is 2 ns and the non-radiative lifetime is 3 ns. What is the overall response time of the LED, and what is the internal quantum efficiency? [10%]

(iii) If the device is to be driven at a current of 50 mA, determine what external quantum efficiency is required for the LED to generate an optical output power of 1 mW at a temperature of 20 ^{o}C. [20%]

(iv) The current to the LED is initially 0 mA, and rises instantaneously to 50 mA at a time, t = 0 ns. What is the output power from the LED at t = 1 ns, assuming that the rise time of the output power is that of the overall carrier response time of the LED? [30%]

2 (a) Describe in detail the operation of a Fabry Perot Laser Diode explaining how efficient performance may be achieved. In your answer, explain the importance of transverse confinement of carriers and photons and describe how this is achieved in a ridge laser device using a double heterostructure. [35%]

(b) A Fabry Perot Laser Diode operates at a wavelength of 1.55 µm, and has a refractive index of 3.6. By deriving an equation for the spacing between the longitudinal modes of the device, determine what the length of the laser should be if the device is to exhibit a mode spacing of 1 nm. [20%]

(c) (i) Explaining all variables and assumptions, show that the differential quantum efficiency may be written as

$$\eta_D = \frac{\ln\left(1/\left(R_1 R_2\right)\right)/\left(2L\right)}{\alpha + \ln\left(1/\left(R_1 R_2\right)\right)/\left(2L\right)}$$

Hence determine the scattering loss of the device in part (b) if the reflectivity of each laser facet is 0.32, and the differential quantum efficiency is 70%. [30%]

(ii) Determine the photon lifetime of the device and hence or otherwise comment on how the choice of facet reflectivity can affect the performance of the laser diode. [15%]

3 An engineer wishes to design a high bandwidth receiver to form part of a communications link, which will operate at a wavelength of 830 nm and at a data rate of 25 Gbit s^{-1}.

(a) Describe, with the help of a diagram, the construction of a high bandwidth p^+-n photodiode. Give two possible materials which would make good design choices for the photodiode. [15%]

(b) Explain what limits the bandwidth of such a p^+-n photodiode and explain how the value of the reverse bias voltage can affect its bandwidth and responsivity. Describe how the operation of a *pin* photodiode differs as a function of reverse bias voltage. [20%]

(a) The engineer decides to construct the receiver front end by connecting a *pin* photodiode, which has a capacitance of 1 pF, to a transimpedance amplifier. The coupling efficiency of the fibre to the photodiode is 80% and the photodiode's quantum efficiency is 90%. The open loop gain of the amplifier is 1000.

(i) Sketch a diagram of the receiver front end circuit. [5%]

(ii) Calculate the value of the transimpedance resistor that results in a receiver bandwidth of 80% of the data rate. You may assume that the resistor has a stray capacitance of 50 fF. [15%]

(iii) Using this value for the resistor, calculate the responsivity of the receiver circuit (i.e. the output voltage of the circuit as a function of the optical power in the fibre in units of V W^{-1}). [10%]

(iv) Calculate the sensitivity of the receiver in units of dBm, stating any assumptions that you make. You may assume that an electrical signal to noise ratio of 20 dB is sufficient to provide suitable performance. The operating temperature of the receiver is maintained at 30 °C. [25%]

(d) Assuming the capacitance of the transimpedance resistor cannot be changed, describe an approach to improving the sensitivity of the receiver whilst maintaining its bandwidth. [10%]

4 (a) There are three main wavelength regions of operation for silica glass. Describe which types of optical fibre are most often used and which applications are most suitable for each wavelength range, giving reasons for your answers. [25%]

(b) Explain why some engineers propose the use of low phonon energy glass to allow operation at longer wavelengths than the three regimes mentioned above. If the fundamental loss of a low phonon energy glass fibre is 0.45 dB km^{-1} at a wavelength of 1.3 µm, estimate the fundamental loss at a wavelength of 2.0 µm. [20%]

(c) A 1.3 µm optical communications system is to operate at a data rate of 10 Gbit s^{-1}. The Fabry Perot laser source emits an average power of 2 mW and has a linewidth of 3.2 nm. The coupling loss from the laser to the fibre is 2 dB. The fibre itself has a dispersion of 1.5 ps km^{-1} nm^{-1} and a loss of 0.5 dB km^{-1} at the operating wavelength. The link contains 4 optical splices, each with a loss of 0.2 dB. The coupling loss to the receiver, which exhibits a sensitivity of 10 µW, is 1 dB.

(i) Electronic dispersion compensation technology allows the received pulse width to have spread by a factor of three times the original bit period. Determine whether the link is dispersion or attenuation limited and calculate the maximum link length. [40%]

(ii) Some time after installation, the network operator wishes to upgrade the capacity and the length of the link to 200 Gbit s^{-1} and 300 km respectively. Describe the technologies which would allow this upgrade to take place. [15%]

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3B6 PHOTONIC TECHNOLOGY 2017

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 $\dfrac{P(T)}{P(T_1)} = \mathrm{e}^{-\left(\frac{T-T_1}{T_0}\right)}$

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

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

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

$$F = M^x$$