ENGINEERING TRIPOS PART IIA

Tuesday 23 April 2013 2 to 3.30

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: Photonic Technology Data Sheet (2 pages)

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS
Engineering Data Book
CUED approved calculator allowed

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

Final version

1 (a) Describe the major processes by which electrical carriers and photons interact in semiconductor materials, explaining how they are used in optoelectronic components. [30%]

(b) A light emitting diode (LED) is to be constructed for operation at a wavelength of 1.3 μm.

(i) What structure might be used in the LED if it is to generate a beam that is particularly suitable for coupling into single mode optical fibres? [20%]

(ii) What bandgap should the semiconductor material have in the active region? [10%]

(iii) At a temperature of 20 °C, the LED material has a non-radiative lifetime of 3 ns. What must its radiative lifetime be limited to, if the overall response time of the LED is to be 2 ns? [10%]

(iv) On this basis, what must the external quantum efficiency of the device be if the overall quantum efficiency is to be 3%? [15%]

(v) The LED is to be operated at a current of 500 mA. What characteristic temperature should it have, if the output optical power must only reduce by 7 mW when the temperature is increased from 20 °C to 80 °C? [15%]

2 (a) Explain the operation of a laser diode, describing the role of population inversion and optical feedback. What steps must be taken to ensure efficient lasing performance? What impact on laser performance does an increase in operating temperature have? [20%]

(b) A coated Fabry Perot laser diode operates at a wavelength of 1.5 μm, and has a threshold current of 20 mA at a temperature of 20 °C. It has a length, L, of 1 mm, an internal scattering loss, α, of 5 cm^{-1}, and an overall differential quantum efficiency, η_d, of 60 %.

(i) Determine the drive current required for the laser to generate a total output power of 5 mW. [15%]

(ii) If the laser has a characteristic temperature of 100 K, what is the maximum temperature that the laser can operate at, if the output power is to be maintained at 5 mW and the drive current is not to exceed 40 mA? [20%]

(iii) Derive an equation for the differential quantum efficiency. [20%]

(iv) Hence estimate the reflectivity of the facets of the laser diode. [15%]

(v) Describe the advantages and disadvantages for a laser diode of increasing or decreasing its facet reflectivities. [10%]

(TURN OVER

3 An engineer is required to design a high bandwidth receiver for a communications link operating at a wavelength of 1550 nm and a data rate of 10 Gbit s^{-1}.

(a) Describe, using a diagram, the construction of a *p+-n* photodiode. [10%]

(b) Explain what limits the bandwidth of a *p+-n* photodiode. Describe how optimising the construction of the photodiode for the required high bandwidth operation might affect its responsivity and how the use of a *pin* photodiode could overcome this problem. [20%]

(c) Describe what material would be the optimum choice for the required operating wavelength, and which of *p+-n*, *pin* or avalanche photodiodes would be the best choice for this application. [10%]

(d) For commercial reasons, it is decided to construct the receiver front end by connecting a *pin* photodiode, which has a capacitance of 6 pF, to an amplifier which has a voltage gain of 300. The coupling efficiency from the input fibre to the photodiode is 90% and the photodiode quantum efficiency is 0.8. The amplifier is to be used in transimpedance mode.

(i) Calculate the maximum value for the transimpendance resistor to allow a receiver bandwidth which is equivalent to the Nyquist frequency of the signal. You may assume that the transimpedance resistor has a stray capacitance of 0.1 pF. [30%]

(ii) Calculate the optical sensitivity of the receiver in units of dBm, assuming that an electrical signal to noise ratio of 18 dB is enough to ensure low error rate operation. You may assume the thermal noise in the transimpedance resistor is the limiting noise process and that the operating temperature of the receiver is 53 °C. [30%]

4 (a) Describe the three most important operating wavelength ranges for optical communications. Explain which types of optical fibres are most commonly used and the types of applications that are most suitable for each of these ranges. [30%]

(b) An optical communications system is to operate at a data rate of 2.5 Gbit s^{-1} at an operating wavelength of 1310 nm. The laser source is measured to have an optical linewidth of 2.5 nm and launches an average power of +2 dBm into the single mode fibre that is to be used for the link. The fibre has a dispersion of 2 ps nm^{-1} km^{-1} and a loss of 0.7 dB km^{-1} at the operating wavelength. The link contains 3 optical splices, each with a loss of 0.25 dB, and the laser and the optical receiver both suffer a 1 dB coupling loss. The receiver has a sensitivity of -21 dBm and employs electronic dispersion compensation.

Determine whether the link is loss or dispersion limited and what is the maximum achievable transmission distance. You may assume that the electronic dispersion compensation in the receiver allows the received pulse width to have spread to three times the original data bit period. [50%]

(c) After a few years, the customer requests an upgraded link. This is specified to have an aggregate data rate of 200 Gbit s^{-1} over a 200 km single mode fibre link. Describe the technologies which would allow the manufacturer of the link described in (b) to upgrade the performance to meet this specification. [20%]

END OF PAPER

3B6 PHOTONIC TECHNOLOGY 2013

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

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

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 factor

$$F = M^x$$