ENGINEERING TRIPOS   PART IIA

Thursday 8 May 2008   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: 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

1 (a) Write notes comparing and contrasting the structure, performance and applications of both a light emitting diode and a laser diode. [25%]

(b) Describe in detail the key features of a Fabry Perot laser structure which ensure efficient operation. Use sketches to illustrate your answer. [30%]

(c) A laser diode is to be used in an application which requires that the delay between the application of a current pulse and the onset of lasing is less than 2 ns.

Assuming that no current is applied to the laser before it is turned on, show that the switch-on delay, τ_{delay}, can be written as, $\tau_{delay} = \tau_s \ln\{I/[I - I_{threshold}]\}$, where τ_s is the carrier recombination time, I is the drive current after turn-on, and $I_{threshold}$ is the threshold current. If the carrier recombination time is 3 ns and the threshold current is 10 mA, determine the drive current, I, required. [30%]

(d) If the laser diode has a differential quantum efficiency of 40% per facet and operates at a wavelength of 1.3 μm, determine the steady state output power of the laser after turn-on at the drive current calculated in section (c). [15%]

2 (a) Explain the main processes involving the interaction of electrons and photons which affect the operation of a laser diode. [10%]

(b) Show how these processes are represented in the rate equations, shown below, by explaining the physical meaning of the different terms and the assumptions on which the equations are based:

$$dP/dt = g(n - n_0)P - P/\tau_p + \beta n/\tau_s ,$$

$$dn/dt = I/eV - n/\tau_s - g(n - n_0)P.$$

[15%]

(c) By solving the rate equations, derive expressions for (i) the threshold current of a Fabry Perot laser diode and (ii) the gradient of the P versus I relationship above threshold. [30%]

Hence sketch graphs for the dependence of photon density and carrier concentration in the laser on drive current. [20%]

(d) The laser has a length L, a scattering loss α, and a reflectivity of R at each facet. By considering the power of the lasing light as it completes one round trip of the laser cavity, show that the optical gain per unit length required for lasing, G, is given by $G = \alpha + (1/L)\ln(1/R)$. Hence derive an equation for the optical output power from each facet as a function of drive current. [25%]

(TURN OVER

3 (a) Describe the construction of a $p+n$ photodiode. Explain the operation of such a photodiode, paying particular attention to carrier transport. Hence describe how the photodiode should be operated to achieve maximum bandwidth. [20%]

(b) Describe the operation of an avalanche photodiode. Explain how avalanche gain can be used to improve the signal to noise ratio of a photocurrent signal. [15%]

(c) An avalanche photodiode is to be part of a receiver for a metropolitan area network optical fibre link. The photodiode operates with a gain of 30, has a quantum efficiency of 85%, a unity gain dark current of 0.8 nA, an excess noise factor of 0.5 and negligible capacitance. It is connected to a TIA circuit which has a transimpedance of 1 kΩ and an electrical bandwidth of 2 GHz. The optical link operates at a wavelength of 1550 nm and at a data rate of 2.5 Gb s^{-1}. The receiver circuit operates at a temperature of 20° C.

(i) Calculate the responsivity of the circuit, defined as the ratio of the output voltage to the received optical power (in units of V W^{-1}).

(ii) Describe the main noise processes in the receiver.

(iii) Calculate the quantum limited receiver sensitivity for a bit error rate of 10^{-10}, stating any assumptions that you have made.

(iv) For the receiver to operate correctly, the signal to noise ratio at the output of the circuit should be at least 23 dB. Calculate the minimum optical input signal power required to achieve this. You may assume that thermal noise is insignificant at this power level. [65%]

4 (a) Give details of the two main forms of degradation of optical signals in optical fibre transmission. Explain how these affect the choice of operating wavelength. [25%]

(b) A step index multimode fibre is constructed with a core diameter of 100 μm, and core and cladding refractive indices of 1.50 and 1.49 respectively. The fibre is to be used in a local area network operating at a data rate of 100 Mbit s^{-1}. Calculate the maximum link length possible, assuming that the receiver can tolerate a 25% broadening of the duration of a single "1". Explain what changes could be made to the fibre design to enable extended link lengths. [25%]

(c) A 10 μm core diameter single mode fibre is to be constructed using the same core material as the fibre described in part (b). Calculate the refractive index of the cladding material required such that the fibre is just single mode at a wavelength of 1550 nm. [15%]

(d) The fibre described in part (c) is found to have an attenuation of 0.15 dB km^{-1}. It is to be used in a 120 km link between Cambridge and London. The laser transmitter operates at a data rate of 10 Gbit s^{-1} and generates an average optical power of 2 mW and has a 4 dB coupling loss into the fibre. The link contains two optical connectors, each with a loss of 0.5 dB, and four splices, each with a loss of 0.25 dB. The receiver sensitivity is -25 dBm. Calculate the link margin. [20%]

(e) Describe how the capacity of the link could be increased to 400 Gbit s^{-1}. [15%]

END OF PAPER

3B6 PHOTONIC TECHNOLOGY 2008

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

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

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

$$F = M^x$$