EGT2
ENGINEERING TRIPOS PART IIA

Tuesday 30 April 2019 9.30 to 11.10

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 at the start of the exam.

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

1 (a) Compare in detail the structure and performance of Surface Emitting Light Emitting Diodes (SELEDs) and Edge Emitting Light Emitting Diodes (EELEDs), stating what application fields the different devices will have. [30%]

(b) An EELED is to generate light at a wavelength of 850 nm.

(i) Explain what materials may be used for the active region of the device, giving physical reasons as to why these materials may be chosen. [10%]

(ii) The EELED is to be driven directly by a voltage source with an internal resistance of 2 Ω in series. If the radiative lifetime is 1.5 ns, the non-radiative lifetime is 2.5 ns, and the external quantum efficiency is 5%, what should the voltage of the source be if the EELED is to emit an optical power of 5 mW? [20%]

(iii) Determine the full width half maximum of the optical spectrum of the EELED in wavelength if it is operating at a temperature of 20 ^{o}C. [20%]

(iv) What is the risetime of the EELED? [10%]

(c) Describe briefly how doping could be used to change the risetime of the device. [10%]

2 (a) Describe in detail the two major fundamental requirements for the operation of a laser diode, and explain how the lasing performance contrasts with that found in a light emitting diode. [25%]

(b) (i) A Fabry Perot laser diode is to be designed to have a threshold current of 20 mA. At a temperature of 20 ^oC, the device gain constant is 3 x 10^{-7} cm^3 s^{-1}, the transparency density is 1.1 x 10^{18} cm^{-3}, the carrier recombination lifetime is 3 ns and the photon lifetime is 3 ps. If the active region depth is 0.2 μm and the width is 3 μm, determine the required device length. State all assumptions made. [30%]

(ii) If the differential quantum efficiency of the device is 0.8 and the operating wavelength is 1.5 μm, determine the total output optical power at a drive current of 50 mA at a temperature of 20 ^oC. [15%]

(iii) If the laser diode has a characteristic temperature of 100 K, what is the output power at a drive current of 50 mA and a temperature of 40 ^oC? [15%]

(iv) By deriving an equation, determine the optical longitudinal mode spacing of the device if the active region refractive index is 3.6. [15%]

3 An engineer is tasked with the design of a sensitive gas sensor. The sensor will operate by measuring the absorption of the gas at a wavelength of 812 nm. The sensor's photo-receiver is to incorporate a *p+-n* photodiode.

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

(b) Describe how *p+-n* photodiodes are usually biased. Explain how varying the bias changes important performance characteristics such as responsivity and bandwidth and provide an explanation for these changes. [20%]

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

(d) The sensor is to be operated at a temperature between 0 and 100 °C. The photodiode has a quantum efficiency of 0.92 at the operating wavelength and a dark current of 1.2 nA. It is connected to an electrical amplifier with a 1.3 kΩ input impedance and a bandwidth of 100 Hz. Estimate the worst case *sensitivity* of the receiver over the temperature range, assuming that a minimum signal to noise ratio of 4 dB is required. State any assumptions that you make and give your answer in units of dBm. [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 amplifier circuit remains the same apart from the new photodiode. [15%]

4 (a) Write a short paragraph on each of the following terms pertaining to optical fibres: *preform; critical angle; normalised frequency*. [20%]

(b) A step index single mode optical fibre is to be designed to operate at a wavelength of 1.532 µm. 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) Calculate the maximum possible diameter of the fibre core using these glasses. Explain why this maximum core diameter design would not normally be used. [15%]

(ii) Calculate the numerical aperture for this design. [10%]

(c) A long haul communications link operating at the design wavelength of the optical fibre is to operate at a data rate of 40 Gbit s^{-1}. The laser transmitter has a spectral linewidth of 0.25 nm and an output power of 5 dBm, though there is a 2 dB coupling loss to the transmission fibre. The fibre has a chromatic dispersion of 16 ps nm^{-1} km^{-1} and an attenuation of 0.25 dB km^{-1} and has two fibre splices, each with a loss of 0.12 dB. The receiver has a thermal noise limited sensitivity of -25 dBm and can accommodate a pulse broadening of 30% of the bit period without inducing significant errors. The link specification requires a power margin of at least 2 dB.

(i) Calculate the quantum limited receiver sensitivity at an error rate of 10^{-12}, assuming the photodiode in the receiver has a quantum efficiency of 0.9. [20%]

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

(iii) Explain how the link technologies might be improved to allow 100 km operation. [10%]

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3B6 PHOTONIC TECHNOLOGY 2019

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

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

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

$$F = M^x$$