Version IHW/1

EGT2
ENGINEERING TRIPOS PART IIA

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Tuesday 3 May 2016 9.30 to 11

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**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 the major processes through which electrons and photons interact, giving examples of how these are used in optoelectronic devices. Explain how the performance of the emission processes depends upon whether one is using a direct or indirect semiconductor material. [30%]

(b) A Light Emitting Diode (LED) is to be used to inject an optical signal into a single mode optical fibre. Describe what LED structure might be used for this application and explain its key features. [20%]

(c) An LED operates at 20 °C at a wavelength of 850 nm, and has a characteristic temperature of 100 K, an activation energy of $5 \times 10^{-20}$ J, and an internal quantum efficiency of 60 %.

(i) 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 °C. [10%]

(ii) What is the maximum temperature at which the LED might be operated if its lifetime (defined as the time taken for the power of the LED to fall to 50% of its initial value when driven at constant current) is to remain at least half that of the value at 20 °C? What is the output optical power at this maximum temperature if the current is maintained at 50 mA, the LED having originally generated 1 mW at a temperature of 20 °C as in part (i) above. [25%]

(iii) Estimate the absolute change in linewidth in nanometres of the LED as the temperature changes from 20 °C to the maximum allowed in (ii). [15%]

2 (a) Describe what assumptions have been made in deriving the laser rate equations as defined below, explaining the variables and physical processes represented by each term:

$$\frac{dn}{dt}=-\frac{n}{\tau_s}+\frac{I}{eV}-g(n-n_o)P,$$

$$\frac{dP}{dt}=g(n-n_o)P+\beta\frac{n}{\tau_s}-\frac{P}{\tau_p}.$$

[20%]

(b) Using the rate equations above, derive equations for the carrier concentration and photon density in the laser as a function of current. State clearly any assumptions made in the derivation. Sketch these functions, drawing attention to key features. [35%]

(c) A Fabry Perot laser diode has the following operating parameters at a temperature of 20 °C: an operating wavelength of 1.5 μm, a carrier recombination lifetime of 3 ns, a photon lifetime of 3 ps, a transparency carrier density of $1.0 \times 10^{18}$ cm$^{-3}$, a gain constant of $3 \times 10^{-7}$ cm$^{3}$s$^{-1}$, and an active region of length 500 μm, width 3 μm and depth 0.2 μm.

(i) Determine the threshold current of the device at 20 °C. [15%]

(ii) Initially the current to the laser diode is set at 0 mA, but then rises instantaneously to a constant value equal to twice the threshold current. Using the electron rate equation, derive an expression for the delay time before the laser diode begins to lase and determine its value. [30%]

3 A high density farming application uses LED lighting to simulate sunlight to stimulate photosynthesis, with solar cells used to harvest the energy from spare light to power temperature and humidity sensors. The irradiance of the light from the LEDs has a triangular shaped irradiance spectrum which has a maximum at a wavelength of 400 nm and which reduces linearly with wavelength until it becomes zero at a wavelength of 730 nm. There is no irradiance for wavelengths shorter than 400 nm or longer than 730 nm.

(a) With the aid of band diagrams and the voltage-current characteristic, describe the operation of a solar cell and contrast this with that of a photodiode. [25%]

(b) Discuss how an engineer might choose the material for the solar cell for this application. In particular, discuss how the bandgap energy of the solar cell might be optimised to produce the highest conversion efficiency. Identify, with a reason, a suitable material for the application. You do not need to calculate the optimum bandgap wavelength. [25%]

(c) A test solar cell is illuminated with 10 mW of incident radiation at a wavelength of 633 nm, at an operating temperature of 30 °C, to simulate the environmental conditions under use. The cell is found to have the following parameters:

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| Quantum efficiency | 0.9 |
| Ideality factor | 0.85 |
| Dark current | 10 nA |
| Shape factor | 0.65 |

(i) Calculate the photocurrent generated under these illumination conditions. [10%]

(ii) Calculate the open circuit voltage and the short circuit current. [20%]

(iii) Sketch the illuminated I-V curve and mark the optimum operating point. Calculate the maximum power that can be generated under these conditions. [20%]

4 (a) Describe the three most important wavelength ranges for optical fibre communications. For each wavelength range, describe the optical source and optical fibre most commonly used and the application scenario that is most suitable. [25%]

(b) A step index multimode fibre has a numerical aperture of 0.15, a core index of 1.47 and a core diameter of 70 μm. Calculate:

(i) the refractive index of the cladding. [5%]

(ii) the acceptance angle of the fibre. [10%]

(iii) the approximate number of modes at an operating wavelength of 850nm. [5%]

(iv) the intramodal dispersion in units of ns $\mathrm{km}^{-1}$. [10%]

(v) the output pulse width for a 2 km length of the fibre for an input pulse width of 20 ns. [10%]

(c) The fibre in part (b) has an attenuation of 4 dB $\mathrm{km}^{-1}$. Calculate the maximum transmission distance for optical communications systems operating at 1 Mb $\mathrm{s}^{-1}$ and 140 Mb $\mathrm{s}^{-1}$ with a transmitted power of 1 mW in each case. For satisfactory operation of the link the received power should be at least 1 nW / ( Mb $\mathrm{s}^{-1}$ ) and the received pulse width should not be greater than 50% longer than the transmitted pulse. [25%]

(d) Explain how graded index multimode fibre would improve the performance of the systems described in part (c). [10%]

**END OF PAPER**

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Version RVP/2

# 3B6 PHOTONIC TECHNOLOGY 2016

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

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| **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)** | $P(t) = P(0)\mathrm{e}^{-\beta t}$<br>$\beta = \beta_0\,\mathrm{e}^{-\frac{E_a}{kT}}$ |
| **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** | $\frac{dn}{dt} = -\frac{n}{\tau_s} + \frac{I}{eV} - g(n - n_o)P$ |

Version IHW/1

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| **Laser: photon lifetime** | $\tau_p = \left(\frac{\mu}{c}\right)\frac{1}{\alpha + \frac{1}{2R}\ln\frac{1}{R_1R_2}}$ |
| **Laser switch on delay** | $\tau_{\text{delay}} = \tau_s \ln\left[\frac{I - I_{bias}}{I - I_{threshold}}\right]$ |
| **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** | $P\langle k \mid N\rangle = \frac{e^{-N}.N^k}{k!}$ |
| **Thermal noise: resistor** | $\overline{i_{thermal}^2} = 4kTB/R\,;\ \overline{v_{thermal}^2} = 4kTRB$ |
| **APD excess noise factor** | $F = M^x$ |