2011 Part IIA 3B6 Photenic technology Prof R Penty

Q.1 (a) This is mainly a bookwork question, and a good answer should describe in some detail the processes of spontaneous emission, stimulated emission and stimulated absorption. The answer should outline the different carrier populations required for each process and contrast the spontaneous with stimulated processes.

A good answer should highlight the properties of the photons (in terms of wavelength, energy and momentum) involved in each process. In addition some students will be expected to comment on the different efficiencies of each process due to type of material (direct and indirect bandgap) and strength of excitation.

(b) This will also have been covered directly in the lecture course. A typical answer will cover the following:

The photon lifetime of the laser cavity can be readily determined by considering the amplification of laser light as it propagates along the laser cavity.

Assume that stimulated emission encounters a gain per unit length (due to stimulated amplification), G, and a loss per unit length due to scattering and absorption, α, as it passes along the laser. The gain G in practice creates extra photons to compensate for those photons lost as the signal travels over a distance of unit length.

Therefore a stimulated optical signal starting at one facet with power A, will be incident on the opposite facet with an optical power, B, such that

$$B = \exp\{(G - \alpha)L\}\, A$$

At that point part of the signal is reflected with a coefficient R and the signal then passes back amplified by the same amount as above and again reflected by the initial facet. Lasing action will occur if the net round trip gain of the signal is unity i.e. if

$$A.\ \exp\{(G - \alpha)L\}.R_1\exp\{(G - \alpha)L\}.R_2 = A$$

$$=> \quad G = \alpha + (1/(2L))\ln(1/(R_1R_2))$$

This value of G is equal to the ratio of photons lost as the signal travels a unit length, and has two components: that required to overcome the internal loss, α, and that to overcome the loss/output of light through the facets $\{(1/(2L))\ln(1/(R_1R_2))\}$. Hence the proportion of photons lost per unit time is simply the gain G times the speed of light in the laser material, v_g. As a result the average time for which one photon will remain in the cavity is given by

$$\tau_p = 1/(Gv_g) = 1/\{v_g\{\alpha + (1/(2L))\ln(1/(R_1R_2))\}\}$$

Since $v_g = \frac{c}{\mu}$ and in this case $R_1 = R_2 = R$ say $\tau_p = \frac{\mu}{c}\left\{\alpha + \left(\frac{1}{L}\right)\ln\left(\frac{1}{R}\right)\right\}^{-1}$

The differential efficiency above threshold is simply the proportion of photons leaving the cavity through the facets over the total number of photons leaving the cavity, ie

$$\eta_D = \frac{\ln(1/(R_1R_2))/(2L)}{\alpha + \ln(1/(R_1R_2))/(2L)}$$

As the constants on the right hand side of this equation (scattering loss, reflectivity and length) do not vary strongly with temperature, the differential quantum efficiency is also relatively invariant.

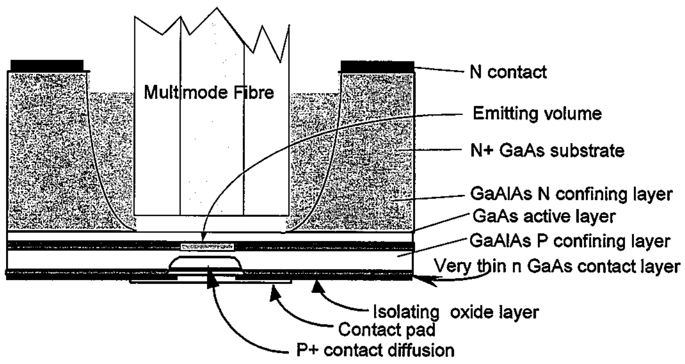
(c) This question requires the determination of the threshold current at 40 °C and then the calculation of the current for an output power of 5 mW, assuming that the differential quantum efficiency does not change:

$J_{th}(T) = J_0 \exp[T/T_0]$ => $I_{th}|T_2 = I_{th}|T1 * \exp((T_2-T_1)/T_0)$ => $I_{th}|_{40} = 20*\exp(20/70) = 26.6$ mA

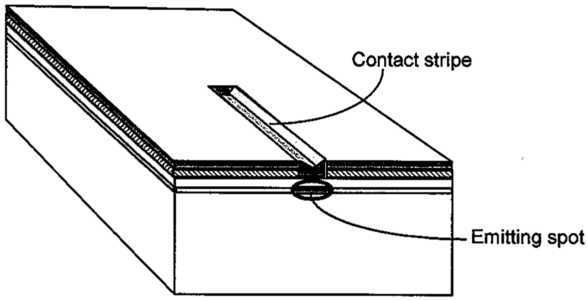
To generate 5 mW, $I = I_{th} + eP\lambda/(hc\eta) = 33.3$ mA

Q.2 (a) This question is primarily bookwork and should involve detailed descriptions of the structure and operation of surface emitting and edge emitting light emitting diodes (LEDs). It would be common for students to use diagrams as part of their answers, the following being typical:

GaAs based Burrus type high radiance LED



Edge emitting LED



Good answers would indicate how the junction is formed, and what steps are taken to ensure high efficiency and/or brightness, effective electrical injection and good thermal performance. It would be expected that answers would indicate the beam properties for the two types of device, and other parameters such as output power and linewidth. Good answers would be expected to indicate clearly the role of heterostructures and other techniques to enhance performance, the range of material systems (and hence operating wavelengths) for which devices have been developed. Finally comments might be made on thermal limitations and lifetime constraints.

A typical surface emitting LED has much of the substrate etched away: this allows high coupling into a multimode fibre, sometimes a spherical micro-lens is interposed as well. In addition, the heat generation is close to the p surface which can be bonded directly to a heatsink and the contact metal also reflects some light back upwards into the fibre.

Edge emitting LEDs operate at similar current densities and currents to surface emitters as above, but the emitting spot is much smaller and the use of optical waveguiding increases the maximum brightness available. They are, therefore, often used where the small spot is useful, particularly in high performance fibre optic transmitters, but only when a laser is inappropriate.

(b) $V = eP\lambda/hc\eta \; R + hc/e\lambda = 1.68$ V

(c) $\eta = \eta_{int}\,\eta_{ext}$ and $\eta_{int} = (1/\tau_{rr})/(\,1/\tau_{rr}+1/\tau_{nr}) \Rightarrow \tau_{nr} = 2$ ns

also $1/\tau_s = 1/\tau_{rr}+1/\tau_{nr} \Rightarrow \tau_s = 1$ ns

(d) $\Delta\lambda \sim \lambda^2\, 2kT/hc = 26\ nm$

Q.3 (a) Bookwork but to include:

(i) diffusion

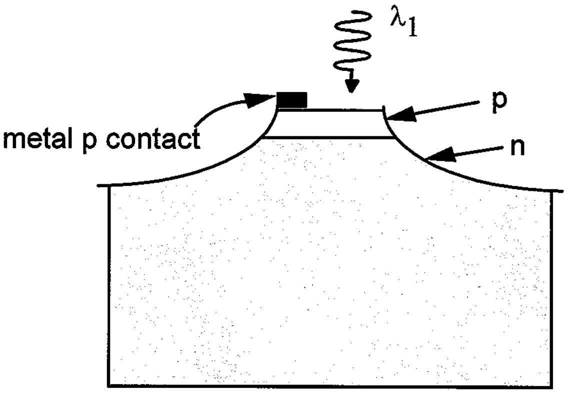
(ii) drift

(iii) capacitance

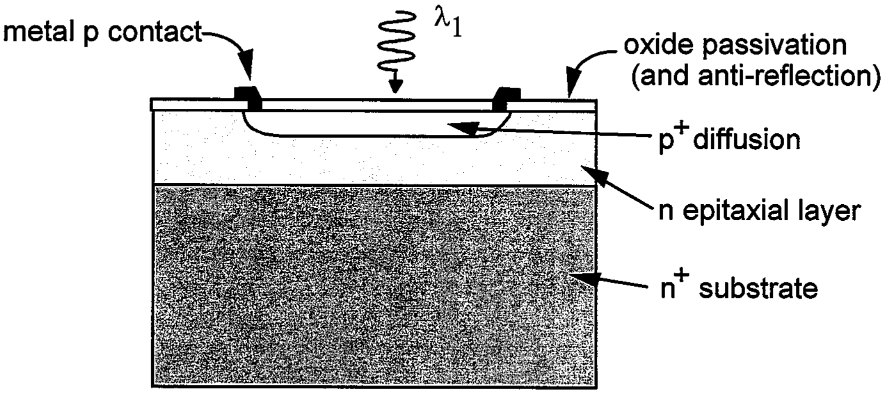
And a discussion of how they affect the performance. Candidates should state the diffusion should be avoided and that the bandwidth is then a trade of between having a wide depletion region (low capacitance but long drift time) and a vice versa.

(b) Bookwork

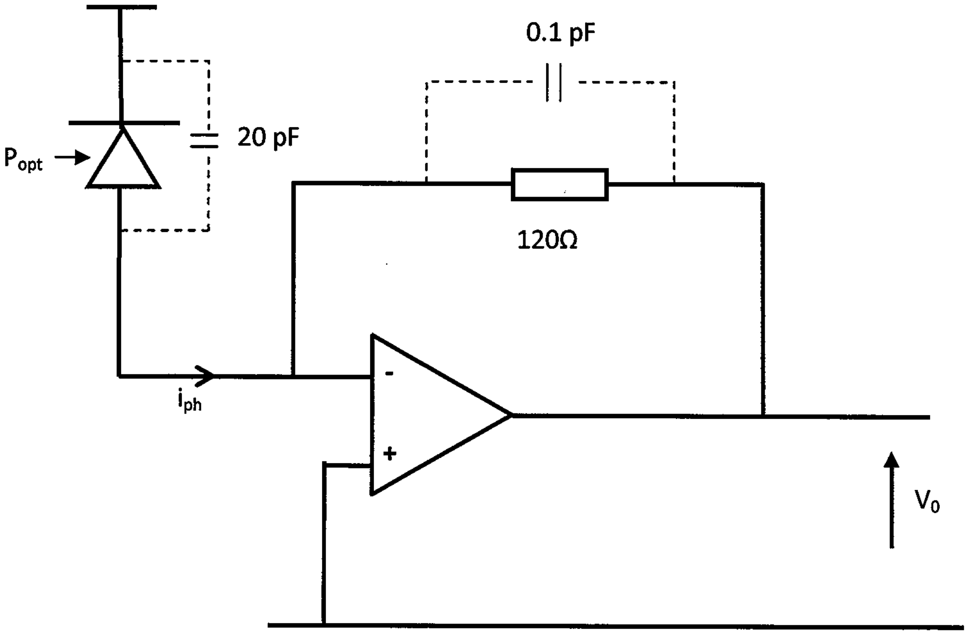
The homojunction mesa photodiode is perhaps the simplest photodiode configuration. A simple etch is used to isolate a section of p doped material and light is coupled through this to be absorbed in the n depletion region.



A more sophisticated design is the planar homojunction photodiode. Here the p regiod is in-diffused into the n region to form the p+-n junction. A ring metal contact and oxide passivation layer (which also can act as an anti-reflection layer – see below) are deposited on top.



(c)



(i) $Eg \mid \max\square \quad = hc/e\lambda \quad = \dfrac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{1.602 \times 10^{-19} \times 1.31 \times 10^{-6}}$

$= 0.947\ eV$

(ii) $V_0 \quad = -i_{ph}R_f$

$= -\eta\dfrac{e\lambda P_{opt}}{hc}R_f$

$\dfrac{V_0}{\Delta P_{opt}} \quad = -0.85 \times \dfrac{1.602 \times 10^{-19} \times 1.31 \times 10^{-6}}{6.63 \times 10^{-34} \times 3 \times 10^{8}} \times 120$

$= -107.6\dfrac{V}{W}$

(iii) $V_0 \quad = -i_{ph}Z$

$= -i_{ph}\dfrac{1}{\frac{1}{R_f}+\frac{j\omega C_{pd}}{G}+j\omega C R_f}$

$= \dfrac{-i_{ph}R_f}{1+j\omega\left(\frac{C_{pd}}{G}+C_{Rf}\right)R_f}$

f_{3dB} when $\omega\left(\frac{C_{pd}}{G}+C_{Rf}\right)R_f = 1$

$f_{3dB} \quad = \dfrac{1}{2\pi\left(\frac{C_{pd}}{G}+C_{Rf}\right)R_f}$

$= \dfrac{1}{2\pi\left(\frac{20 \times 10^{-12}}{500}+0.1 \times 10^{-12}\right)120}$

$= 9.47\ GHz$

(iv) SNR $= (\eta e\lambda/hc\,P_{opt})^2/(4kT/R_f\,B) = 100$ (thermal noise limited)

Sensitivity^2 $= \left(P_{opt}\big|_{SNR=20\,dB}\right)^2 = \dfrac{100\,4kT\,B}{R_f\left(\eta e\left(\frac{\lambda}{hc}\right)\right)^2}$

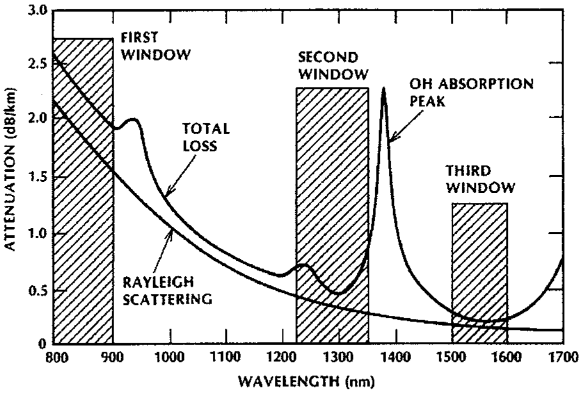
Sensitivity $= \sqrt{\dfrac{100 \times 4 \times 1.38 \times 10^{-23} \times 310 \times 9.47 \times 10^{9}}{120 \times (0.898)^2}}$

$$= 12.9\,\mu W = 0.0129\,mW$$

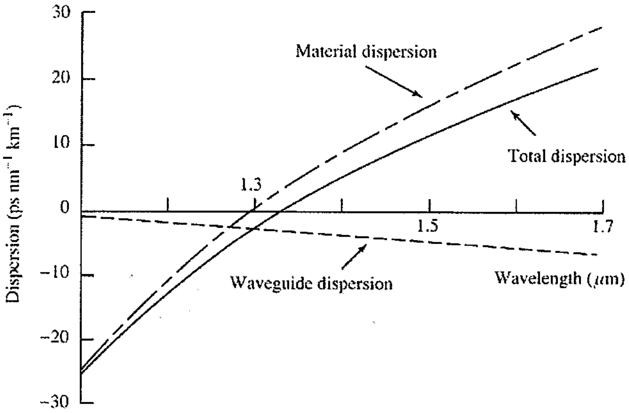
$$= -18.9\,dBm$$

Q.4 (a) Bookwork. However a good answer will cover the two main processes by which optical signals are degraded in single mode fibre and will also discuss how the operating wavelength affects performance.

Attenuation: discuss main attenuation contributors (Rayleigh scattering, absorption due to impurities etc). Sketch a typical attenuation curve e.g.



Dispersion: describe briefly the main dispersion contributions (material and waveguide) and sketch typical dispersion curve: e.g.



A good answer would then state that typically a link is dispersion limited or attenuation limited and that if the former, operating around 1.3 microns is the best wavelength since dispersion is minimised. If attenuation limited, best wavelength is around 1.55 microns since attenuation is a minimum here. There is also the existence of the EDFA at this wavelength.

(b) $V = 2\pi a/(\ (n_{co}^2 - n_{cl}^2)^{1/2} = 2.4$ (for max single mode core size)

$$a_{max} = \frac{2.4\,(}{2\pi\sqrt{n_{co}^2 - n_{cl}^2}}$$

$$= \frac{2.4 \times 1.55 \times 10^{-6}}{2\pi\sqrt{1.51^2 - 1.50^2}} = 3.41\ \mu m$$

$$diameter_{max} = 2\ a_{max} = 6.8\ \mu m$$

(c) (i) Dispersion limit

$$t_{in} = 100\ ps\ ,\ [t_{out}]_{max} = 150\ ps$$

$$[t_{disp}]_{max} = \sqrt{[t_{out}]_{max}^{2} - t_{in}^{2}}$$

$$= \sqrt{150^2 - 100^2}$$

$$= 111.8\ ps$$

$$= .L_{max}$$

$$L_{max} = \frac{[t_{disp}]_{max}}{\Delta\lambda . D} = \frac{111.8\ ps}{\frac{0.2\ nm \times 16 \frac{ps}{nm}}{km}}$$

$$= 34.9\ km$$

Attenuation Limit

$$P_{in} = 3\ dBm \quad)$$

$$) \qquad Power\ budget = 26\ dB$$

$$Sensitivity = -23\ dBm \quad)$$

Losses

Splices	$3 x 0.3\ dB$	$0.9\ dB$
Connectors	$2 x 0.5\ dB$	$1.0\ dB$
Attenuation	$0.23 \frac{dB}{km} x\ L_{max}$	$0.23\ L_{max}\ dB$
Margin		$2\ dB$

	Total	$3.9 + 0.23 L_{max}\ dB$
		$= 26\ dB$

$$0.23\,L_{max} = 22.1$$

$$L_{max} = \frac{22.1}{0.23} = 96.1\ km$$

So link is dispersion limited.

(ii) Would need to improve both dispersion and attenuation performance

Dispersion - use narrower linewidth source

- use dispersion compensation

Attenuation - use optical amplifier (EDFA)

(NB would need 900 km x 0.23 dB/km = 207 dB more launch power without amplifiers = $10^{18}\,W$ rather impractical!)

(iii) Use WDM (for example $10\left(x10\frac{Gb}{s}\right)$ - direct modulation lasers are not possible (NB very modern research methods are using advanced modulation formats (e.g. D-QPSK) to compress 100Gb/s into a narrow spectral linewidth but students are not expected to know this. Obviously if they do, then this would be accepted as a valid answer).