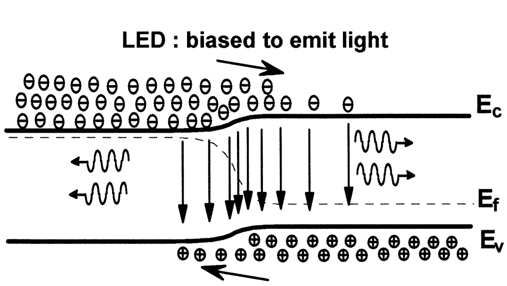
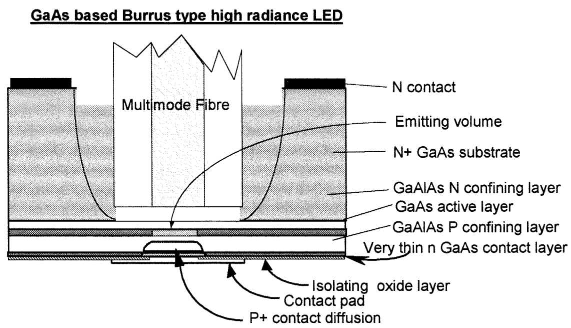
2010 PART IIA 3B6 PHOTONIC TECHNOLOGY
PROFESSOR I H WHITE

3B6 2010 Cribs

Q.1 (a) The answer to this question can be primarily found from bookwork. A good answer should explain the basic principles of operation of a light emitting diode, drawing out the role of spontaneous emission, and how this is achieved using a pn junction. Good answers should describe how the spontaneous processes depend upon material properties (particularly in terms of direct and indirect bandgap materials) and affect device performance such as speed and spectrum.



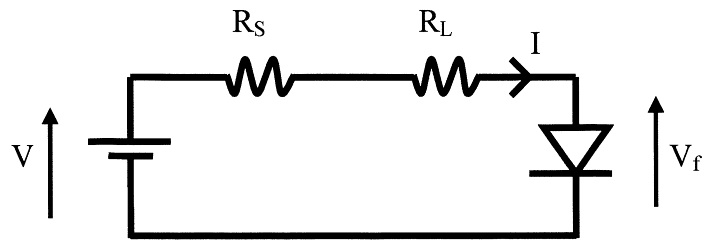


The answer should then move to describing the structure of a SELED, including a diagram, such as above. Good answers will include discussions as to how overall device efficiency depends both on the efficiency of light generation (as encompassed within the internal quantum efficiency) and of light extraction in a useful beam (as encompassed by the external quantum efficiency). Good answers should indicate how the structure is designed to allow enhanced performance, and give exemplar performance properties.

(b) The answer to this section can again be taken largely from bookwork. A good answer should indicate that heat dissipation problems can be severe in semiconductor optoelectronic light emitting devices. Light emitting diodes suffer from saturation of the output optical power at high temperatures and drive levels. This can be due to a variety of effects: (i) current leakage across the junction and the junction resistance both increase with drive and temperature and (ii) by increasing the current drive and operating temperature, increased charge carrier concentrations occur in the conduction band. This can lead to enhanced non-radiative recombination such as Auger recombination where one electron falling from the conduction band gives its energy to another electron in the conduction band rather than to generate a photon. As less light is generated the LED efficiency falls. A good answer will comment on how modelling of such processes is complex and hence empirical equations are used (involving T_0).

Thermal effects in LEDs can be reduced both by materials development and device design. A good answer will comment on exemplar methods for both, for example the use of doping to enhance materials efficiency and hence reduce dissipation, the use of heterojunctions for minimising reabsorption and device thinning for good heat sinking.

(c)



$$V = I(R_S + R_L) + V_f$$

where $V_f = \frac{hc}{e\lambda}$ and $P = \frac{\eta_i \eta_{ext}\ Ihc}{e\lambda}$

$$\Rightarrow V = \frac{e\lambda P}{\eta_i \eta_{ext}\ Ihc}(R_s + R_L) + \frac{hc}{e\lambda} \qquad \text{(A)}$$

$= 0.066 \quad + 1.46$

$= 1.53$ V

(d) $\frac{P(T)}{P(T_1)} = e^{-\left(\frac{T-T_1}{T_0}\right)}$

=> Power at 20^0C equivalent to 1 mW at 70^0C $P(T) = P(T_{70})\, e^{-\left(\frac{20-70}{80}\right)}$

= 1.87 * 1 mW

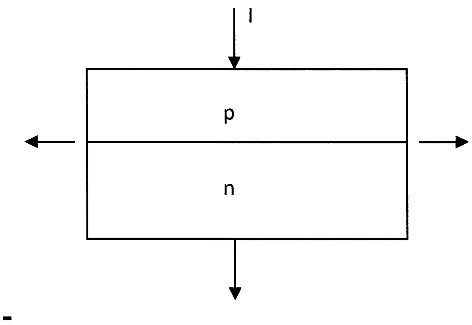
= 1.87 mW

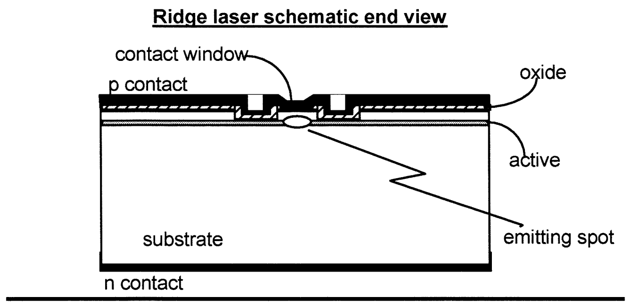
Setting P = 1.87 mW in equation (A) above

=> V = 1.58 V

Q.2 (a) The answer to this section may be primarily taken from bookwork. Good answers should describe in detail the nature of stimulated emission, highlighting the importance of photons being present in a device to cause the generation of additional photons. A description of the use of feedback to achieve this for lasing operation should then be given.

(b) This section again is primarily bookwork. Good answers should describe the formation of a cavity using cleaved facets (giving indication of the facet reflectivities that can readily be achieved using this technique) and then discuss mechanisms used through the introduction of a pn junction and transverse confinement to provide efficient stimulated emission. Diagrams may be included such as those below.



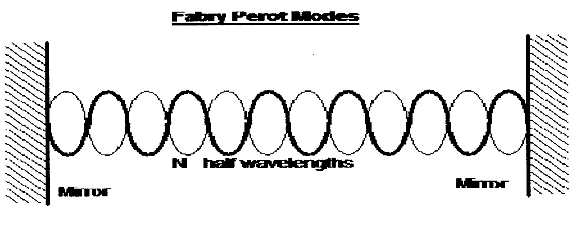


Answers should then comment on how the Fabry Perot cavity then sets boundaries on the wavelength of the lasing emission so that discrete spectral modes are generated. Light therefore is restricted to being generated at wavelengths both where carriers are present to generate such wavelengths and where the cavity allows.

(c) The first part of this question involves a bookwork answer primarily. Due to the Fabry Perot cavity, a result, a series of different wavelengths λ_m can be supported according to, $\lambda_m = 2L/m$ where m is an integer and L is the optical length (equal to the physical length times the effective refractive index). Converting wavelength to frequency, f, we have $f = mc/(2L)$, so that the spacing in frequency between adjacent modes, Δf, is $c/(2L)$. In terms of wavelength, following manipulation, the spacing can be found to be $\Delta\lambda = \lambda^2/(2L)$.

For a cavity length of 0.3 mm, and effective refractive index of 3.6 and an operating wavelength of 1.5 microns, $\Delta\lambda = 1$ nm.

(d)



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 the stimulated light A starting at one facet will be amplified by exp $\{(G - \alpha)L\}$ on reaching the opposite facet with reflectivity R_2. At that point part of the signal is reflected with a coefficient R_2 and the signal then passes back amplified by 1 the same amount as above and again reflected by the initial facet with reflectivity R_1. Lasing action will occur if the nett round trip gain of the signal is unity ie exp $\{(G - \alpha)L\}.R_1\exp\{(G - \alpha)L\}.R_2 = 1$

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

This value of G is equal to the ratio of photons lost as the signal travels a unit length. 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

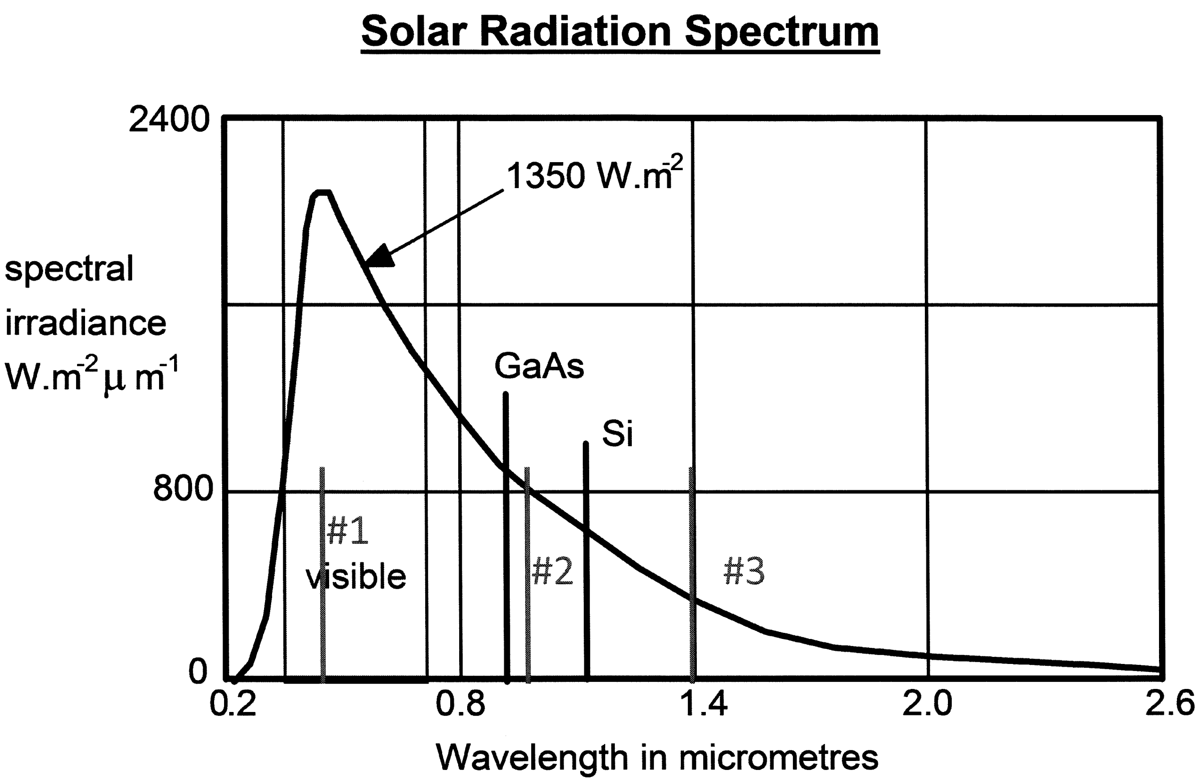
$$\tau_p = 1/(Gv_g) = 1/\{v_g\{\alpha + (1/(2L))\ln(1/(R_1R_2))\}\}$$

Q3 (a) Bookwork

A photodiode is often designed to operate with high bandwidth (ie to avoid the diffusion regime) and to have a low depletion capacitance, which requires a small area. The photodiode is operated in reverse bias (in the bottom LH quadrant of the VI characteristic) and therefore absorbs power.

A solar cell typically doesn't have to be "fast" and needs to collect as much sunlight as possible ie usually has a large area. To generate power it operates in the bottom RH quadrant of the VI characteristic.

(b)



Material #1 has bandgap at Irradiance peak. Only photons with λ <400 nm will be absorbed (~25% of whole) and photon energy >Eg will have excess energy dissipated as heat. Quantum efficiency is low. Material #2 - most photons will be absorbed but energy >Eg will have excess energy dissipated. However, the higher quantum efficiency along with higher proportion of photons absorbed will mean it is more efficient that #1. Material #3 will absorb virtually all solar photons. However, efficiency will be low since most photons will have Eg >>Eph. Hence Material #2 is the best material choice.

(c) Note that appropriate credit will be given if the wrong material choice is made in part (b) and the below analysis is completed with incorrect data.

(i) $I_{ph} = \eta e \frac{P}{\frac{hc}{\lambda}}$ P = Intensity x area

$= 1.2 \text{ kW/m}^2 \times 1.3 \text{ m}^2$

$= 1.56 \text{ kW}$

$$= \frac{0.8 \, x \, 1.602 \, x \, 10^{-19} \, x \, 1.56 \, x \, 10^{3}}{\frac{6.626 \, x \, 10^{-34} \, x \, 3 \, x \, 10^{8}}{10^{-6}}}$$

$= 1005.8$ A

(ii) Open circuit voltage: $I_{ph} = I_0\left(exp\frac{eV_{oc}}{nkT} - 1\right)$

$$\frac{I_{ph} + I_0}{I_0} = \exp\left(\frac{eV_{oc}}{nkT}\right)$$

$$V_{oc} = \frac{nkT}{e} Ln\left(\frac{I_{ph} + I_0}{I_0}\right)$$

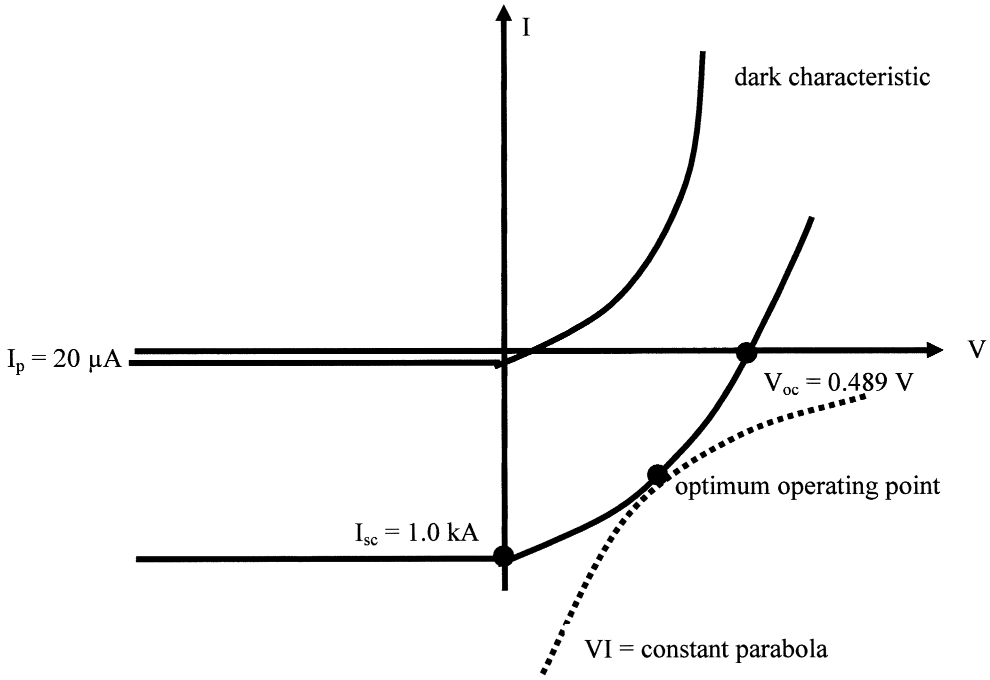
$$= \frac{1 \, x \, 1.38 \, x \, 10^{-23} \, x \, 320}{1.602 \, x \, 10^{-19}} \, Ln \left(\frac{1005.8+20 \, x \, 10^{-6}}{20 \, x \, 10^{-6}}\right)$$

$= 0.489$ V

Short circuit current $I_{sc} = I_{ph}$

$= 1.0$ kA

(iii)



(iv) $P_{max} = AI_{sc}V_{oc}$

$= 0.6 \text{ x } 1.0 \text{ x } 10^3 \text{ x } 0.489$

$= 295$ W

Q4 (a) Attenuation, dispersion The answer to this section is primarily bookwork. A good answer will state the two main degradation mechanisms are attenuation and dispersion. For attenuation it will plot a graph of absorption versus wavelength labelling the main loss mechanisms (absorption tail, Rayleigh scattering, impurity absorption etc) and point out the three main low loss windows for communications. For dispersion, it will mention the three main types – material, waveguide and intermodal – giving a brief description of both.

(b) Bit period T

Width of max broadened pulse = 1.5 T

$T_{out}^2 = T^2 + T_{disp}^2$

$T_{disp}^2 = 1.5^2T^2 - T^2$

$= 1.25\ T^2$

$T_{disp} = 1.118\ T$

Now for MMF

$T_{disp} = t_{max} - t_{min}$

$= \frac{L}{c}\frac{n_1}{n_2}(n_1 - n_2)$ (can be quoted or derived)

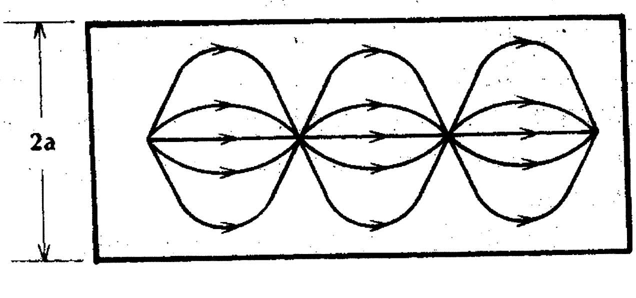
$= \frac{100}{3 x 10^8}\frac{1.52}{1.51}(1.52 - 1.51)$

$= 3.356$ ns

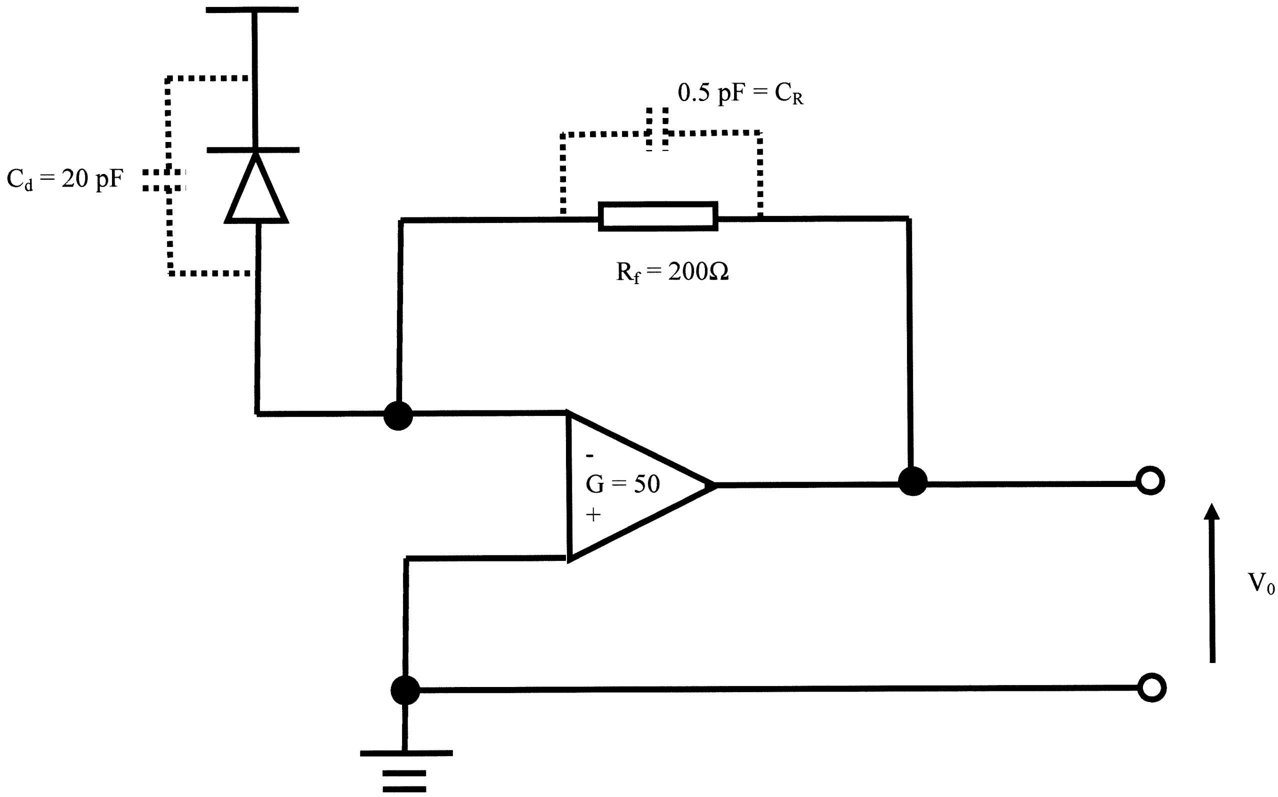
$T = \frac{T_{disp}}{1.118} = \frac{3.356}{1.118} = 3.0$ ns

=> Bit rate $= \frac{1}{T}$ = 333 Mb/s

(c) Use GI - MMF At the optimum grading profile (α~2), then different initial ray angles will pass through the origin with the same frequency, as shown in the lower below. We can now gain an appreciation of why mode dispersion is reduced in GI fibres. Although the rays which have bigger initial angles travel further, they predominantly travel further away from the centre of the fibre and here the refractive index is lower so they travel faster than rays travelling along the fibre axis. Thus these rays can compensate for the longer paths by having a lower average index.



(d) (i) Circuit diagram



(ii) $V_0 = \frac{-I_{ph}R_f}{1+j\omega\left(\frac{C_d}{G}+C_r\right)R_f}$

3dB bandwidth for $\omega = \frac{1}{\left(\frac{C_d}{G}+C_r\right)R_f}$

or $f_{3dB} = \frac{1}{2\pi\left(\frac{C_d}{G}+C_r\right)R_f}$

$= \frac{1}{2\pi\left(\frac{20}{50}+0.5\right)x\ 10^{-12}\ x\ 200}$

= 884 MHz

(iii) Assume shot noise does not affect SNR at low signal levels (ie thermal noise dominates)

$$\text{SNR} = \frac{\left(\eta \frac{e\lambda P}{hc}\right)^2}{4kTB/R_f}$$

$$= \frac{\frac{0.9 \; x \; 1.602 \; x \; 10^{-19} \; x \; 1.55 \; x \; 10^{-6}}{6.62 \; x \; 10^{-34} \; x \; 3 \; x \; 108} \; P^2}{4 \; x \; 1.38 \; x \; 10^{-23} \; x \; 300 \; x \; 884 \; x \; 10^{+6}/200} = 20 \text{ dB} \qquad = 100$$

$$= \frac{1.2662 \, P^2}{0.073 \; X \; 10^{-12}} \qquad = 100$$

$$P^2 = \frac{100 \; X \; 0.073 \; X \; 10^{-12}}{1.2662}$$

$$P = 2.40 \; \mu\text{W} = -26.2 \text{ dB}$$

Numerical Answers

Q.1 (c) 1.53 V, (d) 1.58 V
Q.2 (c) 1 nm
Q.3 (c) (i) 1006 A, (ii) 1 kA, 0.489 V, (iv) 295 W
Q.4 (b) 333 Mb/s, (d) (ii) 884 MHz, (iii) -26.2 dB