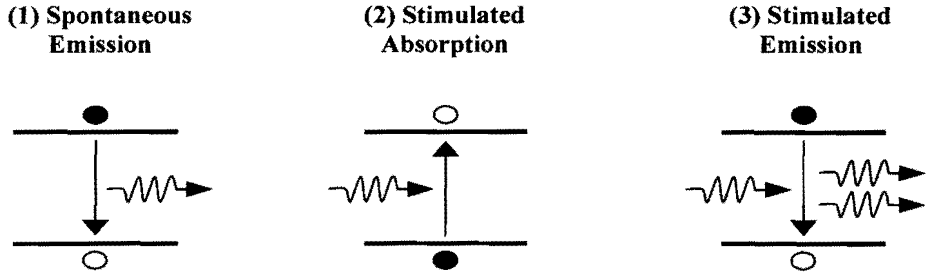
PHOTONIC TECHNOLOGY, 3B6, 2012: OUTLINE ANSWERS (CRIBS)

1 (a) This section requires, as a lead in, a largely a bookwork answer including:

There are three major types of electron/photon interactions in materials.



(1) Spontaneous Emission:

An electron in a high energy level falls losing energy which is emitted as a photon – the basis of operation of a light emitting diode. A *good answer* would comment on requirements for efficient operation and dynamics.

(2) Stimulated Absorption:

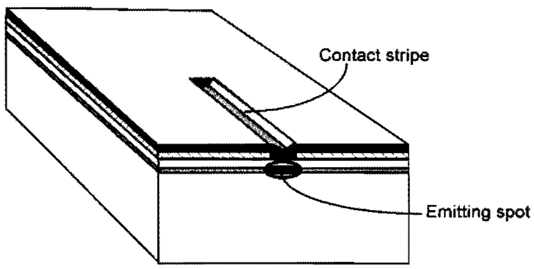
An incident photon is absorbed in a material causing the excitation of an electron to a higher energy level – the basis of operation of a photodiode. A *good answer* would include comments on the impact of the stimulated aspect of the interaction on device dynamics, spectral properties and causes of inefficiency.

(3) Stimulated Emission:

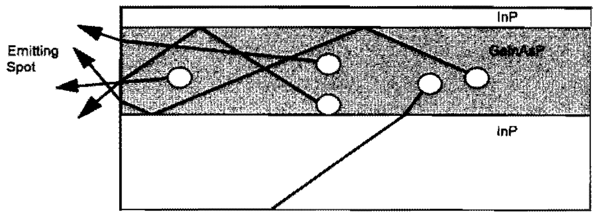
A photon, incident upon an electron in a higher energy level causes the electron to fall to a lower level thus generating a second photon. This is therefore an amplifying action. Two photons are generated from one and in turn they can cause the generation of two further photons. Using this principle, high optical powers can be generated and this operation is the basis of lasing action. The generated photon has the same frequency and phase as the incident photon and therefore very pure monochromatic and coherent light is generated. A good answer would include comments on the relevance and importance of population inversion and manners in which this might be achieved.

(b) (i) Edge emitting LEDs operate at similar current densities and currents to surface emitters, 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. They are *much* better at coupling light into single mode fibres than surface emitters.

Edge emitting LED



Side view of an edge emitting LED



(ii)
$$E = \frac{hc}{\lambda} = 0.96\,\mathrm{eV}$$

(iii)
$$\frac{1}{\tau_c} = \frac{1}{\tau_{rr}} + \frac{1}{\tau_{nr}} \Rightarrow \tau_{rr} = \left(\frac{1}{\tau_c} - \frac{1}{\tau_{nr}}\right)^{-1} = 6\mathrm{ns}$$

(iv)

$$\eta_{\mathrm{tot}} = \eta_{\mathrm{int}}\eta_{\mathrm{ext}}$$

$$\Rightarrow \eta_{\mathrm{ext}} = \eta_{\mathrm{tot}}\left(\frac{\frac{1}{\tau_{rr}} + \frac{1}{\tau_{nr}}}{1/\tau_{rr}}\right) = 9\%$$

(v)

$$P = \eta\frac{hc}{\lambda}\frac{I}{e} = 14.3\ \mathrm{mW}$$

$$\frac{P(T)}{P(T_1)} = \exp\left[-\frac{T - T_1}{T_0}\right]$$

$$\Rightarrow T_0 = -(T - T_1)/\ln\left[\frac{7.3}{14.3}\right] = 90\mathrm{K}$$

Q2 (a) This is primarily a bookwork question. *[In detail]*

In describing *operating* conditions for diode lasing, a typical answer should indicate that two main conditions must be achieved: (i) stimulated amplification must be stronger than absorption so that any optical signal is rapidly amplified in power, and (ii) some form of optical feedback must be provided so that the lasing light generated, can in part be fed back so that stimulated amplification can continue to occur, thus causing sustained emission and hence lasing output.

In order to achieve good power efficiency *(i.e. steps)*, good confinement of current injection and minimisation of unwanted optical losses must be achieved. A good answer will list some structures that can be used in laser diodes to achieve this.

As a result of these requirements, in a typical laser system, much more care must be taken to ensure that the light does not scatter or "leak" out of the lasing region. It is also important to ensure that an optical cavity is bounded by reflectors, so that a lasing filament is formed which oscillates back and forth within the cavity, and that the generated light is confined to cause further stimulated emission. By using partial reflectors, some of the light is emitted from the cavity as the output from the laser.The formation of such a cavity, however, has a major effect on the form of optical spectrum generated.

The explanation *(i.e. impact)* concerning the dependence of laser diode performance on temperature is again largely bookwork. As temperature strongly affects the recombination in a pn junction, it will affect the current required to ensure the high electron charge density necessary in the conduction band for lasing operation. For example, if the temperature increases, the normal time for a carrier to exist in the conduction band before spontaneously falling to the valence band reduces and more current is needed to maintain required charge levels for lasing. A good answer will show that the threshold current can be shown to vary with temperature as

$$J_{th}(T) = J_o \exp\,(T/T_o)$$

Where, e.g. T_o is typically 150 K for GaAs lasers and 70 K for InGaAsP lasers. For small variations in temperature (20°C), η_D may be regarded as constant. The slope efficiency of the device is relatively unaffected as this is dominated by features which are less affected by temperature. At elevated temperatures however, this also does reduce.

(b) (i) The output power equation for the laser diode can be written as

$$P = hc\eta_D\,(I-I_{th})/(e\lambda)$$

$\Rightarrow$ the operating current, $I = I_{th} + Pe\lambda(hc\eta_D) = \underline{30\ \text{mA}}$

(ii) For $I_{th1} = 20$ mA at $T_1 = 293$ K *(given)*

$\Rightarrow I_{th1}/I_{th2} = \exp\{(T_1 - T_2)/T_o\}$

$\Rightarrow T_2 = T_1 + T_o \ln(30/20) = 293 + 100 \ln(3/2) = 333 \text{ K} = \underline{60\ ^oC}$

(iii) *This part is a bookwork question.*

Assume that in a Fabry Perot laser diode, 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.

Therefore the stimulated light A starting at one facet will be incident on the opposite facet with an optical power.

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

At that point part of the signal is reflected with a coefficient R and the signal then passes back amplified by 1 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 ie if

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

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

The gain overcomes the internal losses and the facet losses. As the latter represent useful output power, the differential quantum efficiency is the facet loss over the total loss, ie

$\eta_D = (1/(2L))\ln(1/R_1R_2)) / [\alpha + (1/(2L))\ln(1/R_1R_2))]$

(iv) Assume that there are no leakage currents to degrade quantum efficiency, and $\eta_D = 60\%$ (given).

But $\eta_D = \alpha_f / (\alpha_f + \alpha)$ where α_f is the facet losses.

$\Rightarrow \alpha_f = \eta_D\ \alpha/(1 - \eta_D) = 7.5$ /cm

But $\alpha_f = (1/(2L)).\ln(1/(R_1R_2))$

$\Rightarrow R = R_1 = R_2 = \exp(-\alpha_f L) = \underline{47\%}$

(v) A *good answer* should explain the basic trade-offs, that as reflectivity increases, the threshold current decreases, but the differential quantum efficiency and modulation bandwidth reduces also.

3 (a) Bookwork

(b) Three main limits:
(in decreasing order of severity) diffusion, drift, capacitance

Diffusion should be avoided at all costs as it is a very slow process. Therefore p+n diode must be designed to have depletion region > absorption length.

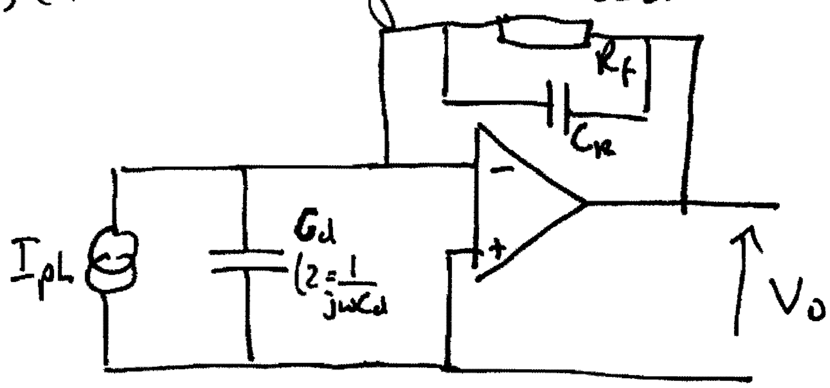
There is then a trade of between speed limited by drift velocity (ie transit time of depletion region) - which would benefit from a narrow dep. region + capacitance - which would benefit from a wide region. Capacitance ~~is~~ also ~~eg~~ reduced by having a small diameter for the photodiode, though this makes coupling difficult.

(c) Bandgap < photon energy ⇒ Si not suitable

~~Ing~~ InGaAs or Ge OK from that perspective but InGaAs diodes have a smaller dark current than Ge ones and are therefore now usually chosen.

Avalanche photodiodes are quite noisy in this wavelength region (Si better) so not usually chosen. For bandwidth reasons, the pin diode would be ~~g~~ better than the p+n.

(d)(i) Small signal circuit



Nyquist frequency of signal $= 8/2 = 5\,GHz$

$$V_o = -I_{ph}\left(R_f \,\|\, \frac{1}{j\omega C_d/G} \,\|\, \frac{1}{j\omega C_R}\right)$$

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

$$\omega_{3dB} \Rightarrow j\omega_{3dB}\left(C_d/G + C_R\right)R_f = 1$$

ignore

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

$$\Rightarrow R_f\big|_{max} = \frac{1}{2\pi\left(C_d/G + C_R\right)f_{3dB}}$$

$$= \frac{1}{2\pi\left(\frac{6\times10^{-12}}{300} + 0.1\times10^{-12}\right)\times 5\times10^{9}}$$

$$= 265.3\,\Omega$$

$$= 265\,\Omega \text{ (3 s.f.)}$$

d) (ii) $$SNR = \frac{I_{ph}^2}{2e(I_{ph}+I_d)B + 4kTB/R_f}$$

But since thermal noise limited

$$SNR = \frac{I_{ph}^2}{4kTB/R_f}$$

$SNR = 18\,dB$
$= 10^{18/10}$
$= 63.1$

$$\Rightarrow I_{ph}^2 = \frac{4kTB\ SNR}{R_f}$$

$$= \frac{4 \times 1.38\times10^{-23} \times 330 \times 5\times10^{9} \times 63.1}{265.3}$$

$$= 2.166\times10^{-11}\ A^2$$

$$I_{ph} = 4.654\ \mu A$$

coupling, quantum

$$I_{ph} = \eta_c \eta \frac{e\lambda P}{hc}$$

$$= \frac{0.9 \times 0.8 \times 1.602\times10^{-19} \times 1.55\times10^{-6}}{6.63\times10^{-34} \times 3\times10^{8}} P$$

$$= 0.899\ P$$

$$\text{Sensitivity } P = \frac{I_{ph}}{0.899} = \frac{4.654\times10^{-6}}{0.899} = 5.18\ \mu W$$

$$= 10\log\left(\frac{5.18\ \mu W}{1\ mW}\right)$$

$$= -22.9\ dBm.$$

4 (a) Bookwork.

Summary table

λ	850nm	1300nm	1550nm
Fibre	MMF	MMF & SMF	SMF
Appl^n	datacom	datacom & telecom (short dist)	telecom
Notes	v. cheap but poor performance (e.g. high loss, dispersion)	zero chromatic dispersion, no amplifier, moderate attenuation	good amp: EDFA – medium dispersion, low attenuation

(b) $2.5\ Gb/s \Rightarrow$ bit period, $T = 400ps$

Dispersion limit: $\Delta t_{disp} = D . L_{disp} . \Delta f$

$= 3 \times 2 \times L_{disp} = 6\ L_{disp}\ (ps)$

$t_{out} = 3 \times t_{in} = 1200\,ps$

$t_{out}^2 = t_{in}^2 + \Delta t_{disp}^2$

$\Delta t_{disp}^2 = t_{out}^2 - t_{in}^2$

$\Delta t_{disp} = \sqrt{1200^2 - 400^2} = 1131\,ps$

$6\ L_{disp} = 1131\ ps$

$L_{disp} = 1131/6 = 189\ km.$

Attenuation limit: use power budget

Budget = launch power − sensitivity

$= 2\,dBm - 21\,dBm = 23\,dB$

Losses $= \underset{\text{splice}}{3 \times 0.25} + \underset{\text{coupling}}{2 \times 1} \quad \times 0.7\ L_{atten}$

$0.7\ L_{atten} = 23 - 0.7 - 2 = 20.3\ dB$

$L_{atten} = 20.3 / 0.7 = 29\ km$

(c) Need to reduce both losses + dispersion.

1. Losses: change λ to 1550nm $\Rightarrow$ losses lower. also can then use EDFAs to overcome losses

2. Dispersion: if λ now 1550nm, dispersion will be higher
~~change~~ employ dispersion compensation fibre

200 Gb/s to high speed for optical sources/receivers
$\Rightarrow$ use WDM

System block diagram: