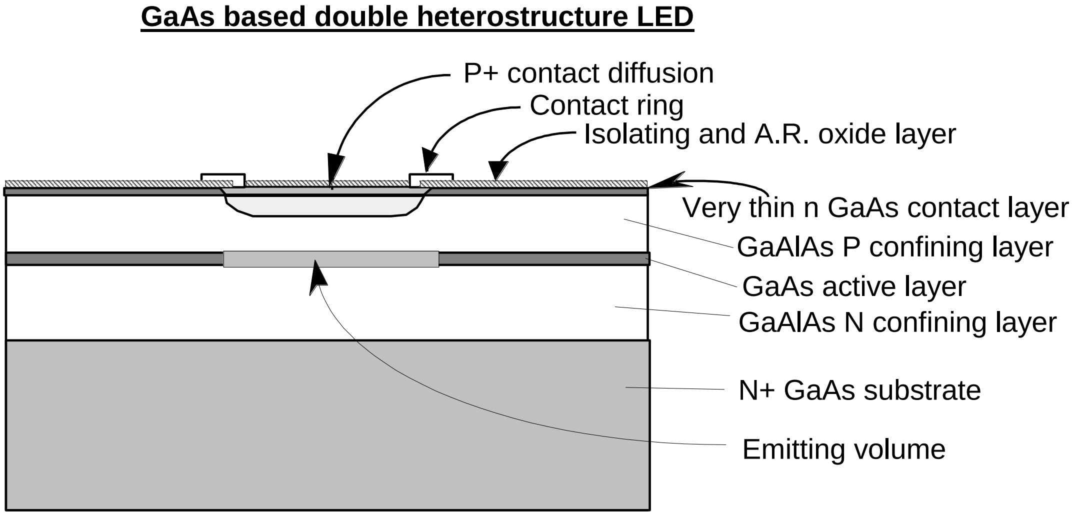
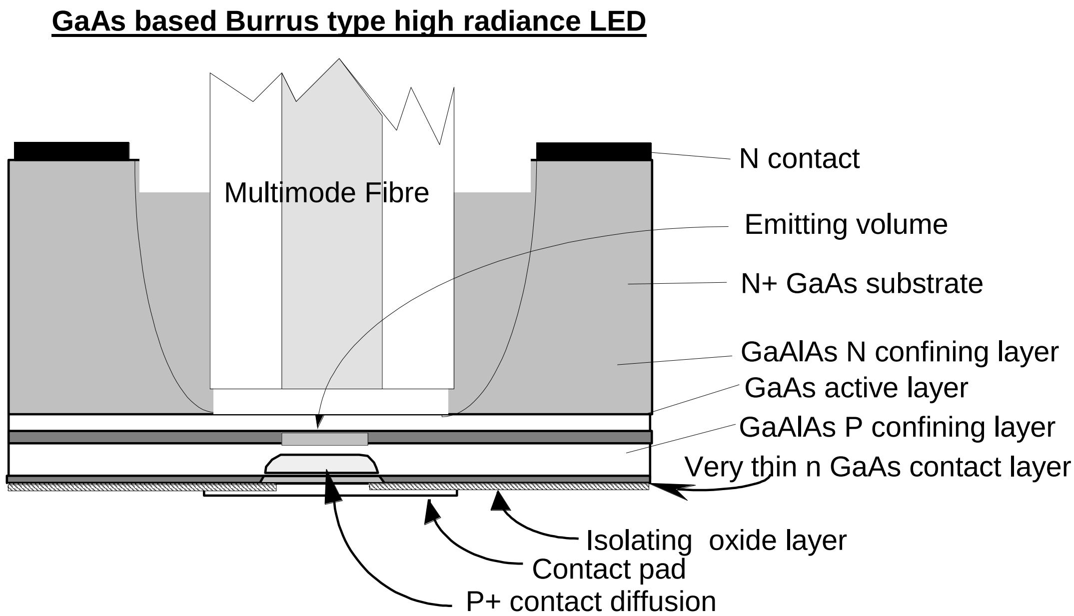
1 a)



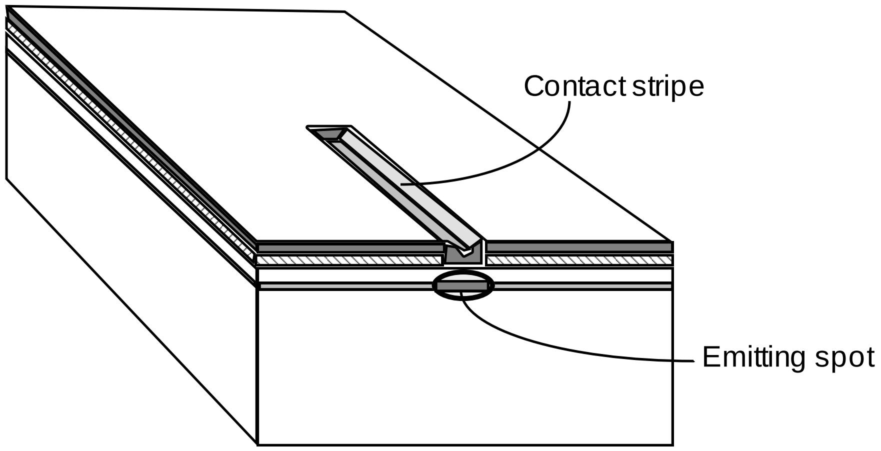
This is a simple LED structure where the pn junction from which the light is emitted is placed near the top of the device so that light, once generated can leave the device out of the top quickly. However light that once generated but travelling to the sides or downwards may be lost.



The Burrus diode 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. Similar devices are made using the InP/GaInAsP materials system at longer wavelengths.

Edge emitting LEDs generate light within a heterostructure and encourage it to be guided along the device and be output at one facet. The devices 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. They are *much* better at coupling light into single mode fibres than surface emitters.

Edge emitting LED



b) i) E_g (in eV) = $E_g = \frac{hc}{e\lambda}$ = 1.495 eV. A good material would be AlGaAs which has a bandgap (tunable by varying the Al concentration), equal to the photon energy.

ii) $1/\tau_s = 1/\tau_{rr} + 1/\tau_{nr}$ => τ_s = 1.43 ns

η_{int} = (no. photons generated/unit time)/(total no. carriers injected/unit time)

= (no. radiative recombinations/unit time)/(total no. recombinations/unit time)

= $(1/\tau_{rr})/(1/\tau_{rr} + 1/\tau_{nr})$ => η_{int} = 0.714 (or 71.4%)

iii) P = photon energy × quantum efficiency × number of injected electrons

$= \left(\frac{hc}{\lambda}\right)\eta\frac{I}{e}$ where $\eta = \eta_{int}\,\eta_{ext}$

So $\eta_{ext} = \frac{P}{\eta_{int}}\frac{\lambda}{hc}\frac{e}{I}$ => $\eta_{ext} = 0.023 = 2.3\%$

iv) Assume $\frac{dP}{dt} = -\frac{P}{\tau_s}$ – the output power is directly proportional to the carrier density in an LED and once the current is turned off, the carrier density will reduce with a characteristic time given by the spontaneous emission time.

Integrating $\int_{P_0}^{P} \frac{dP}{P} = -\int_0^t \frac{dt}{\tau_s}$ or $\ln(P/P_0) = -t/\tau_s$

Rearranging $P = P_0\, e^{-t/\tau_s}$

So the time taken to reduce the power to 1mW is 0.58 ns.

v) From datasheet $\frac{P(T)}{P(T_1)} = e^{-\left(\frac{T-T_1}{T_0}\right)}$ so

$\frac{P(100°C)}{P(20°C)} = \exp\left(-\frac{100-20}{100}\right)$ = 0.45

As the power is proportional to current for both cases (though obviously with a different overall efficiency) to maintain the output power, we need to increase the current by factor 1/0.45, so 60/0.45 = 133.5 mA or 73.3 mA increase.

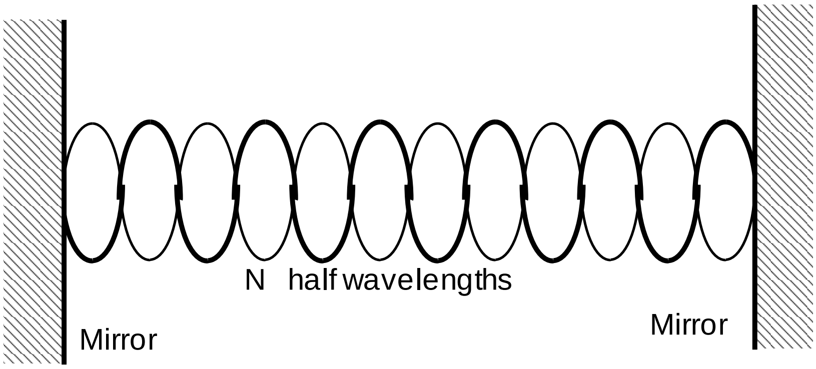
2.. In order for a system to lase, two main conditions must be achieved, (i) stimulated amplification must be stronger than absorption so that any optical signal is rapidly amplified in power, and (ii) some form of optical feedback must be provided so that lasing light generated can in part be fed back so that stimulated amplification can continue to occur, thus causing sustained stimulated emission and hence lasing output.

To achieve continual net stimulated amplification, there must be a larger numbers of free carriers in the upper level than the lower level so that a photon is more likely to stimulate the emission of another photon rather than be absorbed. This therefore requires a “population inversion” to be created as normally carriers gather at the lowest possible energy levels.

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. This can be understood by considering Fig. 2. If the laser cavity is formed by two mirrors with power reflection set a distance, L, apart, the optical filament will oscillate at such a wavelength that nodes occur at both reflectors. Fig. 2

Fabry Perot Modes



As a result, a series of different wavelengths λ_m can be supported by such a cavity where

$\lambda_m = 2L/m$.

where m is an integer. In essence, a series of optical modes that can be generated are given by

$\nu = mc/(2L)$

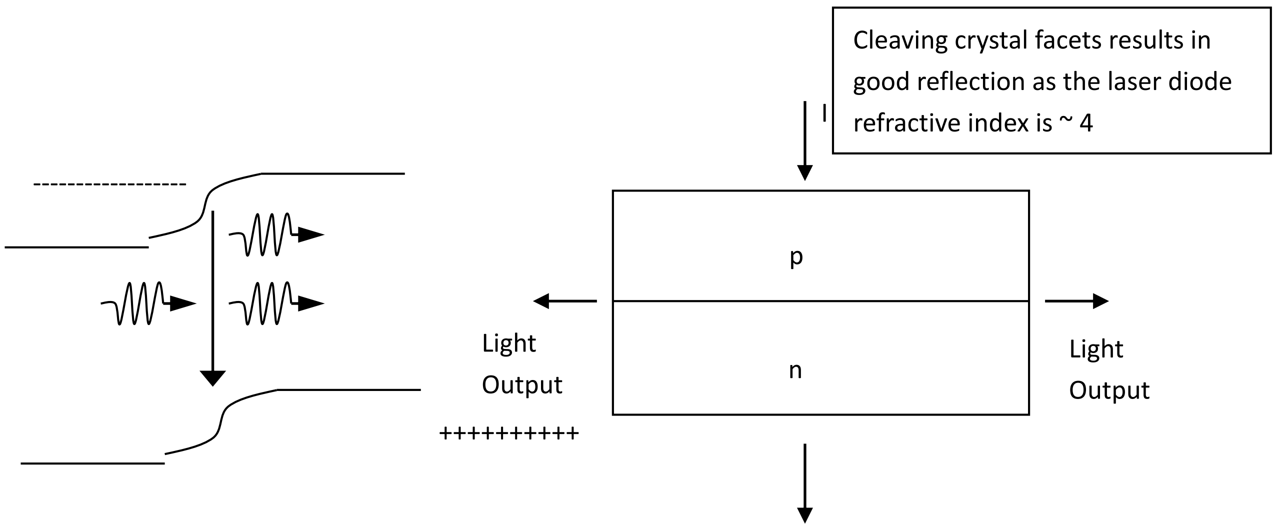
so that the spacing in frequency between adjacent modes, $\Delta\nu_m$, is c/2L.

As $\nu = c/\lambda$, $|\delta\nu| = (c/\lambda^2)|\delta\lambda|$ => $|\delta\lambda_m| = (\lambda^2/c)|\delta\nu_m| = \lambda^2/c.c/2L = \lambda^2/2L$

It should be noted, however, that wavelengths are only generated if electronic transitions occur with the necessary energy spacing. However, a range of optical lasing modes can be generated simultaneously if a range of energy levels are available. By meeting both these requirements, lasing action is achieved.

It should also be noted that the length L is the optical length of the cavity and not the physical length unless the cavity is a vacuum. So if the cavity contains a material with a refractive index n, then the cavity length become n x the physical length.

The diode injection laser is now the most common form of optical source used in fibre communication systems. In order to attain lasing action the following situations must be produced:



- A state must be obtained whereby more electrons exist in the higher electron energy level than the lower (population inversion). Such a condition may be achieved by driving a p-n junction at voltage greater than the bandgap. Here electrons will be injected directly into the conduction band and holes into the valence band so that at the junction, an incident photon is more likely to cause recombination rather than the excitation of a valence electron into the conduction band. Driving a p-n junction at such a high forward bias level can lead to very high power dissipation (10 MW/cm^3) and hence steps are generally taken to ensure that the active light generating region is kept very small.

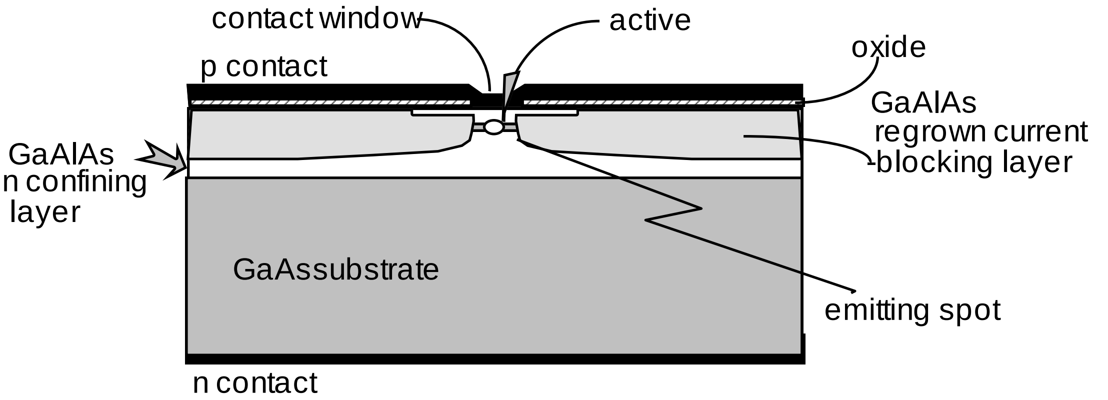
- A method is required to ensure that the photon density in the junction is maintained at a high level. This is generally done by cleaving the p-n diode in chip form so that dielectric mirrors are formed to reflect light back into the device. Typical reflectivities are 30%.

Having a combination of a high concentration of electrons in the conduction band, holes in the valence band and photons in the diode cavity, stimulated emission is more likely than absorption and hence laser action occurs.

At long wavelengths, no absorption or gain occurs, and at short wavelengths the material always absorbs, but near the wavelength corresponding to the bandgap increasing, forward bias will take the material from loss to gain.

To make the laser more efficient, it is important to confine both carriers (so that the threshold carrier concentration can be reached at moderate currents) and photons (so the photons are confined to the same volume where there is gain). This is done best in the buried heterostructure laser where the heterostructure provides both carrier confinement and optical waveguiding in both vertical and lateral operation.

Buried heterostructure laser schematic end view



The Buried Heterostructure laser has excellent current confinement and waveguiding, but is difficult and expensive to make, and is not quite as reliable as the ridge laser. The current confining layers are of $Ga_{0.4}Al_{0.6}As$ doped with germanium, which gives a high resistivity. These structures are actually more popular with InP / GaInAsP materials, where good quality semi-insulating semiconductor cannot be grown, so in this case the current blocking layer consists of a p-n-p sandwich of InP, which together with the n InP of the substrate gives an
n-p-n-p or "thyristor" structure which always has one reverse biased junction and blocks current under low bias conditions.

b) $\Delta\lambda = \lambda^2/2nL$ => L = 429 µm

c) i) A good answer should state that the rate equations make the following assumptions:

- the carrier, photon and current densities are constant in the diode laser throughout its volume,
- that the laser generates purely monochromatic light in one mode,
- that the amplification of light by stimulated emission is linear with carrier concentration and,
- that temperature effects are negligible.

In terms of the electron rate equation:

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

The LHS of the equation concerns the net rate of change of carrier concentration. The RHS has the following terms in order: (i) spontaneous emission, which causes a depletion of carriers per unit time), (ii) current injection (which causes an increase in carrier concentration), and (iii) nett stimulated emission and absorption which causes carrier depletion and enhancement respectively.

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

The LHS of the equation concerns the net rate of change of photon density of the lasing mode. The RHS has the following terms in order: (i) stimulated emission, which causes a growth in photon density, (ii) spontaneous emission (which causes an increase in photon density, but which is diluted by the spectral overlap of the stimulated and spontaneous emission), and (iii) loss of photons from facets and through scattering, as defined by a lifetime.

ii) Assume that the laser is in steady state, dn/dt = dP/dt = 0 and assume that β is very small. Below threshold, when P = 0 (there is no lasing light generated), the electron rate equation becomes simply

$$0 = -n/\tau_s + I/eV \quad => \quad n = I\tau_s/eV$$

so that the overall operation of the laser can be understood. The carrier concentration in the laser increases linearly with current until threshold, when it saturates to a constant value.

(=> $I_{th} = eVn_{th}/\tau_s$)

Rewriting the photon rate equation,

$$0 = g(n - n_o)P - P/\tau_p \quad => \quad P\{g(n - n_o) - 1/\tau_p\} = 0$$

As P may have values greater than 0 (and not less!),

$$g(n - n_o) - 1/\tau_p = 0 \quad => n = n_o + 1/(g\tau_p)$$

However all the terms on the right hand side of the equation are constants. Maintaining a steady state for all values of lasing photon density greater than zero, the carrier constant in the laser is constant. Let this value be called the threshold carrier density, n_{th}.

=> $I_{th} = (eV/\tau_s).(n_o + 1/g\tau_p)$

Considering the electron rate equation, $0 = -g(n - n_o)P - n/\tau_s + I/eV$

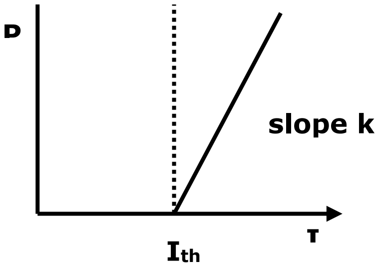
But n = n_{th} for all P>0, so in this regime,

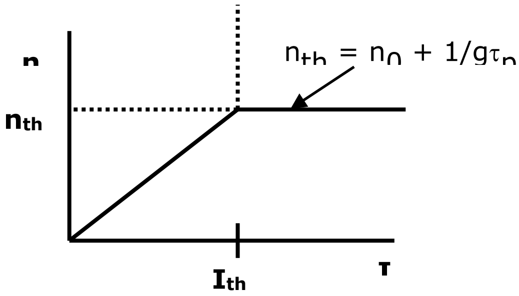
$$P = \frac{\{I/eV - n_{th}/\tau_s\}}{g(n - n_o)}$$

Letting $I_{th} = eVn_{th}/\tau_s$,

$$=> \quad P = \frac{\{I - I_{th}\}}{eV\,g(n_{th} - n_o)} = k(I - I_{th})$$

where the slope, the differential efficiency, $k = 1/eVg(n_{th} - n_o)$





iii) From above $I_{th} = (eV/\tau_s).(n_o + 1/g\,\tau_p)$

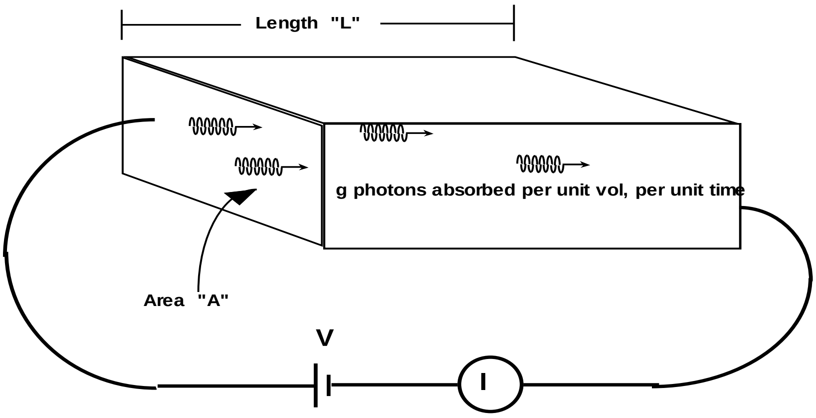
We know all variables apart from the photon lifetime

$$\tau_p = \left(\frac{\mu}{c}\right)\frac{1}{\alpha + \frac{1}{2L}\ln\frac{1}{R_1R_2}} = 2.20\text{ps}$$

So Ith = 23.6 mA

Q3. (a) One of the most common type of photodiodes is the PN junction diode. It consists of an N+ substrate onto which is grown a thin P+ top contact layer. When the structure is reverse biased, some of the N+ region is depleted, most of the potential being dropped across the depletion region. A photodiode can work at high speeds that make them suitable for data communication applications.

A photoconductor is a piece of semiconductor that does not have a PN junction. It operates with external bias voltage. A photoconductor can have a large photoconductive gain but its response time is very long and the device is noisy. It is good for applications were low light levels need to be detected but not where any speed is required (ie communications).



In order to detect wavelengths >about 1.6 µm, we have to use a semiconductor with a bandgap less than the normal Ge or GaInAs/InP. Materials for these wavelengths are difficult to handle and don't produce good junctions, and in any case junction leakage becomes large. We can therefore introduce a donor level inside the bandgap to form a photoconductor, with energy gap between it and the conduction band slightly less than the photon energy to be detected. Thermal excitation will ionise a significant proportion of the donor atoms if the energy gap is less than about 5kT. Using the relationship λ=1.24/Eg, this implies we can use this technique for wavelengths out to about 10 µm at room temperature. Therefore, a photoconductor is suitable for detecting radiation in the wavelengths of 2-10µm.

(b) (i)The photoconductive gain is defined as:

$$G = \frac{\Delta I_{photoconductor}}{\Delta I_{photodiode}} = \frac{\frac{g.\tau_r.e.V.A}{L}\left(\mu_e + \mu_p\right)}{g.e.L.A} = \frac{\tau_r.V}{L^2}\left[\mu_e + \mu_p\right]$$

According to the equation above, the photocondctive gain can be increased by decreasing it's length *L* or increasing it's bias voltage *V*.

(ii) This equation is not obvious in its meaning but some physical understanding can be arrived at as follows:

$$\frac{V}{L} = E \quad and \quad v_e = E.\mu_e \quad and\ similarly \quad v_p = E.\mu_p$$

Substituting

$$G = \frac{\tau_r}{L}\left[v_e + v_p\right]$$

But

$$\frac{v_e}{L} = \frac{1}{\tau_{et}} \quad and \quad \frac{v_p}{L} = \frac{1}{\tau_{pt}}\,, \quad where\ \tau_{et}\,,\ \tau_{pt}\ are\ the\ electron\ and\ hole\ transit\ times\ respectively$$

So

$$G = \frac{\tau_r}{\tau_{et}} + \frac{\tau_r}{\tau_{pt}}$$

Therefore, G=0.5s/2μs + 0.4s/4μs=350000.

(c) (i) B_{min} = 80% × 40 = 32 GHz;

$B_{min}=G_{min} / (2\pi CR_f)$, $G_{min}=B_{min} (2\pi CR_f)=32\times10^9 \times 2\pi \times 1\times10^{-12} \times 10\times10^3=2010.62$

(ii) SNR = 23dB = 200;

$g = \eta\lambda e/(hc) = (0.8 \times 1.3\times10^{-6} \times 1.6\times10^{-19}) / (6.63\text{x}10^{-34} \times 3\times10^8) = 0.837$A/W;

$$\begin{aligned} SNR &= (gP)^2 / (4kTB/R_f) \\ &= (0.837\times P)^2 / (4 \times 1.38\times10^{-23} \times 310 \times 32\times10^9 / 10\times10^3) \\ &= 200 \end{aligned}$$

$P = 3.954\times10^{-6}$W $= 3.954\times10^{-3}$mW = -24.03 dBm

(d) For an APD, the shot noise scaled by the excess noise factor becomes

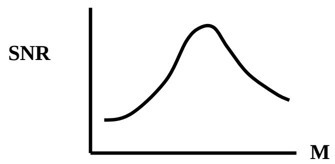
$$\langle i_{ash}^2 \rangle = 2FM2e(gP+I_d)B = 2M^{2+x}e(gP+I_d)B$$

Including the resistive load, the general expression for SNR in photodetectors becomes:

$$SNR = \frac{(MgP)^2}{2M^{2+x}e(gP + I_d)B + 4kTB/R}$$

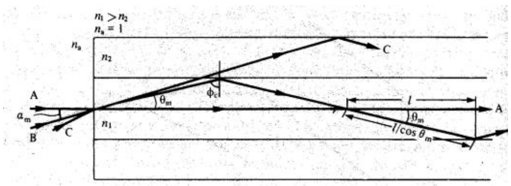
Note for M=1, the expression reduces to that for a pin photodiode.

The thermal noise sets a lower limit on the signal to noise ratio. As the avalanche gain is increased from M=1, the SNR initially rises since the signal power rises as a function of M^2 and the dominant thermal noise is unaffected. However, as a result of the excess noise factor x, the shot noise increases at a faster rate than the signal with increasing power. There is therefore an optimum multiplication factor for the highest signal to noise ratio. This is easily determined by differentiating the signal to noise ratio with respect to the multiplication factor and setting the derivative to zero for the optimum operating point.



Q4. (a) As, by definition, a single mode fibre can only support one mode, by using single mode fibre the problems associated with intermodal dispersion are completely avoided. However, there still remain two other major sources of dispersion, namely material (or chromatic) dispersion and waveguide dispersion. Material dispersion arises because of the wavelength dependence of the refractive index of the material making up thre fibre and applies equally to a plane wave a similar medium as well as in waveguides. Any optical pulse will contain a finite spread of wavelengths. Waveguide dispersion arises because the mode propagation velocity in the fibre itself depends on wavelength regardless of any refractive index variations of the medium. The effects of material and waveguide dispersion are additive. The waveguide dispersion increases with decreasing values of V. Therefore reducing the core diameter will give an increased waveguide dispersion, and will thus shift the zero dispersion wavelength to higher wavelengths. The actual value of the zero dispersion wavelength depends on the fibre dimensions, the material refractive index profile. By a suitable design it is possible to make the zero dispersion wavelength lie anywhere between 1300 and 1600nm.

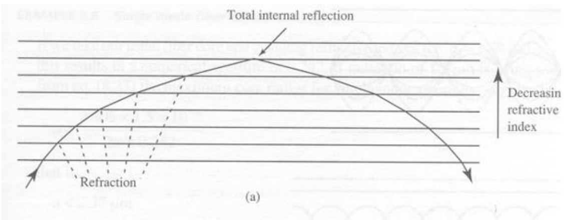
(b) (i) Graded index multi-mode fibres are better since they have smaller intermodal dispersion. For step index multi-mode fibres:



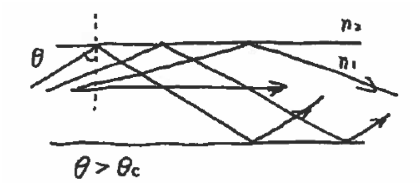
The speed at which the ray travels down the optical fibre is dependent on its internal angle. Ray AA travels down the centre of the fibre and so travels less far than ray BB. The velocity of ray AA along the axis of the fibre will be c/n_1. The component of the velocity of ray BB along the axis will be $(c/n_1)\cos(90-\phi_c)$ or $(c/n_1)\sin\phi_c$. Hence the time difference between the fastest and the slowest ray is:

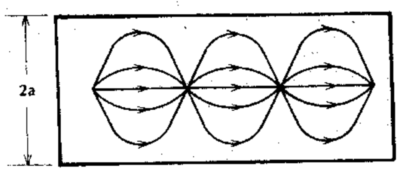
$$\Delta t = t_{\max} - t_{\min} = \frac{L}{c}\frac{n_1}{n_2}(n_1 - n_2)$$

For graded index multi-mode fibres:



The ray will undergo a series of small refractions and the value of ϕ increases. Eventually ϕ will be big enough that the ray undergoes total internal reflection, rather than further refraction and then is directed back towards the centre of the fibre. If we then assume that the refractive index step between layers becomes smaller and the layers become closer together, then the path becomes close to a sinusoid. At the optimum grading profile (α~2), then different initial ray angles will pass through the central axis with the same spatial frequency. The rays which have bigger initial angles travel further. However 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.





(ii) Consider a diffuse light source such as an isotropic radiator (also known as a Lambertian source). The power radiated per unit solid angle for such a source at an angle θ to the normal of its surface is given by

$$I(\theta) = I_0 \cos\theta$$

The total power emitted is found by integrating over all forward directions

$$P_0 = \int_0^{\pi/2} 2\pi I_0 \cos\theta \sin\theta d\theta$$
$$= \pi I_0$$

The power that can be collected by a fibre is given by

$$P = \int_0^{\alpha_m} 2\pi I_0 \cos\theta \sin\theta d\theta$$
$$= \pi I_0 \sin^2 \alpha_m$$

Thus the collection efficiency is given by

$$\frac{P}{P_0} = \sin^2 \alpha_m = \frac{n_1^2 - n_2^2}{n_a^2}$$

Thus, the maximum collection efficiency can be obtained by having n_1=1.58, and n_2=1.50.

(c) (i) As the arrival time of each photon is random, the interaction is statistical. The best distribution to model the process is the Poisson distribution.

$$P(k|N) = \exp(-N)\, N^k / k!$$

where P(k|N) is the probabily of k carriers being photogenerated in a given bit period for an average carrier number N. Assume we have a perfect thresholding device which will give a "1" output if 1 or more carriers are generated in a bit period and a "0" if no carriers are generated. Hence the probability of error is given by:

P.E. = prob of "1" being interpreted as "0" + prob of "0" being interpreted as "1"
= 0.5 { P(0|N) + P(1|0) }
= 0.5 exp (-N) N^0 / 0! = 0.5 exp (-N)

For a probability of error < 6×10^{-5}, we need N ≥ 9. Since η=0.9, N′ = N/η = 9/0.9 = 10;
Assume the probability for "0" and "1" equals, thus each bit has 10/2=5 photons on average.
For a long haul communications link, λ=1.55μm. Photon energy: hc/λ = 1.283×10^{-19} J
P = 5 × 1.283×10^{-19} × 40×10^9 = 2.566×10^{-8} W = 2.566×10^{-5} mW
Quantum limited sensitivity = -45.91 dBm

(ii) Δt_{smf} = D L Δλ = 17 × L × 0.01 = 0.17L ps;
Bit period = 1 / (40×10^9) = 25 ps;

Output pulse width = 25 × 1.3 = 32.5 ps;

$t_0^2 - t_{in}^2 = \Delta t_{smf}^2$

$32.5^2 - 25^2 = (0.17L)^2$, L = 122.16 km.

Sensitivity = 2dBm – 2×2dB – 2dB – 3dB – 0.1dB – 122.16×0.22dB = -33.97 dBm

(iii) At wavelengths greater than about 1.6μm, the main losses are due to transitions between vibrational states of the lattice itself. The actual fundamental absorption peaks occur at wavelengths well into the infrared (in SiO_2, for example, the main peak is at 9μm). However an incoming photon can simultaneously excite two or more fundamental lattice vibrations (or phonons). Thus a number of strong absorption bands extend all the way down to about 3μm with appreciable absorption still occurring below 2μm. Therefore, a low phonon energy glass fibre is needed when longer wavelength lasers (over 1550nm in this case) are used.

The fundamental loss is due to Rayleigh scattering and can be characterised by an absorption coefficient that varies as λ^{-4}. Since the fundamental loss 0.22 dB km^{-1} at a wavelength of 1.55μm, the fundamental loss is thus 0.108 dB km^{-1} at a wavelength of 1.85μm.