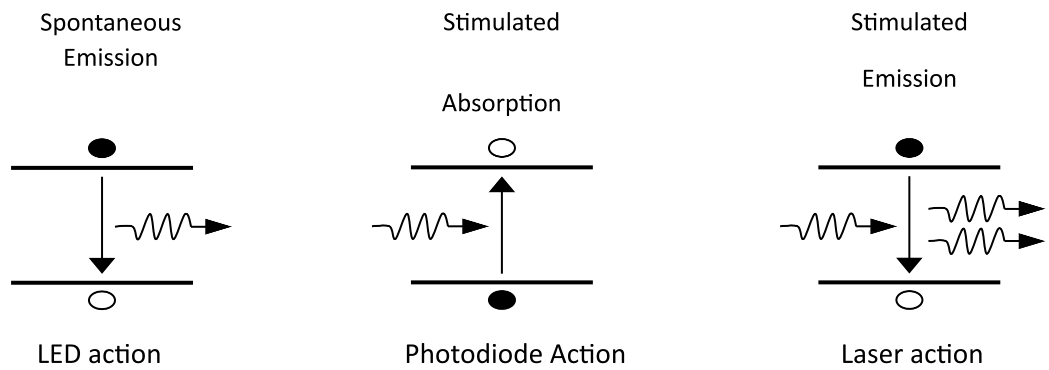
1 (a) There are three major types of electron/photon interactions in materials.

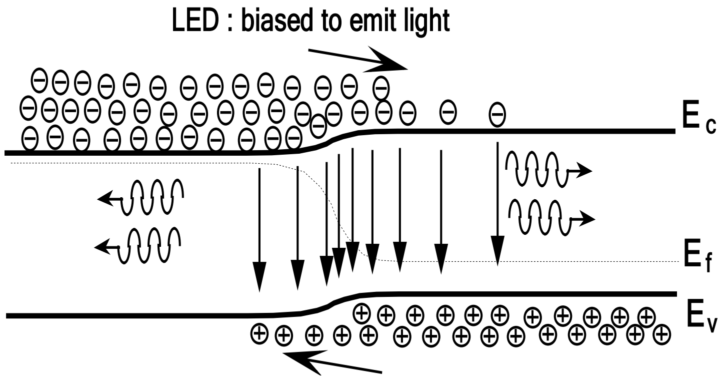


In its simplest form, a light emitting diode consists of a p-n semiconductor junction at which electrons and holes recombine to generate photons by spontaneous emission. The relation linking the energy lost by the charged particles in the recombination process E_g and the frequency of light is given by:

$$E_g = h\nu = hc / \lambda$$

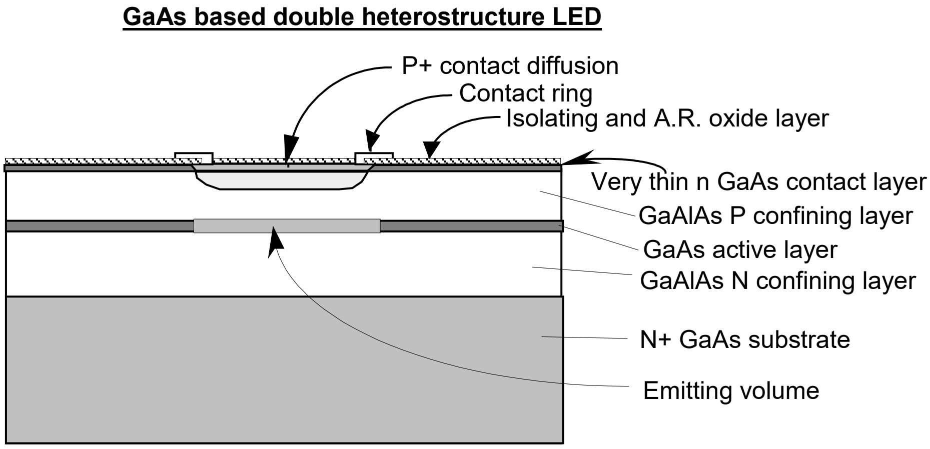
where h is Planck's constant, c is the speed of light and λ is the wavelength.

All LEDs must have a junction, and therefore be compatible with P and N doping. Also indirect materials are likely to be inefficient at best.



LEDs response time is approximately the same as the spontaneous recombination time (few ns) so modulation speeds are limited to 100s MHz. Hence they are used for low cost but low performance optical communications (such as in car or domestic optical networks). LEDs have a good internal quantum efficiency but typically a poor external efficiency. That said they are still much more efficient than incandescent lightbulbs, and have a much longer lifetime. Hence they are replacing most lighting sources.

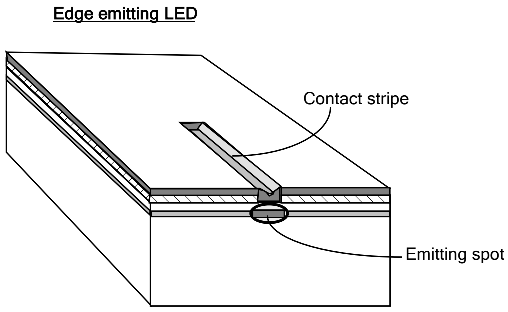
(b) Surface Emitting LED Structures

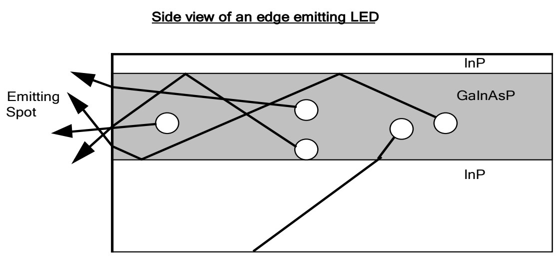


This is a simple LED structure where the pn junction from which the light is emitted is placed near the top of the device so that light, once generated can leave the device out of the top quickly. However light that once generated but travelling to the sides or downwards may be lost. Almost identical structures are used in the InP/GaInAsP system for wavelengths of 1300 nm and 1500 nm. In this case the substrate and both confining layers are InP, and the active layer and thin top contact layer are GaInAsP. In fact, the thin top contact layer is often composed of GaInAs, since this is easy to grow and, although this will absorb the generated light, its thickness is very small, so the total light absorbed is small.

Edge Emitting LEDs

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.





(c)(i)

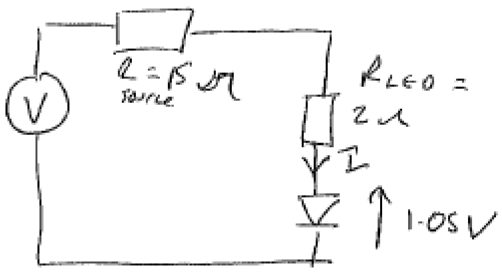
$$E_g = \frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{\mathrm{E}}$$
$$= \frac{6.63 \times 10^{-34} \quad \times 3 \times 10^{8}}{1.05 \times 1.602 \times 10^{-19}} = 1.18\mu m$$

$$\Delta\lambda = \frac{2kT\lambda^2}{hc6.63 \times 10^{-34} \times 3 \times 10^{8}}$$
$$= \frac{2 \times 1.388 \times 10^{-23} \times (1.18 \times 10^{-6})^2 \times 293}{6.63 \times 10^{-34} \times 3 \times 10^{8}}$$
$$= 57\mathrm{nm}$$

(ii)

$$\eta_{\text{int}} \quad = \frac{1/\tau_r}{1/\tau_r + 1/\tau_{nr}} = \frac{1}{1 + 1/3} = 0.75$$
$$\eta = \eta_{int} \ \times \eta_{ext}$$
$$= 0.75 \times 0.07$$
$$= 0.0525$$
$$= 5.3\% \text{ (2 s.f.)}$$

(iii)



$$P_0 = \eta \frac{hc}{\lambda} \frac{I}{e}$$
$$\Rightarrow \qquad I = \frac{e\lambda}{\eta hc} P$$
$$= \frac{1.602 \times 10^{-19} \times 1.18 \times 10^{-6}}{0.0525 \times 6.63 \times 10^{-34} \times 3 \times 10^{8}} \times 10^{-3}$$
$$= 18.1\mathrm{mA}$$
$$V = I(R_{\text{souce}} \ + R_{LED}) + 1.05\mathrm{V}$$
$$= 18.1 \times 10^{-3} \times (15 + 2) + 1.05\mathrm{V}$$
$$= 1.36\mathrm{V}$$

(iv)

$$\frac{P(T)}{P(T_1)} = e^{-\left(\frac{T-T_1}{T_0}\right)} \text{ (from data sheet)}$$
$$T = 70^\circ\mathrm{C} = 343\mathrm{K}$$
$$T_1 = 20^\circ\mathrm{C} = 293\mathrm{K}$$
$$\Rightarrow P(70^\circ\mathrm{C}) = e^{-\left(\frac{343-293}{100}\right)} \times 1\mathrm{mW}$$
$$= 0.61\mathrm{mw}$$

(v)

$$\frac{1}{\tau_s} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$
$$= \frac{1}{1} + \frac{1}{3}$$
$$\Rightarrow \tau_s = 0.75 \text{ ns}$$

Bandwidth $\sim \frac{1}{\tau_s}$ so approx.. 1 GHz

To make faster need to reduce τ_s Can improve by doping, but this reduces the efficiency of the device.

2 (a) 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.

(b)(i)

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

Nett change of carrier concentration in laser/s

Rate of increase of carrier cone by current injection

Depletion of carriers through generation of photons by spontaneous emission

Depletion of carriers through generation of photons by stimulated emission

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

Nett change in photon density of lasing mode/s

Increase in photon density of lasing mode by spontaneous emission

Increase in photon density by stimulated emission

Decrease due to losses in laser and from facets

(ii) β is the proportion of spontaneous emission coupled into the lasing mode. Because the spontaneous photons can be emitted in any direction, they are very unlikely to be coupled into the waveguide so β is typically around 10^{-5}

below threshold: Using the electron rate equation for operation below threshold, the charge concentration in the active region is

$dn/dt = I/eV - n/\tau_s$

If the diode is initially at a steady state, $dn/dt = 0$, then

$n_o = I_o\tau_s/eV$

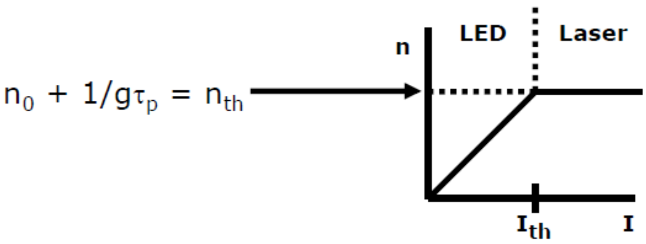
Above threshold: Consider the steady state situation, $dn/dt = dP/dt = 0$ and assume that β is very small. Rewriting the photon rate equation,

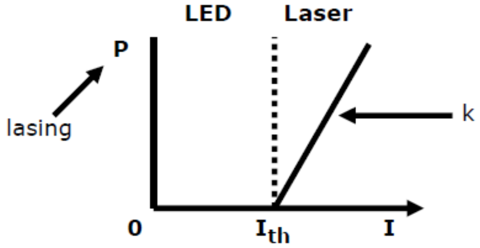
$$0 = g(n - n_o)P - P/\tau_p$$

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

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

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





(iii) All the terms on the right hand side of the bove 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}. From part (ii) $n_{th} = n_o + 1/(g\tau_p)$

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,

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

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

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

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

(c) (i) $\qquad \frac{m\lambda_m}{2} = L$

freq. of individual mode $\qquad f_m = \frac{c}{\lambda_n} = \frac{mc}{2L}$

so $\qquad \Delta f_m = \frac{c}{2L}$

But $\qquad \Delta f_m = \frac{d}{d\lambda}\left(\frac{c}{\lambda}\right)\Delta\lambda$

$$\Rightarrow \Delta\lambda \quad = \frac{\lambda^2}{c}\Delta f$$

$$= \frac{\lambda^2}{2c}$$

Note this is for free space and need to take into account refractive index of the medium

So $$\Delta\lambda = \frac{(1.55\times10^{-6})^2}{2\times3.3\text{x } 500\times10^{-6}}$$
$$= 0.73 \text{ nm}$$

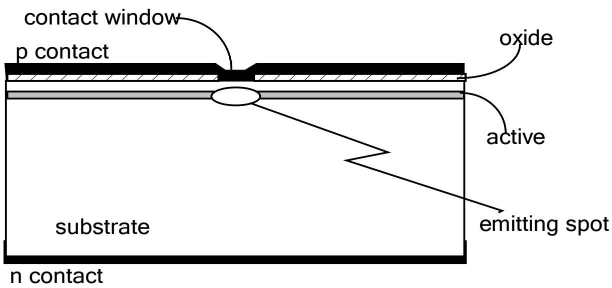
(ii) for lasing round trip gain = 1 (i.e. lasing condition)

So $$A\exp\left((G-\alpha)L\right)\cdot R\cdot \exp\left((G-\alpha)L\right)R = A$$

$$\Rightarrow G = \alpha + (1/2L)\ln\left(\frac{1}{R^2}\right)$$
$$= 10 + (1/2\times0.05)\ln\left(\frac{1}{0.3^2}\right) = 34.1 \text{ cm}^{-1}$$

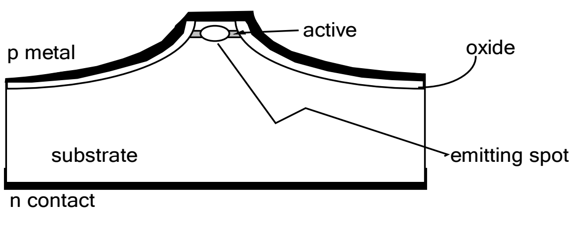
(d) In order to get a low threshold current, we need to confine the current to as small an area as possible across the width of the chip, eg a typical laser with the whole chip area pumped, might have a threshold current density of 1000 A/cm^2 (10 A/mm^2) on a chip 0.5 mm long and 0.2 mm wide. In other words a current of 1 Amp. However, typically we might confine the current to a region between 1 and 2 μm wide, which will reduce the operating threshold current to 10 mA: much more compatible with high speed drive electronics.

Stripe laser schematic end view

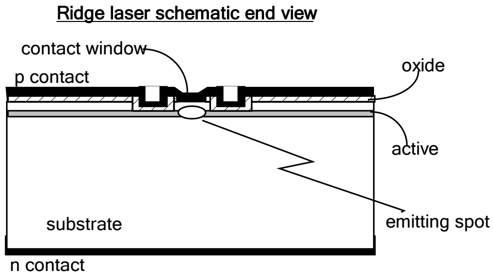


The stripe laser is simple, but current leaks out sideways, and there is no strong lateral waveguiding mechanism.

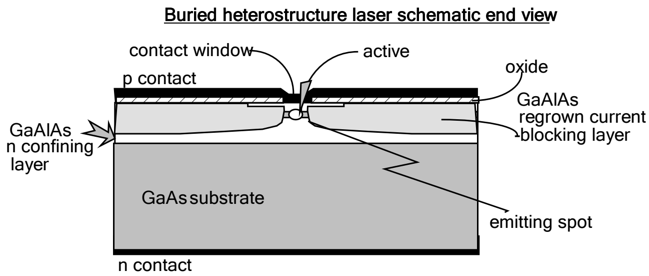
Mesa laser schematic end view



The mesa laser has excellent current confinement and waveguiding, but the process of etching through the active layer leaves it very vulnerable, and these lasers tend to have short and erratic lives.



The ridge laser has reasonable current confinement, and the shaped surface provides a weak but adequate lateral waveguide. This design is very widely used for telecommunications.

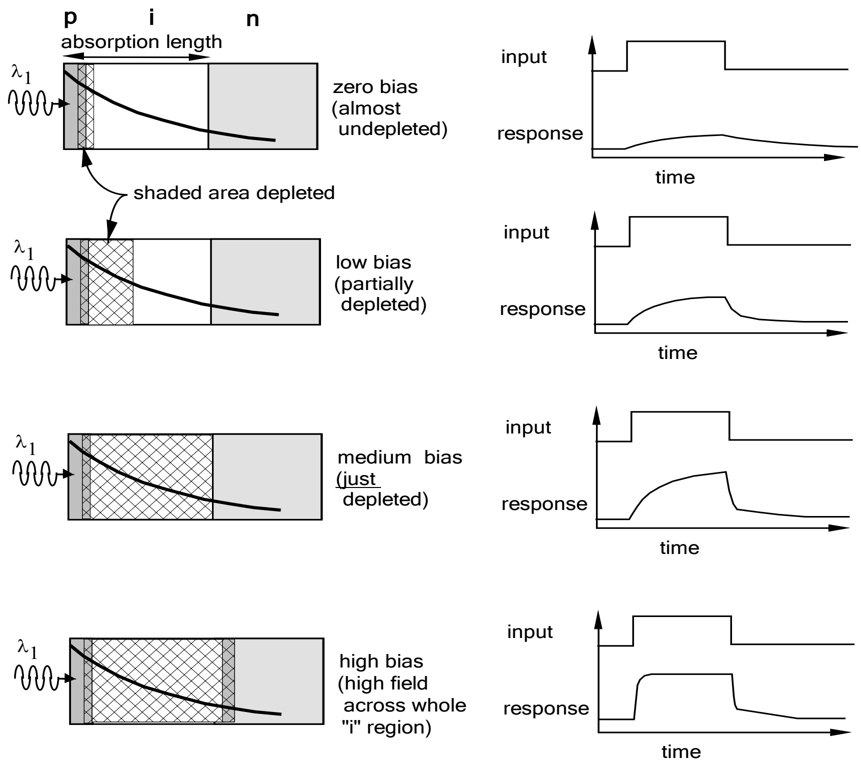


The Buried Heterostructure laser has excellent current confinement and waveguiding, but is difficult and expensive to make, and is not quite as reliable as the ridge laser. The current confining layers are of $Ga_{0.4}Al_{0.6}As$ doped with germanium, which gives a high resistivity. These structures 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.

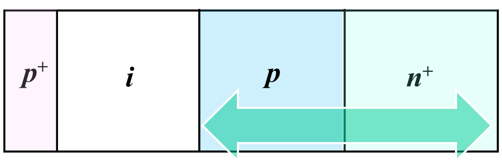
Q3 (a) Answers must outline that $p^{+}n$ type photodiode relies on the pn junction, while the MSM photodiode replies on the metal-semiconductor junction, which is also known as Schottky barrier. MSM detector normally has a sandwich structure and one side acts as blocking Schottky barrier whilst the other side acts as a forward biassed Schottky barrier.

Very good answers can also indicate that Schottky barriers are small junction and so relatively large draft current. Also, MSM detectors are only used for surface-illumination case while *p+n* photodiodes can be implemented as surface-illuminated PD and also waveguide-integrated PD.

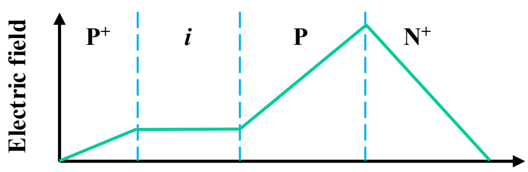
(b) The final photodiode configuration is the p-i-n photodiode. Here the p and n regions of the diode are separated by an intrinsic (i) region. This is chosen to have a width greater than (or equal to) the absorption length. In this case, the applied voltage is dropped only across the i region. This means that, just so long as the depletion region extends across the i region, then a fast response is achieved. P-i-n photodiodes are probably the most common form of high bandwidth photodiode, with 10GHz bandwidths being readily achievable.

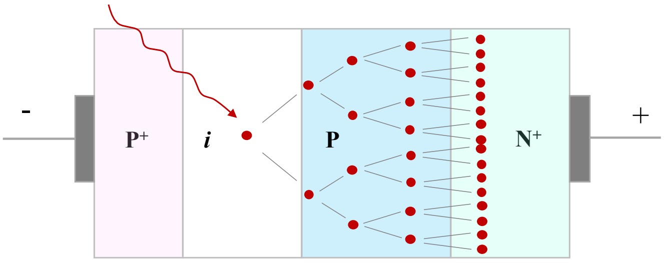


(c) An avalanche photodiode is a semiconductor-based photodiode which is operated with a relatively high reverse voltage just below breakdown (*typically tens or even hundreds of volts*). High resistivity in PN junction increases electric field (carrier depletion). In the avalanche regime, carriers are strongly accelerated in the strong internal electric field. A high energy hole or electron hits an atom in the lattice and ionises it, thereby generating more current



PN junction





(d) (i) SNR = 23dB = 200;

For *pin* photodiode, M=1,

$$SNR = \frac{(gP)^2}{2e(gP + I_d)B + {}^{4kTB}/_{R_f}}$$

Assuming thermal noise limited,

$$SNR = \frac{(gP)^2}{{}^{4kTB}/_{R_f}} = 200$$

$$g = \eta\frac{e\lambda}{hc} = 1.122$$

$$P^2 = 200\,{}^{4kTB}/_{1.122^2 R_f}$$

$$P^2 = 5.26\ \text{x}\ 10^{-11} W^2$$

$$P = 7.25\ \text{x}\ 10^{-6} W = -21.39 dBm$$

(ii) for APD

$$SNR = \frac{(MgP)^2}{2M^{2+x}e(gP + I_d)B + {}^{4kTB}/_{R_f}} = 179.5$$

$$SNR = 22.5\ dB$$

At the same input power, the *pin* photodiode has slightly better SNR, and thus *pin* is more sensitive.

(iii) For APD to be more sensitive than then *pin* photodiode,

$$SNR = \frac{(MgP)^2}{2M^{2+x}e(gP + I_d)B + {}^{4kTB}/_{R_f}} > 200$$

The largest M=40 as an integer.

Q4 (a) Bookwork:

The number of modes in a step index circular waveguide is determined by a V parameter, often called the normalised frequency. V is a function of the fibre radius, the wavelength of light and the refractive indices of the core and cladding respectively:

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^{\,2} - n_2^{\,2}}$$

The fibre can only support one mode if V<2.405 and is then called a single mode fibre (SMF).

In terms of core radius, from the definition of V, we can see that the condition for single mode operation is

$$a < \frac{2.405\lambda}{2\pi\sqrt{n_1^{\,2} - n_2^{\,2}}} = \frac{2.405\lambda}{2\pi NA}$$

Thus, there is a cut-off wavelength for SMF that:

$$\lambda_c = \frac{2\pi a NA}{2.405}$$

The wavelength of signal in the fibre must be greater than the cut-off wavelength.

Very good answers can also indicate that you can always lower such a cut-off wavelength in the fibre as the radius a and NA can be reduced.

(b) Answers would include fibre loss and dispersion.

Both impairments will degrade the signal integrity by reducing the system link budget, i.e., increasing power penalty.

(c) (i) The minimum core diameter is:

$$a = \frac{2.405\lambda}{2\pi\sqrt{n_1^2 - n_2^2}} = \frac{2.405\ \times 850\ \times 10^{-9}}{2 \times 3.14 \times \sqrt{1.52^2 - 1.51^2}} = 1.87\ \times\ 10^{-6}\, m$$

Therefore, the core diameter is larger than 2 x 1.87um = 3.74um.

(ii) Bookwork:

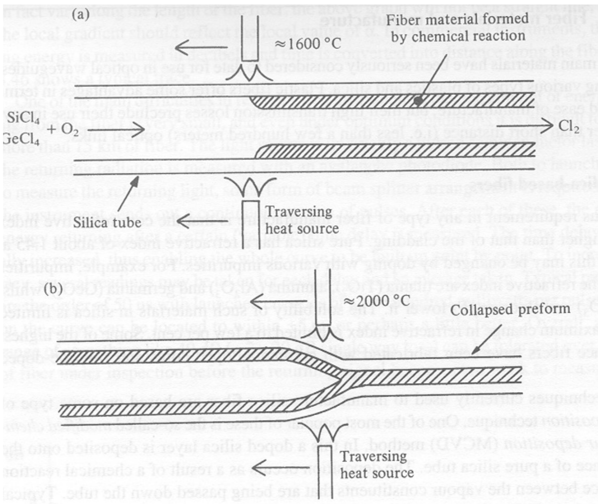
Silica Based Fibres

As we now know, it is necessary for optical fibres to have a core refractive index which is higher than that of the cladding. Pure silica has a refractive index of about 1.45 (at a wavelength of 1μm) and this may be raised or lowered by doping with various impurities. The impurities which are most often used to raise the index are TiO_2, Al_2O_3 and GeO_2 whilst F can be used to lower it. The solubility of such materials in silica is not high and so the maximum change in refractive index possible is only a few percent – though this is sufficient for most applications.

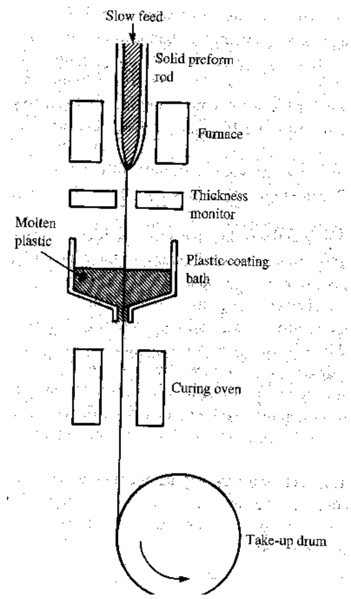
The technique currently most commonly used to manufacture silica based fibre is the modified chemical vapour deposition (MCVD) technique. In this technique, doped material is deposited onto the inner surface of a pure silica tube via a chemical reaction between the vapours that are being passed down the tube and the silica. The area of the tube where this takes place is defined by heating the tube to a high temperature (1200-1600°C) by moving a flame up and down the tube (see figure). Typical reactions are

$SiCl_4 + O_2 \rightarrow SiO_2 + 2Cl_2$, $GeCl_4 + O_2 \rightarrow GeO_2 + 2Cl_2$

If the process is repeated with different compositions of the vapours being passed down the tube, layers with differing dopants can be built up. Once the deposition process is completed, the tube is heated to the softening temperature of silica (~2000°C) and then the tube is collapsed by surface tension into a solid rod called a perform.



The optical fibre can be produced from the perform by drawing from the heated tip of the perform as it is lowered into the furnace. It is very important to exercise tight control of the overall fibre diameter, and by extension the core diameter, and so a feedback loop incorporating a thickness monitor controls the draw rate from the perform. A plastic coating to provide protection from cracking is also added to the glass fibre.



(iii) Thus, the collection efficiency is given by

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

When the outside medium is air, $n_a = 1$ and so the collection efficiency becomes NA^2.

Therefore, the collection efficiency is $(1.52^2 - 1.51^2)$=3.03%

In order to increase the collection efficiency, it would need to increase the NA, i.e. enlarging the difference between n_1 and n_2.

(d) (i) The total link budget is 20dB as the launched optical power is 0 dBm and receiver sensitivity is -20 dBm.

For a multi-mode fibre, the pulse broadening is:

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

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

$$\Delta t = 3.36 \times 10^{-11} L$$

$$t_{in} = \frac{1}{10 \times 10^9} = 10^{-10} S$$

$$t_{out} = \sqrt{10^{-20} + (3.36 \times 10^{-11} L)^2}$$

The power penalty is:

$$P = 10log\left(\sqrt{1 + (3.36 \times 10^{-1} L)^2}\right) = 10\log\left(\sqrt{1 + 0.113L^2}\right)$$

The total fibre loss is:

$$Loss = 1 \times L = L\, dB$$

The power that can be used to cover the fibre loss and broadening:

20 – 3 – 3 – 3 = 11 dB

Thus, we have:

$$L + 10\log\left(\sqrt{1 + 0.113L^2}\right) = 11$$

Use numerical approximation to find an integer solution:

$$L = 7km$$

(ii) $L = 7km$

$$P = 10log\left(\frac{\sqrt{(4 \times 10^{-11})^2 + (3.36 \times 10^{-11} \times 7)^2}}{4 \times 10^{-11}}\right) = 7.75\, dB$$

Sensitivity = 0 dBm – 3 dB – 3 dB – 4 dB – 7.75 dB – 7 dB = -24.75 dBm