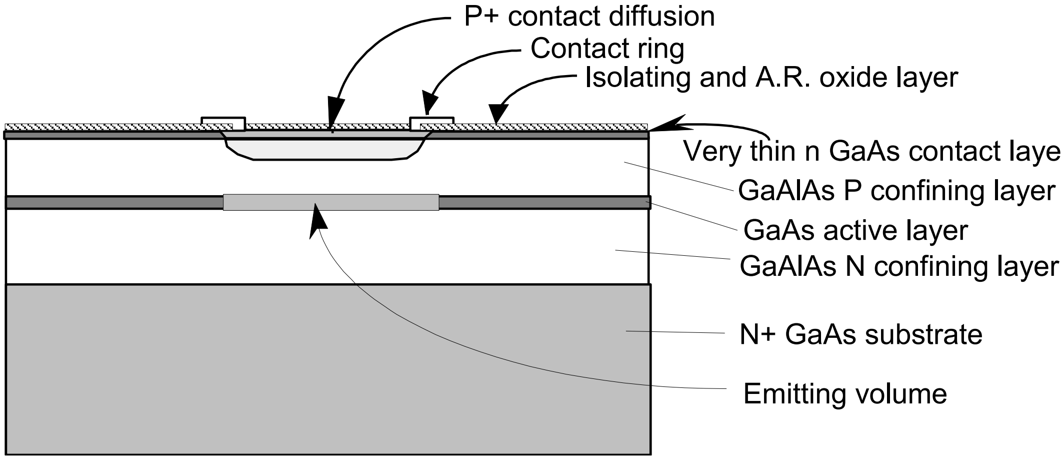
Answers to 3B6 Pt IIA Examination Questions, 2019

Q1(a) This part of the question primarily requires knowledge of the course content.

A Surface Emitting LED Structures

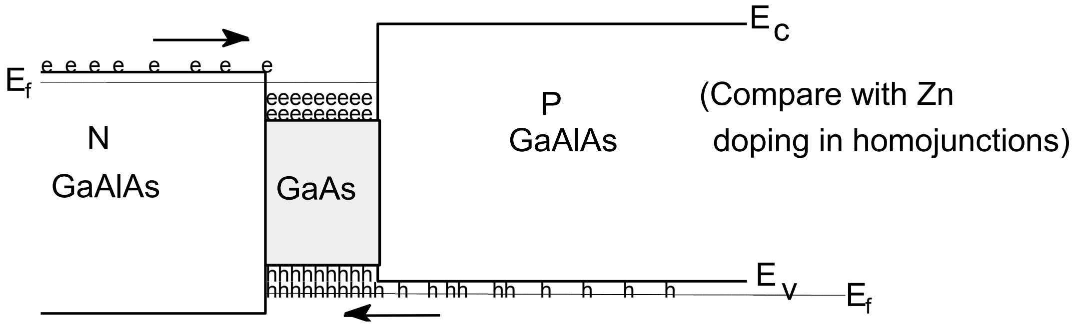
GaAs based double heterostructure LED



This is a simple surface emitting 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.

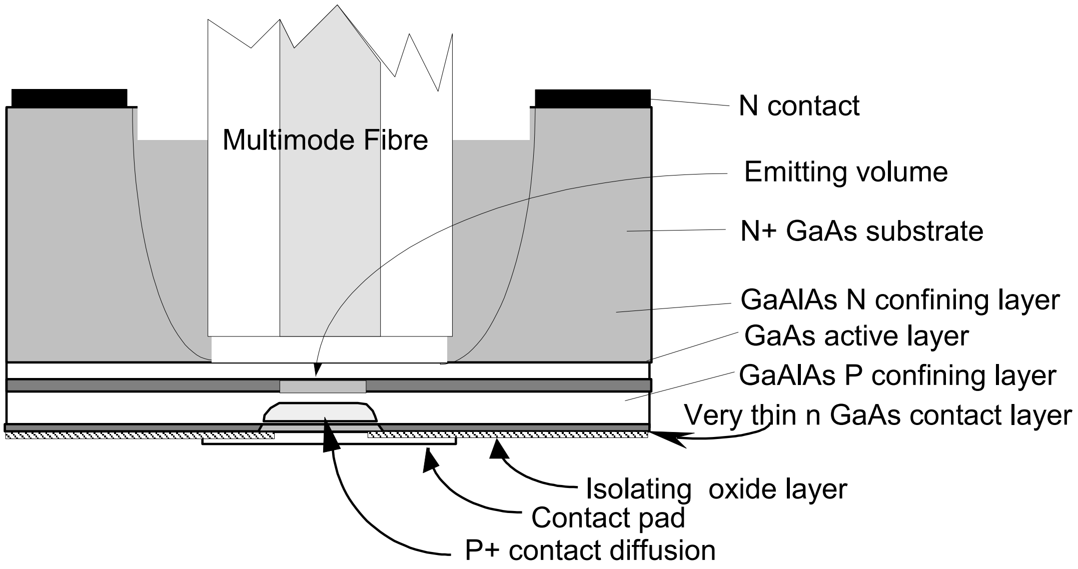
A good answer should also describe the properties of double heterostructures. Double heterostructures allow one to confine carriers very tightly in an LED in that both electrons and holes gather at the lowest or highest energy levels respectively which are in the central region (the GaAs layer in this case). The double heterostructure also has the advantage that photons are not re-absorbed by the wider bandgap material when travelling to the surface.This increases the speed of the LED (because of the strong overlap between holes and electrons) and also its brightness in that the generated photons sees the heterostructure layers (GaAlAs in this case) as transparent and are not absorbed before leaving the LED as may occur in conventional LED structures. GaAs materials typically emit in the 700-800 nm region. The index of the central layer is larger than the others and hence can be used as an optical waveguide, as in an edge emitting LED or indeed laser diode.

Double Heterostructure



To improve performance further, a Burrus structure can be used.

GaAs based Burrus type high radiance LED

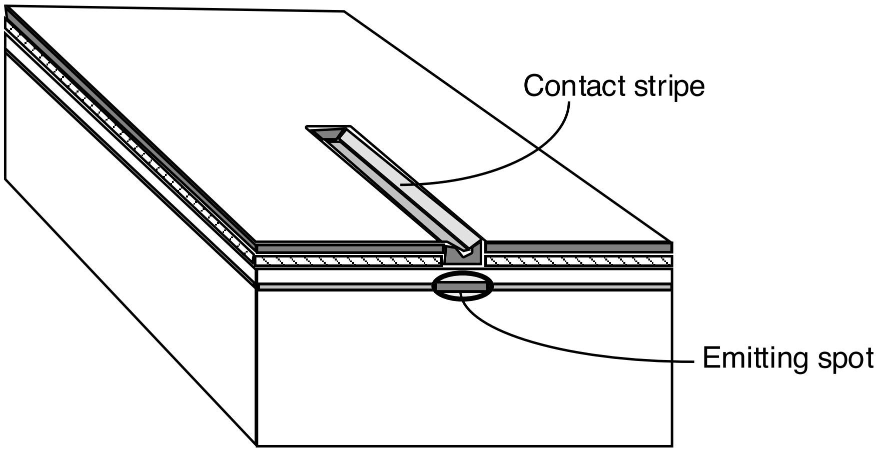


The Burrus diode has much of the substrate etched away: this allows high coupling into a multimode fibre, sometimes a spherical micro-lens is interposed as well. In addition, the heat generation is close to the p surface which can be bonded directly to a heatsink and the contact metal also reflects some light back upwards into the fibre. Similar devices are made using the InP/GaInAsP materials system at longer wavelengths.

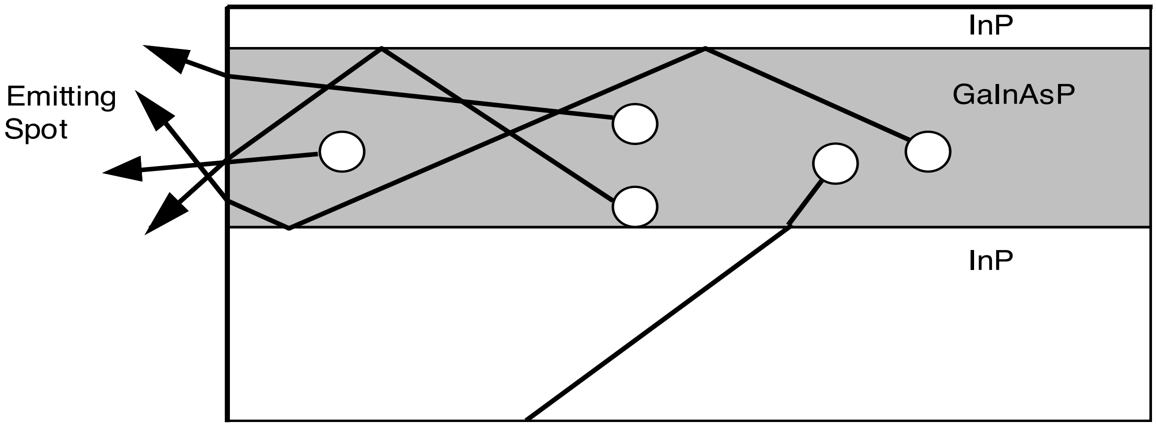
B Edge Emitting LEDs

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.

Edge emitting LED



Side view of an edge emitting LED



A good answer should then draw out the different performance levels of the two devices, and highlight how surface emitting devices are excellent for general applications, but edge emitters are particularly useful for those requiring high intensities or for the light to be coupled into small spots, such as in optical fibre systems applications.

(b)(i) This is a bookwork section also, and should explain how preferably direct bandgap materials should be chosen as these exhibit higher efficiencies. For 850 nm applications, the GaAs/GaAlAs system would be very appropriate as the bandgap can be set to the required wavelength and the materials allow a ready heterostructure to be formed.

(ii) $\eta_{int} = \frac{\frac{1}{\tau_{rr}}}{\frac{1}{\tau_{rr}}+\frac{1}{\tau_{nr}}} \Rightarrow \eta_{int} = 0.625 \quad \Rightarrow 62.5\ \%$

$$P_{out} = \eta_{int}\eta_{ext}\frac{hc}{\lambda}\frac{I}{e} \Rightarrow I = \frac{P_{out}}{\eta_{int}\eta_{ext}}\frac{\lambda e}{hc} \Rightarrow I = 109\ mA$$

$V_{bg} = \frac{hc}{\lambda e} = 1.461\ V$

$V_o = V_{bg} + IR = 1.461\ V + 109.47\times10^{-3}\times2 = 1.64\ V$

(iii) $\Delta\lambda = 2\lambda^2\frac{kT}{hc} = 29.4\ nm$

(iv) $\tau_s = \left(\frac{1}{\tau_{rr}} + \frac{1}{\tau_{nr}}\right)^{-1} = \frac{\tau_{nr}\tau_{rr}}{\tau_{nr}+\tau_{rr}} = 0.938\ ns$

Q2(a) This part of the question requires a qualitative answer. 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 nett 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.

Fabry Perot Modes

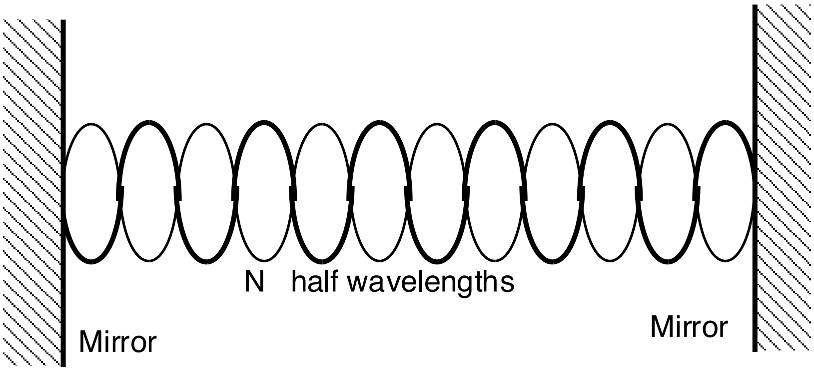


Fig. 2

In respect of the contrast between lasing light and light from an LED, a good answer should describe in detail the threshold required for lasing, that does not exist for an LED, the much higher (differential) quantum efficiency and the potentially greater high power operation , the much narrower though multimode optical spectra, the much greater modulation bandwidth, the greater sensitivity of laser operation to temperature, and dependence on back reflections, but the greater need for tight electrical drive control.

(b) (i) $I_{th} = \frac{eVn_{th}}{\tau_s} = \frac{eV}{\tau_s}(n_o + \frac{1}{g\tau_p}) \Rightarrow V = \frac{I_{th}\tau_s}{e(n_o+\frac{1}{g\tau_p})} = 16.959\times10^{-11}\ cm^3 = 170\ \mu m^3$

$\mathrm{L} = \frac{V}{h\times d} = 280\ \mu m$

(ii) $\delta P = \frac{hc}{\lambda e}\eta_D \delta I = 19.9\ mW$

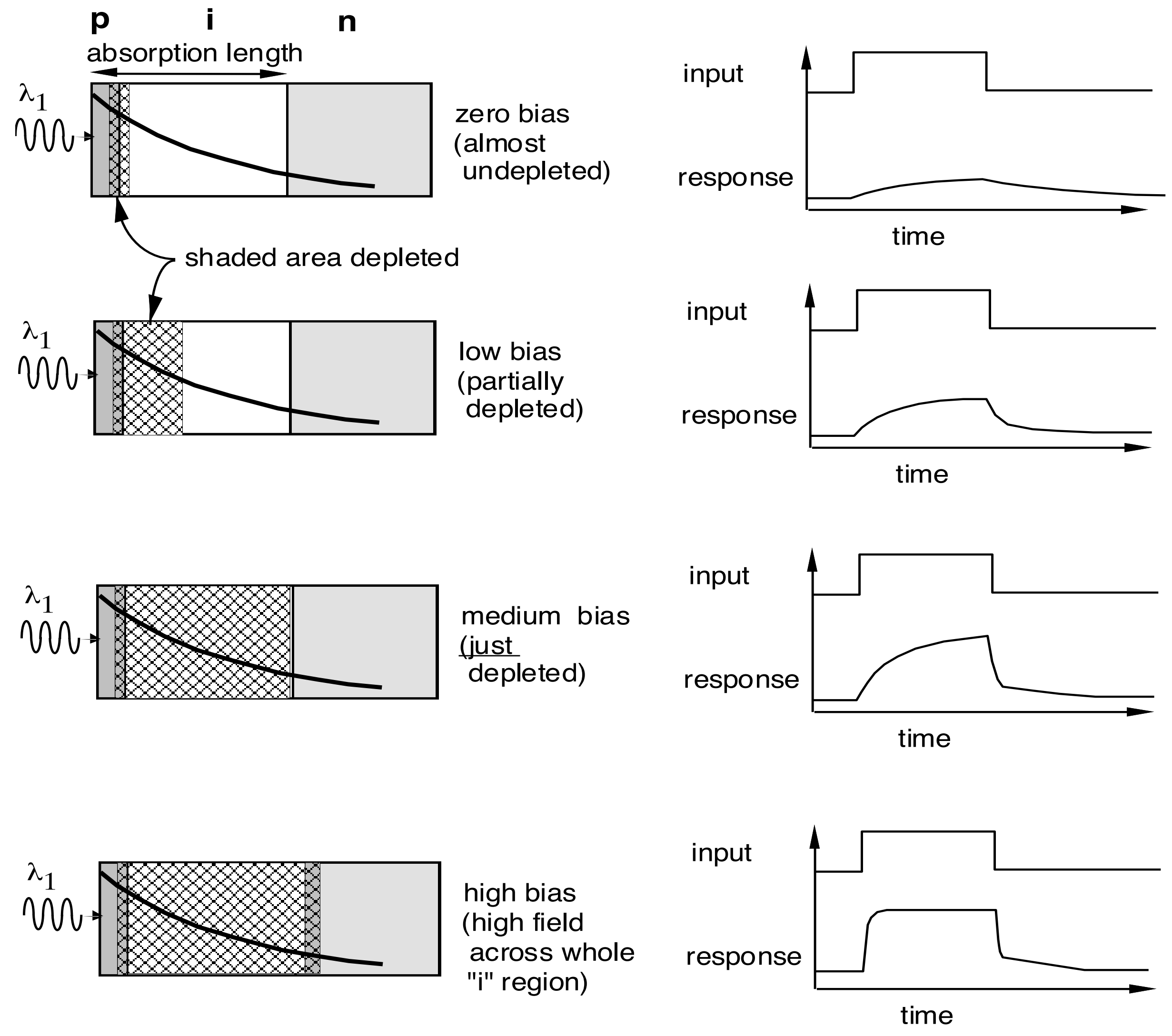
(iii) $\frac{I_{th}^{T_1}}{I_{th}^{T_2}} = \frac{e^{\frac{T_1}{T_0}}}{e^{\frac{T_2}{T_0}}} \Rightarrow I_{th}^{40°\mathrm{C}} = I_{th}^{20°\mathrm{C}} e^{\frac{\Delta T}{T_0}} = 24.428\ mA \Rightarrow \delta P = \frac{hc}{\lambda e}\eta_D \delta I = 16.9\ mW$

(iv) $\Delta\lambda = \frac{\lambda^2}{2nL} \Rightarrow \Delta\lambda = 1.18\ nm$

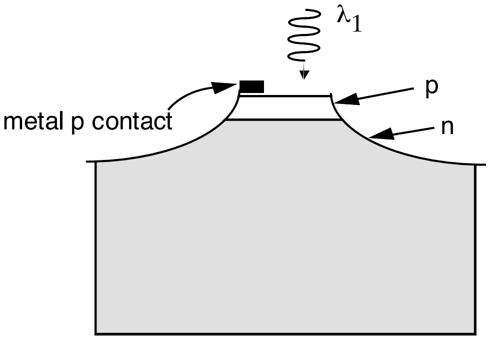
Q3(a) $E_g < \frac{hc}{\lambda} = 24.48\times10^{-20}\ W = 1.53\ eV$. A suitable material would be Si. GaAs would also be suitable but is much more expensive.

(b) Photodiodes are usually biased in reverse bias so that a depletion region is formed in order that all photogenerated carriers are swept to the contacts (if they can only diffuse they will often recombine before reaching the contacts and hence some of the signal is lost). It's also important to remove the diffusion region (ie make sure all photo-carriers are generated in the depletion region) for speed reasons. Diffusion is much slower than carrier drift. Note there is a trade off between capacitance (which is lower for a wide depletion region) and drift (longer drift time). A *pin* photodiode can be useful to control this.

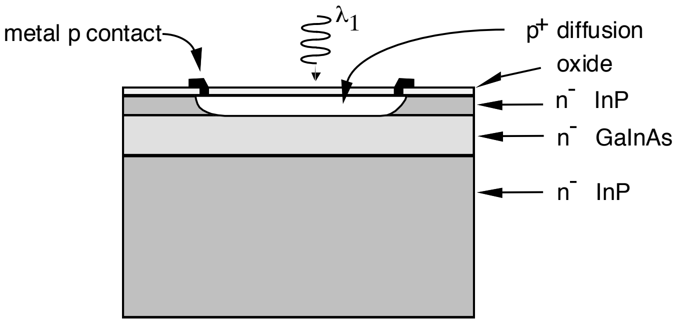
Here the p and n regions of the diode are separated by an intrinsic (i) region. This is chosen to have a width greater than (or equal to) the absorption length. In this case, the applied voltage is dropped only across the i region. This means that, just so long as the depletion region extends across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



(a) Mesa Homojunction



Planar diffused heterojuntion



(d) $SNR_{min} = \frac{I_{PD}^2}{<i_n^2>} = \frac{(gP_{opt})^2}{2e(gP_{opt}+I_d)BW+\frac{4kTBW}{R_{in}}} = 4dB \; = 2.512, \quad g = \frac{e\eta\lambda}{hc} = 0.6013\, A/W$

Worst-case sensitivity when T=100°C due to larger thermal noise. Assume at low optical powers, the thermal noise dominates and hence it's possible to ignore shot noise.

$$\Rightarrow \; (gP_{opt})^2 = 3.979\times10^{-21}(gP_{opt})$$

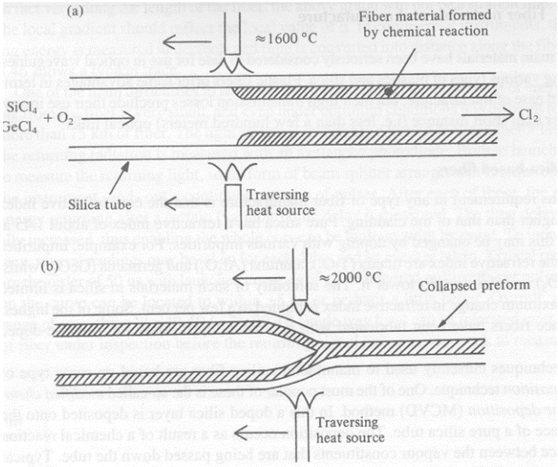
$$\Rightarrow \; gP_{opt} \approx 0.631\times10^{-10}A \Rightarrow \; P_{opt} \approx 1.05\times10^{-10}\, W = 0.105\, nW = \; -69.8\, dBm$$

(b) An APD would increase the SNR (and hence improve sensitivity) as it would increase the signal current (and shot noise) without affecting the thermal noise. Given the excess noise factor for the shot noise, there is an optimum avalanche gain

Q4(a) Bookwork but typical answers would be similar to -

Preform: Standard optical fibres are made by first constructing a large-diameter "preform" with a carefully controlled refractive index profile, and then "pulling" the preform to form the long, thin optical fibre. The preform is commonly made by chemical vapour deposition. 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).

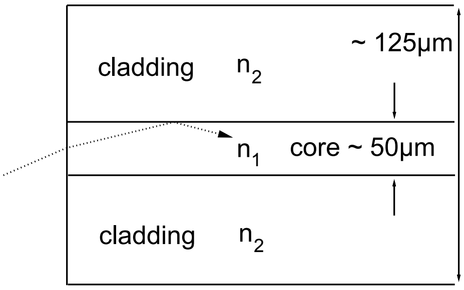
If the process is repeated with different compositions of the vapours being passed down the tube, layers with differing dopants can be built up. Once the deposition process is completed, the tube is heated to the softening temperature of silica (~2000°C) and then the tube is collapsed by surface tension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



Critical Angle: The simplest way of thinking about how light is transmitted down an optical fibre is to use Snell's Law of Refraction and the principle of total internal reflection (TIR). Snell's law states that

$$n_1 \sin \phi_i = n_2 \sin \phi_t$$

It can easily be shown that ϕ_t becomes 90° when the incident angle becomes ϕ_c where ϕ_c is usually called the *critical* angle. For an incident angle greater than the critical angle, all of the incident light is reflected. Consequently all light stays within the optical fibre. The critical angle is therefore given by $\sin\phi_c = \dfrac{n_2}{n_1}$



Normalised frequency:

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:

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

1

The fibre can only support one mode if V<2.405 and is then called a single mode fibre (SMF). If V>>1, then the number of modes, N, that can propagate is approximated by

$$N \approx V^2 / 2$$

(b)

(i) $V = \frac{2\pi\alpha}{\lambda}\sqrt{n_1^2 - n_0^2} > 2.405 \Rightarrow a > \frac{2.405\,\lambda}{2\pi\sqrt{n_1^2 - n_0^2}}$

Radius maximised when the refractive index difference between core and cladding is minimised

→ n_1=1.545 and n_0=1.53 $\Rightarrow d_{max} = 2 \times a_{max} = 2 \times 2.73\ \mu m = 5.46\ \mu m$

Normally a fibre would not be constructed with this core diameter as it would be almost bimoded. Hence the diameter would be typically be slightly smaller (so V ~ 2.2)

(ii) $NA = \sqrt{n_{co}^2 - n_{clad}^2} = 0.215$

(c)

(i) $BER = \frac{1}{2}e^{-N} = 10^{-12} \Rightarrow N = 27$ photogenerated carriers for bit 1 $\Rightarrow N/\eta = 29.9$ incident photons for bit 1 → average N_p=15 photons / bit

$$P_{rec} = N_p \frac{hc}{\lambda} R = 77.85 \times 10^{-9} W = 77.5\ nW = -41.1\ dBm$$

(ii) dispersion limit

$$t_{out} = 1.3 \times t_{in}\ , t_{out}^2 = t_{in}^2 + \Delta t^2 \Rightarrow\ \Delta t_{max}^2 = 0.69\ t_{in}^2\ \ , \Rightarrow \Delta t_{max} = 0.83\ t_{in} = \frac{0.83}{R} = 20.766\ ps$$

$L_{max} = \frac{\Delta t_{max}}{D\Delta\lambda} = 5.19\ km$

Received power at length Lmax

$$P_{Rx}(dBm) = \ P_{Tx}(dBm) - \ Tot\_Loss\ (dB) - \ Margin\ (dB)$$

Total link loss includes attenuation (0.25 dB/km × L), coupling loss (2 dB) and splice losses (0.24 dB)

Minimum power at the receiver is equal to receiver sensitivity (-25 dBm)

$$-25 = \ 5 - \ 0.25 \times L_{max} - 2 - 0.24 - 2 = 0.76 - 0.25 \times L_{max}$$
$$\Rightarrow L_{max} = 103.4\ km$$

So link is heavily dispersion limited.

(iii) The attenuation is OK at 100km (just) so the link needs to have its dispersion improved. This could be done by reducing the source linewidth. However given the modulation bandwidth, it can't be reduced by much (students wouldn't be expected to appreciate this) without using complicated modulation techniques and so dispersion compensating fibre would be necessary.