UNIT-III

Fiber Optical Sources and Coupling:

Direct and indirect Band gap materials

Light Emitting Diodes (LEDs):

- LED Structures
- Light Source Materials
- Quantum efficiency and LED Power
- Modulation of LED

LASER Diodes:

- Laser Diode Modes and Threshold Conditions
- Laser Diode Rate Equations
- External Quantum Efficiencies
- Resonant Frequencies
- Temperature effects

Fiber –to- Fiber joints

Fiber splicing

Source-to-fiber Power Launching

Lensing schemes

Introduction to Quantum laser

INTRODUCTION:

A basic fiber optic communication system consists of essentially three components, viz. an optical source, an optical fiber of the required length, and a photo detector. The role of an optical source is to convert the input electrical signal into an optical signal.

The major requirements of the optical sources are: ability to directly modulate the intensity, compatibility to optical fibers- in terms of the operating wavelengths and power coupling, smaller spectral widths, and reasonable optical power outputs. Because of these requirements the most suitable optical sources are semiconductor Light Emitting Diodes [LEDs] and Laser Diodes [LDs].

OPTICAL SOURCES: BASIC CONCEPTS:

Semiconductors are special materials whose conduction properties lie between those of metals and insulators. The conduction properties of a semiconductor can be explained with the help of energy band diagrams. The valence electrons occupy a band of energy levels called the Valance band, which is the lowest band of allowed states. The next higher band of allowed energy levels for electrons is called the Conduction band. The valance and conduction bands are separated by an energy gap where no energy levels exist.

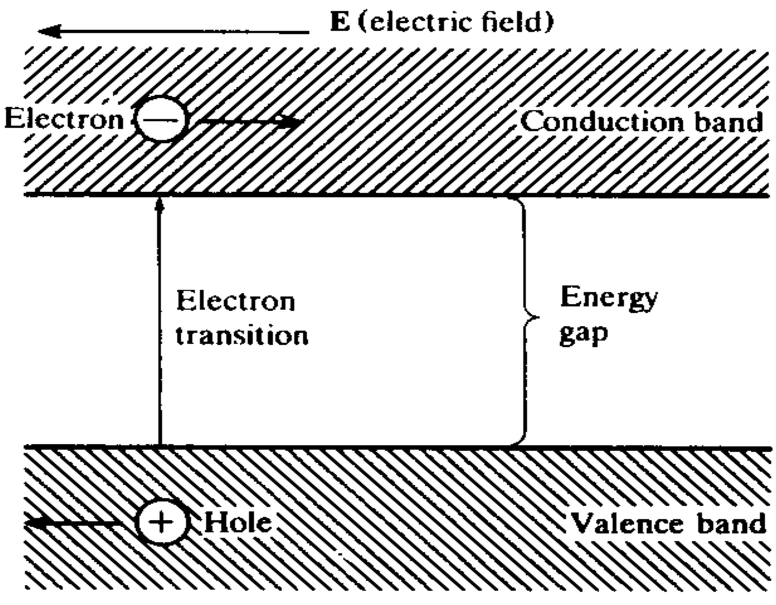


Figure: Energy level diagram

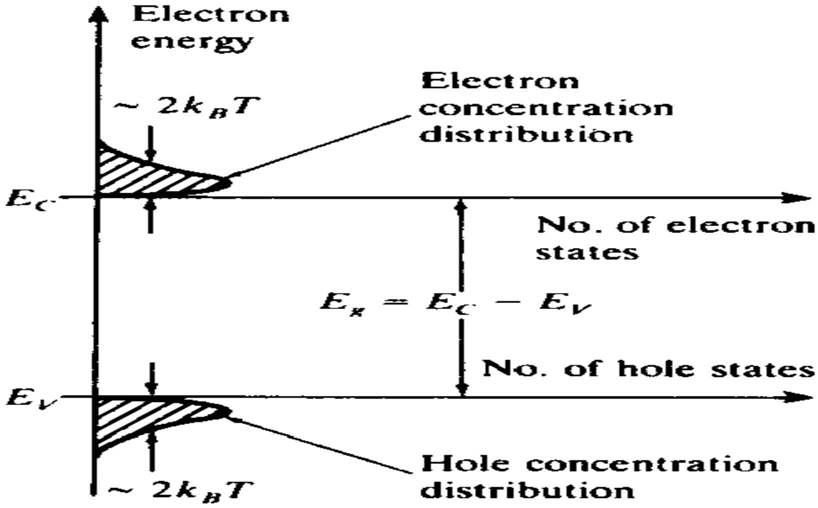


Figure: Electron & Hole concentration

At absolute zero temperature with no applied electric field, all the electrons will be in the valance band [energy level E_1]. When some external energy is provided to the electrons at the valence band, some of them acquire enough energy [the excited electrons] to jump over the energy gap and reached to conduction band[energy level E_2]. The excited electron will get de-excited after every 10^{-8} sec itself or recombine with hole in valance band. When excited electron falls from the conduction band [energy level E_2] to valance band [energy level E_1], it releases [radiates] a quantum of energy called Photon [emission]. If $E = E_2 – E_1$ then $E = hf = hc/\lambda$, where $h=6.626 \times 10^{-34}$ J = Planck's constant, c is the speed of the light, λ is wavelength.

Since many energy levels in the conduction and valance bands can participate in the radiation process, many close wavelengths can be radiated. Because of this multi wavelength radiation, the light emitted by the semiconductor will have a wide spectral width.

In order to have radiation it is necessary to excite many electrons to the conduction band. This needs to be done in the form of an external energy. The most suitable way of doing this is by passing an electric current through the semiconductor.

When a p-type material is brought in contact with a n-type material a pn junction is formed. PN junction can be formed by either direct band gap material [Ex: GaAS, GaN, InAs, InP] or indirect band gap material [Si, Ge] . In direct band gap materials the maxima of valence band and the minima of the conduction band occur at the same value of crystal momentum k. But k is different in indirect band gap materials.

When an external voltage is applied to a forward bias pn junction made of direct band gap material, electron and holes recombine radiatively or non-radiatively. For every radiative recombination of electron hole pair, energy equal to photon will be released [radiated] in the form of light. For non-radiative recombination energy will be dissipated in the form of heat.

LIGHT EMITTING DIODES (LEDs):

LED's are best light sources for OC systems. LED's require less complex driven circuitry than laser diodes. No thermal or optical stabilization circuits are needed. They can be fabricated less expensively with higher yields. In fiber transmission applications, LED must have a high radiance O/P, a fast emission response time & high quantum efficiency.

RADIANCE O/P is optical power radiated into a unit solid angle per unit area of the emitting surface. It is measured in Watts.

EMISSION RESPONSE TIME is the time delay between application of current pulse and the unset of optical emission.

QUANTUM EFFICIENCY is related to fraction of injected electron-hole pairs that recombine radiatively.

To achieve a high radiance and high quantum efficiency, the LED structure must provide a means of confining the charge carriers and stimulated optical emission to active region of pn junction where radiative recombination takes place.

LED STRUCTURES:

A simple LED may be constructed by forming a pn junction using one of the direct band gap semiconductors. Such an LED is called a HOMOJUNCTION LED as the pn junction is made the same material.

Homojunction LEDs are not good from point of view of high radiance and high quantum efficiency. In order to have a device with high radiance and high quantum efficiency the LED structure must provide means of carrier confinement and optical confinement. Carrier confinement would improve the radiance and internal quantum efficiency. Emitted photons can get absorbed by the surrounding materials, which can be prevented by better optical confinement.

Carrier and optical confinement can be achieved by the use of single and double HETEROJUNCTIONS. In a heterojunction pn device, the junction is formed out of dissimilar crystalline semiconductors. A combination of multiple heterojunctions together in a device is called heterostructure.

In a heterostructure LED the device has an active region, catering to radiative recombination, sandwiched between two different alloy layers [small direct band gap material [Ex:GaAs] is sandwiched between two large band gap materials [AlGaAs]]. Small band gap material will acts as active region, where radiative recombination takes place and have low emitted light absorption. So most of the light produced in this region will emitted outside.

The 2 basic LED configurations used for fiber optics are

[1] Surface emitters or Burrus or front emitters.
[2] Edge emitters.

SURFACE EMITTER LEDS [SELEDs]:

In SELEDs, the emitting area is defined by oxide isolation, with the circular metal contact area of diameter 10µm-15µm. The active region is made narrow to aid in carrier confinement. The metallization layers are used to supply external energy. Heat sink is used to absorb heat generated in non-radiative recombination.

The plane of active light emitting region is oriented perpendicularly to the axis of the fiber. A well is etched through the substrate of the device, into which a fiber is then cemented in order to accept the emitted light.

The emission pattern is essentially isotropic with a 120 degrees half power beam width. This isotropic pattern from a surface emitter is called Lambertian pattern. In this pattern the source is equally bright when viewed from any direction, but the power is diminishes as Cosθ where θ is angle between viewing direction and normal to the surface.

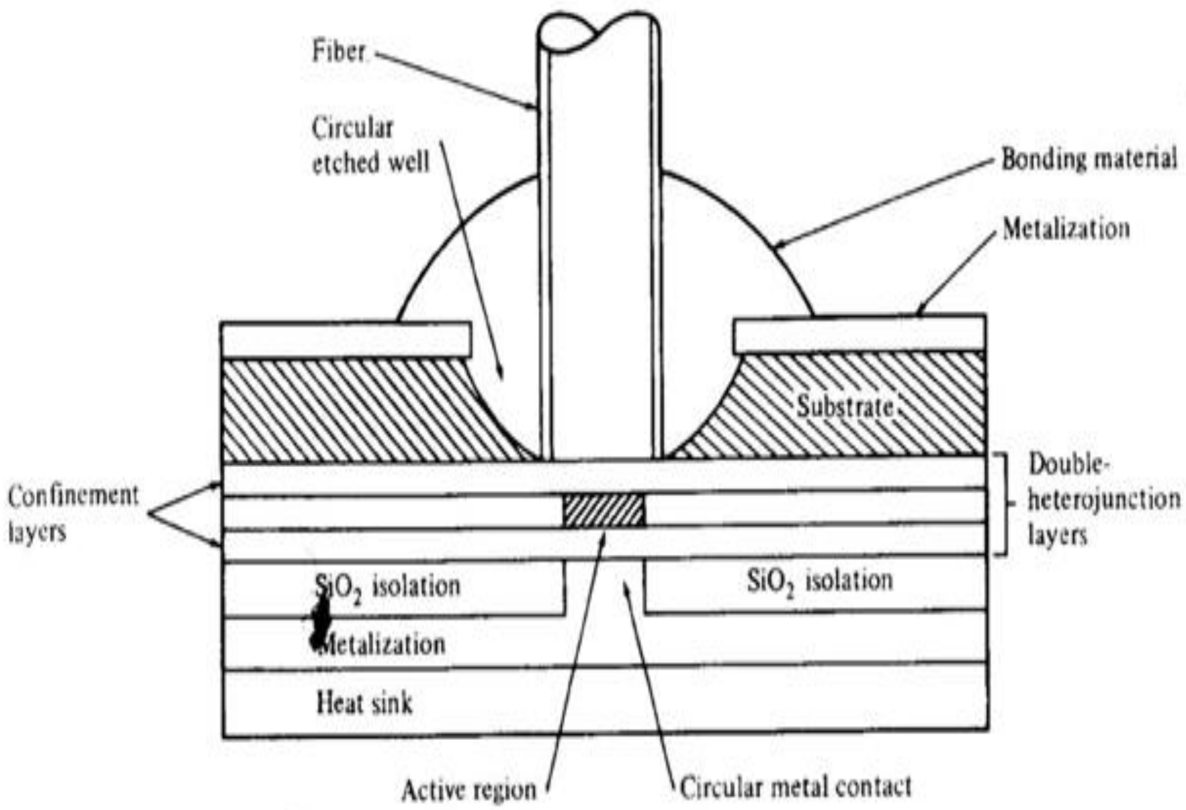


Figure 3.1: Schematic of a high radiance surface-emitting LED. The active region is limited to a circular section having an area compatible with the fiber-core end face.

EDGE EMITTER LED:

The edge emitter consists of an active junction region, which is source of the incoherent light and two guiding layers. The guiding layers both have a refractive index which is lower than that of active region but higher than index of surrounding material.

This structure forms a wave guide channel that directs the optical radiation towards the fiber core. The radiation emits to air from the active area edge of the device.

Contact strips are made to match the edge emitter active area compatible to optical fibers. The beam emitting from the edge emitter LED is more directional than SELED. The beam is generally elliptical. Due to wave guiding effect the beam is narrower in the plane perpendicular to the pn junction-the full width at half maximum [FWHM] is typically 25 to 35^0. However, since there is no wave guiding in lateral direction, i.e. in the plane parallel to the junction, the beam in the plane is Lambertian with a FWHM OF 120^0.

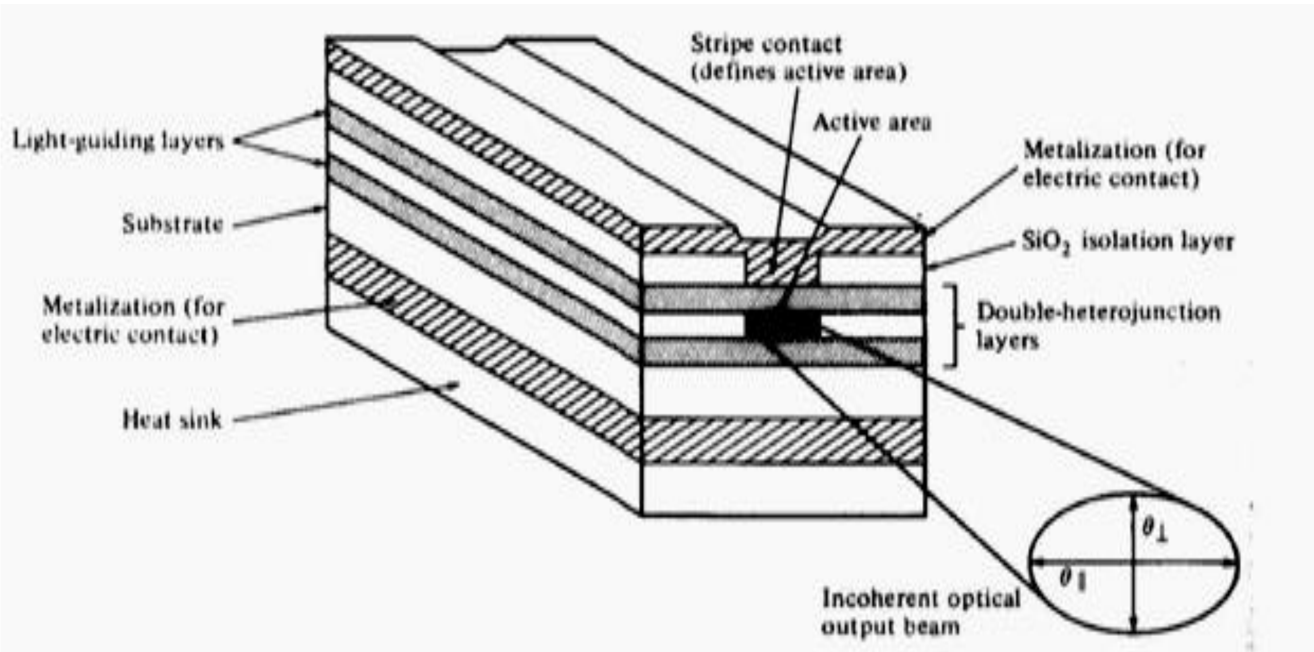


Figure 3.2: Schematic of an Edge-emitting double hetero-junction LED.

LIGHT SOURCE MATERIALS:

The semiconductor material that is used for active layer of an optical source must have direct band gap. In a direct-band-gap electrons & holes can recombine directly without third particle to conserve momentum.

III & V group elements are used. III group elements (Al, Ga or In) & V group elements (P, As or Sb) compounds are used. Combinations of binary compounds of these elements are also direct gap materials and are suitable for optical sources.

For operation in the 800-900 nm spectrum, principal material is $Ga_{(1-x)}\ Al_x\ As$. The value of x for active area material is usually chosen to give an emission wave length of 800 to 850 nm.

At longer wave lengths $In_{(1-x)}\ Ga_x\ As_y\ P_{1-y}$ is one of primary material. By varying mole fractions x & y in active area, LEDs with peak out power can be constructed. Other notations such as AlGaAs, (AlGa)As, (GaAl)As, GaInPAs & $In_xGa_{1-x}As_yP_{1-y}$ are also used.

INTERNAL QUANTUM EFFICIENCY:

An excess of electrons & holes in P-type & N-type materials respectively is created in a semiconductor light source by carrier injection at the device contacts. When the carrier injection stops the carrier density returns to equilibrium value.

Excess carrier density decays exponentially with time according to relation

$$\Delta n = \Delta n_0\, e^{-t/\tau}$$

where n_o = initial injected excess electron density. τ= carrier life time.

The excess carriers can recombine either radiatively or non-radiatively. In radiative recombination a photon of energy hv, equal to band gap energy is emitted.

In non-radiative recombination, the energy is emitted the form of heat. Internal quantum efficiency in active region is fraction of electron-hole pair that recombines radiatively.

Internal quantum efficiency $n_o = (R_r /[R_r + R_{nr}]) = (1/[1+ R_{nr}/R_r])$

Where R_r = radiative recombination rate per unit volume.

R_{nr} = non-radiative recombination rate per unit volume.

n_o in terms of life time $n_o= 1/[1+(\tau_r/ \tau_{nr})]$

The radiative recombination life time $\tau_r= n/R_r$

The non-radiative recombination life time $\tau_{nr}= n/R_{nr}$.

The bulk recombination life time τ is $1/ \tau = [1/ \tau_r]+ [1/ \tau_{nr}]$

therefore $n_o = \tau/\tau_r$

POWER BANDWIDTH PRODUCT:

$$w*P =(hc/q\lambda)* (1/ \tau_r)\ J$$

LED POWER:

It may be noted that the surface emitter radiates significantly more optical power into air than the edge emitter, and that both devices are reasonably linear at moderate drive currents.

The internal quantum efficiency of LEDs decreases exponentially with increasing temperature. Hence the light emitted from these devices decreases as the *p–n junction temperature increases.*

It may be observed that the edge-emitting device exhibits greater temperature dependence than the surface emitter.

MODULATION OF LED:

In order to transmit information via an optical fiber communication system it is necessary to modulate a property of the light with the information signal. This property may be intensity, frequency, phase or polarization (direction) with either digital or analog signals.

The choices are considered by the characteristics of the optical fiber, the available optical sources and detectors, and considerations of the overall system. Intensity modulation – Direct detection at the optical detector. Easy to implement - electroluminescent sources available at present (LEDs and injection lasers).

These devices can be directly modulated simply by variation of their drive currents at rates up to many gigahertz. Intensity modulation may be utilized with both digital and analog signals. Analog intensity modulation is usually easier to apply but requires comparatively large signal-to-noise ratios and therefore it tends to be limited to relatively narrow-bandwidth, short-distance applications.

Alternatively, digital intensity modulation gives improved noise immunity but requires wider bandwidths, although these may be small in comparison with the available bandwidth. It is therefore ideally suited to optical fiber transmission where the available bandwidth is large. Hence at present most fiber systems in the medium- to long-distance range use digital intensity modulation.

LASER DIODE:

Light Amplification Stimulated Emissive Radiation diode. Laser action is the result of 3 key process 1] Absorption 2] Spontaneous emission 3] Stimulated emission. These 3 processes are represented by simple two-energy-level diagrams in Figure 3.3, where E_1 is the ground-state energy and E_2 is the excited-state energy. According to Plank's law, a transition between these two states involves the absorption or emission of a photon of energy hv_{12} = E2-E1.

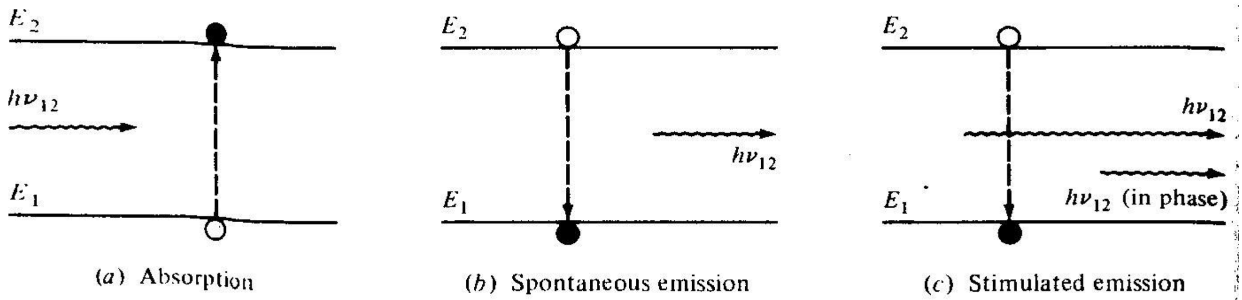


Figure 3.3: The 3 key transition processes involved in laser action.

Normally the system is the ground state. When a photon energy hv_{12} impinges on the system, an electron in state E_1 can absorb the photon energy and be excited to state E_2 as shown in figure 3.3, Since this is unstable state, the electron will shortly return to the ground state, thereby emitting a photon of energy. This occurs without any external stimulation and is called spontaneous emission. These emissions are isotropic and random phase, and thus appear as a narrowband Gaussian output.

If a photon of energy impinges on the system while the electron is still in its exited state, the electron is immediately stimulated to drop to the ground state and give off a photon of energy. This emitted photon is in phase with the incident photon, and the resultant emission is known as Stimulated emission.

In thermal equilibrium the density of excited electrons is very small. Stimulated emission is essentially negligible. Stimulated emission will exceed absorption only if the population of the excited states is greater than that of ground state. This condition is known as POPULATION INVERSION. Since this is not an equilibrium condition, population inversion is achieved by various PUMPING techniques. In a semiconductor laser, population inversion is accomplished by injecting electrons into the material at the device contacts to fill the lower energy states of the conduction band.

The radiation in one type of laser diode configuration is generated within a Fabry-Perot resonant cavity. This cavity is much smaller, being approximately 250-500µm long in longitudinal, 5-15µm wide in lateral, 0.1-0.2µm thick in transverse.

Two flat, partially reflecting mirrors are directed towards each other to enclose Fabry-Perot resonator cavity. The purpose of mirrors is to establish a strong optical feedback in the longitudinal direction. The feedback mechanism converts the device into an oscillation.

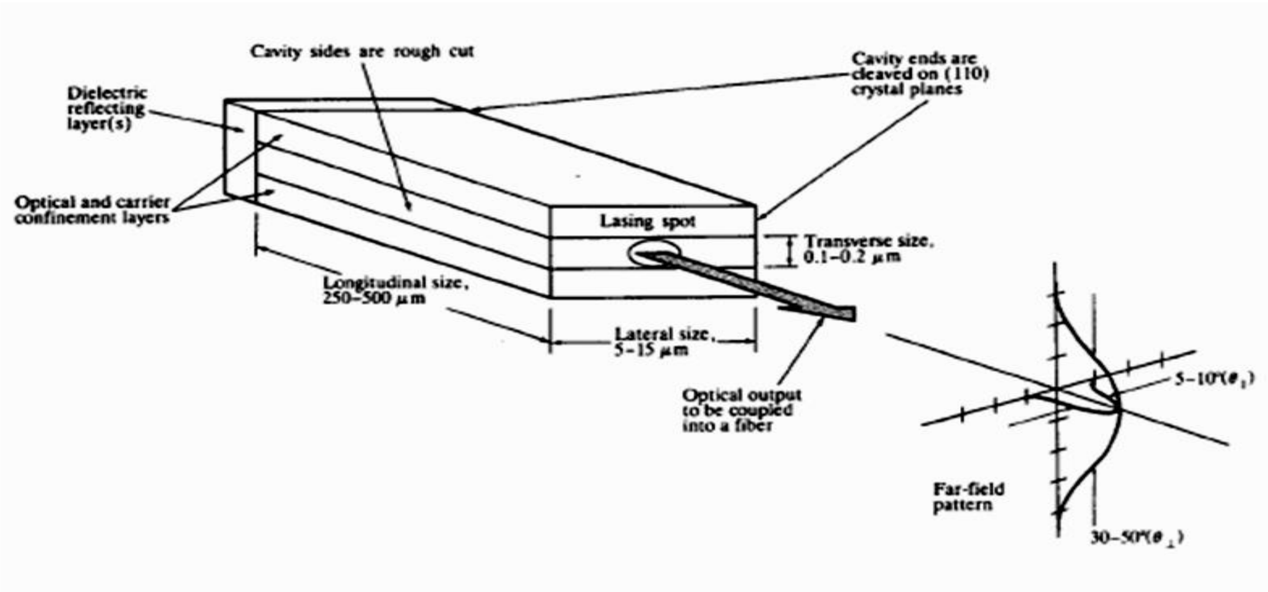
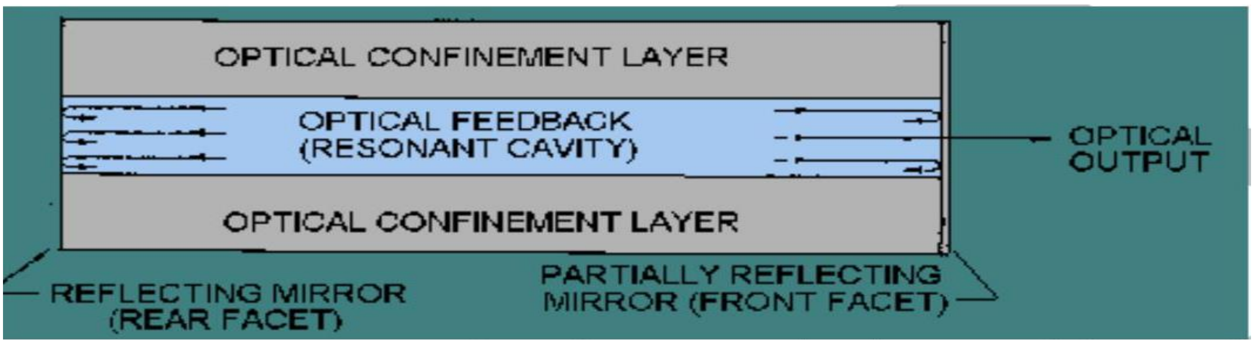


Figure 3.4: Fabry-Perot resonator cavity for a laser diode.

Only a portion of the optical radiation is amplified. For a particular laser structure, there are only certain wavelengths that will be amplified by that laser. Amplification occurs for selected wavelengths, also called laser modes; reflect back and forth through the cavity. For lasing to occur, the optical gain of the selected modes must exceed the optical loss during one round-trip through the cavity. This process is referred to as optical feedback, shown in figure 3.5.



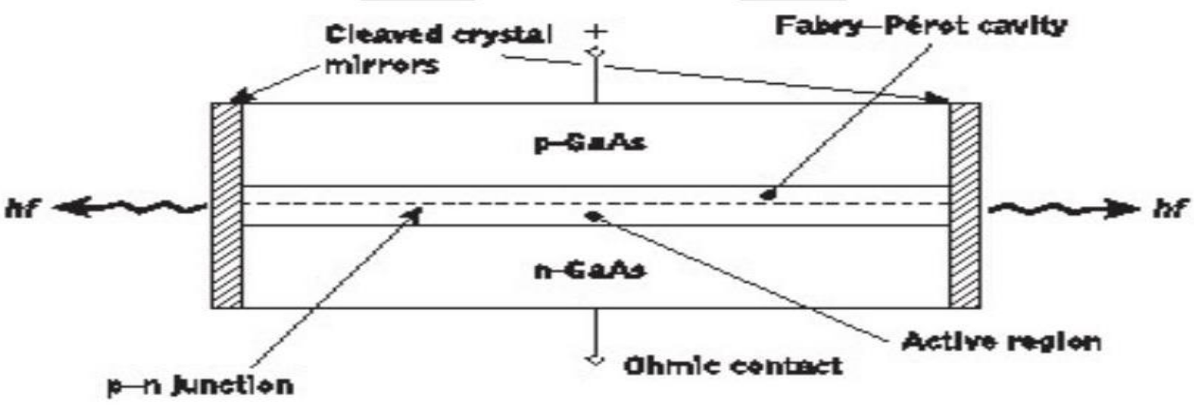


Figure 3.5: Optical Cavity for producing Lasing

MODES & THRESHOLD CONDITIONS:

The optical radiation within the resonance cavity of laser diode sets up a pattern of electric & magnetic field lines called the modes of cavity. These lines are separated into 2 independent set of TE & TM modes.

Each set of modes can be described in terms of longitudinal, lateral & transverse half-sinusoidal variations of EM fields along the major axes of the cavity.

LONGITUDINAL MODES are related to the length L of cavity & determine the principal structure of the frequency spectrum of emitted optical radiation.

LATERAL MODES lie in the plane of pn junction. These modes depends upon side walls & width of the cavity, determines shape of lateral profile of laser beam.

TRANSVERSE MODES associated with EM field & beam profile in the direction perpendicular to the plane of pn junction, determines laser characteristics & threshold current density.

LASING is the condition at which light amplification becomes possible in the laser diode. Requirement for lasing is that population inversion be achieved. To determine lasing condition, consider EM propagation in longitudinal direction

$$E(z,t) = I(z) \exp(j[\omega t - \beta z]) \text{ ------------ (1)}$$

Where $I(z)$ = optical field intensity = $I(0) \exp([\tau g(hv) - \tilde{\alpha}(hv)]z)$, $\tilde{\alpha}$ = effective absorption co-efficient in optical path, τ = optical field confinement factor, g = gain co-efficient in Fabry-Perot cavity, z = distance along lasing cavity.

Lasing occurs when the gain of one or several guided modes is sufficient to exceed the optical loss during one round trip through the cavity i.e $z = 2L$

During this round trip, only the fractions R_1 & R_2 of the optical radiation are reflected from the 2 laser ends 1& 2 respectively, where R_1 & R_2 are mirror reflexives or Fresnel reflection co-efficient, which are given by $R = [(n_1 - n_2)/ (n_1 + n_2)]^2$.

The lasing condition becomes

$$I(2L) = I(0)R_1R_2\exp[2L(\tau g(hv) - \tilde{\alpha}[hv])] \text{ -------(2)}$$

At lasing threshold, a steady-state oscillation takes place. The magnitude & phase of the returned wave must be equal to those of the original wave. This gives the condition $I(2L) = I(0)$ for amplitude -------------- (3)

$$\exp(-j2\beta L) = 1 \text{ for phase --------------- (4)}$$

Equation (4) gives information about resonant frequency of the Fabry-Perot cavity. Equation (3) gives information about which modes have sufficient gain for sustained oscillations.

LASING THRESHOLD is the point at which the optical gain is equal to the total loss α_t in the cavity. From equation (3) laser gain threshold

$$g_{th} = \alpha_t = \tilde{\alpha} + [1/2L]\text{In}[1/R_1]\, R_2 = \tilde{\alpha} + \alpha_{end} \text{ ---------------- (5)}$$

where α_{end} = the mirror loss in lasing cavity.

Therefore lasing may occur when gain $g \geq g_{th}$ i.e. pumping source that maintain strong population inversion must be sufficiently strong to support or exceed all energy consuming mechanisms within the lasing cavity. The mode that satisfies equation (5) reaches threshold first.

The relationship between optical output power & laser diode driven current is shown in figure 3.6.

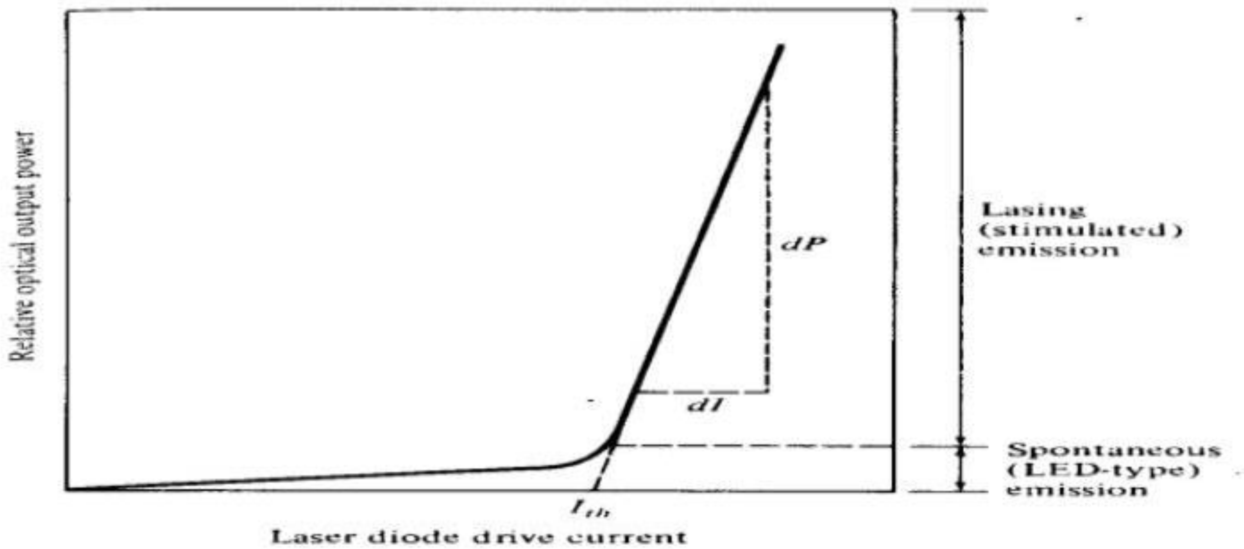


Figure 3.6: Relationship between optical output power vs Laser Diode driven current.

At low diode currents, only spontaneous radiation is emitted. The spectral beam and lateral beam width of emission are broad as like that of an LED.

Sharp increase in power output occurs at lasing threshold. At this transition approach, the spectral width & beam width both get narrowed with increase in current.

The threshold current I_{th} is conventionally defined by extrapolation of the lasing region of the power vs current curve.

At the higher output, the slope of the curve decreases because of junction heating. The relationship between lasing threshold optical gain & threshold current density J_{th} is

$g_{th} = \beta J_{th}$ --------------------(6) where β is constant.

LASER DIODE RATE EQUATION:

The relation between optical output power and the diode driven current can be determined by rate equations. The total carrier population is determined by carrier injection, spontaneous recombination & stimulated emission.

For a pn junction with a carrier-confinement region of depth 'd', the rate equations are given by $[d\phi/dt]=cn\phi + R_{SP} - [\phi/\tau_{ph}]$ ---------------(1)

= stimulated emission + spontaneous emission – photon loss

$[dn/dt] = [J/qd] - [n/\tau_{sp}] - [cn\phi]$ ---------------- (2)

= injection – [spontaneous recombination] + stimulated emission]

Where n=no. of electrons, c = strength of the optical absorption & emission,
R_{SP} = rate of spontaneous emission in to lasing mode, τ_{ph} = photon life time,
τ_{sp} =spontaneous recombination life time, J = injection carrier density.

In equation (1), 1st term is photons resulting from stimulated emission, 2nd term is photons resulting from spontaneous emission, 3rd term is no. of photons caused by loss mechanism in lasing cavity.

In equation (2), 1st term is increase in electron concentration in conduction band as current flow in to device, 2nd & 3rd terms are electrons lost from conduction band owing to spontaneous & stimulated emission respectively.

The output power can be calculated by considering steady state conditions on equations (1) & (2). The steady state conditions can be obtained by making LHS of equations (1) & (2) to zeros.

In equation (1), R_{SP} is negligible. $[d\phi/dt]$ is positive when ϕ is small then

$cn - [1/\tau_{ph}] \geq 0$. -------------- (3)

In equation (2), consider threshold values in steady state when no. of photons $\phi = 0$.

$n=n_{th}$, $J=J_{th}$. Then $[J_{th}/qd] = [n_{th}/ \tau_{sp}]$. ------------------- (4)

Equation (4) defines the current required to sustain an excess electron density in the laser.

Consider rate equation in steady state conditions at laser threshold, then

$0= cn_{th}\, \phi s + RSP - [\phi s/\tau_{ph}]$ ---------------(5)

$0= [J/qd] - [n_{th} / \tau_{sp}] - [cn_{th}\phi]$ ---------------- (6)

Where ϕs = steady state photon density.

Adding equations (5) & (6) using (4), then no. of photons per unit volume can be written as

$0 = [J/qd] - [J_{th} / qd] + R_{SP} - [\phi s/\tau_{ph}]$

Therefore $[\phi s/\tau_{ph}] = [1/qd][J-J_{th}] + R_{SP}$

$\phi s = [\tau_{ph} /qd][J-J_{th}] + \tau_{ph} R_{SP}$ ---------------------- (7)

In equation (7), the first term is no. of photons resulting from stimulated emission. The power generated in concentrated in one or two modes. The second term gives spontaneously generated photons. The power resulting from these photons is not mode selective but spread over all the possible modes.

EXTERNAL QUANTUM EFFICIENCY:

The external quantum efficiency ηext is defined as no. of photons emitted per radiative electron-hole pair recombination above threshold. $\eta_{ext} =[\eta_i(g_{th} - \tilde{\alpha})] / g_{th}$.

$\eta_{ext} =[\eta_i(g_{th} - \alpha)] / g_{th}$

In the above equation, η_i is internal quantum efficiency ≈ 0.6 to 0.7.

Experimentally ηext is calculated from straight line portion of the curve for emitted optical power P vs I.

$\eta_{ext} =[q/E_g][dP/dI] = 0.8065\lambda(\mu m)[dP(mw)/dI(mA)]$.

In the above equation, Eg = band gap energy in electron volts, dP = incremental change in emitted optical power in mwatts, dI = incremental change in drive current in mA, λ=emission wavelength in micro meters.

RESONANT FREQUIENCIES:

We know that lasing conditions are

$I(2L) = I(0)$ for amplitude -------------- (1)

$\exp(-j2\beta L) = 1$ for phase --------------- (2)

The condition in equation (2) holds when $2\beta L = 2\pi m$, where m is an integer, β propagation constant = $2\pi n / \lambda$

Therefore $2[2\pi n / \lambda]L = 2\pi m$

$m = 2Ln / \lambda = 2Ln[f/c]$ ------ (3) where $c=f\lambda$. This states that the cavity resonates [i.e., a standing wave pattern exits within it] when an integer number m of half wavelengths span, the region between the mirrors.

Since in all lasers the gain is a function of frequency or wavelength, there will be a range of frequencies or wavelengths for which equation (3) holds. Each of these frequencies corresponds to a mode of oscillation in the laser. Depending on the laser structure, any number of frequencies can satisfy equation (1) & (2).

Thus some lasers are single-mode and some are multimode. The relationship between gain and frequency can be assumed to have the Gaussian form

$$g(\lambda) = g(0)\exp\left[-\frac{(\lambda-\lambda_0)^2}{2\sigma^2}\right]$$ ------------(4)

Where λ_0 is the wavelength at the center of the spectrum, σ is the spectrum width of the gain, and the maximum gain g(0) is proportional to the population inversion. The frequency or wavelength spacing between the modes can be derived by considering only the longitudinal modes. For each longitudinal mode there may be several transverse modes that arise from one or more reflections of the propagating wave at the sides of the resonator cavity. To find frequency spacing, consider two successive modes of frequencies f_{m-1} & f_m represented by the integer's m-1 & m. From equation (3)

$m - 1 = [2Ln/c]f_{m-1}$ --------(5)

$m = [2Ln/c]f_m$ --------------(6)

Subtracting (5) from (6) gives $m - [m-1] = [2Ln/c](f_m - f_{m-1})$

$1 = [2Ln/c]\Delta f$

which gives the frequency spacing $\Delta f = [c/2Ln]$.

From the relationship $\Delta f/f = \Delta\lambda/\lambda$

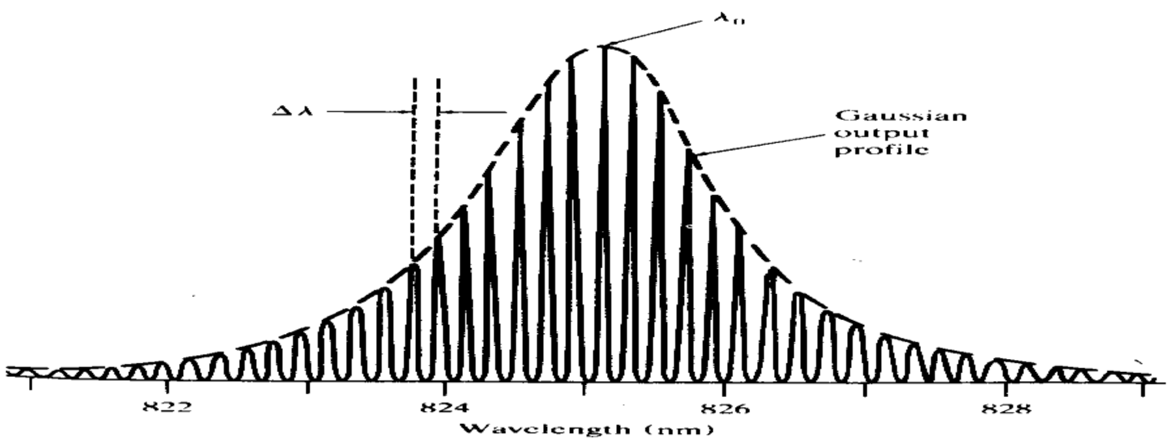
$\Delta\lambda = \lambda\Delta f/f$

$\Delta\lambda = [c\,\lambda/2Ln\,f]$

$= [f\,\lambda\,\lambda/2Ln\,f]$

$= [\lambda^2/2Ln]$

The exact no. of modes, spacing depends upon the laser construction.



Typical spectrum from a gain-guided GaAlAs/GaAs laser diode.

TEMPERATURE EFFECTS:

An important factor to consider in the application of laser diodes is temperature dependence of the threshold current $I_{th}(T)$. This parameter creases with temperature in all types of semiconductor lasers because of various complex temperature-dependent factors. The complexity of these factors prevents the formulation of a single equation holding for all devices temperature ranges. However, the temperature variation of I_{th} can be approximated by the empirical expression

$$I_{th}(T) = I_Z\, e^{T/T_o}$$

where T_0 is a measure of the relative temperature insensitivity and I_z *is* constant. For a conventional stripe geometry GaAlAs laser diode *To* is typically 120 to 165°C in the vicinity of room temperature. The temperature dependence behavior of particular laser diode is shown in Figure 3.7.

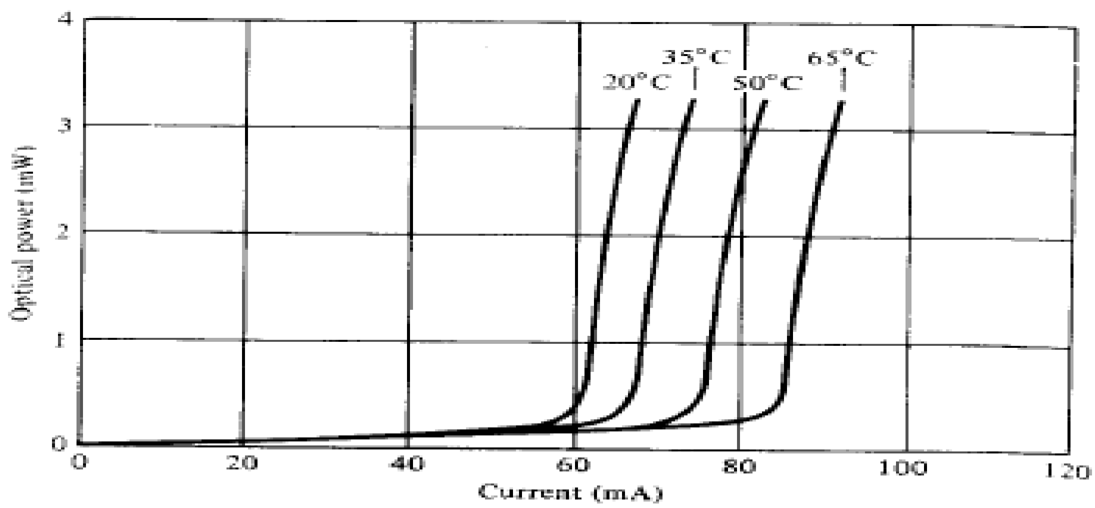


Figure 3.7: Temperature-dependent behavior of the optical output power as a function of the bias current for a particular laser diode.

The variation of I_{th} with temperature is 0.8 percent/°C, as is shown in Figure 3.8.

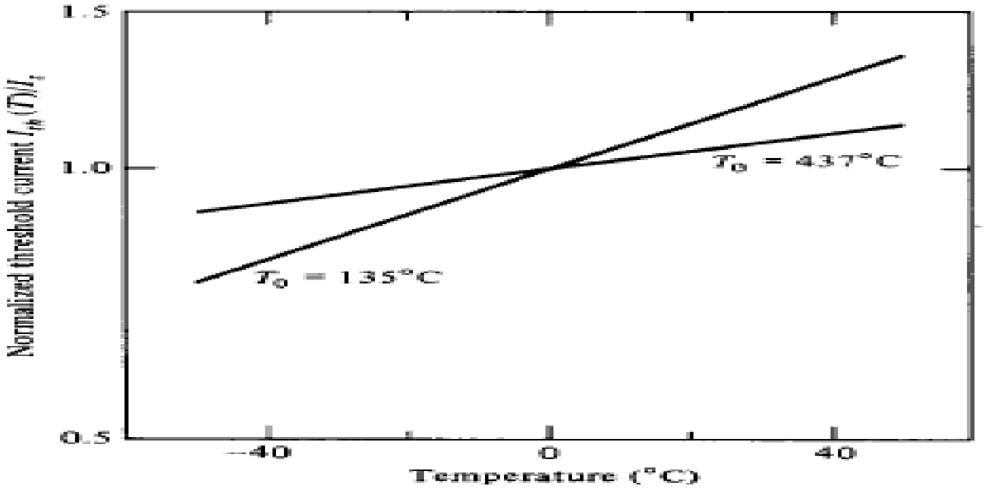


Figure 3.8: Variation with temperature of the threshold current I_{th} for two types of laser diodes.

For the laser diode shown in Figure 3.7, the threshold current increases by a factor of about 1.4 between 20 and 60°C. In addition, the lasing threshold can change as the laser ages. Consequently, if a constant optical output power level is to be maintained as the temperature of the laser changes or as the laser ages it is necessary to adjust the dc bias current level. Possible methods for achieving this automatically are optical feedback schemes, temperature-matching transistors, and threshold-sensing circuits.

FIBER ALIGNMENT AND JOINT LOSS:

In any communication system, both jointing and termination of transmission medium is a common requirement. The number of intermediate fiber connections or joints is dependent upon the link length [between repeaters], the continuous length of fiber cable that may be produce by preparation methods.

There are 2 major categories of fiber joints. 1] Fiber Splices 2] Connectors

Fiber splices: These are semi permanent or permanent joints [analogous to electrical soldered joints]

Demodulated fiber connectors or connectors: These are removable joints which allow easy fast manual coupling and uncoupling of fibers [analogous to electrical plugs and sockets]

Optical loss is encountered at interface of 2 fibers [fiber-fiber]. Even two jointed fiber ends are smooth, perpendicular to fiber axes & 2 fibers are perfectly aligned, a small portion of light may be reflected back in to transmitting fiber causes attenuation at the joint which is known as FRESNEL REFLECTION.

The magnitude of reflected light can be written as

$$r = \left(\frac{n_1 - n}{n_1 + n}\right)^2$$

where r = fraction of light reflected at a single interface, n_1 = RI of fiber core, n = RI of medium between 2 jointed fibers [n = 1 for air].

The loss in db due to Fresnel reflection at a single interface is given by

$$Loss_{Fres} = -10 \log_{10} (1-r)$$

The effect of Fresnel reflection at a fiber-fiber connection can be reduced to a very low level through the use of an index matching fluid in the gap between the jointed fibers.

PROBLEM 3.1: An OF has a core RI of 1.5. Two lengths of fiber with smooth and perpendicular end faces are butted together. Assuming the fiber axes are perfectly aligned, calculate the optical loss in db's at the joint due to Fresnel reflection when there is small air gap between the fiber end faces.

Any deviations in the geometrical and optical parameters of the two optical fibers which are jointed will affect the optical attenuation through the connection. There are inherent connection problems when jointing fibers with

[a] Different core and / or cladding diameters;

[b] Different NA and/or RI differences;

[c] Different RI profiles;

[d] Fiber faults.

The losses caused by above factors together with Fresnel reflection are referred as intrinsic joint losses.

Misalignment may occur in 3 dimensions

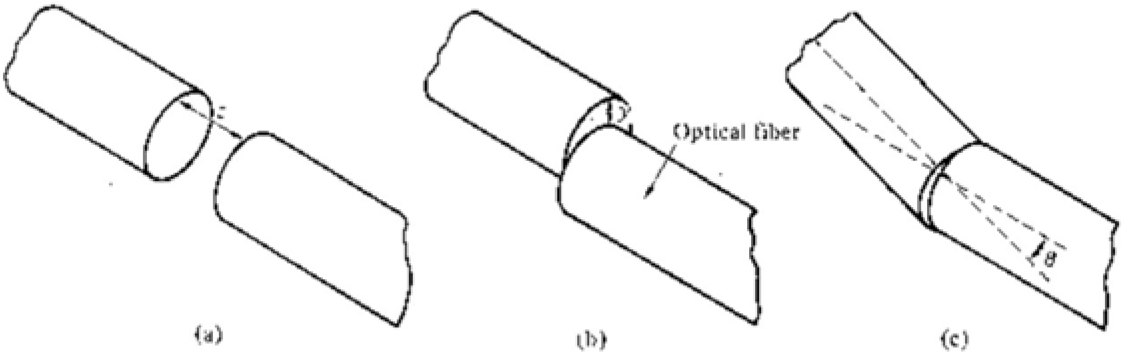


Figure 3.9: Three possible misalignments

3 possible misalignments occur when joining compatible optical fibers [a] Longitudinal misalignment [b] Lateral misalignment [c] Angular misalignment.

Lateral misalignment gives greater loss than longitudinal misalignment.

Optical losses resulting from these three types of misalignment depend upon the fiber type, core diameter and the distribution of the optical power between the propagating modes.

MULTIMODE FIBER JOINTS:

Lateral misalignment reduces the overlap region between two fiber cores. Assuming uniform excitation of all the optical modes in a multimode step index fiber the overlapped area between both fiber cores approximately gives the lateral coupling efficiency η_{lat}. The lateral coupling efficiency for two similar step index fiber is

$$\eta_{lat} \simeq \frac{16(n_1/n)^2}{(1+(n_1/n))^4} \frac{1}{\pi} \left\{ 2\cos^{-1}\left(\frac{y}{2a}\right) - \left(\frac{y}{a}\right)\left[1-\left(\frac{y}{2a}\right)^2\right]^{\frac{1}{2}} \right\}$$

Where n_1 = core RI, n = RI of medium between fibers, y = lateral offset of the fiber core axis, a = fiber core radius.

The misalignment loss in db's is

$$Loss_{lat} = -10 \log_{10} \eta_{lat} \text{ dB}$$

If the joint is considered as index matched [no air gap] then n1/n =1

$$[16(1)/(1+1)^4] = 1$$

We know that

$$\eta_{lat} \simeq \frac{16(n_1/n)^2}{(1+(n_1/n))^4} \frac{1}{\pi} \left\{ 2\cos^{-1}\left(\frac{y}{2a}\right) - \left(\frac{y}{a}\right)\left[1-\left(\frac{y}{2a}\right)^2\right]^{\frac{1}{2}} \right\}$$

$$\eta_{lat} \simeq \frac{1}{\pi} \left\{ 2\cos^{-1}\left(\frac{y}{2a}\right) - \left(\frac{y}{a}\right)\left[1-\left(\frac{y}{2a}\right)^2\right]^{\frac{1}{2}} \right\}$$

Lateral misalignment loss in graded index fiber in terms of RI profile

$$L_t = \frac{2}{\pi}\left(\frac{y}{a}\right)\left(\frac{\alpha+2}{\alpha+1}\right) \quad \text{for } 0 \leqslant y \leqslant 0.2a$$

Where lateral coupling efficiency

$$\eta_{lat} = 1 - L_t$$

For parabolic RI profile α =2

$$L_t = \frac{8}{3\pi}\left(\frac{y}{a}\right) = 0.85\left(\frac{y}{a}\right)$$

For guided & leakey modes

$$L_t = 0.75\left(\frac{y}{a}\right)$$

For multimode step index fiber, the lateral misalignment loss for guided modes only is

$$L_t = 0.64\left(\frac{y}{a}\right)$$

PROBLEM 3.2: A step index fiber has refractive index of 1.5 and a core diameter of 50µm. The fiber is jointed with a lateral misalignment between the core axes of 5µm. Estimate the insertion loss at the joint due to the lateral misalignment assuming a uniform distribution of power between all guided modes when:

(a) there is a small air gap at the joint;
(b) the joint is considered index matched.

PROBLEM 3.3: A graded index fiber has a parabolic refractive index profile (α=2) and a core diameter of 50µm. Estimate the insertion loss due to a 3µm lateral misalignment at a fiber joint when there is index matching and assuming:

(a) there is uniform illumination of all guided modes only;
(b) there is uniform illumination of all guided and leaky modes.

<u>ANGULAR MISALIGNMENT LOSSES</u>:

Angular misalignment losses at joints in multimode step index fibers may be predicted with reasonable accuracy using an expression for angular coupling efficiency

$$\eta_{ang} \simeq \frac{16(n_1/n)^2}{(1+(n_1/n))^4}\left[1 - \frac{n\theta}{\pi n_1 (2\Delta)^{\frac{1}{2}}}\right]$$

Where θ = angular displacement, Δ= RRID, n_1 = core RI, n = RI of medium between two fibers.

Insertion loss due to angular misalignment

$$\text{Loss}_{ang} = -10 \log_{10} \eta_{ang}$$

PROBLEM 3.4: Two multimode step index fibers have numerical apertures of 0.2 and 0.4 respectively, and both have the same core refractive index which is 1.48. Estimate the insertion loss at a joint in each fiber caused by 5^0 angular misalignments of the fiber core axes. It may be assumed that the medium between the fibers is air.

SINGLE MODE FIBER JOINTS:

In the absence of angular misalignment loss T1 due to lateral offset ý' can be written as

$$T_l = 2.17\left(\frac{y}{\omega_0}\right)^2 \text{ dB}$$

Where

ω0 = normalized spot size of fundamental mode

$$\omega_0 = a\frac{(0.65 + 1.62V^{-1.5} + 2.88V^{-6})}{2^{1/2}}$$

a = core radius, v = normalized frequency.

Insertion loss due to angular misalignment θ [in radians]

$$T_a = 2.17\left(\frac{\theta\omega_0 n_1 V}{a\,\mathrm{NA}}\right)^2 \text{ dB}$$

Total insertion loss

$$T_T \sim T_l + T_a$$

PROBLEM 3.5:

A single mode fiber has the following parameters:

normalized frequency (V) = 2.40

core refractive index(n1) = 1.46

core diameter (2a) = 8μm

numerical aperture (NA) = 0.1

Estimate the total insertion loss of a fiber joint with a lateral misalignment of 1 μm and an angular misalignment of 1^0 .

CORE DIAMETER MISMATCH:

Assuming all the modes are equally excited in a multimode SIF or GIF. NA & index profiles are same, and then the loss resulting from a mismatch of core diameter is given by

$$\text{Loss}_{CD} = \begin{cases} -10\log_{10}[a_2/a_1]^2 \text{ db} & \text{when } a_2 < a_1 \\ 0 \text{ db} & \text{when } a_2 >= a_1 \end{cases}$$

Where a_1, a_2 are core radius of transmitter and receiver fibers respectively. No loss is included if receiver fiber has a larger core diameter than the transmitter one.

NUMERICAL APERTURE MISMATCH:

When the transmitting fiber has a higher NA than the receiving fiber, then some of emitted light rays will fall outside the AA of receiving fiber & therefore not be coupled through the joint.

Assuming fibers with equivalent RI profiles, core diameters & uniform modal power distribution, then loss caused by mismatch of NA is

$$Loss_{NA} = \begin{cases} -10\log_{10} [NA_2 / NA_1]^2 \text{ db} & \text{when } NA_2 < NA_1 \\ 0 \text{ db} & \text{when } NA_2 >= NA_1 \end{cases}$$

Where NA_1, NA_2 are the NA for Tx, Rx fibers.

MISMATCH IN RI PROFILE:

When the Tx fiber has different RI profile from Rx fiber, then loss caused by mismatch of RI profiles is

$$Loss_{RIP} = \begin{cases} -10\log_{10} (\alpha_2[\alpha_1+2]) / (\alpha_1[\alpha_2+2]) \text{ db when} & \alpha_2 < \alpha_1 \\ 0 \text{ db} \quad \text{when} & \alpha_2 >= \alpha_1 \end{cases}$$

Where α_1 & α_2 are RI profiles of Tx & Rx fibers.

The intrinsic losses obtained at multimode fiber joints

$$Loss_{INT} = \begin{cases} -10\log_{10} [(a_2 NA_2)^2 (\alpha_1+2)\alpha_2] / [(a_1 NA_1)^2 (\alpha_2+2)\alpha_1] \text{ db when} \\ \quad a_2 < a_1, NA_2 < NA_1, \alpha_2, < \alpha_1 \\ 0 \text{ db} \quad \text{when when } a_2 >= a_1, NA_2 >= NA_1, \alpha_2 >= \alpha_1 \end{cases}$$

FIBER SPLICING:

A fiber splice is a permanent or semi-permanent joint between two fibers. Fiber splicing is typically used to create long optical fiber links or in situations where frequent connections & disconnections are not needed.

It is necessary to consider geometrical differences in two fibers, fiber misalignments at the joint & the mechanical strength of the splice.

Several splicing techniques were developed during the evaluation of optical fiber technology. Among these are Fusion splicing [permanent joint], V-groove mechanical splicing & Elastic tube splicing [semi-permanent joint].

FUSION SPLICING:

Fusion splices are made by thermally bonding together to the prepared fiber ends as shown in figure 3.10.

The fiber ends are first pre-aligned and butted together. This is done in grooved fiber holder or under a microscope with micromanipulator.

The butt joint is then heated with an electronic arc or laser, so that fiber ends are melted & bonded together.

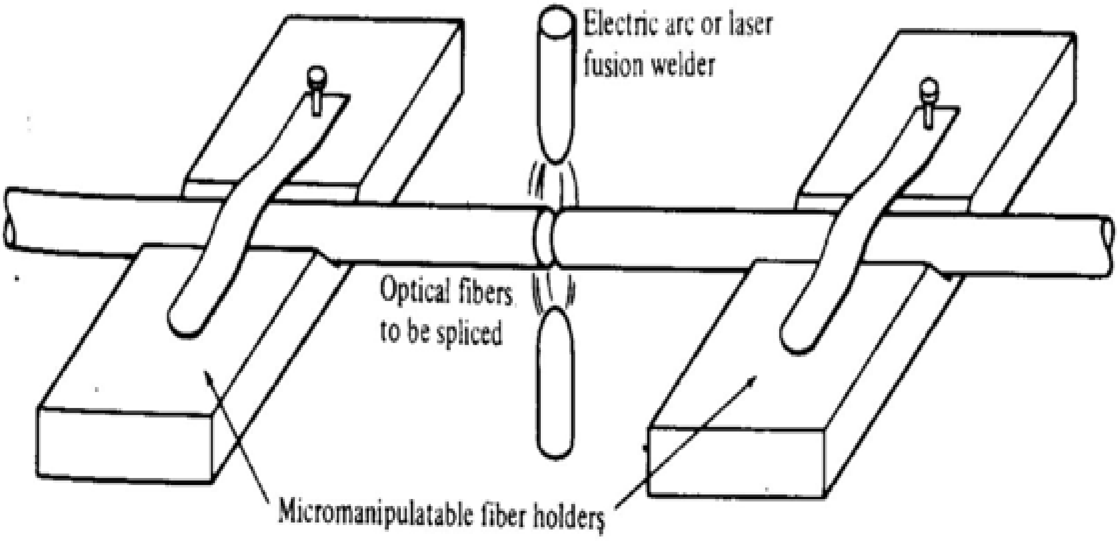


Figure 3.10: Fusion splicing of optical fibers.

Care must be taken, since surface damage due to handling, surface defect growths created during heating & residual stress near joint due to change in chemical composition arising from the material melting, can produce a week splice.

V-GROOVE SPLICE TECHNIQUE:

In V-grooved splicing technique, prepared fiber ends are first butted together in a V shaped groove. Then they are bonded together with adhesive or arc held in place by means of cover plate.

The V-shaped channel could be either grooved silicon, plastic, ceramic or metal substrate. The splice loss in this method depends strongly on the fiber size [outside dimensions and core diameter variations]

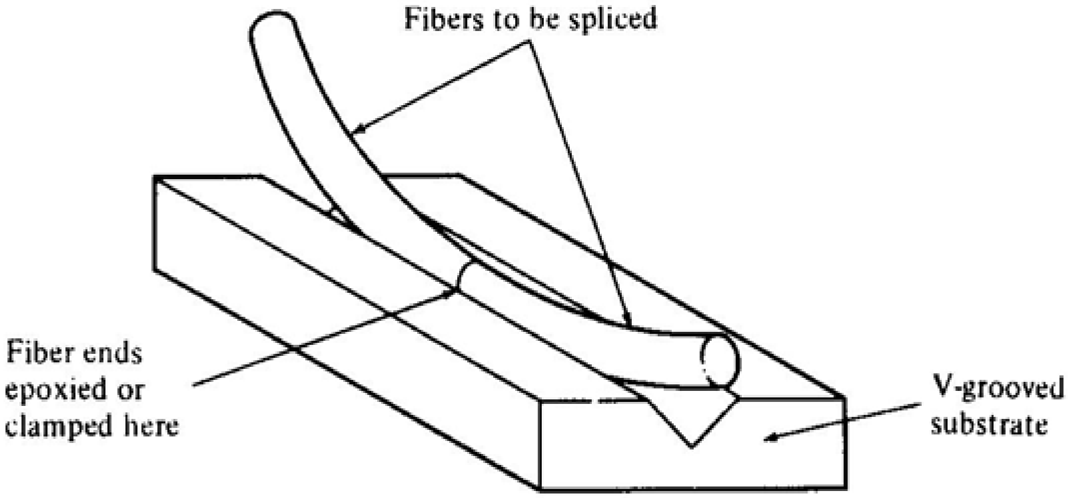


Figure 3.11: V-grooved optical fiber splicing technique.

ELASTIC TUBE SPLICE:

The elastic tube splice shown in fig 4.4 is a unique device that automatically performs lateral, longitudinal & angular alignment. This splicing requires much less equipment and skill.

This mechanism contains basically a tube made of elastic material. The central hole diameter is slightly smaller than that of fiber to be spliced & tampered on each end for easy insertion.

When a fiber is inserted, it expands the hole diameter so that elastic material apply a symmetrical forces on the fiber. This symmetry feature allows an accurate & automatic alignment of the axis of two fibers to be joined.

The fibers to be spliced do not have to be equal diameter. Each fiber moves into position independently relative to the tube axis.

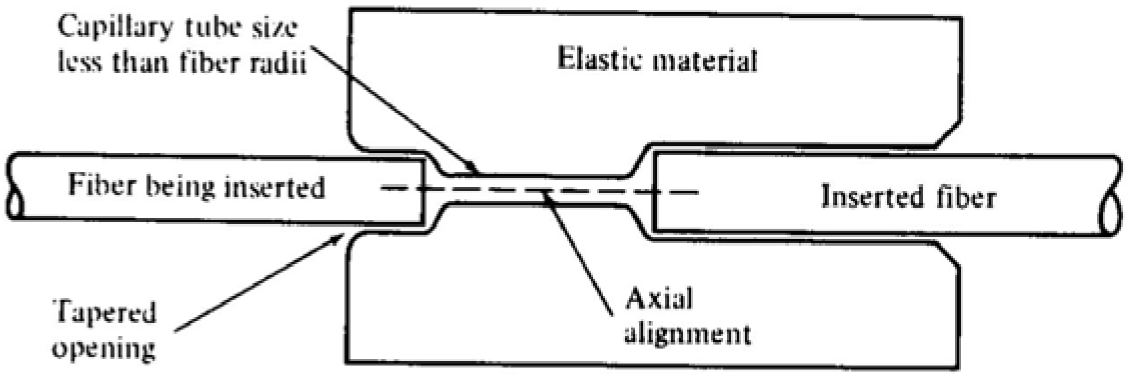


Figure 3.11: Schematic of an elastic tube splice.

SPLICING SINGLE MODE FIBER:

In single mode fibers the lateral [axial] offset loss presents the most serious misalignment. This loss depends on the shape of the propagating mode.

For Gaussian shaped beams the loss between identical fibers is

$$L_{SM;lat} = -10 \log\left\{\exp\left[-\left(\frac{d}{W}\right)^2\right]\right\}$$

Where W = mode field radius, d = lateral displacement.

For angular misalignment in single mode fiber, the loss at wavelength λ is

$$L_{SM;ang} = -10 \log\left\{\exp\left[-\left(\frac{\pi n_2 W\theta}{\lambda}\right)^2\right]\right\}$$

Where n_2 = RI of cladding, θ = angular misalignment.

For gap‘s’ [longitudinal] with a material index of n_3, the gap loss for identical single mode splice is

$$L_{SM;gap} = -10 \log \frac{4(4Z^2 + 1)}{(4Z^2 + 2) + 4Z^2}$$

Where

$Z = s\lambda/(2\pi n_2 W^2)$ with ‘s’ being the end space separation

POWER LANCHING & COUPLING:

SOURCE OUTPUT PATTERN

The spatial radiation pattern of the source must first be known to determine the optical power-accepting capability of a fiber. Figure 3.12 shows a spherical coordinate system characterized by R, θ and Ø, with the normal to the emitting surface being the polar axis. The radiance may be a function of both θ and Ø, and can also vary from point to point on the emitting surface.

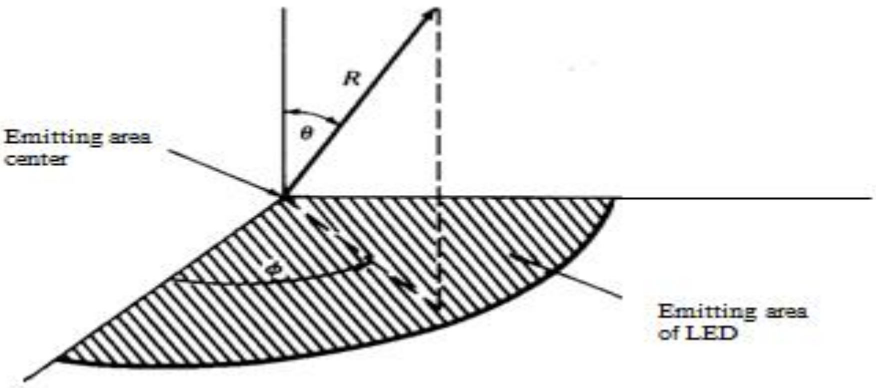


Figure 3.12: Spherical coordinate system for characterizing the emission pattern from an optical source.

Surface-emitting LEDs are characterized by their Lambertian output patter. The emission pattern for a Lambertian source follows the relationship.

$$B(\theta, \phi) = B_0 \cos \theta$$

In the above equation B_0 is the radiance along the normal to the radiating surface. The radiance pattern for this source is shown in figure 3.13.

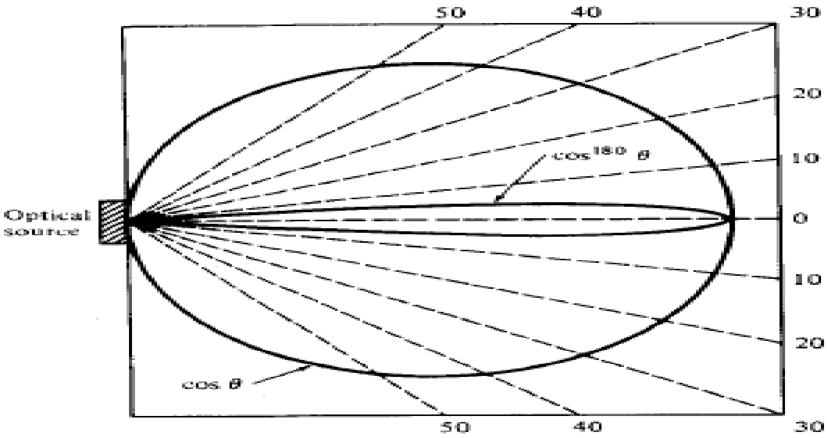


Figure 3.13: Radiance patterns for a lambertian source and the lateral output of highly directional laser diode.

Edge-emitting LEDs and laser diodes have more complex emission pattern. These devices have different radiance $B(\theta,0^0)$ & $B(\theta,90^0)$ in the planes parallel and normal, respectively, to the emitting-junction plane of the device. These radiances can be approximated by

$$\frac{1}{B(\theta, \phi)} = \frac{\sin^2 \phi}{B_0 \cos^T \theta} + \frac{\cos^2 \phi}{B_0 \cos^L \theta}$$

The integers T and L are the transverse and lateral power distribution coefficients, respectively.

POWER-COUPLING CALCULATION:

To calculate the maximum optical power coupled into a fiber, consider a symmetric source of brightness $B(A_s,\Omega_s)$, where A_s & Ω_s are the area and solid emission angle of the source, respectively. The fiber end face is centered over the emitting surface of the source and is positioned as close to it as possible. The coupled power can be found using the relationship

$$P = \int_{A_f} dA_s \int_{\Omega_f} d\Omega_s \, B(A_s, \Omega_s)$$
$$= \int_0^{r_m} \int_0^{2\pi} \left[\int_0^{2\pi} \int_0^{\theta_{0,max}} B(\theta, \phi) \sin\theta \, d\theta \, d\phi \right] d\theta_s \, r \, dr$$

In the above equation the area and solid acceptance angle of the fiber define the limits of the integrals.

The radiance B(θ, Ø) from an individual radiating point source on the emitting surface is integrated over the solid acceptance angle of the fiber.

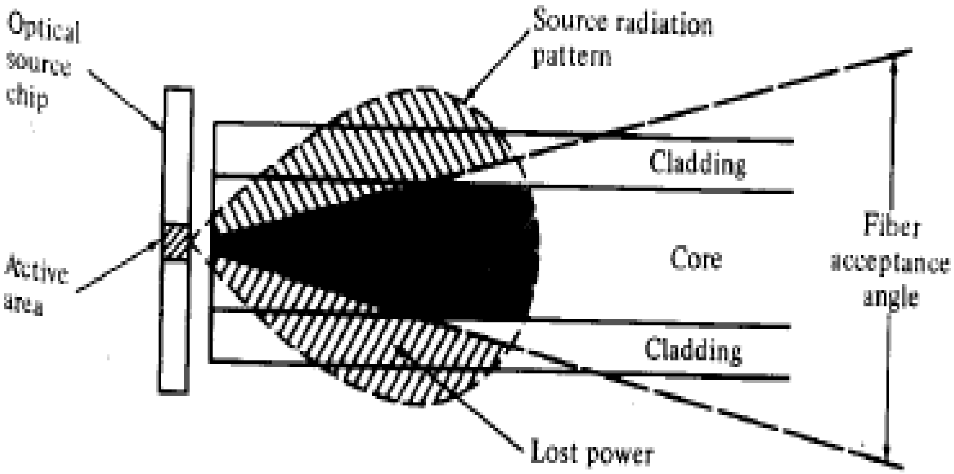


Figure 3.14: Schematic diagram of optical source coupled to an optical fiber. Light outside the acceptance angle is lost.

For step-index fiber the NA is independent of positions θ_s and r on the fiber face, so the equation Becomes (for r_s<a)

$$P = \int_0^{r_s}\int_0^{2\pi}\left(2\pi B_0\int_0^{\theta_{0,\max}}\cos\theta\sin\theta\,d\theta\right)d\theta_s\,r\,dr$$

$$= \pi B_0\int_0^{r_s}\int_0^{2\pi}\sin^2\theta_{0,\max}\,d\theta_s\,r\,dr$$

$$= \pi B_0\int_0^{r_s}\int_0^{2\pi}\mathrm{NA}^2\,d\theta_s\,r\,dr$$

The total optical power P, that is emitted from the source area A, into a hemisphere(2π sr) is given by

$$P_s = A_s\int_0^{2\pi}\int_0^{\pi/2}B(\theta,\phi)\sin\theta\,d\theta\,d\phi$$

$$= \pi r_s^2\,2\pi B_0\int_0^{\pi/2}\cos\theta\sin\theta\,d\theta$$

$$= \pi^2 r_s^2 B_0$$

$$P_{\mathrm{LED,step}} = \pi^2 r_s^2 B_0(\mathrm{NA})^2 \simeq 2\pi^2 r_s^2 B_0 n_1^2\Delta$$

It can also be expressed as

$$P_{\mathrm{LED,step}} = P_s(\mathrm{NA})^2 \qquad \text{for} \quad r_s \le a$$

When the radius of the emitting area is larger than the radius a of the fiber area then

$$P_{\mathrm{LED,step}} = \left(\frac{a}{r_s}\right)^2 P_s(\mathrm{NA})^2 \qquad \text{for} \quad r_s > a$$

In the case of graded-index fiber, the NA depends of distance r from the fiber axis, the power coupled from a surface-emitting LED into a graded-index fiber becomes (for r_s<a)

$$P_{\text{LED, graded}} = 2\pi^2 B_0 \int_0^{r_s} [n^2(r) - n_2^2]\, r\, dr$$
$$= 2\pi^2 r_s^2 B_0 n_1^2 \Delta \left[1 - \frac{2}{\alpha + 2}\left(\frac{r_s}{a}\right)^\alpha\right]$$
$$= 2P_s n_1^2 \Delta \left[1 - \frac{2}{\alpha + 2}\left(\frac{r_s}{a}\right)^\alpha\right]$$

The foregoing analyses assumed perfect coupling conditions between the source and the fiber. This can only be achieved if the RI of the medium separating the source and the fiber end matches the index n_1 of the fiber core. If the RI n of this medium is different from n_1, then for perpendicular fiber end faces, the power coupled into the fiber reduces by the factor

$$R = \left(\frac{n_1 - n}{n_1 + n}\right)^2$$

Where R is Fresnel reflection coefficient at the fiber core end face.

POWER LAUNCHING

The optical power launched into a fiber does not depend on the wavelength of the source but only on its brightness. WKT number of modes which can propagate in a graded-index fiber of core size and index profile ά is

$$M = \frac{\alpha}{\alpha + 2}\left(\frac{2\pi a n_1}{\lambda}\right)^2 \Delta$$

The radiated power per mode, Ps/M, from a source at a particular wavelength is given by the radiance multiplied by the square of the nominated source wavelength

$$\frac{P_s}{M} = B_0 \lambda^2$$

EQUILIBRIUM NA

A light source is often supplied with a short (1to2 m) fiber fly lead attached to it in order to facilitate coupling the source to a system fiber. To achieve a low coupling loss, this fly lead should be connected to a system fiber having a nominally identical NA and core diameter.

In addition to the coupling loss, an excess power loss will occur in the first few tens of meters of the system fiber. This excess loss is a result of non-propagating modes scattering out of the fiber as the launched modes come to an equilibrium condition.

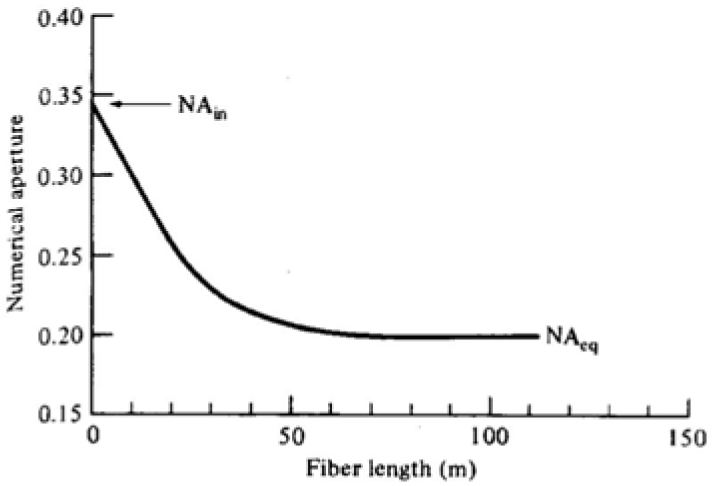


Figure 3.15: Example of the change in numerical aperture as a function of fiber length.

At the input end of the fiber the light acceptance is described in terms of launch numerical aperture NA_{in}. If the light emitting area of the LED is less than the cross-sectional area of the fiber core, then at this point the power coupled into the fiber, where $NA=NA_{in}$.

When the optical power is measured in long fiber lengths after the launched modes have come to equilibrium, the effect of the equilibrium NA [NA_{eq}] becomes apparent.

At this point the optical power in the fiber is

$$P_{eq} = P_{50}\left(\frac{NA_{eq}}{NA_{in}}\right)^2$$

Where P_{50} is the power expected in the fiber at the 50-m point based on the launch NA.

LASER DIODE TO FIBER COUPLING

Laser diodes have an emission pattern which has a full width at half-maximum (FWHM) of 30 to 50d in the plane perpendicular to the active-area junction and an FWHM of 5 to 10d in the plane parallel to the junction.

The angular output distribution of the laser is greater than the fiber acceptance angle and the laser emitting area is much small than the fiber core, spherical or cylindrical lenses or optical fiber tapers can also be used to improve the coupling efficiency between laser diodes and optical fibers.

LENSING SCHEMES:

The optical power launching analysis is based on centering a flat fiber end face directly over the light source as close to it as possible. If the emitting area of source is smaller than the core area, a miniature lens may be placed between the source and the fiber to improve the power coupling efficiency. The function of the micro lens is to magnify the emitting area of the source to match exactly the core area of the fiber end face exactly. If the emitting area is increased by a magnification factor M, the solid angle within which open power coupled to the fiber from the LED is increased by the same factor.

Several possible lensing schemes are shown in figure 3.16. These are a rounded-end fiber, a small glass sphere(nonimaging microsphere) in between the fiber and the source, a larger spherical lens is used to image the source on the core area of the fiber end, cylindrical lens is formed from a short section of fiber, spherical-surfaced LED spherical ended fiber, a taper-ended fiber generally used between source and fiber.

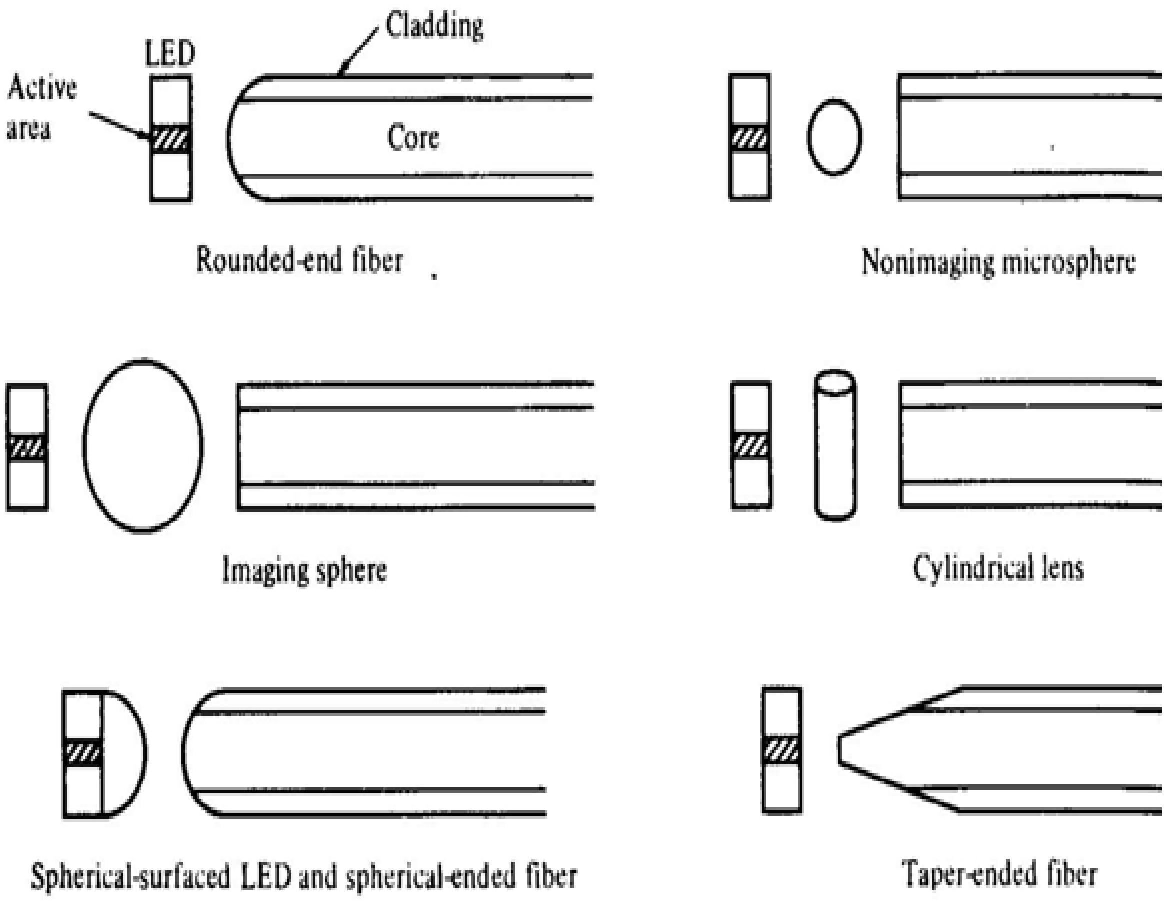
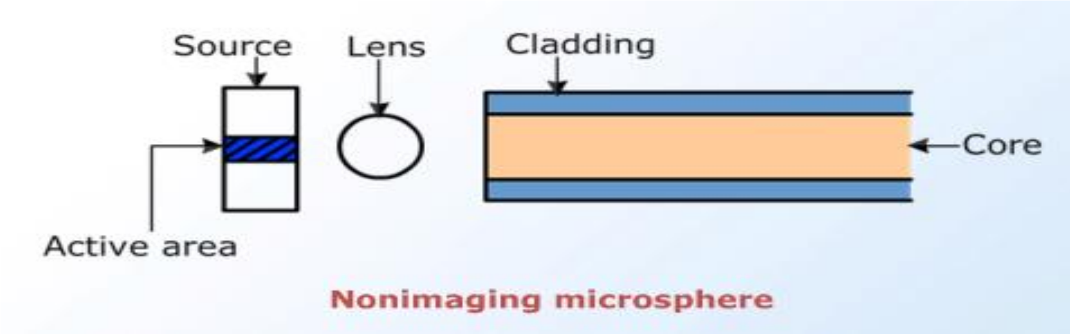


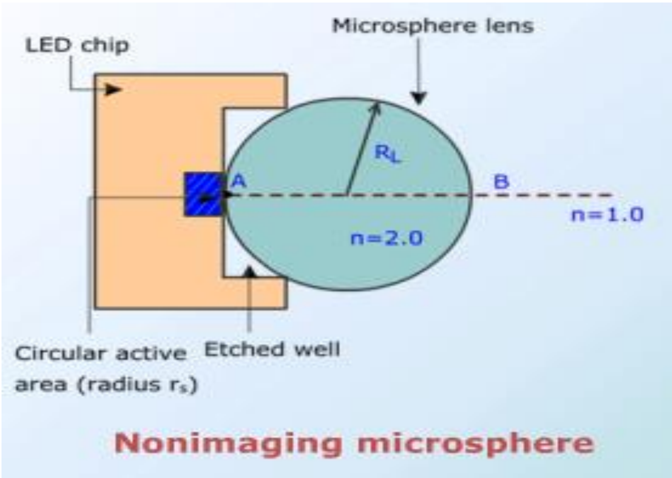
Figure 3.16: Possible Lensing schemes to improve the optical source to fiber coupling efficiency.

NONIMAGING MICROSPHERE:

Nonimaging microsphere is one of the most efficient lensing method.



Example



- Consider that the spherical lens has a refractive index of about 2.0, the outside medium is air (n=1.0), and the emitting area is circular
- To collimate the output from the LED, the emitting surface should be located at the focal point of the lens.
- The focal point is given as:

$$\frac{n}{s} + \frac{n'}{q} = \frac{n' - n}{r}$$

Where,
s= object and
q= image distances
n= refractive index of the lens
n'= refractive index of the outside medium
r= radius of curvature of the lens surface

INTRODUCTION TO QUANTUM LASERS:

Double Heterostructure lasers have also been fabricated with very thin active layer thickness of around 10 nm instead of the typical range for conventional Double

Heterostructures of 0.1 to 0.3 µm. The carrier motion normal to the active layer in these devices is restricted, resulting in a quantization of the kinetic energy into discrete energy levels for the carriers moving in that direction. This effect is similar to the well-known quantum mechanical problem of a one-dimensional potential-well and therefore these devices are known as quantum-well lasers.

In this structure the thin active layer causes drastic changes to the electronic and optical properties in comparison with a conventional Double Heterostructure laser. These changes are due to the quantized nature of the discrete energy levels with a step-like density of states which differs from the continuum normally obtained. Hence, quantum-well lasers exhibit an inherent advantage over conventional Double Heterostructure devices in that they allow high gain at low carrier density, thus providing the possibility of significantly lower threshold currents.

Both single-quantum-well (SQW), corresponding to a single active region, and multiquantum-well (MQW), corresponding to multiple active regions, lasers are utilized. In the latter structure, the layers separating the active regions are called barrier layers. Energy band diagrams for the active regions of these structures are displayed in Figure 3.17. It may be observed in Figure 3.17(c) that when the bandgap energy of the barrier layer differs from the cladding layer in an MQW device, it is usually referred to as a modified multiquantum-well laser.

Better confinement of the optical mode is obtained in MQW lasers in comparison with SQW lasers, resulting in a lower threshold current density for these devices.

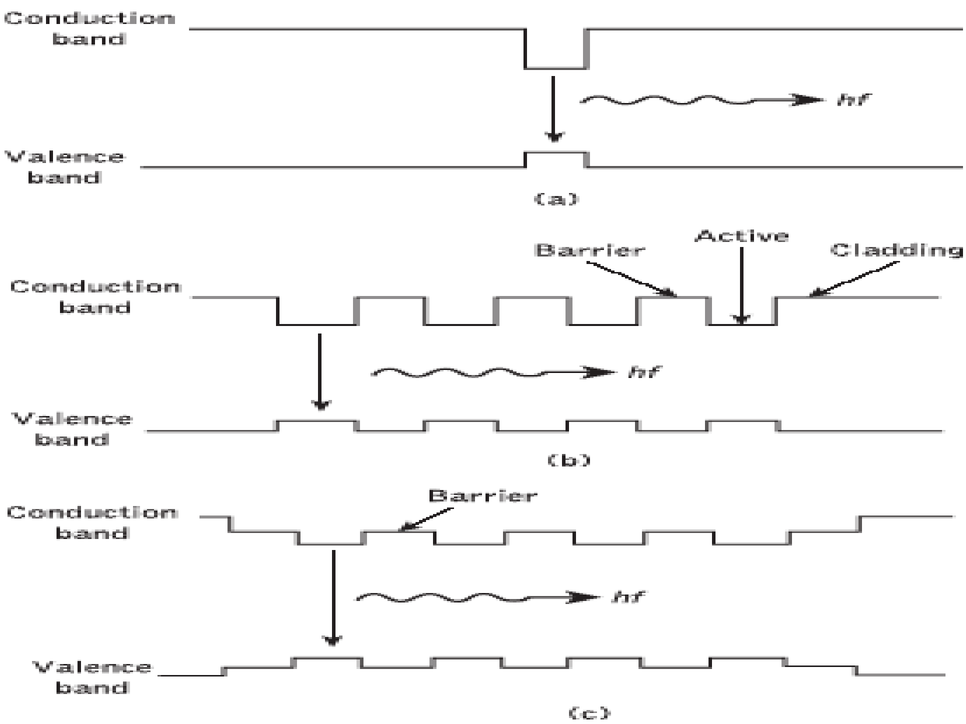


Figure 3.17: Energy band diagrams showing various types of quantum-well structure: (a) single quantum well; (b) multiquantum well; (c) modified multiquantum well