Unit-2

Optical sources: Light emitting diodes (LED): structures, materials, quantum efficiency, LED power, modulation of an LED. Laser diodes: modes, threshold conditions, laser diode rate equations, external quantum efficiency, resonant frequencies, structure and radiation patterns, single mode lasers, modulation of laser diodes.

Power launching and coupling: source to fiber power launching, fiber to fiber joints, LED coupling to single mode fibers, fiber splicing, and optical fiber connectors.

LED (Light Emitting Diode) : To be useful for fiber transmission LED must have high radiance output; a fast response time ; and high quantum efficiency. Its radiance (brightness) is a measure of optical power radiated into unit solid angle per unit area of the emitting surface. The emission response time is the time delay between application of a current pulse and onset of optical emission.

1.1 LED structure

To achieve a high radiance and high quantum efficiency, the LED structure must provide a means of confining the charge carriers and the stimulated emission to the active region of PN junction where radiative recombination takes place. Carrier confinement is used to achieve a high level of radiative recombination in the active region of the device, which yields high quantum efficiency. Optical confinement is of importance for preventing absorption of the emitted radiation by material surrounding the PN junction.

The most effective structure for achieving carrier and optical confinement is double hetero-structure device as shown in Fig.2.1 because of the two different alloy layers on each side of the active region.

Metal Contacts	N-type GaAs subtrate	N-type GaAlAs Light and Carrier Confinement	N-type GaAlAs Recombination Region	P-type GaAlAs Light and Carrier Confinement	P-type GaAs subtrate	Metal Contacts

The two basic LED configurations used for fiber optics are:

1) Surface Emitters LED: In the surface emitter the plane of the active light region is oriented perpendicularly to the axis of the fiber, as shown in Fig.2.2. In this configuration 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 circular active area in practical surface emitters is normally 50µm in diameter and up to 25µm thick. The emission pattern essentially isotropic with 120^0 half power beam width. In this pattern source is equally bright when viewed from any direction, but power decreases as cos θ , where θ is the angle between the viewing direction and normal to the surface. Thus power is down to 50 percent of its peak when $\theta=60^0$, so that the total half power beam width is 120^0 .

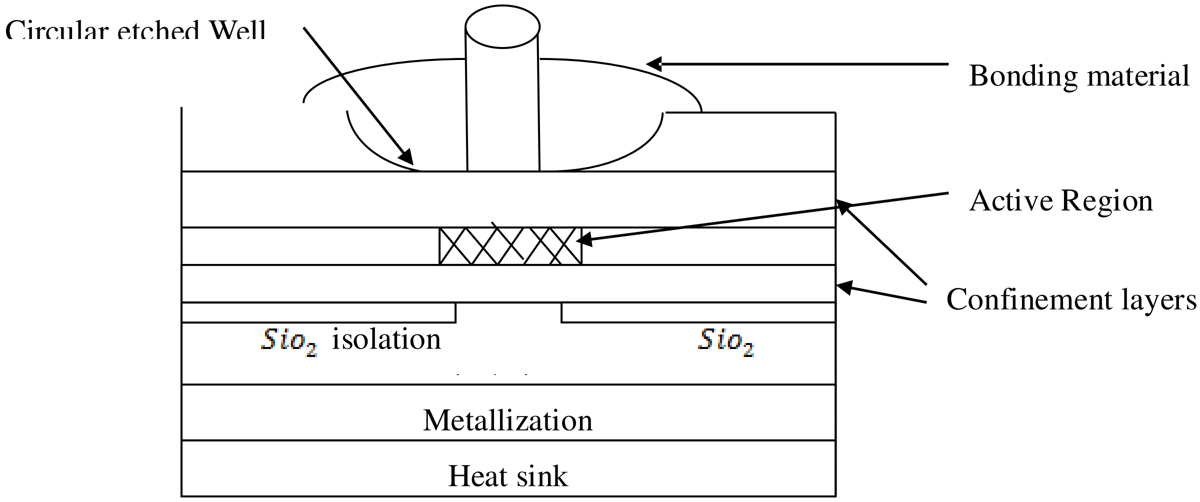

Fig. 2.2 Structure of Surface emitter LED

2) Edge Emitter depicted in Fig.2.3 consist of an active junction region, which is the source of 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 the surrounding material. This structure forms a waveguide channel that directs the optical radiation towards the fiber core. To match the typical core diameters, the contact strips are 50 to 70µm wide. Length of the active regions usually ranges from 100 to 150µm. The emission pattern of edge emitter is more directional than that of surface emitter.

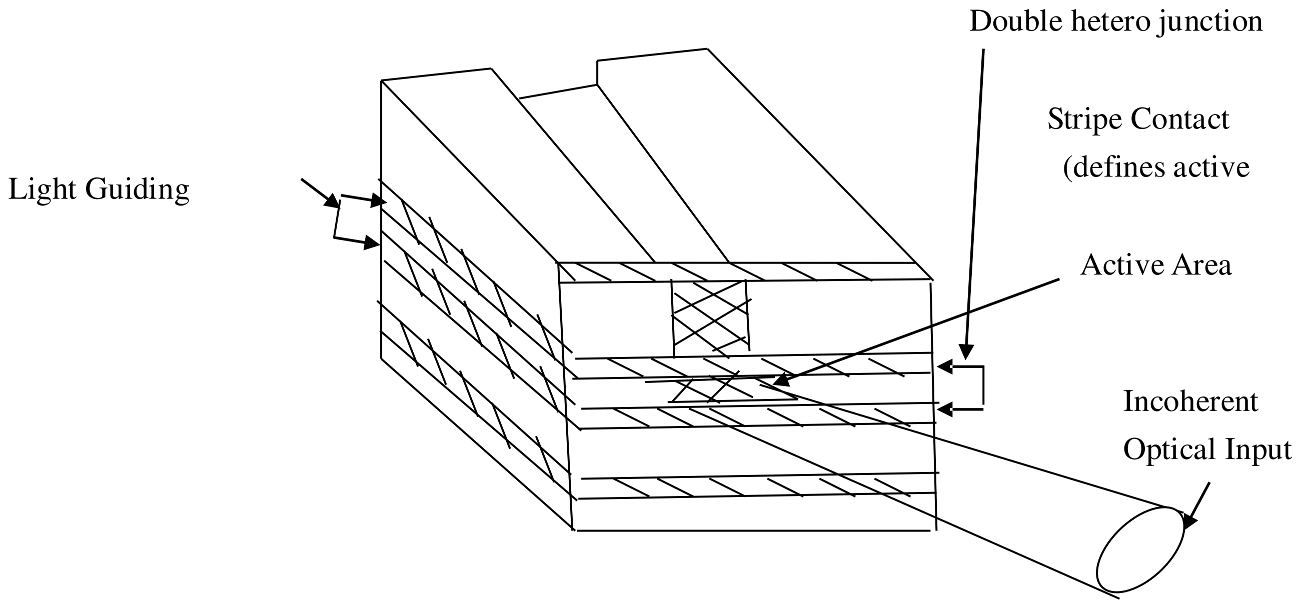

Fig. 2.3 Structure of Edge emitter LED

2.2 Light Source materials

Semiconductor material that is used for the active layer of an optical source must have direct band gap. Only in direct band gap material is the radiative recombination sufficiently high to produce a adequate level of optical emission. Although none of the normal single element semiconductors are direct band-gap materials, many binary compounds are. These are made from compounds of a group III (such as Al, Ga or In) and a group V element (such as P, As or Sb). At longer wavelengths the quaternary alloy $Al_{1-x}Ga_xAs_yP_{1-y}$ is one of the primary material candidates.

2.3 LED Quantum Efficiency and Power

Internal Quantum Efficiency (IQE) is the fraction of electron-hole pairs that recombine radiatively. If Radiative recombination rate per unit volume is R_r the internal quantum efficiency η_{int} is the ratio of radiative recombination rate to the total recombination rate. (IQE - also termed Radiative Efficiency).

For exponential decay of excess carriers, the radiative recombination life time is $\tau_r=\frac{\Delta n}{R_r}$ and non radiative

recombination life time is $\tau_{nr}=\frac{\Delta n}{R_{nr}}$. Thus internal quantum efficiency $\eta_{int} = \frac{\tau}{\tau_r}$.Where

The bulk recombination lifetime is

$$\tau=\frac{\tau_r*\tau_{nr}}{\tau_r+\tau_{nr}}$$

Internal quantum efficiency of homo junction LED is 50% and that of double hetero-junction structure LED is 60-80%. If the current injected into the LED is I then the total number of recombinations per second is

$R_r + R_{nr} = \frac{I}{q}$

From the definition of internal quantum efficiency,

$\eta_{int} = \frac{R_r}{\frac{I}{q}}$ Or $R_r = \frac{I}{q} * \eta_{int}$

R_r is the total number of photons generated per second and each photon has energy hν then optical power generated internally to the LED is

$$P_{\rm int} = \eta_{\rm int} \frac{hcI}{q\lambda}$$

Where, I=current, c=velocity of light, λ=wavelength of emitted light, q=electron charge

Q.1 A double hetero junction InGaAsP LED emitting at peak wavelength of 1310 nm has radiative and non-radiative recombination time 30 ns and 100 ns respectively. For the injected current of 40nA, find bulk recombination lifetime and internal power level yield.

Sol. The bulk recombination lifetime is

$$\tau = \frac{\tau_r * \tau_{nr}}{\tau_r + \tau_{nr}} = \frac{30 * 100}{30 + 100} = 23.1.ns$$

Where,

τ=Bulk recombination time

τ_r =Radiative recombination time

τ_{nr} = Non-Rdiative recombination time

$$\eta_{int} = \frac{\tau}{\tau_r} = \frac{23.1\, ns}{30 ns} = 0.77$$

η_{int} =Internal Efficiency

P_{int} =Internal Power

$$P_{int} = \eta_{int} \frac{hcI}{q\lambda} = 0.77 \frac{(6.62X10^{-34} J)(3X10^8 m/s)(0.04A)}{(1.602X10^{-19} C)(1.31X10^{-6} m)} = 2.92 \text{ mW}$$

External Quantum Efficiency (EQE)

External Efficiency (also termed Optical Efficiency) once the photons are produced within the semiconductor device, they have to escape from the crystal in order to produce a light-emitting effect. External efficiency is the proportion of photons generated in the active region that escape from the device. The ratio of the number of photons emitted from the LED to the number of electrons passing through the device - in other words, how efficiently the device coverts electrons to photons and allows them to escape.

$$\eta_{ext} \approx \frac{1}{n(n+1)^2}$$

From this it follows that optical power emitted from LED is

P=$\eta_{ext}\, P_{int}$ =$\frac{P_{int}}{n(n+1)^2}$

2.4 Modulation of LED

If the device current is modulated at a frequency w the output power of the device will vary as

P(w)=$P_0[1+(W\tau)^2]^{-1/2}$

P_0 is the power emitted to zero modulation frequency. Modulation bandwidth of LED can be defined as the point where electrical signal power designated P(w) has dropped to half its constant value resulting from the modulated portion of the optical signal. Thus is electrical 3dB point that is the frequency at which the output electrical power is reduced by 3dB with respect to input electrical power which corresponds electrical power attenuation of 6dB.

2.5 LASER Diode Modes and Threshold Conditions

For optical fiber communication systems requiring bandwidths greater than approximately 200Mhz the semiconductor injection LASER diode is preferred over the LED.LASER diodes have response time less then 1ns, can have spectral widths of 2nm or less and are capable of coupling several tens of mille watts of useful luminescent power into optical fibers with small cores and small mode field diameters.

Simulated emission in semiconductor LASERS arises from optical transitions between distributions of energy states in the valence and conduction bands. This differs from gas and solid-state LASERS, in which radiative transitions occur between discrete isolated or molecular levels. The radiation in the laser diode is generated within a Fabri-Parot cavity as in most types of lasers. However this cavity is much smaller being approximately 250 to 500μm, 5 to 15 μm wide and 0.1 to 0.2µm thick. These dimensions are commonly referred as the longitudinal, lateral and transverse dimensions of the cavity, respectively.

In the laser diode Fabry-Parot resonator a pair of flat, partially reflecting mirrors are directed towards each other to enclose the cavity. The mirror facets are constructed by making two parallel cleaves along natural cleavage planes of the semiconductor crystal. The purpose of these mirrors is to provide strong optical feedback in the longitudinal direction, thereby converting the device into an oscillator with a gain mechanism that compensates for optical losses in the cavity. The laser cavity can have many resonant frequencies for which the gain is sufficient to overcome the losses. The sides of the cavity are simply formed by roughening the edges of the device to reduce unwanted emissions in these directions.

In another laser diode type, commonly referred to as distributed feedback (DFB) laser the cleaved facet are not required for optical feedback. The fabrication of this device is similar to the Fabry-Parot types, except that lasing action is obtained from bragg reflectors (gratings) or periodic variations of the refractive index (called distributed feedback corrugations) which are incorporated into a multilayer structure along the length of the diode.

The optical radiations within the resonant cavity of a laser sets up a pattern of electric and magnetic field lines called modes of the cavity. These can conveniently be separated into two independent sets of transverse electric (TE) and transverse magnetic modes. The longitudinal modes are related to the length L of cavity and determine the principal structure of the frequency spectrum emitted optical radiation. Since L is much larger than the lasing wavelength of approximately 1µm, many longitudinal modes can exist.

Lateral modes lie in the plane of pn junction. These modes depend on side wall preparation and width of the cavity. And determine the shape of the lateral profile in the direction perpendicular to the plane of the PN junction.

Lasing is the condition at which light amplification becomes possible in the laser diode. The requirement of the lasing is that a population inversion be achieved. This condition can be understood by considering the fundamental relationship between the optical intensity I , the absorption coefficient α and the gain coefficient g in the fabry-parot cavity. The simulated emission rate into a given mode is proportional to the intensity of radiation in that mode. The radiation intensity at a photon energy hv varies onal prop distance z that it transverses along the lasing cavity according to the relationship.

$$I(2L)=I(0)R_1R_2\exp(2L[\Gamma_g(h\nu)-\alpha(h\nu)]) \qquad ....(2.1)$$

Where α is the absorption coefficient of the material in the optical path and Γ is the optical confinement factor (fraction of optical power in active layer).

Optical amplification of selected modes is provided by the feedback mechanism of the optical cavity. In the repeated passes between the partially reflecting mirrors, a portion of radiation associated with those modes having the highest optical gain coefficient is retained and further amplified during each trip through the cavity. Lasing occurs when gain of one Or several guided modes is sufficient to exceed the optical the optical loss during the roundtrip through the cavity, that is for z=2L.During the round only the fractions $R_1 and\ R_2$of the optical radiation are reflected from the two laser ends where $R_1 and\ R_2$ are mirror reflectivities. At the lasing threshold a steady state oscillations take place, and the magnitude of phase of the returned wave must be equal to those of the original wave. This gives condition

$$I(2L)=I(0) \qquad ...(2-2)$$

From the above equation condition for reaching lasing threshold optical gain $g_{th}$is the point at which gain g is greater than or equal to total loss α_t in the cavity.

$$\Gamma g_{th} \geq \alpha_t=\alpha+\frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right) \qquad ...(2\ -3)$$

The mode that satisfies Eq. (2-3) reaches the threshold first. Theoretically, at the onset of this condition, all additional energy introduced into the laser should augment the growth of this particular mode. A dramatic and sharply defined increase in the power output occurs at the lasing threshold.

2.3 Laser Diode rate Equations

The relationship between optical output power and diode drive currents can be determined by examining the rate equations that govern the interaction of photons and electrons in the active region. Total population is determined by carrier injection, spontaneous recombination and stimulated emission. For a *pn* junction with carrier confinement region of depth d, the rate equations

$$\frac{d\Phi}{dt} = Cn\Phi + R_{sp} + \frac{\Phi}{\tau_{ph}} \qquad ...(2\ -4)$$

=stimulated emission+ spontaneous emission+ photon loss

Which governs the number of photons Φ. And

$$\frac{dn}{dt} = \frac{J}{qd} - Cn\Phi - \frac{\Phi}{\tau_{sp}} \qquad ...(2\ -4)$$

=Injection +spontaneous recombination +stimulated emission

This governs the number of electrons n. Here, C is the coefficient describing the strength of the optical absorption and emission interaction, R_{sp} is the of spontaneopus emission into the lasing mode (which is much smaller than the total spontaneous emission rate). τ_{ph} is the photon life time, τ_{sp} is spontaneous recombination lifetime, and J is the injection current density.

2.4 External Quantum Efficiency

External quantum efficiency is defined as the number of photons emitted per radiave-electron hole pair recombination above threshold. Under the assumption that above threshold the gain coefficient the gain coefficient remains fixed at g_{th}, external quantum efficiency is given by.

$$\eta_{ext} = \eta_i \frac{(g_{th-\alpha})}{g_{th}} \qquad ----(2\text{-}5)$$

Here, η_i is the internal quantum efficiency.

2.5 Resonant Frequencies

To examine the resonant frequencies of the laser. The condition to be satisfied is $2\beta L = 2\pi m$ ---(2-6)

Where, m is an integer. Using $\beta = \frac{2\pi n}{\lambda}$ for the propagation constant. From Eq. (2-6).

$$m = \frac{L}{\lambda/2n} = \frac{2nLv}{\lambda} \qquad ---(2\text{-}7)$$

Where, c=νλ. This states that cavity resonates when a integer number m of half-wavelength spans in the region between the mirrors. Since in all lasers gain is the function of frequency there will be a range of frequencies for which the Eq. (2-7) holds. Each of these frequencies corresponds to a mode of oscillation of the laser. Depending on the laser structure, any number of frequencies can satisfy Eq. (2-7). Thus some lasers are single mode and some are multimode.

2.6 Laser Diode Structures and Radiation Patterns

Lasers can be made using one of the four fundamental structures. These are:

1)Buried Heterostructure(BH)laser: To make the buried hetero structure laser shown in Fig. 2.4, one etches a narrow mesa stripe (1-2μm wide) in double heterostucture material. The mesa is then embedded in high resistivity lattice matched n-type material. The mesa is then embedded in high resistivity lattice-matched n-type material with an appropriate band gap and low refractive index. This material is GaAlAs in 800-90nm lasers with GaAs active layer, and is InP for 1300-1600nm lasers with an InGaAsP active layer. This configuration thus strongly traps generated light in a lateral waveguide. A number of of this fundamental s been used to fabricate high performing laser diodes.

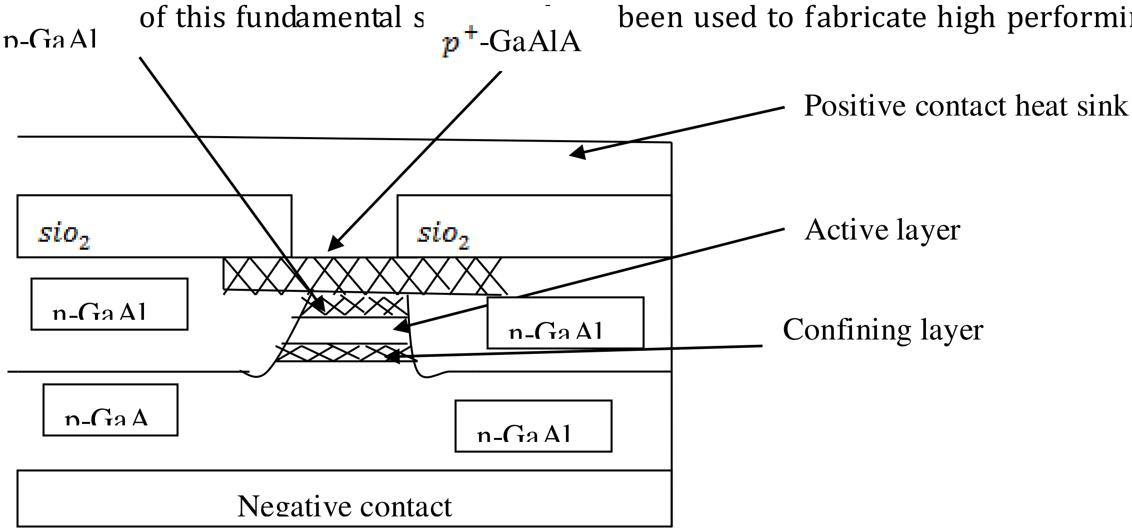

Fig.2.4 InGaAsP Buried Hetero structure laser diode

2) Selectively Diffused Construction: Here, a chemical dopant , such as zinc for GaAlAs lasers and cadmium for InGaAsP lasers, is diffused into the active layer immediately below the metallic contact stripe. The dopant changes the refractive index of the active layer in the form of the lateral waveguide channel. In the varying thickness structure shown in Fig. 2.5, a channel is etched into the substrate. Layers of crystal are then regrown into chnnel using liquid phase-epitaxy. This process fills in the depressions and partially dissolves the protrusions, thereby creating variations in the thickness of the active and confining layers.

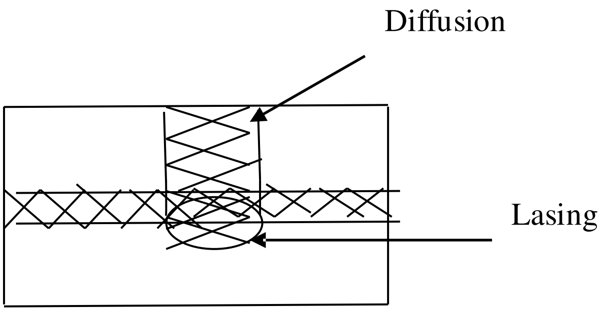

Fig.2.5 selectively diffused structure laser diode

2.7 Fiber Splicing:

Is used to create long optical links or in situations where optical connections and disconnections are needed. splicing techniques are as follows:

1)Fusion Splice: Is normally thermally bonding together prepared fiber ends as shown in Fig. 2.6. In this method fiber ends are first prealigned and butted together. This is done in a groove fiber holder, the butt joint is then heated with an electric arc or laser pulse so that fiber ends are momentarily melted and hence bonded together.

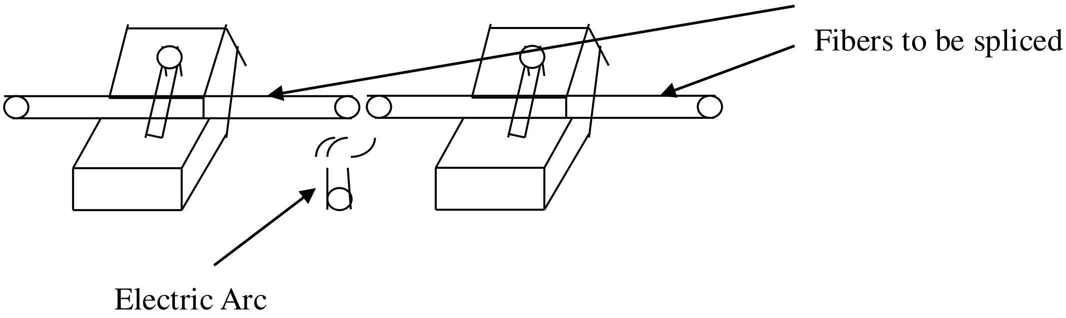

Fig. 2.6 Fusion Splicing of optical fibers.

2)V-Groove Splice: The prepared fiber ends are first butted together in a V shaped groove as shown in Fig. 2.7.They are then bonded together with an adhesive or held in a place by means of cover plate.

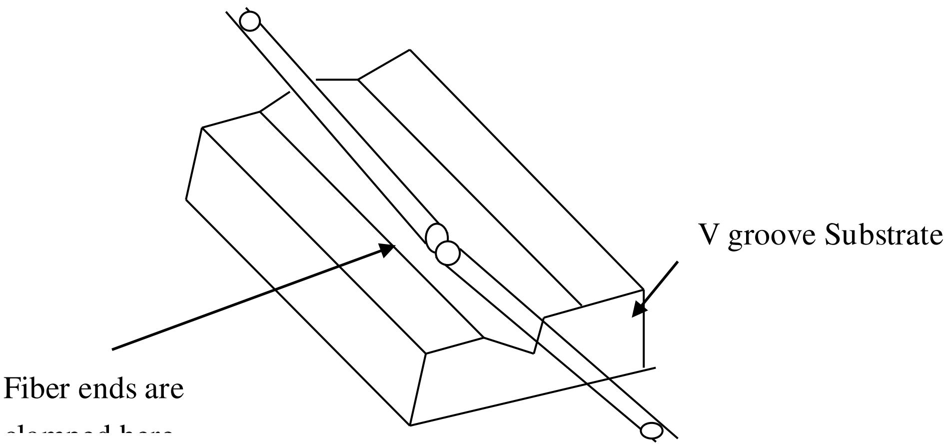

Fig. 2.7 V Groove splice.