UNIT-4

Introduction:-

* The signal tramitting through the fiber is degraded by two mechanisms.

(1) Attenuation

(2) Dispersion.

Both are important to determine the transmission characteristics of the fiber at operating wavelength.

Attenuation:-

* The most Important characteristics of the cable is the power loss. This power loss is called as Attenuation.

* It is defined as the ratio of the I/p (transmitted) optical power P_i into a fiber to the o/p (received) optical power P_o from the fiber.

$$A = 10 \log_{10} \left(\frac{P_i}{P_o} \right) \text{ in dB}$$

* by converted to numerical value

$$\frac{P_i}{P_o} = 10^{(dB/10)}$$

* Per unit length, $\alpha_{dB} L = 10 \log_{10} \frac{P_i}{P_o}$

α_{dB} - Signal Attenuation, L - fiber length.

* The basic Attenuation in a fiber are,

(1) Absorption
(2) Scattering
(3) Radiative losses of the optical fiber

* → Absorption is related to the fiber material.

→ Scattering is related to material and imperfect structure of the optical waveguide.

→ Radiation losses occur whenever an optical fiber undergoes a bend (both microscopic or macroscopic) of finite radius of curvature.

Absorption losses in Silical Glass Fibers

* The Absorption losses is related to the material composition and fabrication process of fiber.

* Absorption is caused by 3- different mechanism.

(1) Absorption by atomic defects in the glass composition

(2) Extrinsic absorption by impurity atoms in the glass material.

(3) Intrinsic absortion by the basic constituent atoms of the fiber material.

(1) Absorption by Atomic Defects:-

* It is represent imperfections of the atomic Structure of the fiber material.

* Such as missing molecules high-density clusters of atom groups, or oxygen defects in the glass structure.

* It is negligible compared with intrinsic and impurity absorption effects

(2) Intrinsic Absorption:-

* It is occurs when material is in absolutely pure state with no density variations, impurities and material is homogeneities

* The results from electronic absorption band in the ultra violet region and from atomic vibration bands in the near-infrared region.

* Ultra violet (uv) absorption decays exponentially with increasing wavelength (λ). The UV loss at any wavelength is expressed as

$$\alpha_{uv} = C e^{E/E_0} = \frac{154.2x}{46.6x+60} \times 10^{-2} e^{\left(\frac{4.63}{\lambda}\right)}$$

where, C & E_0 - empirical constant

E - photon energy

x - mole fraction of GeO_2

λ - operating wavelength

α_{uv} - Attenuation in dB/km.

*Atomic Vibration:-

* The loss in Infrared (IR) region (above 1.2 μm) is given by expression.

$$\alpha_{IR} = 7.81\times10^{11} \times \exp\left(\frac{-48.48}{\lambda}\right)$$

The expression is derived for $GeO_2 - SiO_2$ glass fiber.

(3) Extrinsic Absorption:-

* Occur due to Impurities in the fiber material.
  (1) Transition metal Impurities
  (2) OH Ions.

⇒ Transition metal Impurities:-

* Iron, Cobalt, chromium, copper and Nickel- metal Impurities
* producing losses from 1 to 10 dB/km.
* Reduced by glass refining techiques.

⇒ OH (water) Ions Impurities:-

* These OH impurity results from the oxyhydrogen flame used for the hydrolysis reaction of the $SiCl_4$, $GeCl_4$ and $POCl_3$.
* Absorption reduced by reducing water content in the fiber around one ppb (Parts per billion).
* In single mode fiber have nominal Attenuations of,
  - 0.5 dB/km in 1300 nm window
  - 0.3 dB/km in 1550 nm window.

Scattering Losses:-

Scattering Losses in glass arise due to following factors,

(1) Microscopic variations in the material density

(2) Compositional fluctuations

(3) ~~St~~ Structural in homogeneities and

(4) Structual defects occurring during fiber fabrication.

(5) As glass is composed by randomly connected network of molecules and several oxides (~~ex~~; SiO_2, GeO_2 and P_2O_5)). there are the major cause of compositional structure fluctuation.

* Types of scattering losses.

(1) Linear Scattering loss.

(a) Rayleight Scattering

(b) Mie Scattering

(2) Non-Linear Scattering loss

(a) Stimulated Brillouin Scattering

(b) Stimulated Raman Scattering.

Linear Scattering Losses

Linear scattering ~~losses~~ transfers Linearly the optical Power in one propagation mode to different mode. These losses will occurs in the leaky mode or radiation mode.

It will ~~can~~not contine to propagate within the core of fiber and is radiated out from the fiber.

All linear processes there is no change of freq. on scattering.

(a) Rayleigh Scattering :

This loss occurs in the ultra violet region. It tail extends upto Infrared region.

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F$$

where, γ_R - rayleigh scattering coeffi

λ - optical wavelength

n - refractive index of the medium

p - average photoelastic coeffi.

β_c - Isothermal compressibility at a Fictive temp

K - Boltzmann's Constatn

T_F - Fictive temp.

* Fictive Temp:-

It is defined as the temp at which the glass can reach a state of thermal equilibrium and closely related to the anneal temp

(2) Mie Scattering:-

* When the scattering inhomogeneity size is greater than $\lambda/10$, scattered intensity, which has an angular dependence can be verly large.

* The scattered created by such inhomogeneities is mainly is the forward direction and is called Mie-Scattering.

* Inhomogeneities may be reduced by
(1) removing Imperfections due to the glass manufacturing process.
(2) Carefully controlled extrusion and coating of the fiber
(3) Increasing the fiber guidance by increasing the relative refractive Index difference.

Non-Linear Scattering Losses:-

* It causes the optical power from one mode to be transferred in either forward or backward direction to the same or other modes, at a different freq.

* It depends on optical power density in the fiber. Hence losses occur above threshold power level.

(1) Stimulated Brillouin scattering (SBS)

* SBS may be regarded as the modulation of light through thermal molecular vibration within the fiber.

* freq ~~shi~~ shift is maxi. in backward direction and reducing to zero in forward direction making SBS a mainly in backward process.

Threshold optical power is, → $P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB}\, \nu$ (watts)

where, d - fiber core diameter (micrometer)

λ - operating wavelength (micrometer)

α_{dB} - fiber Attenuation in decible/km

ν - source bandwidth in GHz.

(2) Stimulated Raman Scattering :- (SRS)

* It is stimulated with a high freq optical Phonon is generated in the scattering process.

* occur in both Forward and backwar direction in an optical Fiber.

$$P_R = 5.9 \times 10^{-2} d^2 \lambda\, \alpha_{dB} \quad \text{(watts)}$$

* Non-Linear scattering may be avoided by use of a suitable optical signal level (i.e below the threshold optical power).

Fiber Bend Loss:-

* Radiative losses occur whenever ~~an~~ an optical fiber undergoes a bend of finite radius of Curvature.

* Two types:

(1) Macroscopic bending losses

(2) Microscopic bending losses

Macroscopic Bending losses:-

It occurs when the radius of Curvature that are large compared with the fiber diameter.

Example:- when a fiber cable turns a corner.

$$\alpha_r = C_1 \exp(-C_2 R)$$

where, R - Radius of Curvature of the fiber band

C_1, C_2 - Constants which are independent of R

α_r - radiation Attenuation co-efficient.

Macroscopic losses Reduced by:

(1) Desiging fibers with large relative refractive index difference

(2) operating at the Shortest wavelength possible.

(2) Microscopic Bending losses

Microscopic Bending due to small-scale fluctuations in the radius of curvature of the fiber axis. This situation arises when the fibers are is corporated into cables.

Microscopic losses can be minimized by introducting compressible jacket over the fiber.

Core & Cladding losses:-

The core and cladding have different refractive indices b/w they are having different composition. Therefore core and cladding have different attenuation co-efficients, denoted by α_1 & α_2.

Dispersion:-

* Dispersion of the transmitted optical signal causes distortion for both digital and analog transmission along optical fibers.

* The term dispersion refers to spreading of light pulse as it propagates through fiber.

* It introduces Intersymbol Interference (ISI). It limits the Information carrying capacity of fiber

* Types : (1) Intramodal Dispersion

  (a) Material (or) Chromatic Dispersion

  (b) Waveguide Dispersion

  (c) Group velocity Dispersion (or) Model Dispersion.

  (2) Intermodal Dispersion.

* Group velocity:- is the speed at which energy in a particulal mode travel along the fiber.

Intramodal Dispersion:-

(a) Material Dispersion:-

* Intramodal dispersion is pulse spreading that occurs within a single mode.

* Material Dispersion, which arises from the variation of the refractive index of the core material as a function of wavelength.

* Pulse spreading occurs even when different wavelengths follows the same path.

* Material dispersion parameter (M).

$$M = \frac{1}{L}\frac{d\tau_m}{d\lambda} = \frac{L\lambda}{Lc}\left|\frac{d^2 n_1}{d\lambda^2}\right| = \frac{\lambda}{c}\left|\frac{d^2 n_1}{d\lambda^2}\right|$$

when, τ_m - Pulse delay $= \frac{L}{c}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right)$

(b) Waveguide Dispersion:-

* It occurs because a single-mode fibers confines only about 80% of the optical power to the core.

* Dispersion thus arises, since the 20% of the light propagating in the cladding travels faster that the light confined to the core.

* The amount of waveguide dispersion depends on the fiber design.

(c) Group velocity Dispersion:-

* Intramodal dispersion is pulse spreading that occurs within a single mode. The spreading arises from the finite spectral emission width of an optical source.

Intermodal Dispersion

Intermodal dispersion arises due to the variation in the group delay for each individual mode of a single freq. when the group velocity of different mode varies.

* This distortion is available in multimode fibers. This dispersion mechanisum creates the 3-type of fiber.

(1) Multimode Step Index fiber,

(2) Multimode Graded Index fiber

(3) Model Noise.

Model Noise:-

The speckle patterns observed in multimode fiber as fluctuations which have characteristic times longer than the resolution time of the detector and is known as model (or) speckle noise.

Light-Emitting Diodes (LEDs)

- Light sources are hetrojunction- structured semiconductor laser diode and Light-emitting diodes.

- Hetrojunction: It consists of two adjoining semiconductor materials with different band-gap energies.

- Active or recombination region: Laser/LED are a pn junction semiconductor materials, electron and holes are injected into p and n region, respectively. These injected minority carriers can recombined either radiatively, in which case a photon of energy *hv* is emitted is known as the active region.

- LED:
  1. Optical output is inchoherent
  2. No optical resonant cavity
  3. Output radiation has broad spectral width
  4. No spatial and temporal coherence.

Laser:

1. Optical output is coherent
2. Optical energy from optical resonant cavity
3. Highly monochromatic
4. It has spatial and temporal coherence.

- For photonic communications requiring data rate 100-200 Mb/s with multimode fiber with tens of microwatts, LEDs are usually the best choice.
- LED emitter power is proportional to the diode current
- No thermal or optical stabilization circuits are needed.
- Principle of operation: LED must have,
  - High radiance output or brightness: are required to couple sufficiently high optical power levels into a fiber.
  - Fast emission response time: reduced time delay
  - High quantum efficiency: it is related to the fraction of the electron-hole pairs that recombine radiatively.

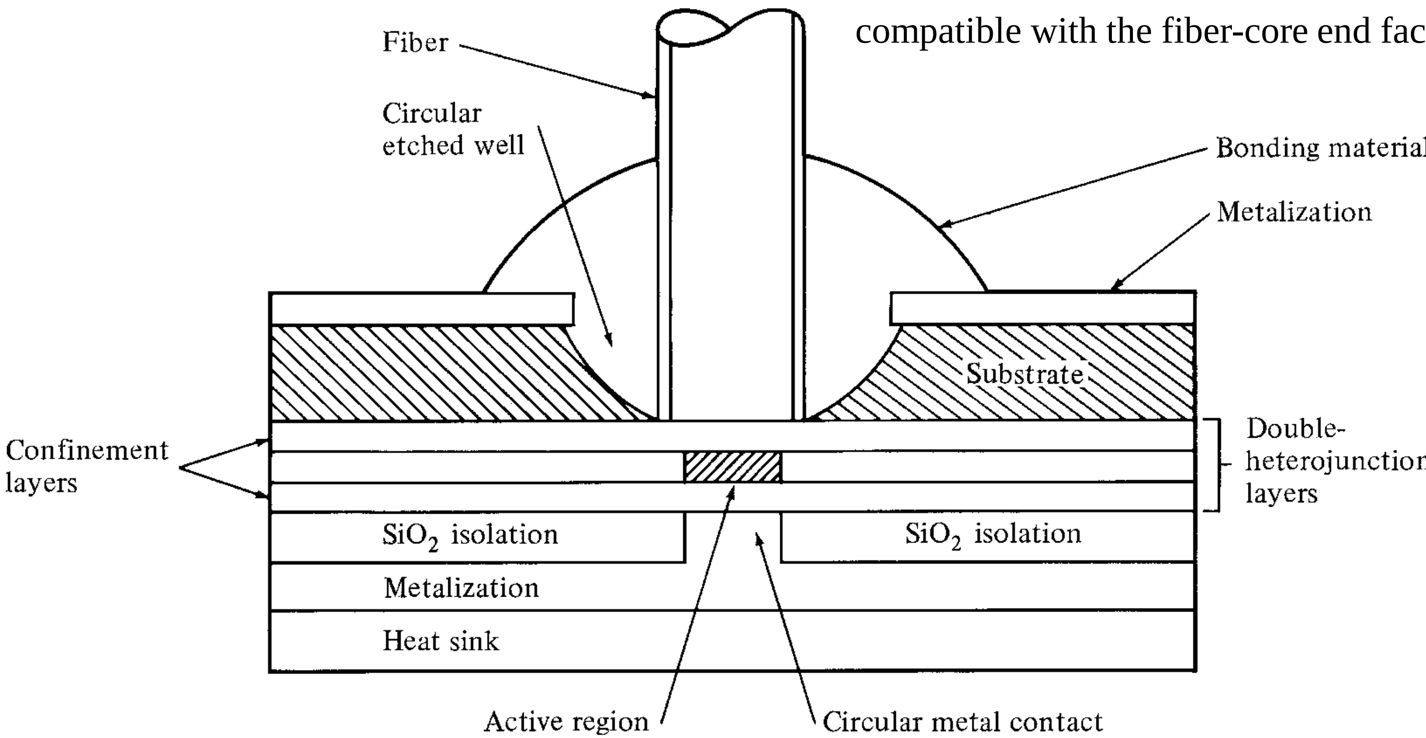
- LED provide high radiance and high quantum efficiency. It must be achieved by using optical and carrier confinement.
- Carrier confinement: is used to achieve a high level of radiative recombination in the active region of the device.
- Optical confinement: is used for preventing absorption of the emitted radiation by the material surrounding the pn junction.
- LED configurations being used in photonic communications:

  1- Surface Emitters (Front Emitters)

  2- Edge Emitters

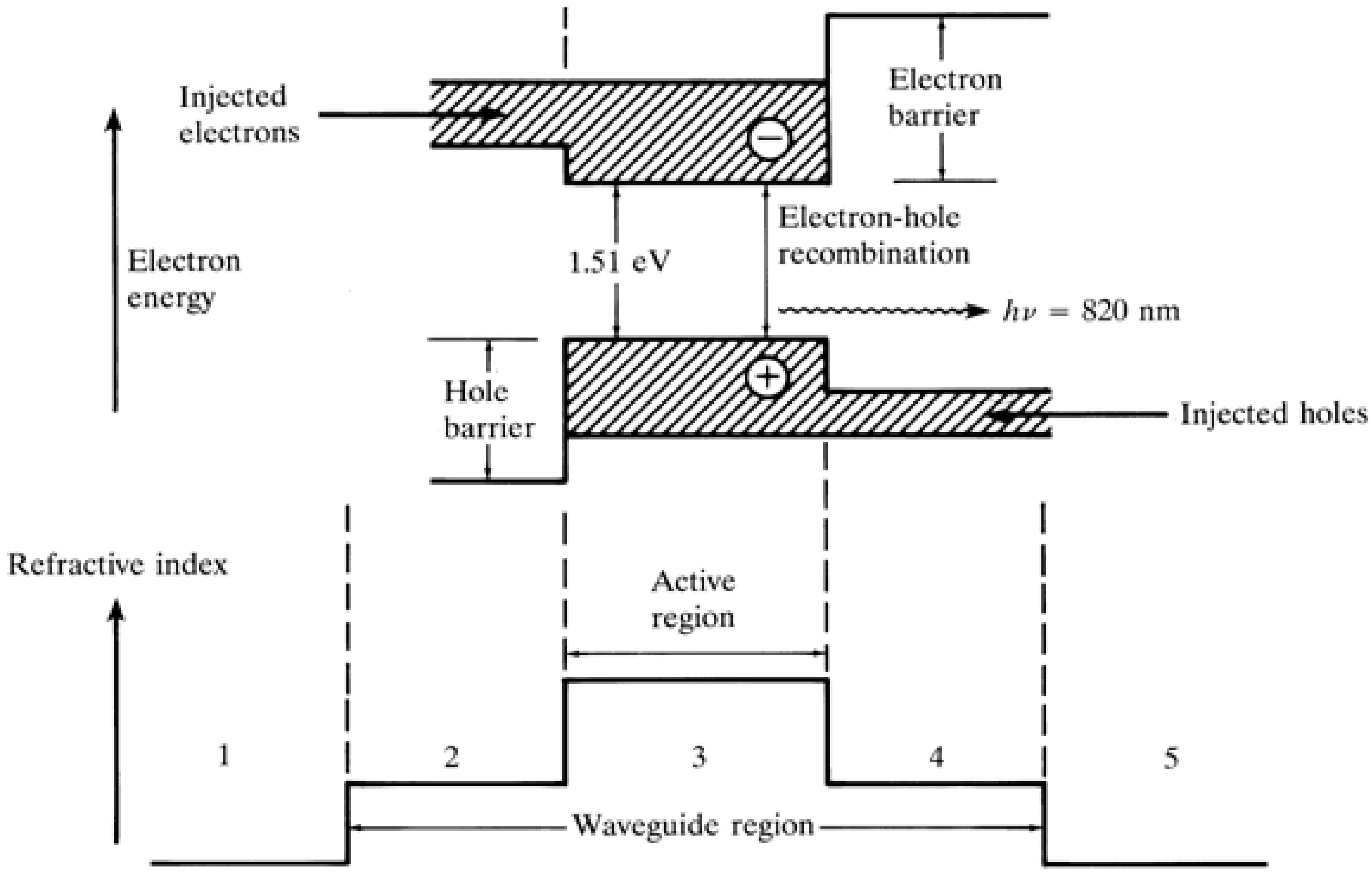
Surface-Emitting LED

Schematic of high-radiance surface-emitting LED. The active region is limitted to a circular cross section that has an area compatible with the fiber-core end face.



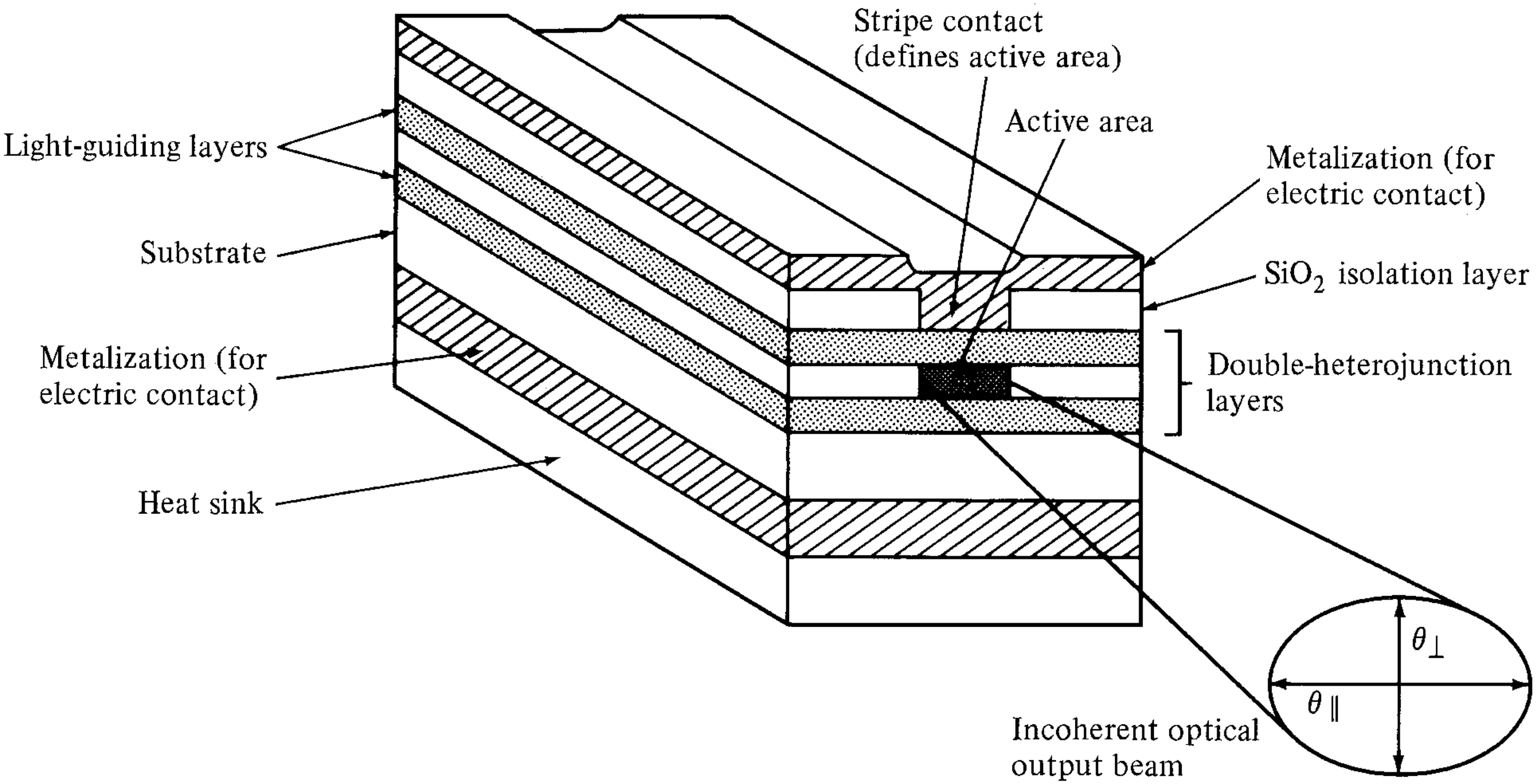
- Where data rate is excess of 100 Mbps are required.
- Active light emitting region is perpendicular to the fiber axis

- A well is etched in a substrate(GaAs) to avoid the heavy absorption of the emitted radiation and the fiber is then connected to accept the emitted light.
- The circular active area in practical surface emitter is nominally 50 micrometer in diameter and upto 2.5micrometer thick. The emission pattern is isotropic with a 120 degree half power beam width.
- Isotropic pattern from a surface emitter is called Lambertain pattern. In this pattern, source is equally bright when viewed from any direction.



Energy band Diagram in the active region and variation in refractive index

Edge-Emitting LED



Schematic of an edge-emitting double heterojunction LED. The output beam is lambertian in the plane of junction and highly directional perpendicular to pn junction. They have high quantum efficiency & fast response.

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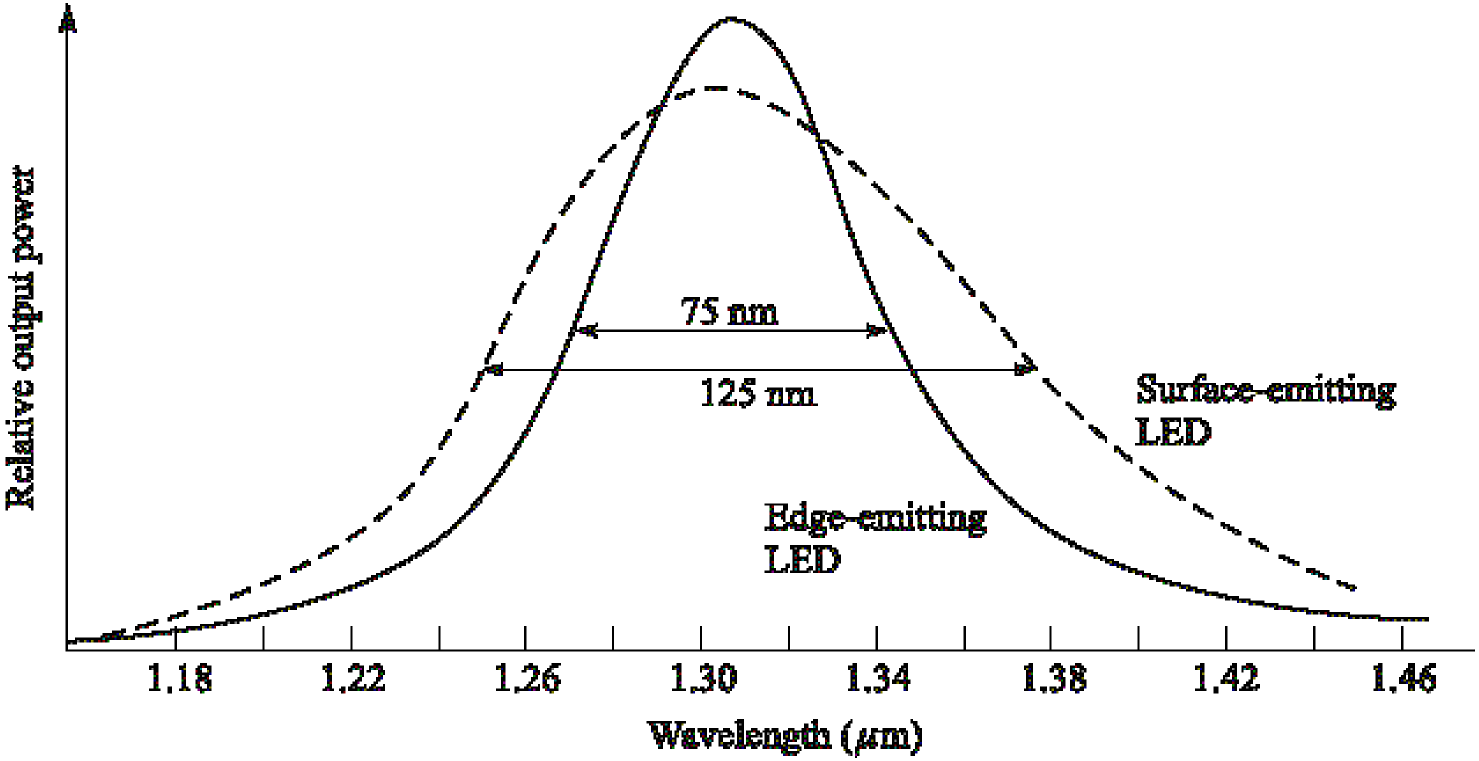
- Edge emitter LED emitts a more directional light pattern than surface emitting LEDs.
- Light collect from edge of the LED. Reduced absorption losses.
- Light produced in active layer and spread into transparent guiding layer, reduced self absorption in the active layer.
- Guiding layer refractive indices is less than active layer but higher than outer material.
- Suitable for 50-100 micrometer diameter fiber cable.

Spectral width of LED types



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Rate equations, Quantum Efficiency & Power of LEDs

- When there is no external carrier injection, the excess carrier density decays exponentially due to electron-hole recombination.

$$n(t) = n_0 e^{-t/\tau} \qquad [4\text{-}4]$$

- n is the excess carrier density,

n_0 : initial injected excess electron density

τ : carrier lifetime.

- Bulk recombination rate R:

$$R = -\frac{dn}{dt} = \frac{n}{\tau} \qquad [4\text{-}5]$$

- Bulk recombination rate (R)=Radiative recombination rate + nonradiative recombination rate

$$\text{bulk recombination rate } (R = 1/\tau) =$$

$$\text{radiative recombination rate } (R_r = 1/\tau_{\mathrm{r}}) + \text{nonradiative recombination rate} (R_{nr} = 1/\tau_{nr})$$

With an external supplied current density of J the rate equation for the electron-hole recombination is:

$$\frac{dn(t)}{dt} = \frac{J}{qd} - \frac{n}{\tau} \qquad [4\text{-}6]$$

q : charge of the electron; d : thickness of recombination region

In equilibrium condition: *dn/dt=0*

$$n = \frac{J\tau}{qd} \qquad [4\text{-}7]$$

Internal Quantum Efficiency & Optical Power

$$\eta_{\text{int}} = \frac{R_r}{R_r + R_{nr}} = \frac{\tau_{nr}}{\tau_r + \tau_{nr}} = \frac{\tau}{\tau_r} \qquad [4\text{-}8]$$

η_{int} : internal quantum efficiency in the active region

Optical power generated internally in the active region in the LED is:

$$P_{\text{int}} = \eta_{\text{int}} \frac{I}{q} h\nu = \eta_{\text{int}} \frac{hcI}{q\lambda} \qquad [4\text{-}9]$$

P_{int} : Internal optical power,

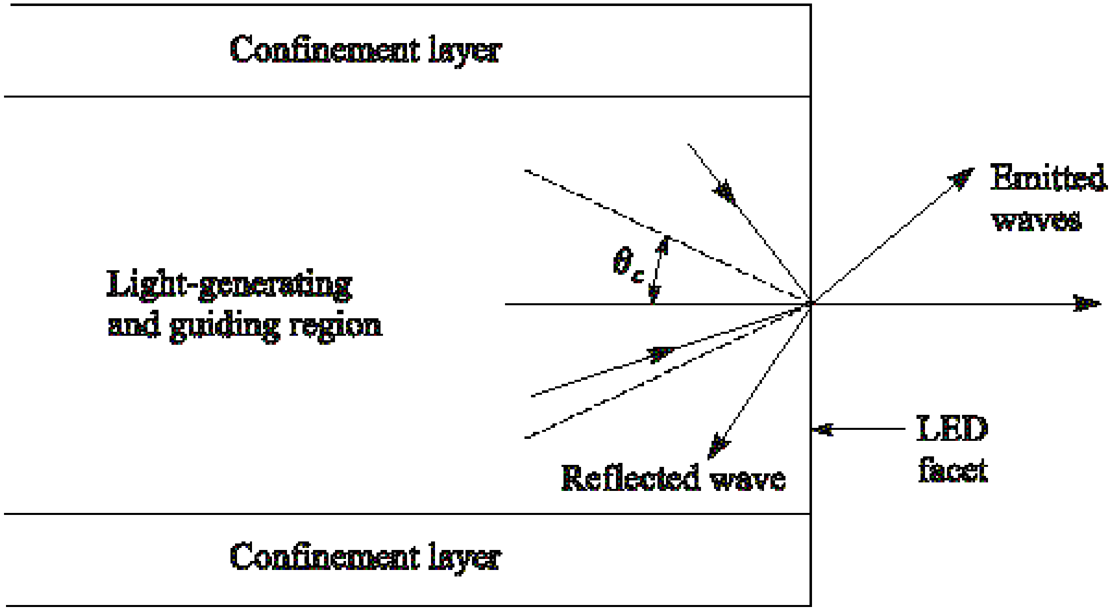
I : Injected current to active region

External Quantum Eficiency

$$\eta_{ext} = \frac{\#\text{ of photons emitted from LED}}{\#\text{ of LED internally generated photons}} \qquad [4\text{-}10]$$

- In order to calculate the external quantum efficiency, we need to consider the reflection effects at the surface of the LED.

- If we consider the LED structure as a simple 2D slab waveguide, only light falling within a cone defined by critical angle will be emitted from an LED.



$$\eta_{\text{ext}} = \frac{1}{4\pi}\int_0^{\phi_c} T(\phi)(2\pi\sin\phi)\,d\phi \qquad [4\text{-}11]$$

$$T(\phi): \text{Fresnel Transmission Coefficient} \approx T(0) = \frac{4n_1 n_2}{(n_1+n_2)^2} \qquad [4\text{-}12]$$

$$\text{If } n_2 = 1 \Rightarrow \eta_{\text{ext}} \approx \frac{1}{n_1(n_1+1)^2} \qquad [4\text{-}13]$$

$$\boxed{\text{LED emitted optical powr}, P = \eta_{\text{ext}} P_{\text{int}} \approx \frac{P_{\text{int}}}{n_1(n_1+1)^2}} \qquad [4\text{-}14]$$

Modulation of LED

- The frequency response of an LED depends on:

  1- Doping level in the active region

  2- Injected carrier lifetime in the recombination region, τ_i .

  3- Parasitic capacitance of the LED

- If the drive current of an LED is modulated at a frequency of ω the output optical power of the device will vary as:

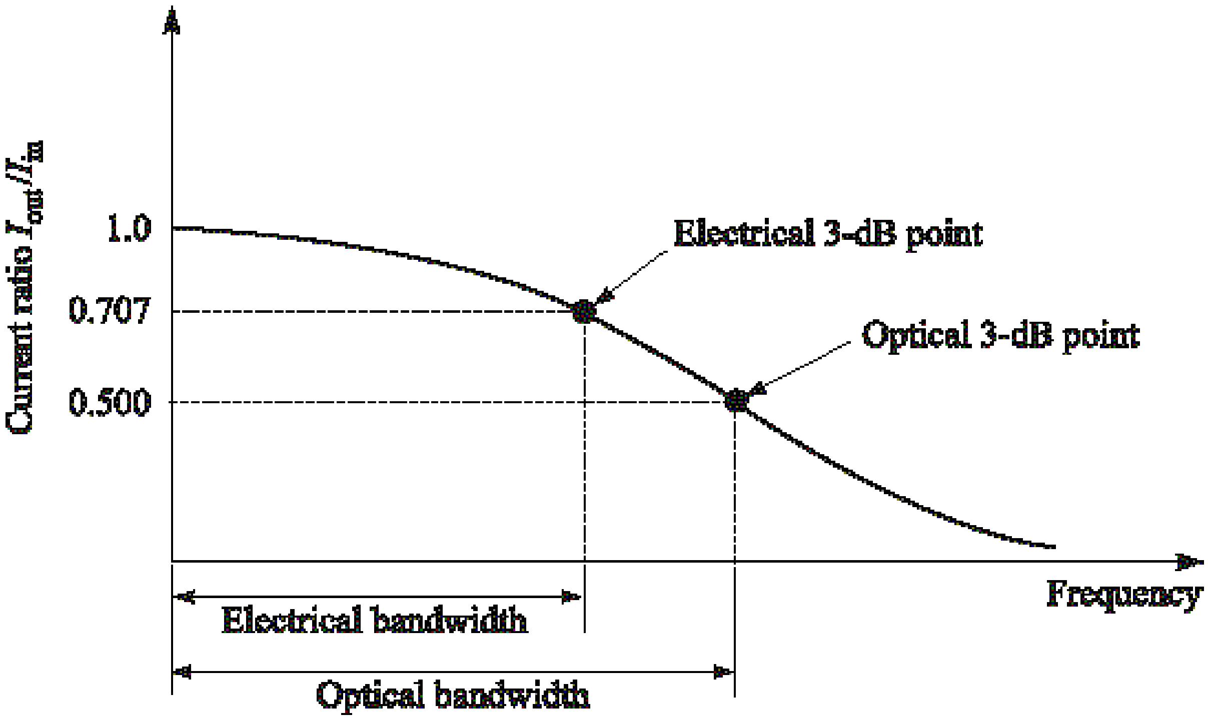
$$P(\omega) = \frac{P_0}{\sqrt{1+(\omega\tau_i)^2}} \qquad [4\text{-}15]$$

- Electrical current is directly proportional to the optical power, thus we can define electrical bandwidth and optical bandwidth, separately.

$$\text{Electrical BW} = 10\log\left[\frac{p(\omega)}{p(0)}\right] = 20\log\left[\frac{I(\omega)}{I(0)}\right] \qquad [4\text{-}16]$$

p : electrical power, I : electrical current

$$\text{Optical BW} = 10\log\left[\frac{P(\omega)}{P(0)}\right] = 10\log\left[\frac{I(\omega)}{I(0)}\right] \qquad [4\text{-}17]$$



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LASER

(Light Amplification by the Stimulated Emission of Radiation)

- Laser is an optical oscillator. It comprises a resonant optical amplifier whose output is fed back into its input with matching phase. Any oscillator contains:

  1- An amplifier with a gain-saturated mechanism

  2- A feedback system

  3- A frequency selection mechanism

  4- An output coupling scheme
- In laser the amplifier is the pumped active medium, such as biased semiconductor region
- feedback can be obtained by placing active medium in an optical resonator, such as Fabry-Perot structure, two mirrors separated by a prescribed distance.
- Frequency selection is achieved by resonant amplifier and by the resonators, which admits certain modes.
- Output coupling is accomplished by making one of the resonator mirrors partially transmitting.

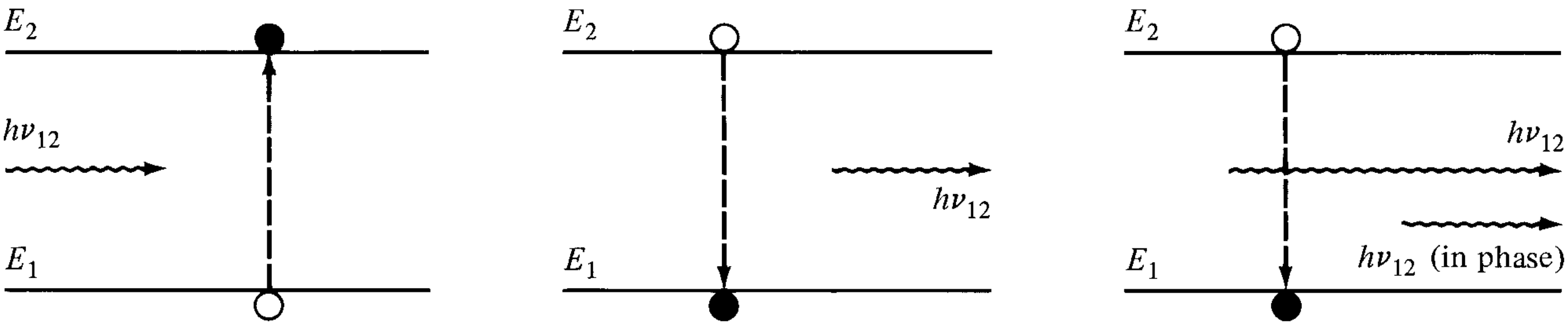
Pumped active medium

- Three main process for laser action:

1- Photon absorption

2- Spontaneous emission

3- Stimulated emission



(a) Absorption (b) Spontaneous emission (c) Stimulated emission

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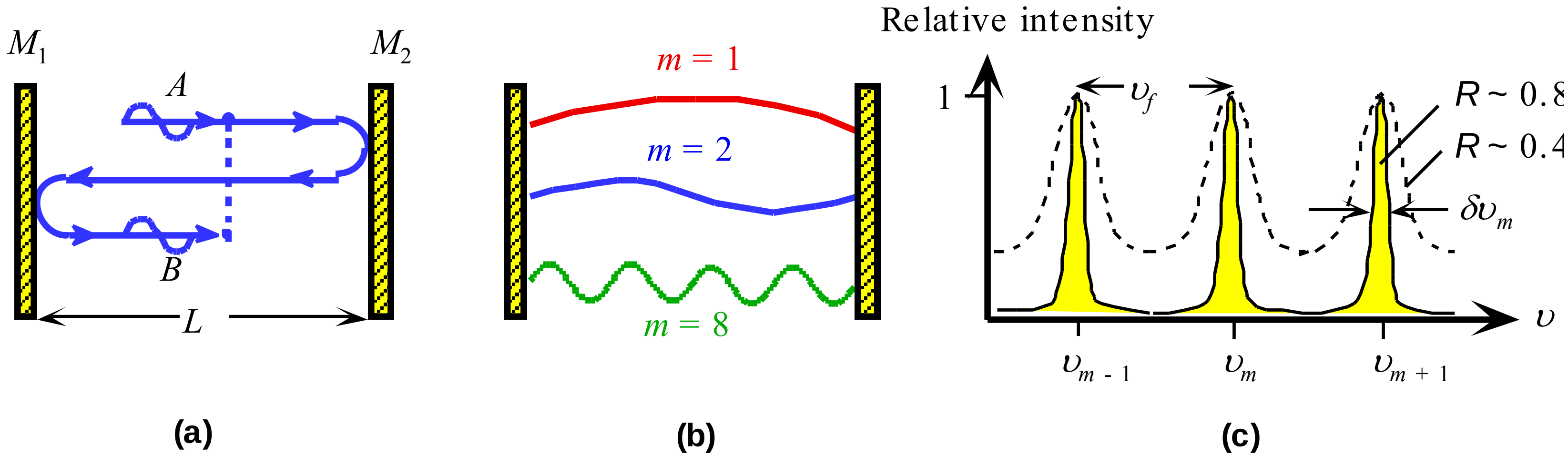
Lasing in a pumped active medium

- In thermal equilibrium the stimulated emission is essentially negligible, since the density of electrons in the excited state is very small, and optical emission is mainly because of the spontaneous emission. Stimulated emission will exceed absorption only if the population of the excited states is greater than that of the ground state. This condition is known as **Population Inversion**. Population inversion is achieved by various **pumping** techniques.

- In a semiconductor laser, population inversion is accomplished by injecting electrons into the material to fill the lower energy states of the conduction band.

Fabry-Perot Resonator



$$\text{Resonant modes} : kL = m\pi \quad m = 1,2,3,..$$

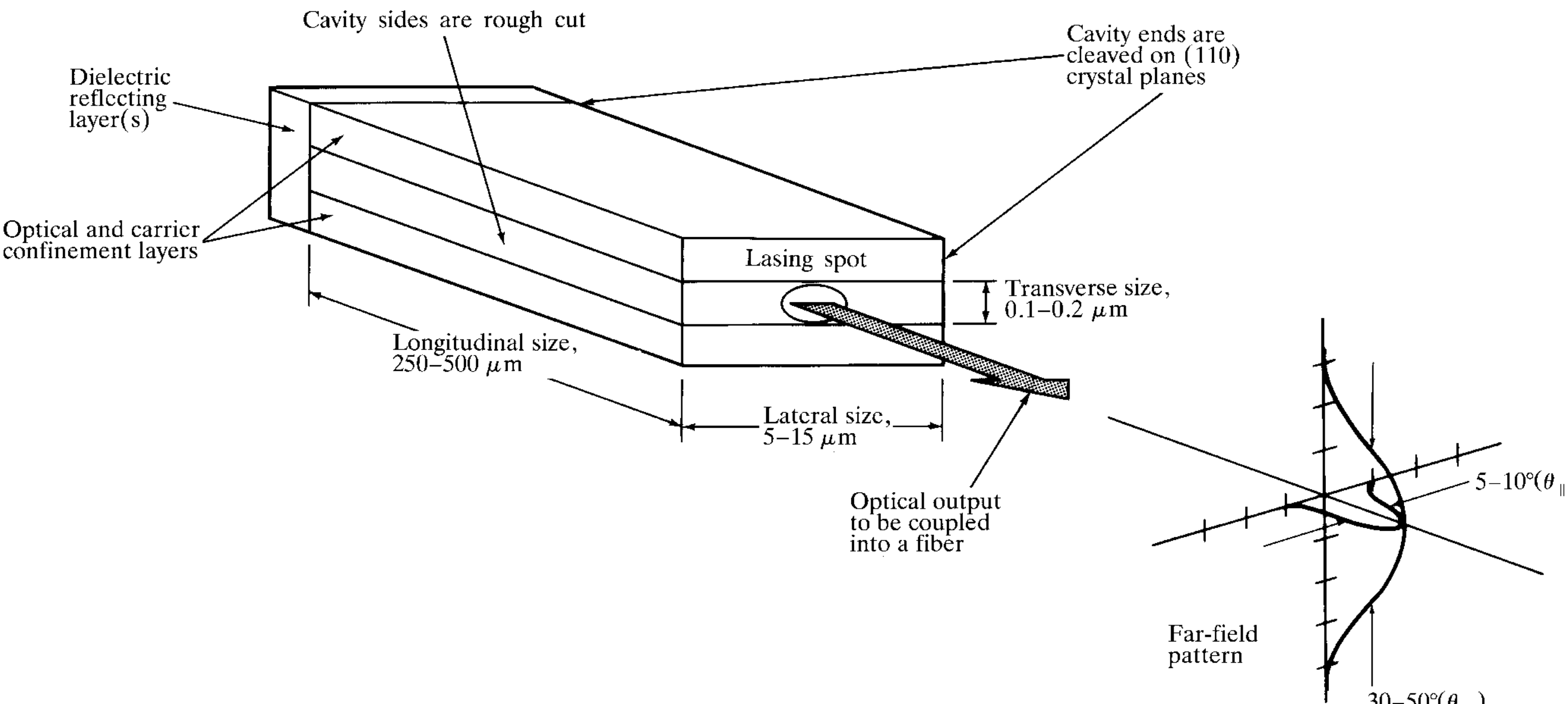
Schematic illustration of the Fabry-Perot optical cavity and its properties. (a) Reflected waves interfere. (b) Only standing EM waves, *modes,* of certain wavelengths are allowed in the cavity. (c) Intensity vs. frequency for various modes. *R* is mirror reflectance and lower *R* means higher loss from the cavity.

$$I_{trans} = I_{inc} \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2(kL)} \qquad [4\text{-}18]$$

R: reflectance of the optical intensity, *k*: optical wavenumber

Laser Diode Modes and Threshold Condtions

- Laser diode is an improved LED, in the sense that uses stimulated emission in semiconductor from optical transitions between distribution energy states of the valence and conduction bands with optical resonator structure such as Fabry-Perot resonator with both optical and carrier confinements.



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Laser Diode Characteristics

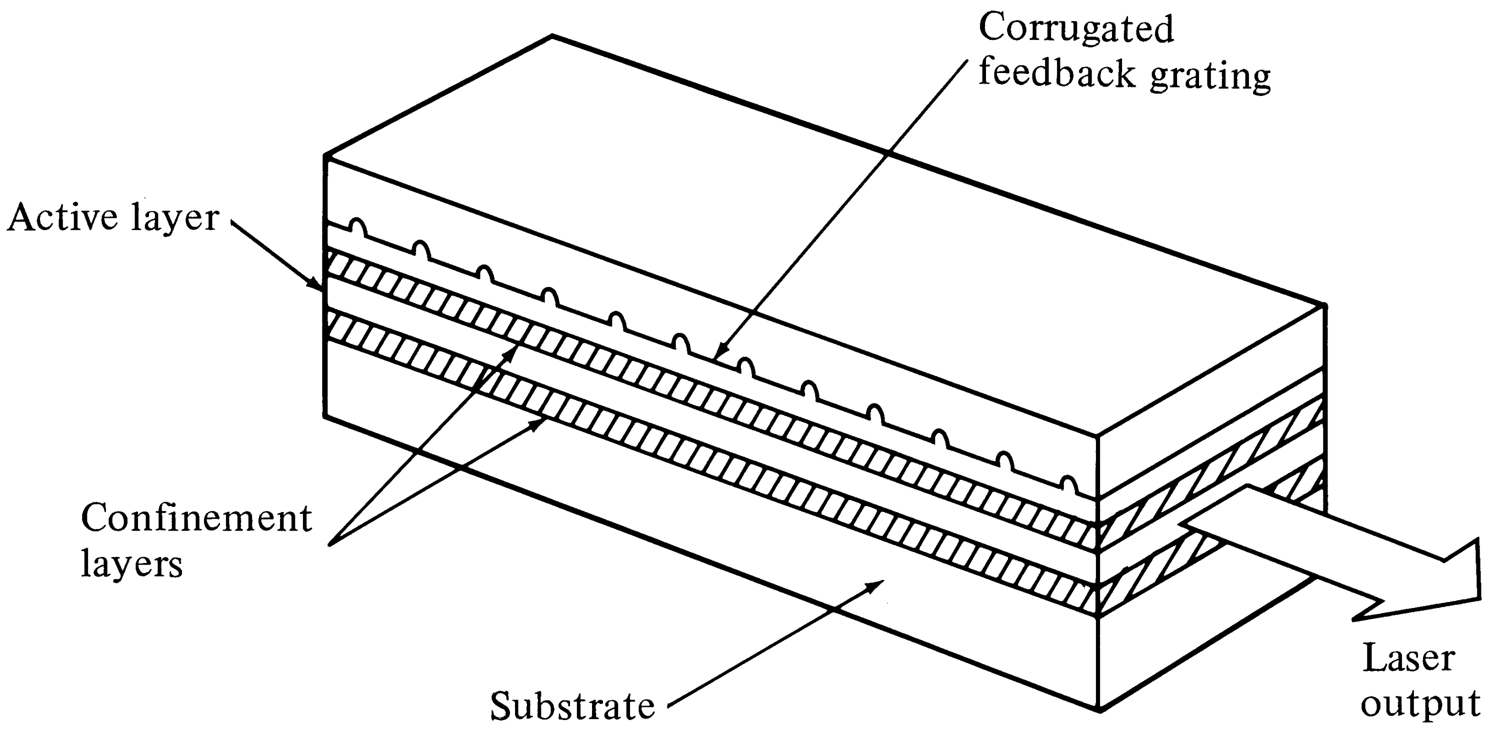
- Nanosecond & even picosecond response time (GHz BW)
- Spectral width of the order of nm or less
- High output power (tens of mW)
- Narrow beam (good coupling to single mode fibers)

- Laser diodes have three distinct radiation modes namely, longitudinal, lateral and transverse modes.

- In laser diodes, end mirrors provide strong optical feedback in longitudinal direction, so by roughening the edges and cleaving the facets, the radiation can be achieved in longitudinal direction rather than lateral direction.

DFB(Distributed FeedBack) Lasers

- In DFB lasers, the optical resonator structure is due to the incorporation of Bragg grating or periodic variations of the refractive index into multilayer structure along the length of the diode.



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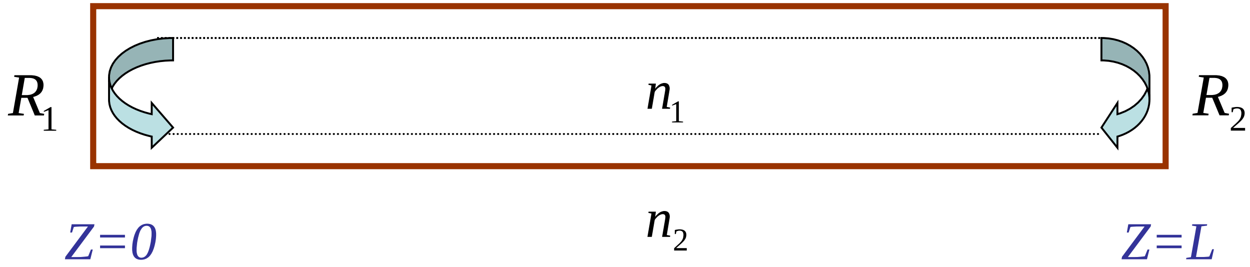
Laser Operation & Lasing Condition

- To determine the lasing condition and resonant frequencies, we should focus on the optical wave propagation along the longitudinal direction, *z*-axis. The optical field intensity, *I*, can be written as:

$$I(z,t) = I(z)e^{j(\omega t - \beta z)} \qquad [4\text{-}19]$$

- Lasing is the condition at which light amplification becomes possible by virtue of population inversion. Then, stimulated emission rate into a given EM mode is proportional to the intensity of the optical radiation in that mode. In this case, the loss and gain of the optical field in the optical path determine the lasing condition. The radiation intensity of a photon at energy $h\upsilon$ varies exponentially with a distance z amplified by factor *g*, and attenuated by factor $\overline{\alpha}$ according to the following relationship:

$$I(z) = I(0)\exp\left[\left(\Gamma g(h\upsilon) - \overline{\alpha}(h\upsilon)\right)z\right]$$ [4-20]



$$I(2L) = I(0)R_1R_2\exp\left[\left(\Gamma g(h\upsilon) - \overline{\alpha}(h\upsilon)\right)(2L)\right]$$ [4-21]

Γ : Optical confinement factor, g : gain coefficient

$\overline{\alpha}$: effective absorption coefficient, $R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$

Lasing Conditions:

$$\boxed{\begin{aligned} I(2L) &= I(0) \\ \exp(-j2\beta L) &= 1 \end{aligned}}$$ [4-22]

Threshold gain & current density

$$\Gamma g_{th} = \overline{\alpha} + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right) \qquad [4\text{-}23]$$

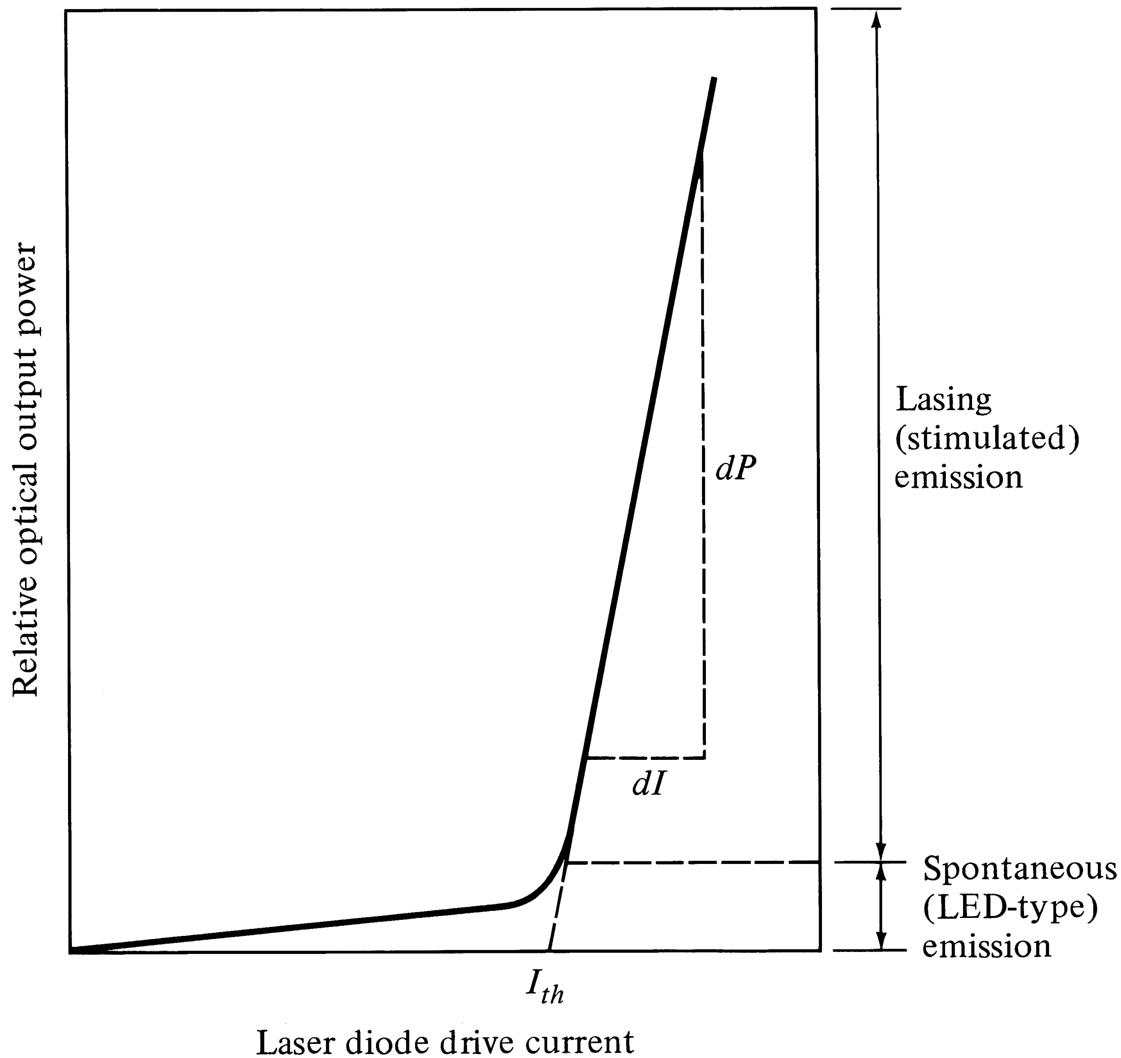
$$\text{Laser starts to "lase" iff} : g \geq g_{th}$$

For laser structure with strong carrier confinement, the threshold current Density for stimulated emission can be well approximated by:

$$g_{th} = \beta J_{th} \qquad [4\text{-}24]$$

$$\beta : \text{constant depends on specific device construction}$$

Optical output vs. drive current



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Laser Diode Rate equations

- Rate equations relate the optical output power, or # of photons per unit volume, Φ , to the diode drive current or # of injected electrons per unit volume, *n.* For active (carrier confinement) region of depth *d*, the rate equations are:

$$\frac{d\Phi}{dt} = Cn\Phi + R_{sp} - \frac{\Phi}{\tau_{ph}}$$

Photon rate = stimulated emission + spontaneous emission + photon loss [4-25]

$$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau_{sp}} - Cn\Phi$$

electron rate = injection + spontaneous recombination + stimulated emission

C : Coefficient expressing the intensity of the optical emission & absorption process

R_{sp} : rate of spontaneous emission into the lasing mode

τ_{ph} : photon life time

J : Injection current density

Threshold current Density & excess electron density

- At the threshold of lasing: $\Phi \approx 0,\ d\Phi / dt \geq 0,\ R_{sp} \approx 0$

$$\text{from eq.}\,[4\text{-}25] \Rightarrow Cn\Phi - \Phi / \tau_{ph} \geq 0 \Rightarrow \boxed{n \geq \frac{1}{C\tau_{ph}} = n_{th}} \qquad [4\text{-}26]$$

- The threshold current needed to maintain a steady state threshold concentration of the excess electron, is found from electron rate equation under steady state condition *dn/dt=0* when the laser is just about to lase:

$$0 = \frac{J_{th}}{qd} - \frac{n_{th}}{\tau_{sp}} \Rightarrow \boxed{J_{th} = qd\,\frac{n_{th}}{\tau_{sp}}} \qquad [4\text{-}27]$$

Laser operation beyond the threshold

$$J > J_{th}$$

- The solution of the rate equations [4-25] gives the steady state photon density, resulting from stimulated emission and spontaneous emission as follows:

$$\boxed{\Phi_s = \frac{\tau_{ph}}{qd}(J - J_{th}) + \tau_{ph} R_{sp}} \qquad [4\text{-}28]$$

External quantum efficiency

- Number of photons emitted per radiative electron-hole pair recombination above threshold, gives us the external quantum efficiency.

$$\eta_{ext} = \frac{\eta_i (g_{th} - \bar{\alpha})}{g_{th}}$$

$$= \frac{q}{E_g} \frac{dP}{dI} = 0.8065 \lambda [\mu \mathrm{m}] \frac{dP(\mathrm{mW})}{dI(\mathrm{mA})} \quad [4\text{-}29]$$

- Note that: $\eta_i \approx 60\% - 70\%; \qquad \eta_{ext} \approx 15\% - 40\%$

Laser Resonant Frequencies

- Lasing condition, namely eq. [4-22]:

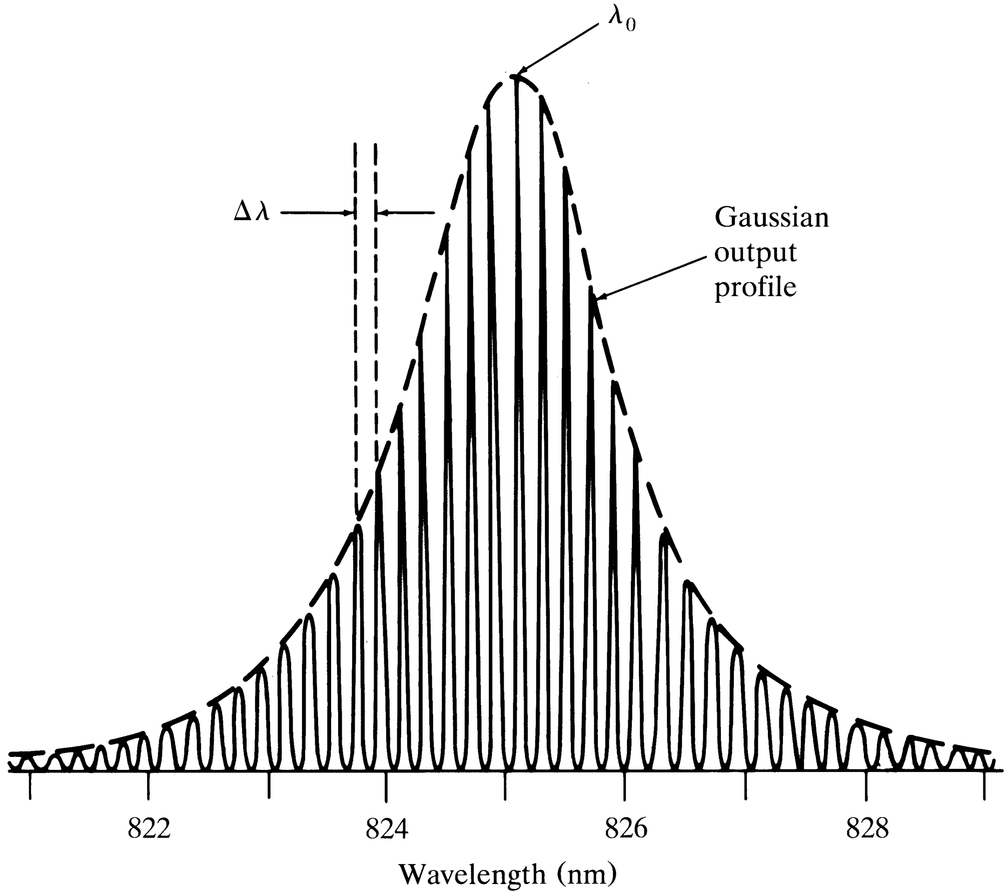
$$\exp(-j2\beta L) = 1 \Rightarrow \qquad 2\beta \mathrm{L} = 2m\pi, \quad m = 1,2,3,\ldots$$

- Assuming $\beta = \dfrac{2\pi n}{\lambda}$ the resonant frequency of the *m*th mode is:

$$\boxed{\upsilon_m = \frac{mc}{2Ln}} \qquad m = 1,2,3,\ldots \qquad \text{[4-30]}$$

$$\Delta\upsilon = \upsilon_m - \upsilon_{m-1} = \frac{c}{2Ln} \Leftrightarrow \boxed{\Delta\lambda = \frac{\lambda^2}{2Ln}} \qquad \text{[4-31]}$$

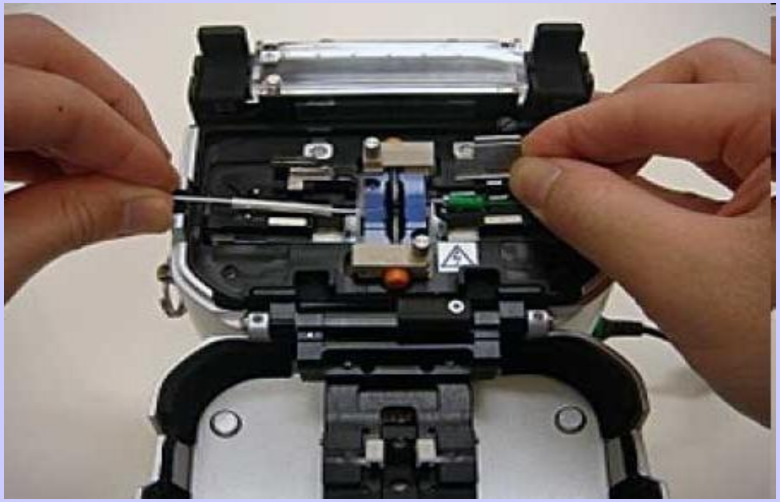
Spectrum from a laser Diode



$$g(\lambda) = g(0)\exp\left[-\frac{(\lambda-\lambda_0)}{2\sigma^2}\right] \quad \sigma : \text{spectral width}$$

[4-32]

OPTICAL FIBER JOINTS & CONNECTIONS



OPTICAL FIBER JOINTS

- Technical requirement for both jointing & termination of transmission media

- **Number of Joints or Connections**
  - Link length between repeaters
  - Continuous length of fiber
  - Length of fiber cable practically or conveniently installed as continuous length

- **Repeaters Spacing** (A continuously increasing parameter)
  - Ranges from ≈ 40-60 km at 400 Mbits/s

    ≈ 100 km at 2.4 Gb/s

    ≈ 300 km at 1.7-10 Gb/s using SMDSFs

FIBER JOINTS

- **Source- Fiber**
- **Fiber- Fiber**
- **Fiber- Detector**

❖ Manufacturers supply ***Electro-optical devices*** (Sources and Detectors) with fiber optic ***pigtail*** to facilitate direct fiber-fiber connection

❑ **IMPORTANT ASPECT IS FIBER-TO- FIBER CONNECTION WITH LOW LOSS AND MINIMUM DISTORTION**

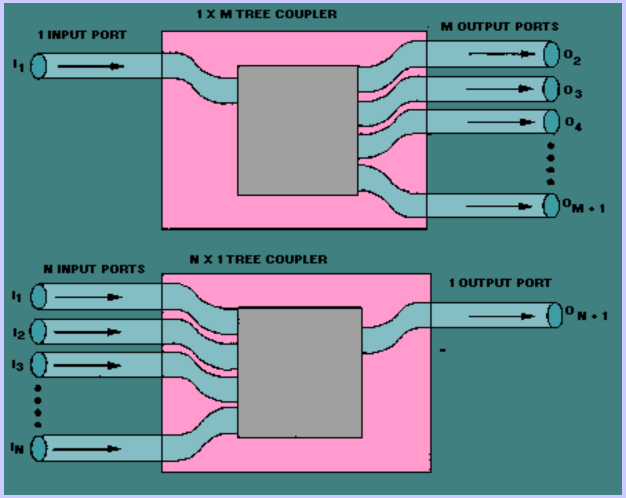
Two major categories of fiber joints

- ❑ **FIBER SPLICES:** Permanent or Semi-permanent joints
  - ✓**Soldering**

- ❑ **FIBER CONNECTORS:** Demountable or Removable joints
  - ✓Plugs or Sockets

❖**FIBER COUPLERS:** Branching devices

- ➢ Splitters or Combiners
- ➢ Importance in Networks



- **Crucial aspect of fiber joints concerning *Optical Losses* associated with the connection**

  - **Fiber Alignment**

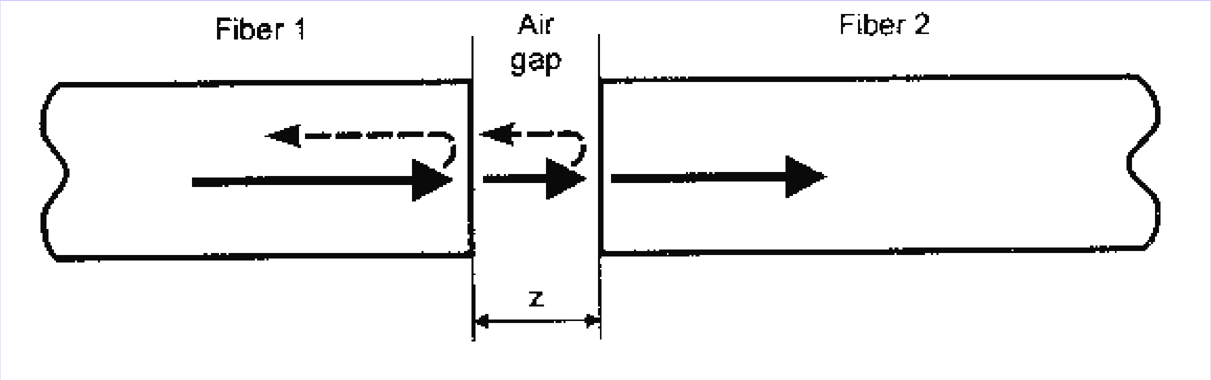
LOSS MECHANISMS AT JOINTS

1. **Fresnel Reflection**

   - **Optical Loss encountered at the interfaces** (Even when two fiber ends are smooth, perpendicular to fiber axes and perfectly aligned)

   - **A small proportion of light may be reflected back into transmitting fiber causing attenuation at the joint.**

     - **Fresnel Reflection**



Reflection Loss

- **Occurs due to step changes in refractive index at jointed interface**

Glass – Air - Glass

Fraction of light reflected at a single interface

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

n_1 : R.I. of core, n : R.I. of interfacing medium (= 1 for air)

Loss in decibel due to FR at single interface

$$\mathrm{Loss}_{\mathrm{Fres}} = -10 \log_{10}(1-r)$$

- **Can be reduced to a very low level using index matching fluid in the gap between jointed fibers.**

2. Deviation in Geometrical & Optical Parameters

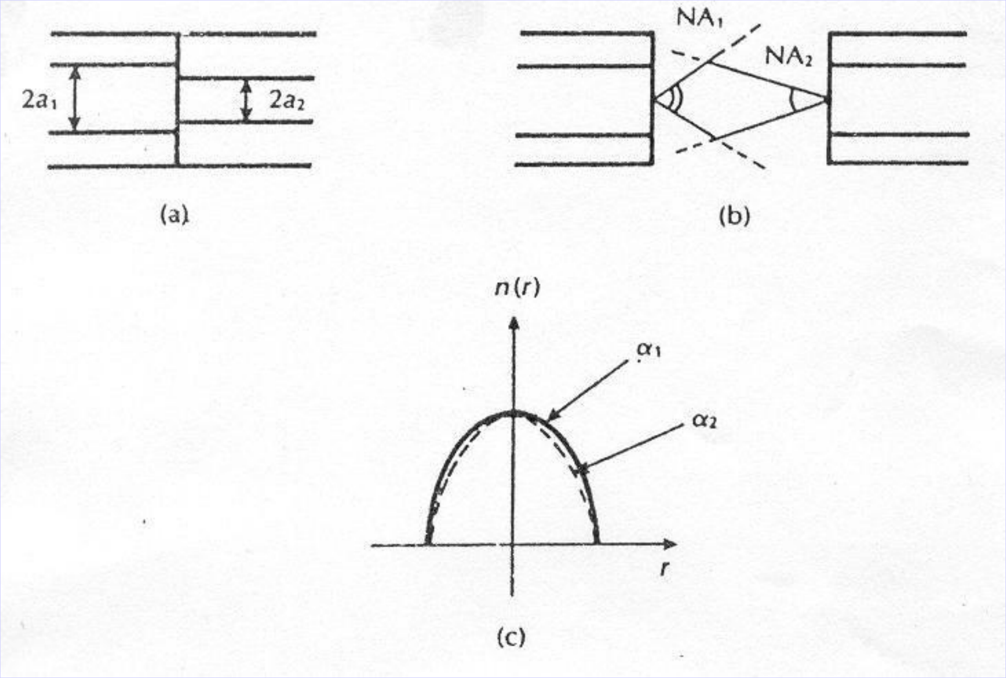
- All light from one fiber is not transmitted to another fiber ; **Because of mismatch of mechanical dimension**

Three major cases :

a) **Core mismatch**

b) **NA mismatch**

c) **Index Profile**



Intrinsic Losses

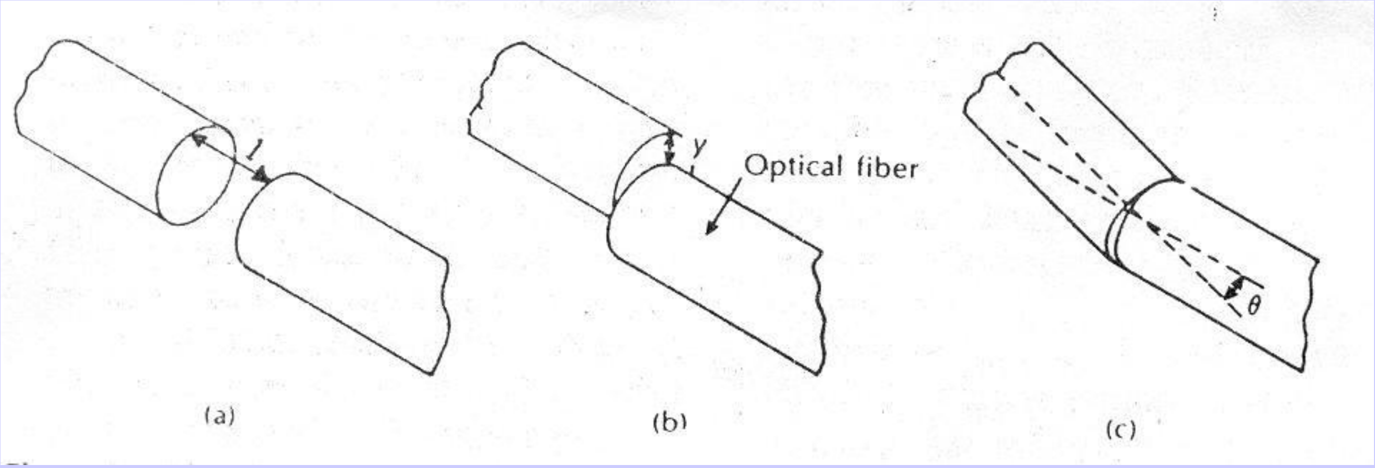
Losses due to:

- Fresnel Reflection
- Deviation in Geometrical & Optical parameters

> ➢ **Minimized using fibers manufactured with lowest tolerance i.e.(same fiber)**

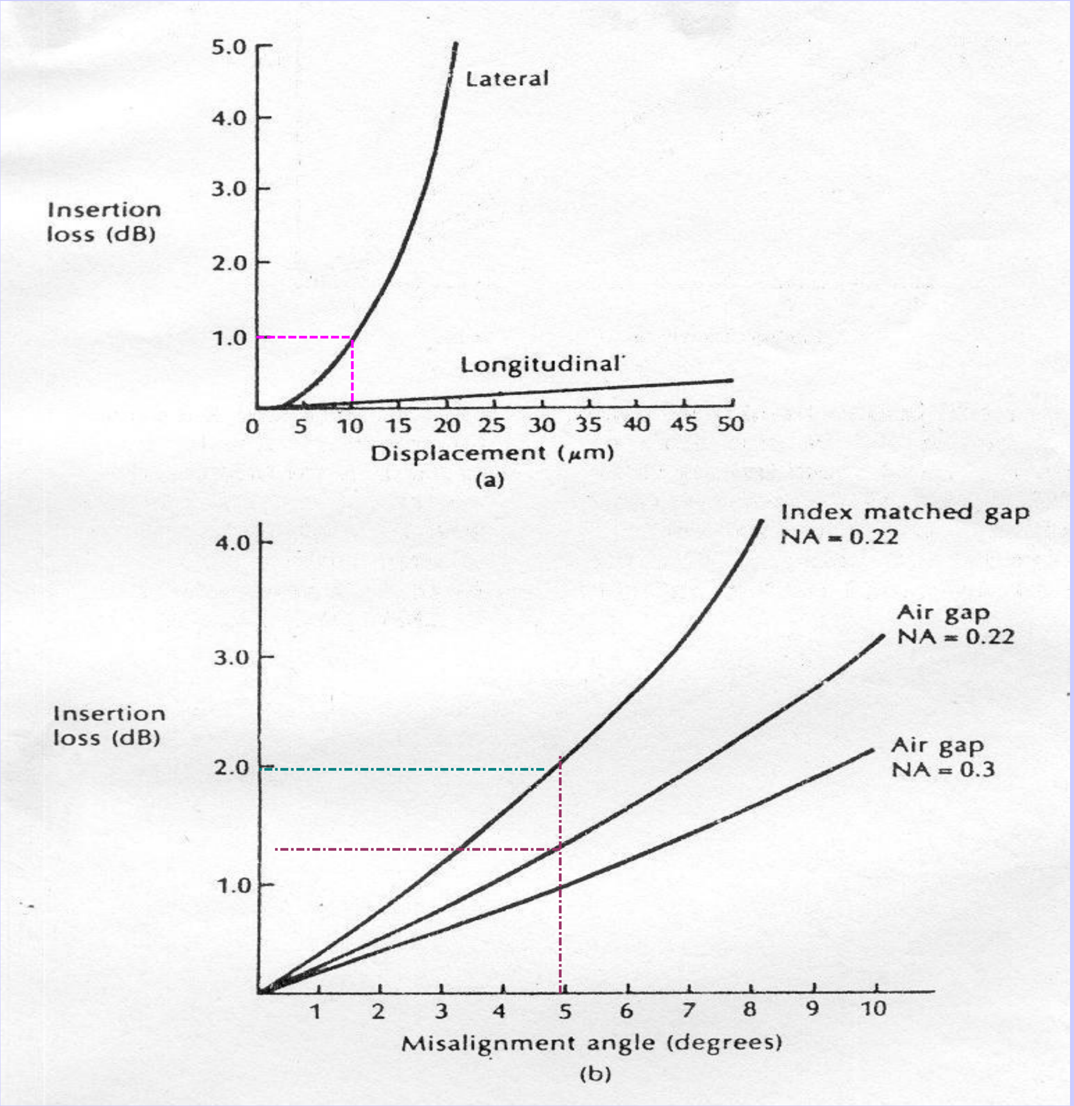
Extrinsic Losses

- Losses due to some imperfection in splicing
  - Caused by Misalignment



Three possible types of misalignment at joint

(a) Longitudinal misalignment
(b) Lateral misalignment;
(c) Angular misalignment



(a) Loss due to lateral and longitudinal misalignment for a 50 μm core diameter GI fiber; (b) insertion loss due to angular misalignment for joints in two MMSI fibers with NA of 0.22 and 0.3.

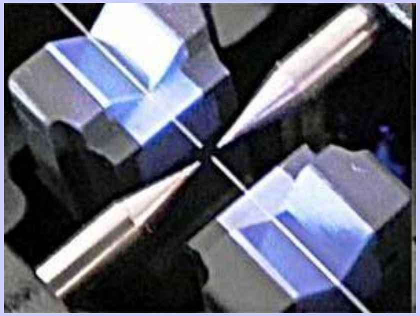
FIBER SPLICES

- A permanent joint formed between two fibers

TWO BROAD CATEGORIES

- **Fusion Splicing or Welding**

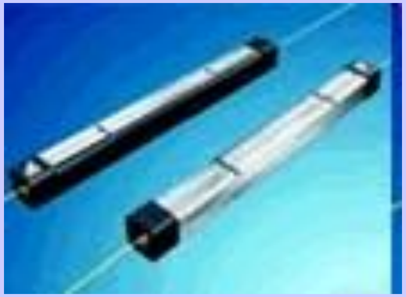
  Accomplished by applying localized heating (a flame or an electric arc) at the interface between two butted, prealigned fiber ends causing them to soften and fuse.



- **Mechanical Splicing**

  Fibers are held in alignment by some mechanical means

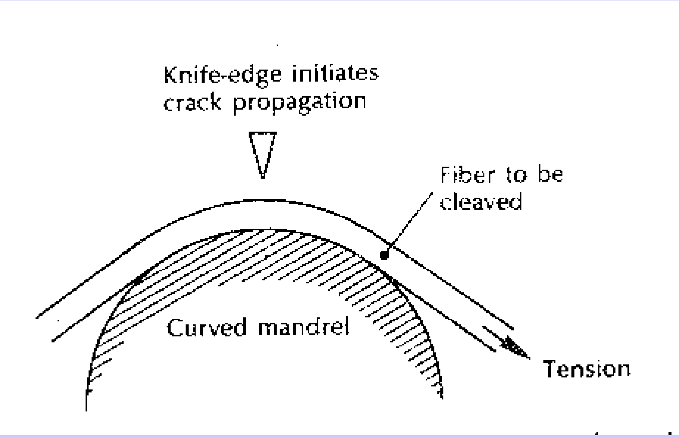
  - **Achieved by various methods;**
    - **Tube Splices**
    - **Groove Splices**



☞ MUST HAVE SMOOTH AND SQUARE END FACES

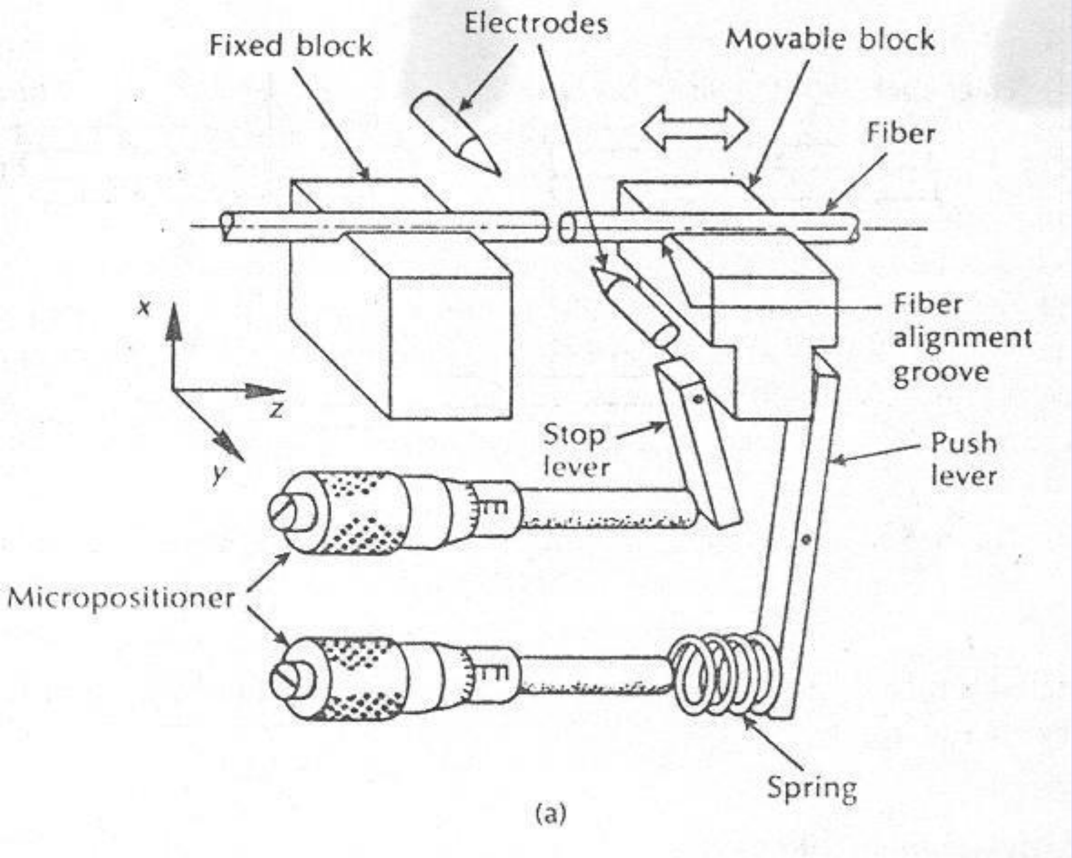
- ❑ **End preparation achieved using suitable tools - “ Cleavers” “ Scribe and Break” or “Score and Break”**

  - ➢ Scoring of fiber surface under tension with cutting tool **(Sapphire, Diamond or Tungsten Carbide blade)**



Optical fiber end preparation: the principle of scribe and break cutting.

Fusion Splicing of Optical Fibers

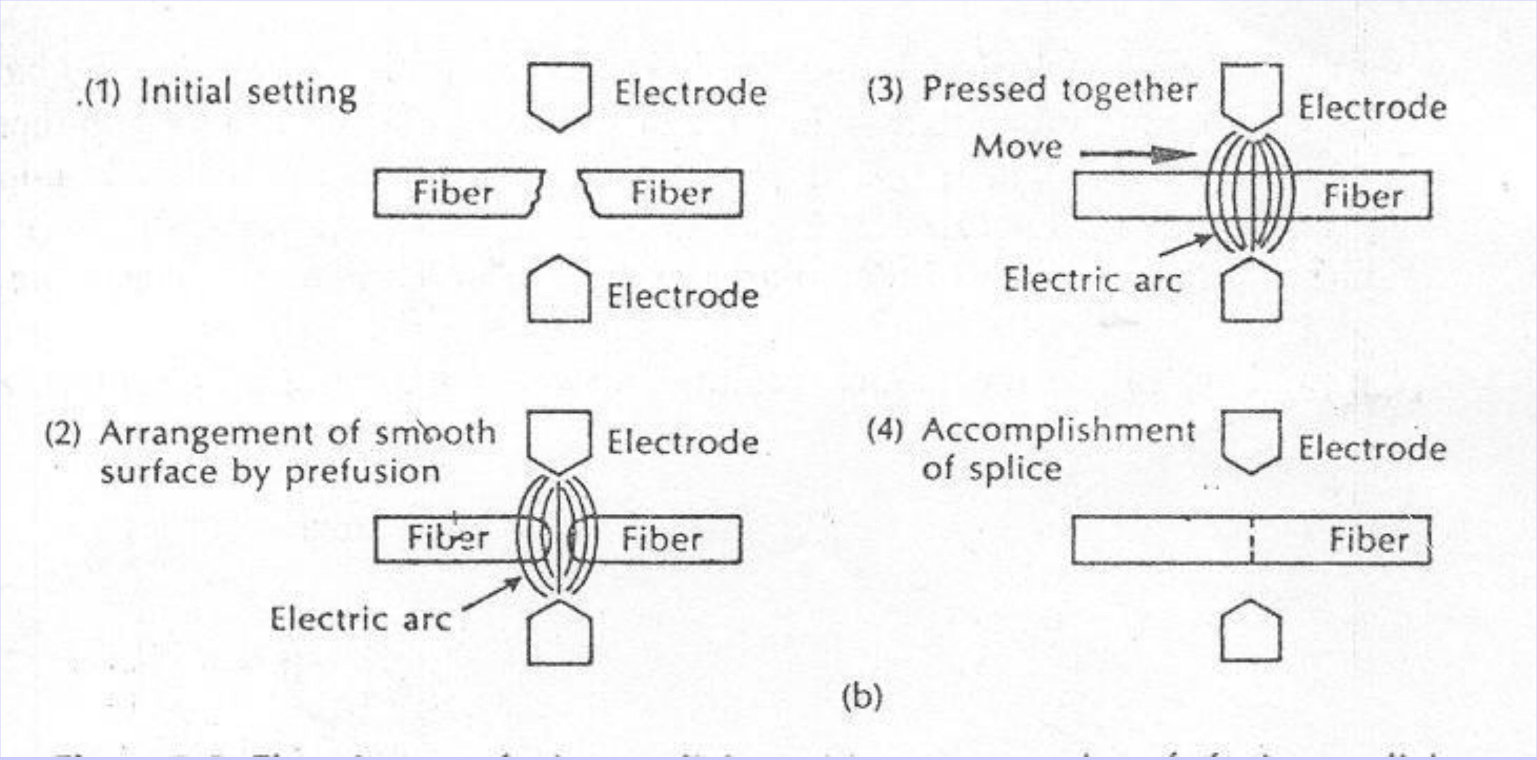


Electric Arc Fusion splicing

- **Require Fiber end surfaces to be prepared for joint**
- **Heating of prepared fiber ends to fusion point with application of axial pressure between two fibers.**
- **Positioning & alignment using microscopes**

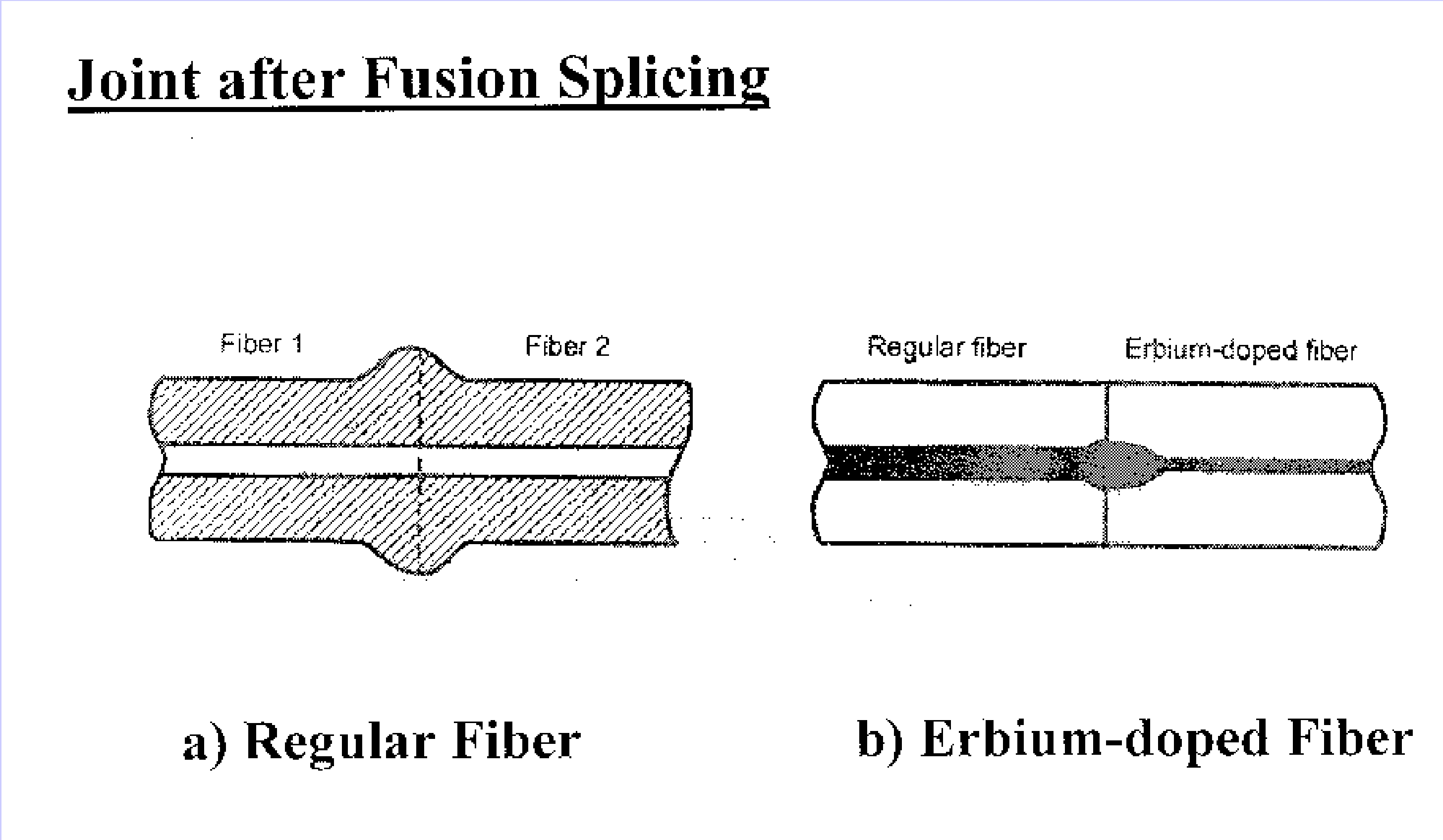
Prefusion Method

- No need for end preparation



Prefusion method for accurate splicing

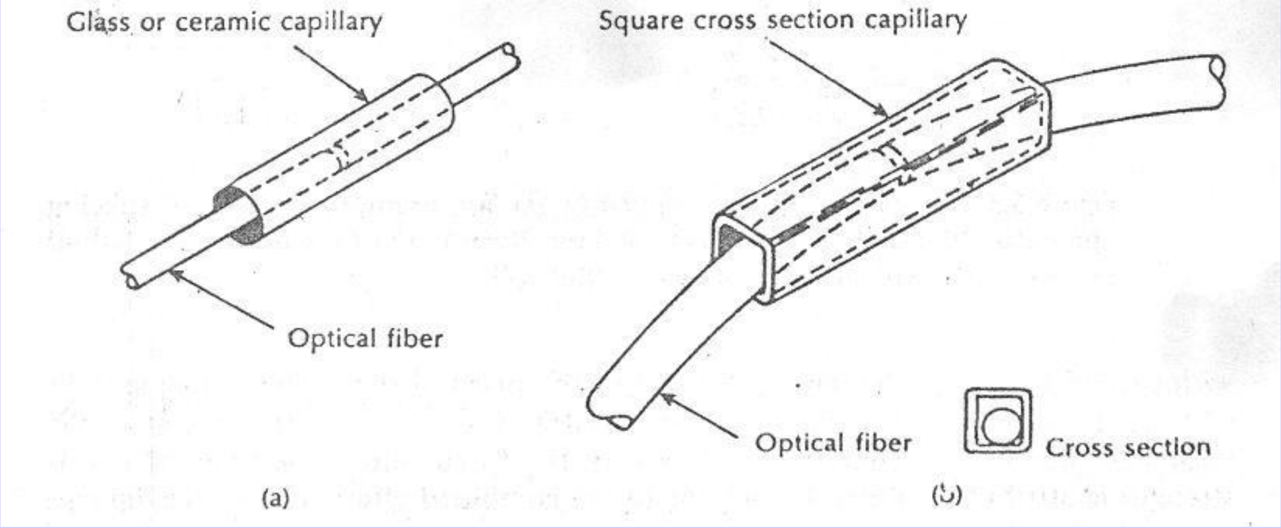
- **Smaller Fresnel Reflection loss**
- **Typical Losses : 0.1 to 0.2 dB for MMF**



- Drawback: Fiber get weakened near splice (≈30%)
  - Fiber fracture occurs near the heat-affected zone adjacent to the fused joint.
  - Splice be packaged to reduce tensile loading

Mechanical Splicing

- Uses accurately produced rigid alignment tubes into which the prepared fiber ends are permanently bonded.



- **Techniques for tube splicing of optical fibers**:

  (a) Snug Tube Splice
  (b) Loose Tube Splice; Square Cross section Capillary

Comparison of Two Approaches

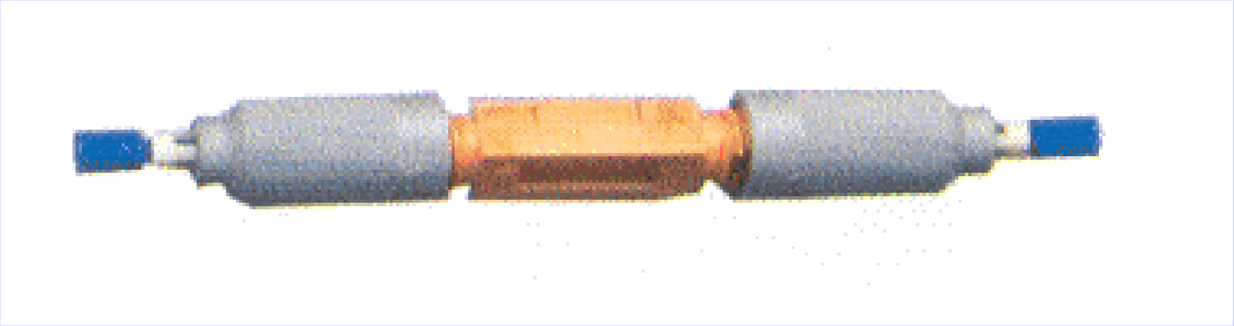
Snug Tube Splices

- Exhibits problems with capillary tolerance requirements
- Losses ≈ up to 0.5 dB with Snug tube splice (ceramic capillaries) using MMGI and SM fibers.

Loose Tube Splices

- Avoids the critical tolerance requirements.
- Losses ≈ 0.1 dB with loose tube splice using MMGI fibers.

Ultra Splice

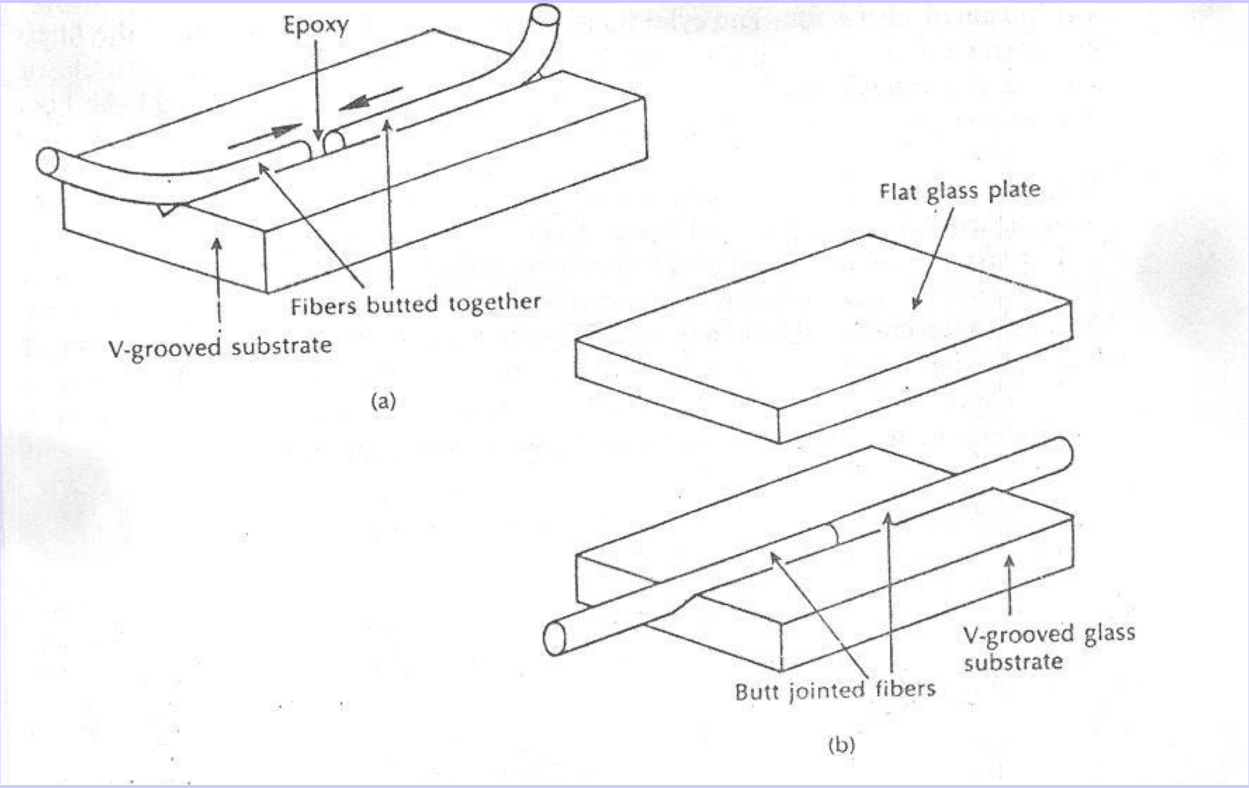


Ultra Splice: Reusable mechanical splice.

Average Loss ≅ 0.2 dB

Groove Splices

- **Use of grooves to secure the fibers to be jointed**
  - ➢ better alignment to the prepared fiber ends.

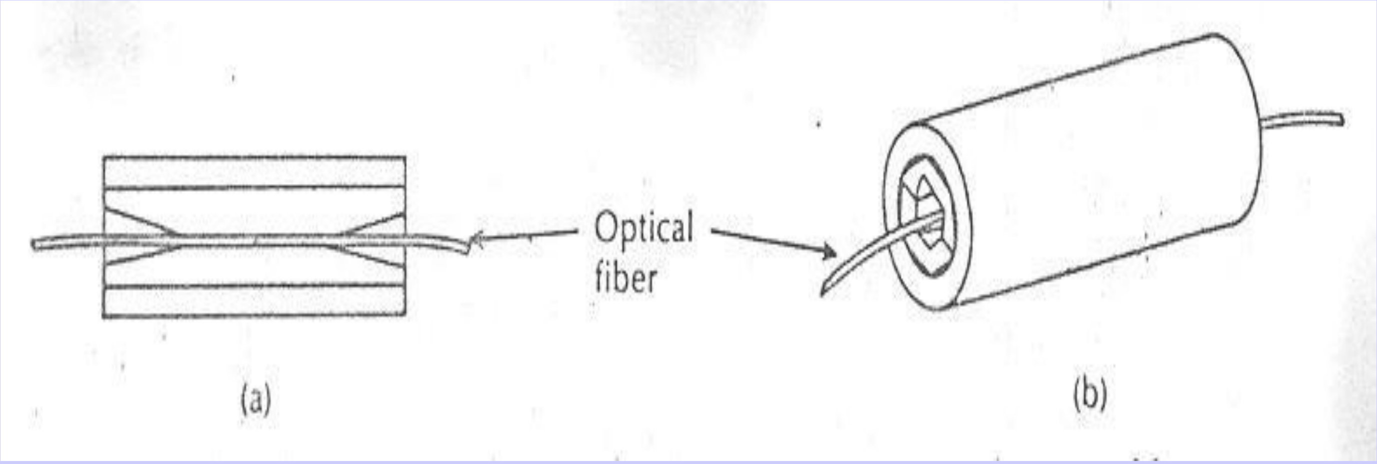


V-groove splices

➢ **Insertion losses** ≈ 0.1 dB using jigs for producing V-groove splice.

Elastic Tube or Elastomeric Splice

- **Comprises of two elastic parts (inner with V-groove) in compression to ensure alignment of fibers.**

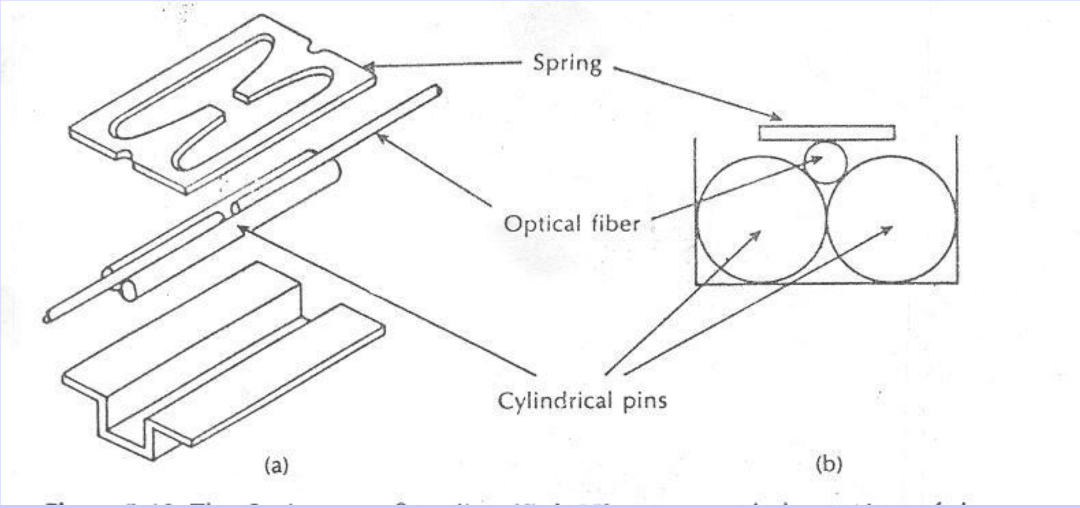


Elastomeric Splice: (a) Cross section (b) Assembly

- Fibers of different diameters tend to be centred and hence successfully spliced.
- General loss ~ 0.25 dB for commercial product

Spring Groove Splice

- Utilizes **a bracket** containing **two cylindrical pins**, which serve **as an alignment guide** for two prepared fibers.
- **An elastic element** (a spring) used to **press the fibers** into groove and maintain alignment of fiber ends.



Springroove Splice : (a) Expanded overview
(b) Cross-section Schematic

Mean Losses ≈ 0.05 dB with MMGI Fibers.

- **Practically used in Italy.**

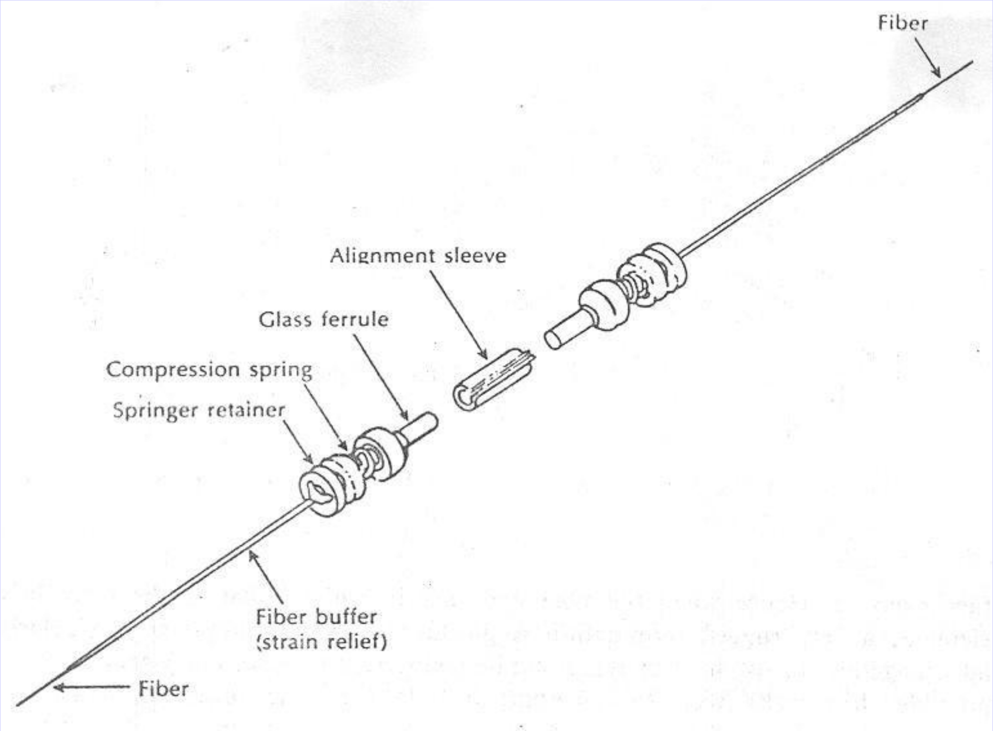
Secondary Alignment Techniques

- **Alignment of secondary elements around the bare fibers**
  - Increased ruggedness
  - Easy ground and polish of fiber end
  - Better termination

Drawbacks:

- **Time consuming for termination**
- **Increased losses due to tolerances on secondary elements**
  $\Rightarrow$ Fiber misalignment.

Glass capillary tubes (Ferrules)

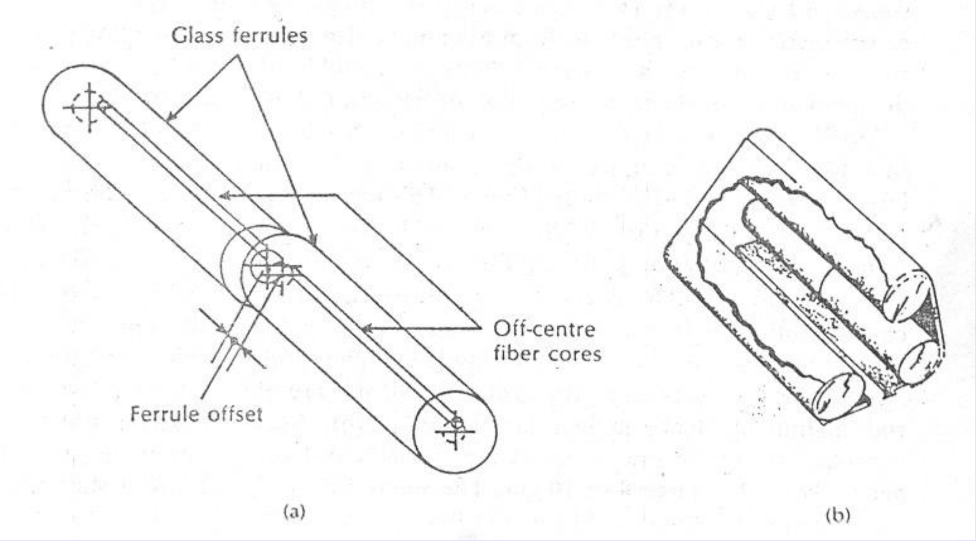


MMF mechanical splice using glass capillary tubes.

- **Fixing of glass ferrules**
- **Alignment sleeve of metal or plastic in which glass tube fibers are aligned**
- **Average loss** ≅ 0.2 dB

Rotary Splice

- **Use glass capillary tubes for fiber termination with small eccentricity.**



Rotary Splice for SMF:

(a) Alignment using glass ferrules

(b) Glass rod alignment sleeve

- Built-in offset and rotation, for excellent alignment
- Alignment accuracy of 0.05 μm using three glass rod alignment sleeve. (necessary for SMFs; 8-10 μm MFD)
- **Mean Losses** ≅ 0.03 dB using Index matching gels (Not affected by skill levels of the splicer).

❖ **Used in large installations in USA**

MULTIPLE SPLICES

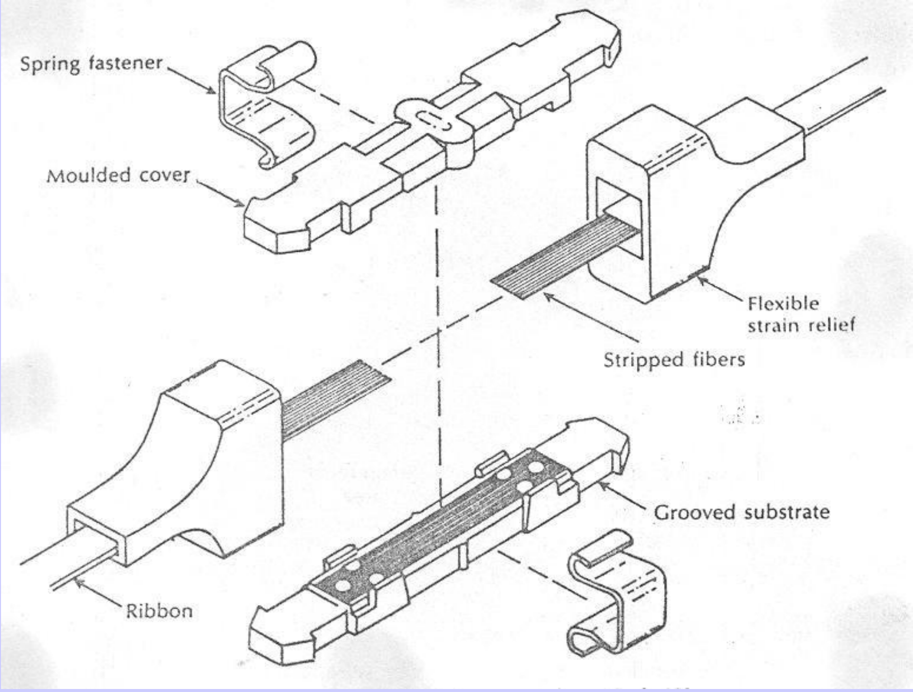
- **Commercially available for splicing number of fibers simultaneously**
  - **Simultaneous Splicing of Five fibers in 5 minutes;**
  - **15 minutes for five single fusion splicing.**

❖ Splice Losses:

- **Ranging 0.04 to 0.12 dB- MM GI fibers**
- **0.13 to 0.4 dB – SM fibers.**

B. V-groove flat Chip

- Moulded from glass filled polymer resin
- Direct mass splicing of 12 fiber ribbons with simultaneous end preparation using ribbon grinding and polishing procedures.
- Fibers positioned in grooves in glass filled plastic substrate.
- Vacuum technique to hold fibers at position whilst cover plate is applied.

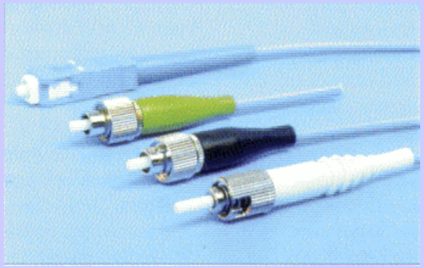


V-groove polymer resin ribbon fiber splice.

- Spring clips to hold assembly and hole in cover plate for index matching gel.

- **Average Splice Losses**
  ≈0.18 dB with MM fiber.

FIBER CONNECTORS



❑ Demountable fiber connectors

- ➢ More difficult to achieve than fiber splices

- Must maintain similar tolerance requirements, but in a ***removable fashion.***
- Must allow for repeated connection and disconnection without problems for fiber alignment - ***without degradation in performance***.
- Must protect the fiber ends from damage – due to handling
- Must be insensitive to environmental factors (e.g. moisture & dust)
- Must cope with tensile load on the cable and can be fitted with relative ease.
- Should ideally be a ***low cost component***,

Three Major Parts:

- **Fiber Termination** : protects and locates the fiber ends

- **Fiber end Alignment :** provide optimum optical coupling

- **Outer shell** : maintains the connection and fiber alignment, protects the fiber ends from the environment and provides adequate strength at the joint.

➢ **Losses in the range 0.2 to 0.3 dB**

A. Butt Jointed Connectors

- Alignment of two prepared fiber ends in close proximity (butted) to each other so that the fiber axes coincide.

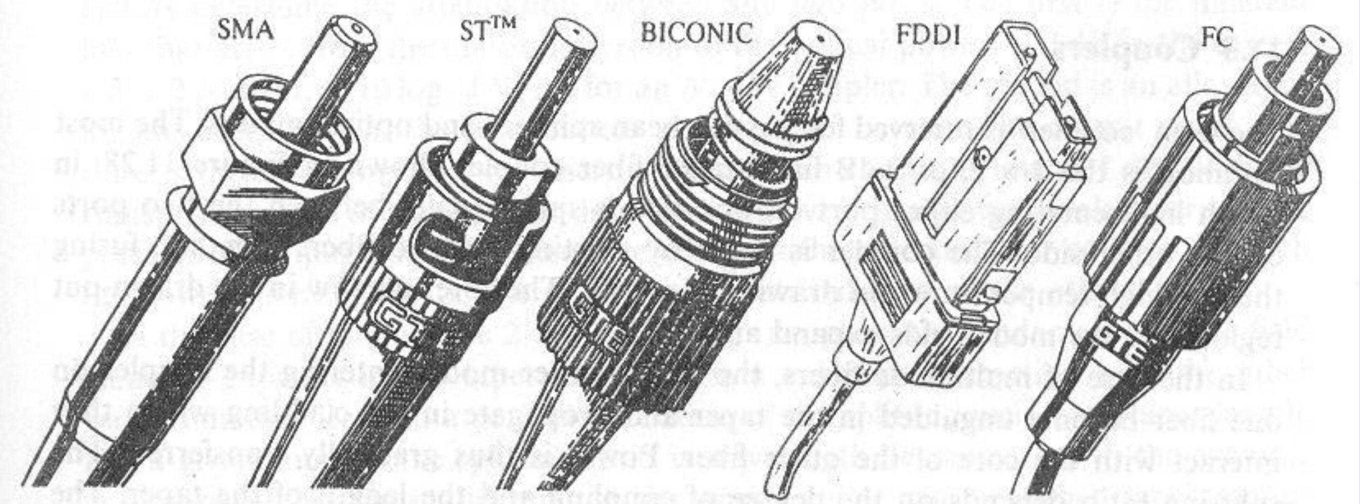


Figure 11.26 An illustration of some of the more common types of connector.

B. Expanded-Beam Connectors

- Utilize interposed optics at the joint in order to ***expand*** the beam from the transmitting fiber end before ***reducing*** it again to a size compatible with the receiving fiber end.

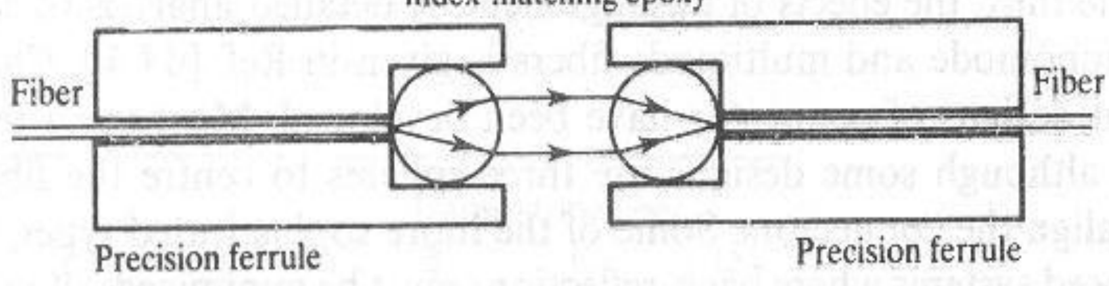
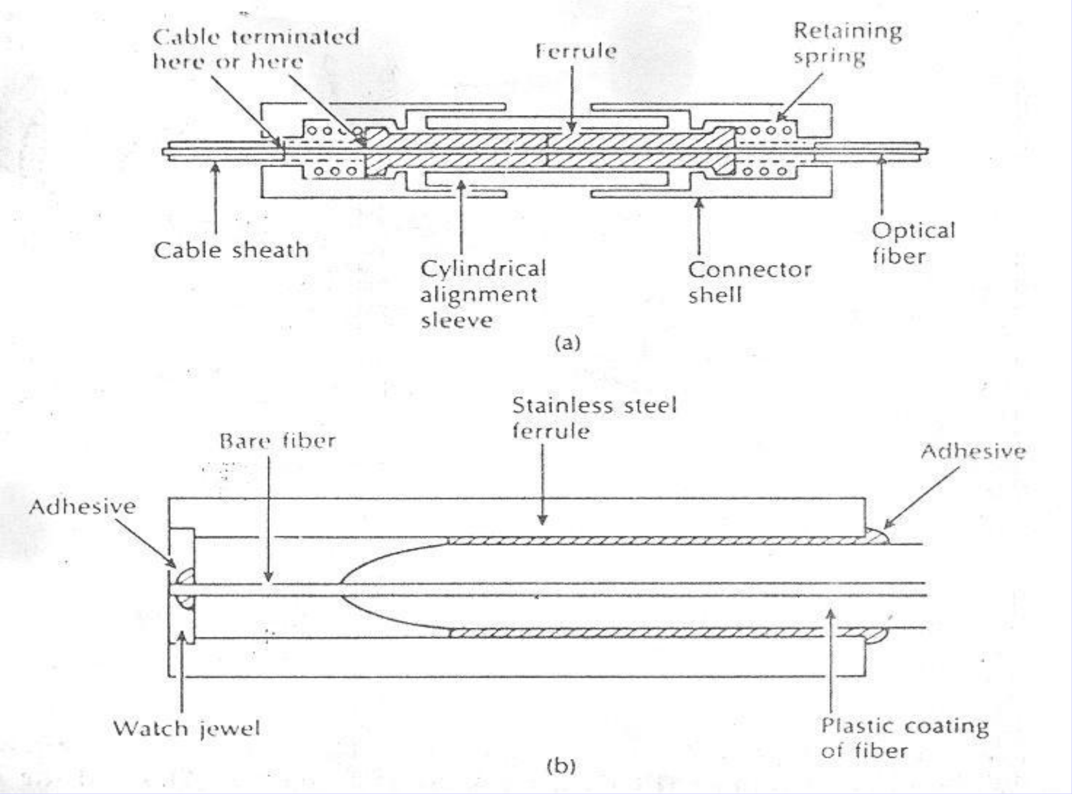


Figure 11.27 An expanded-beam connector.

Cylindrical Ferrule Connector

- **Glass Ferrules with central drilled hole**
- **Concentric alignment sleeve**

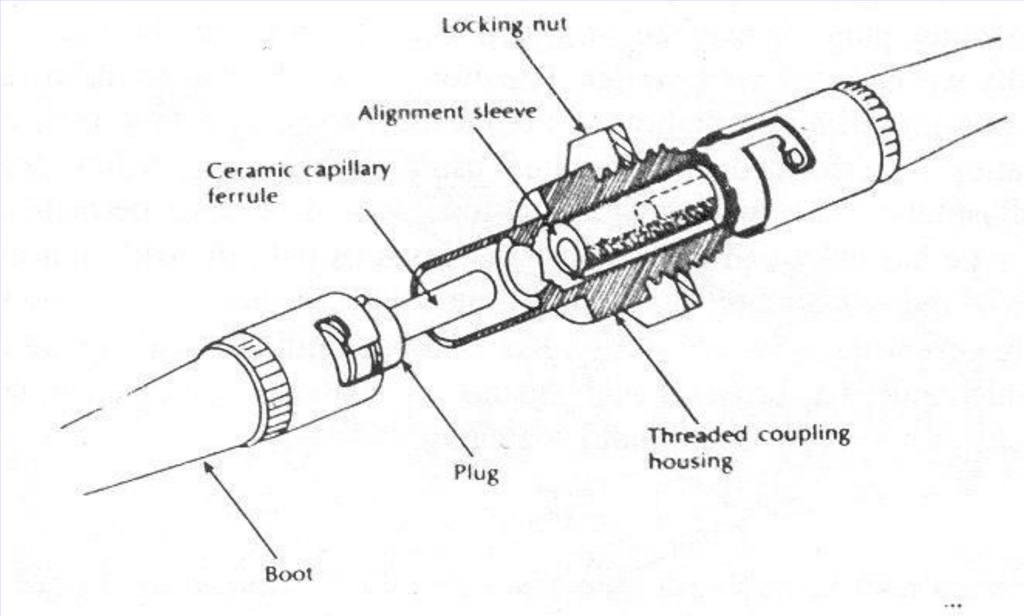


Ferrule Connectors: (a) structure of a basic ferrule connector; (b) structure of a watch jewel connector ferrule.

- **Preparation of fiber ends before fixing the ferrules**
- **Insertion Losses** ≈ 1 to 2 dB with MMSIF
- **Watch jewel for close end approach and tolerance requirement**

Ceramic Capillary Ferrules

- Ferrules made from ceramic material
- End preparation after fixing ceramic ferrules



ST series multimode fiber connector using ceramic capillary ferrules.

❑ **Outstanding**

- Thermal,
- Mechanical
- Chemical Resistance

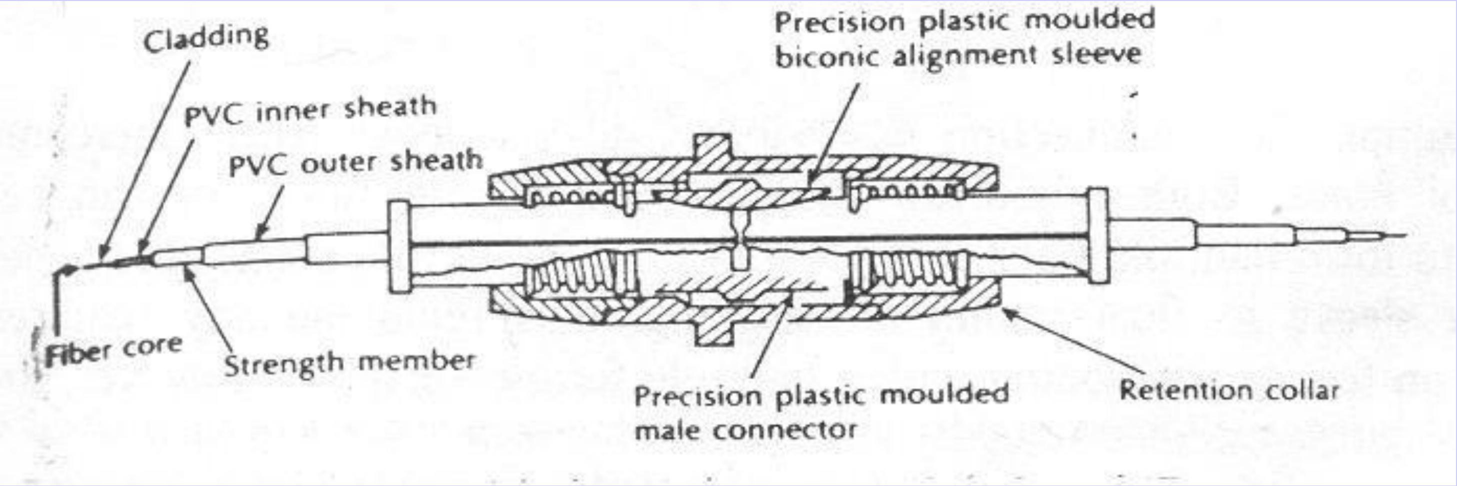
❑ **Average Losses**

≈ 0.2 dB with MMGI

≈ 0.3 dB with SMF

Biconical Connectors

- **Widely used as part of jumper cable**
- **Fiber end faces polished after plug attachment**

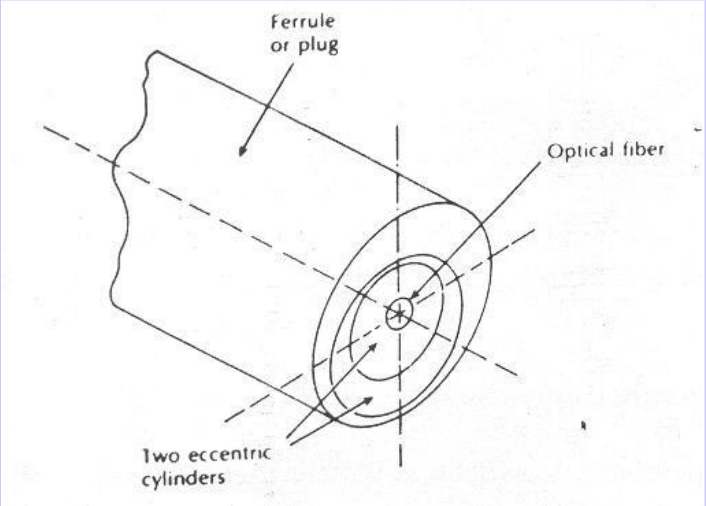


Cross-section of biconical connector

✓ **Mean insertion losses** ≈ 0.21 dB with connectors of 50μm diameter GI fibers.

Double Eccentric Connector

- **Does not rely on a concentric sleeve approach**
- **Consists of two eccentric cylinders within outer plug.**



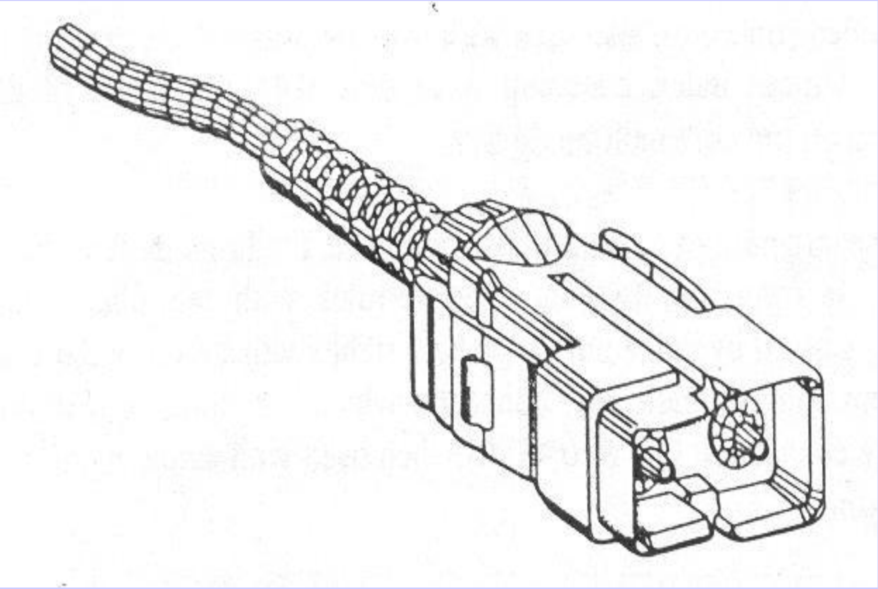
Connector Structure

- An active assembly adjustable, allowing close alignment of fiber ends
- Operation performed under inspection microscope or peak optical adjustment.

- **Mean insertion loss** ≈ 0.48 dB with MMGIFs reduces to 2. dB with index matching gel.
  - ✓ Also used with SMFs giving losses 0.46 dB.

Duplex Fiber Connector

- Developed to provide two way communications
- Uses ferrules of different types

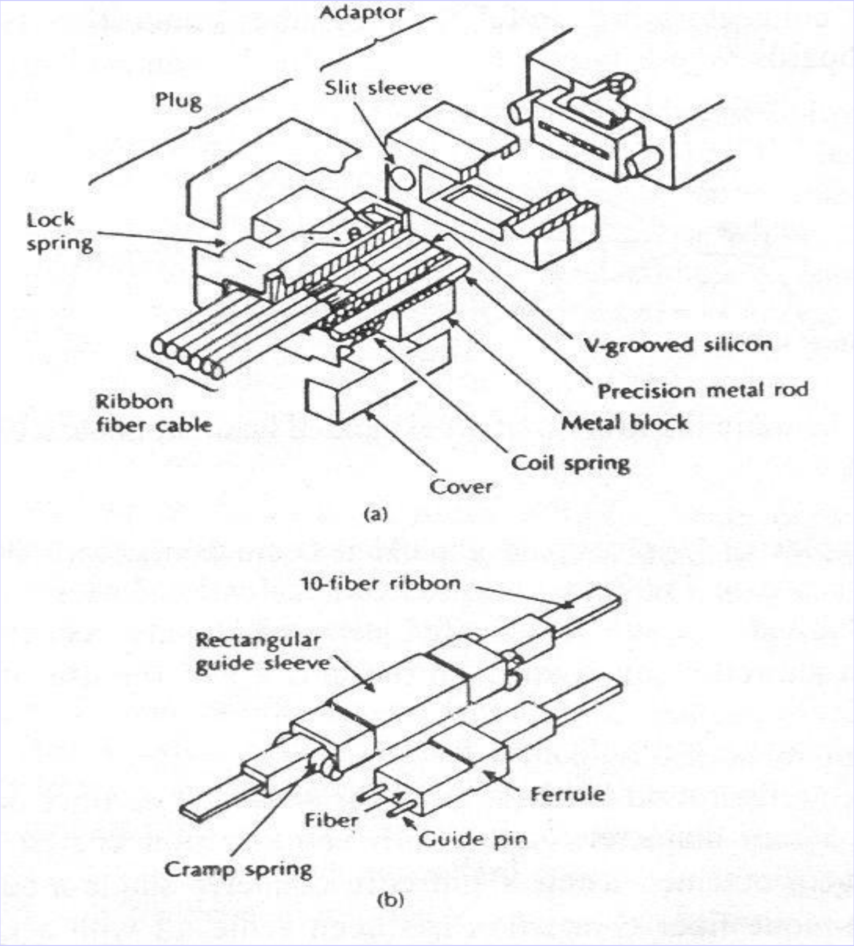


Media interface plug with DFC

- Mostly used in LANs
- Commercially available for use in FDDI ≈ loss of 0.6 dB.

Multiple Fiber Connectors

- **Utilizes V grooved Silicon chips for mounting**

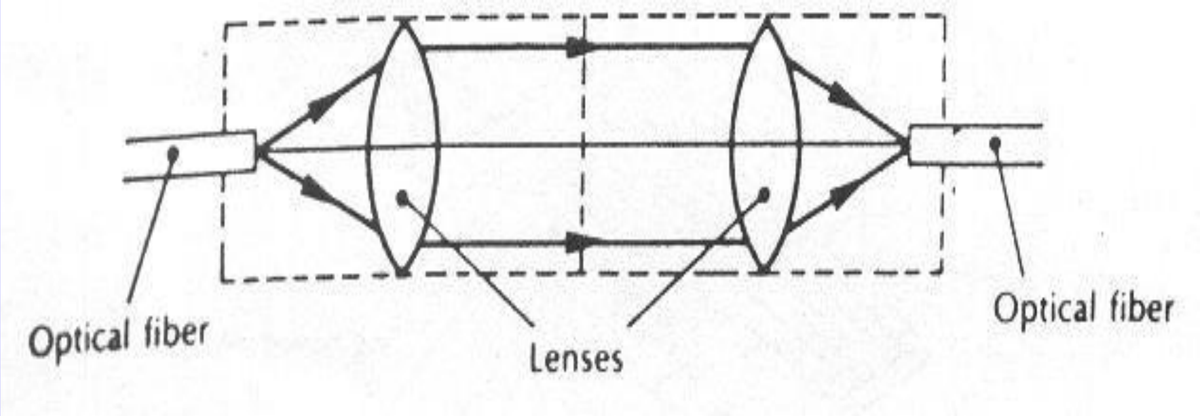


(a) Fiber ribbon connector (b) SM Ten fiber connector.

- **Metal guiding rods and coil springs for precise alignment**
- **Average Losses**
  - ≈ 0.8 dB with MMFs
  - Reduced to 0.4 dB using index matching fluids

EXPANDED BEAM CONNECTORS

- **Collimating and refocusing the light from one fiber into the other.**

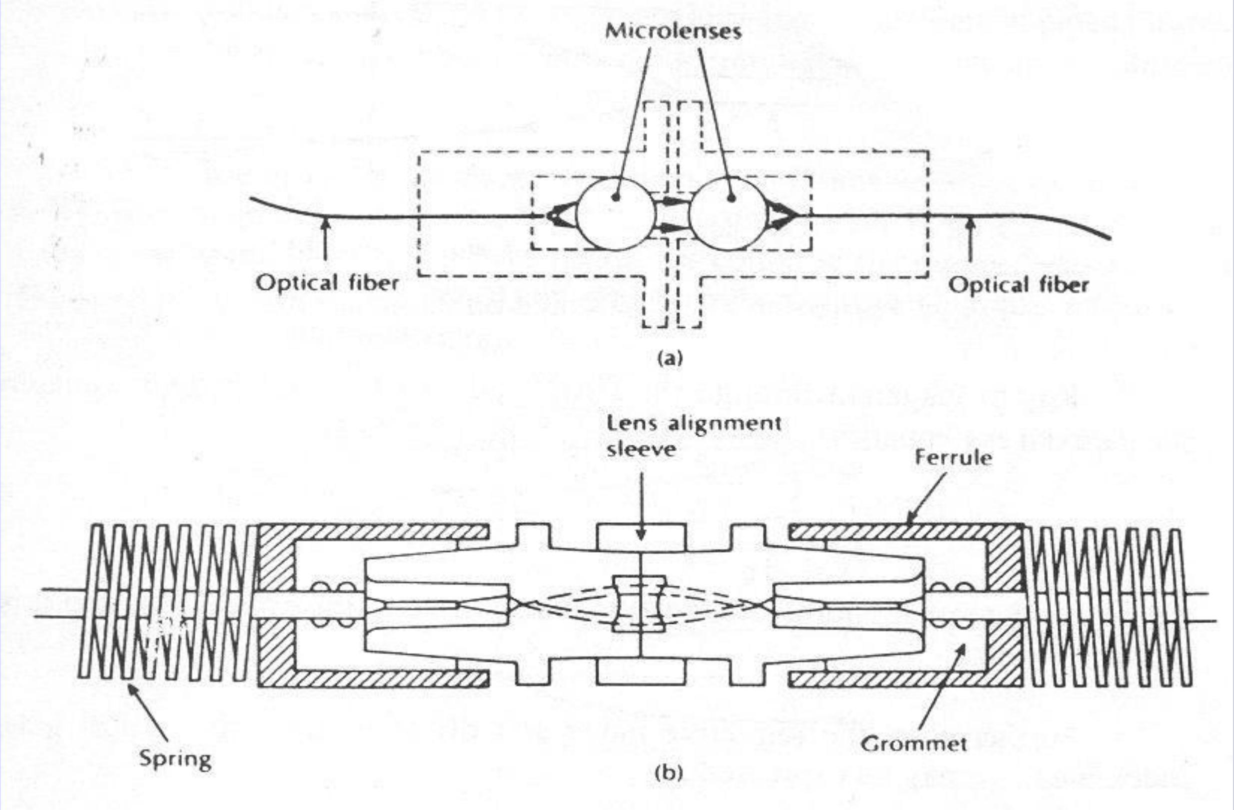


Principle of Operation

- **Very attractive for multi-fiber connections and edge connections for PCBs**

Lens Coupled Expanded beam connectors

- **Utilize spherical micro-lenses (50 μm Φ) for beam expansion and reduction**



(a) Two Micro lenses connector (b) Moulded plastic lens connector

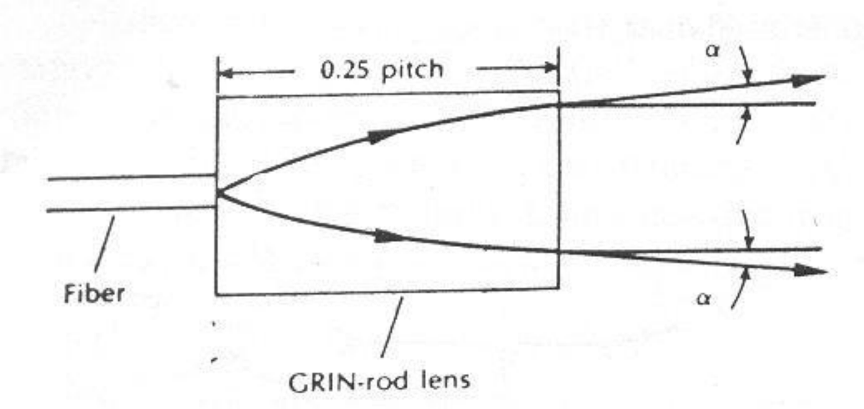
❖ **Average Loss** ≈ 1 dB, reduced to 0.7 dB with AR coating

GRIN-rod Lenses

- **An alternative lens geometry to facilitate efficient beam expansion and collimation**

  - Arose from development of GI fiber waveguides
  - A cylindrical glass rod 0.5 to 2 mm in diameter with parabolic refractive index profile.
  - Light propagation is determined by the lens dimension and wavelength of the light.
  -
  - Produce a collimated output beam with divergent angle of 1^o to 5^o from light source.onto the opposite face of lens

GRIN-rod Lenses



- **Ray propagation determined by paraxial ray equation**

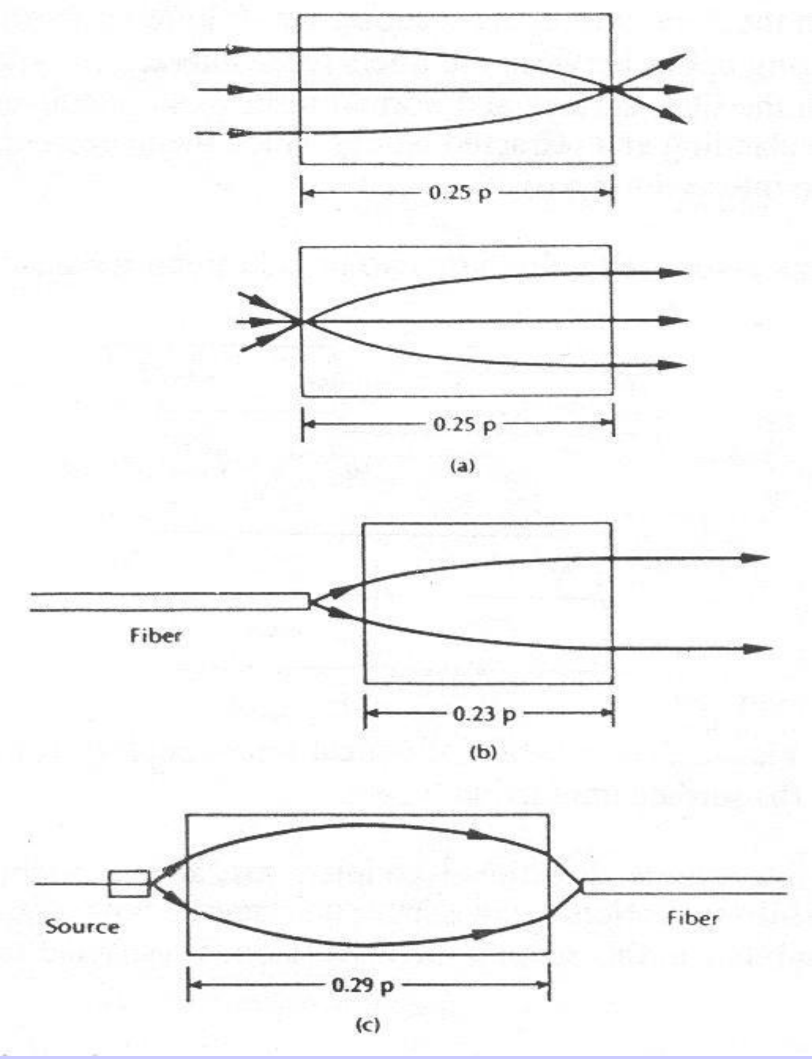
$$\frac{d^2 r}{dz^2} = \frac{1}{n}\frac{dn}{dr}$$

  - **Solution is**

$$r = k_1 \cos A^{1/2}\, r + k_2 \sin A^{1/2}\, r$$: ⟶ **A sinusoidal path**

- Traversing of one sinusoidal period : **one full pitch**

Various fractional pitch GRIN-rod lenses



- 0.25, 0.23, 0.29 etc.

➢ SELFOC from Nippon Sheet Glass Co. Ltd.

❖ Losses $\cong$ 1 dB

❖ Average Losses

$\approx$ 0.2 dB with MMGI

$\approx$ 0.3 dB with SMF