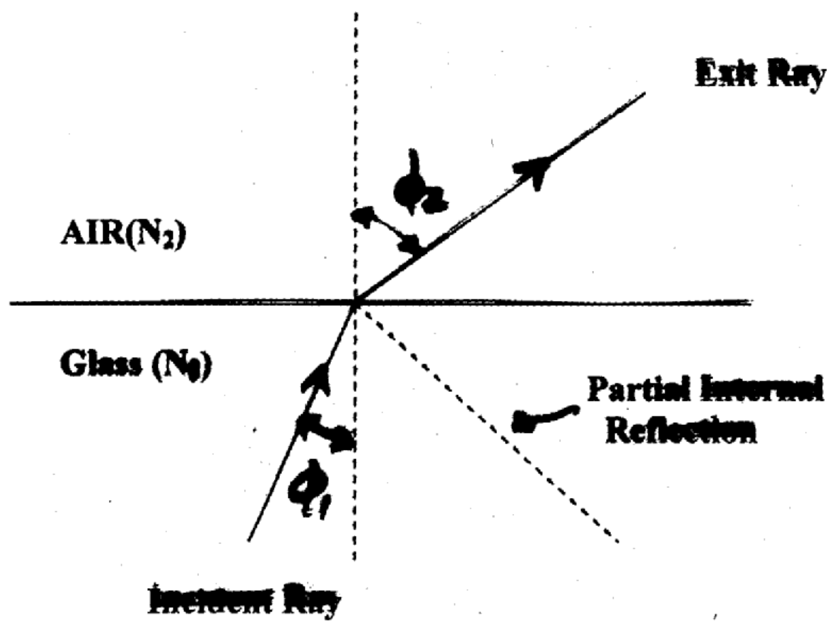
RAY THEORY TRANSMISSION

REF INDEX $\mu = \dfrac{\text{VELOCITY OF LIGHT IN VACCUM}}{\text{VELOCITY OF LIGHT IN THE MEDIUM}}$

- THE DENSER THE MEDIUM, THE LOWER IS THE VELOCITY OF LIGHT



$N_2 < N_1$

SNELL'S LAW $\quad N1 \sin \phi_1 = N2 \sin \phi_2$

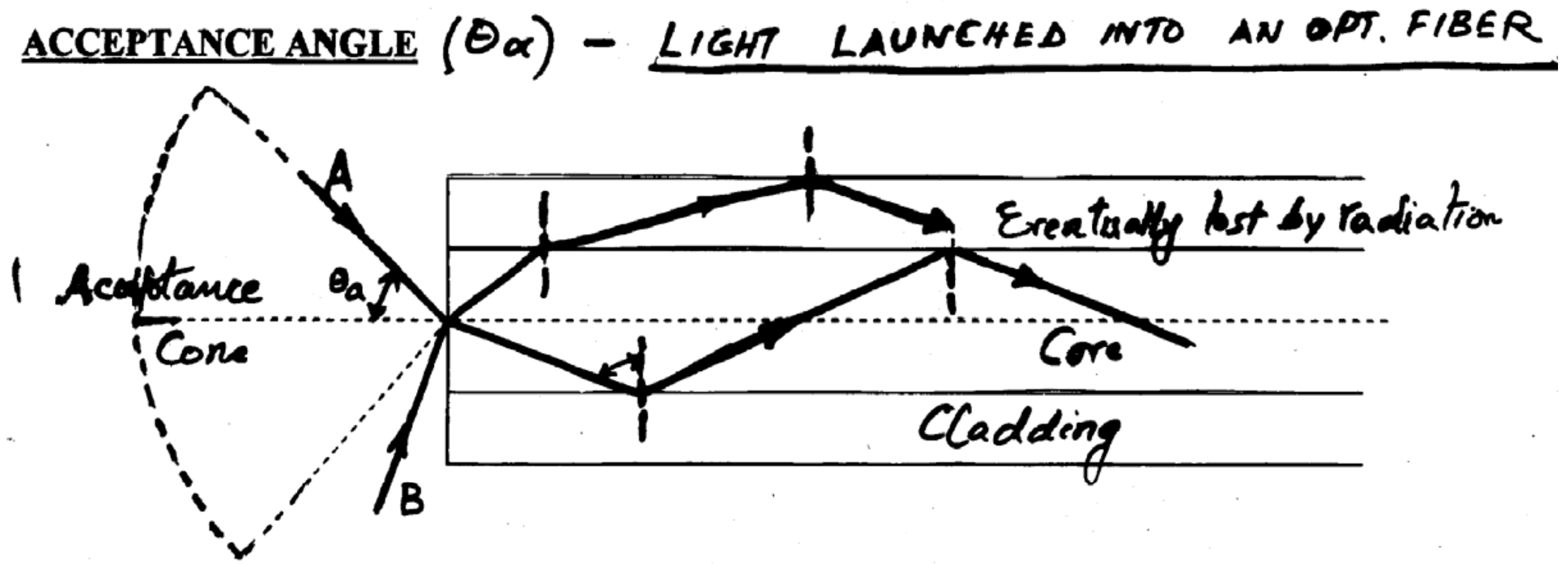
CRITICAL ANGLE(ϕ_C) ANGLE OF INCIDENCE FOR WHICH ANGLE OF REFRACTION IS 90^0

$NI \sin \phi_C = N2$

$N1/N2 = 1/\sin \phi_C$ OR $\sin \phi_C = N2/N1$

AT ANGLE OF INCIDENCE, GREATER THAN ϕ_C, THE LIGHT IS REFLECTED BACK INTO THE ORGINATING DIELECTRIC MEDIUM (η = 99.9%)

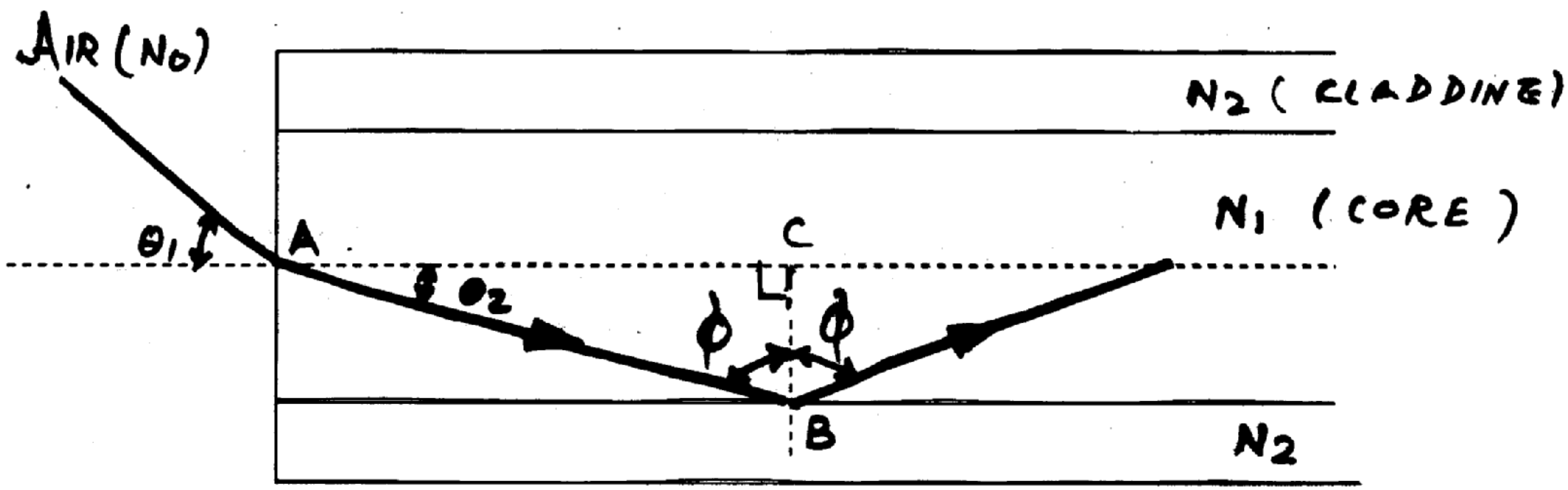
$\rightarrow$ TOTAL INTERNAL REFLECTION .



- NOT ALL RAYS ENTERING THE FIBER CORE WLL CONTINUE TO BE PROPAGATED DOWN ITS LENGTH.
- RAYS TO BE TRANSMITTED BY TIR WITHIN THE FIBER CORE MUST BE INCIDENT ON THE FIBER CORE WITHIN THE ACCEPTANCE CONE(HALF ANGLE= ϕ_a)

$\phi_{a=}$ MAXIMUM ACCEPTANCE ANGLE FOR THE FIBER.

NUMERICAL APERTURE (NA)

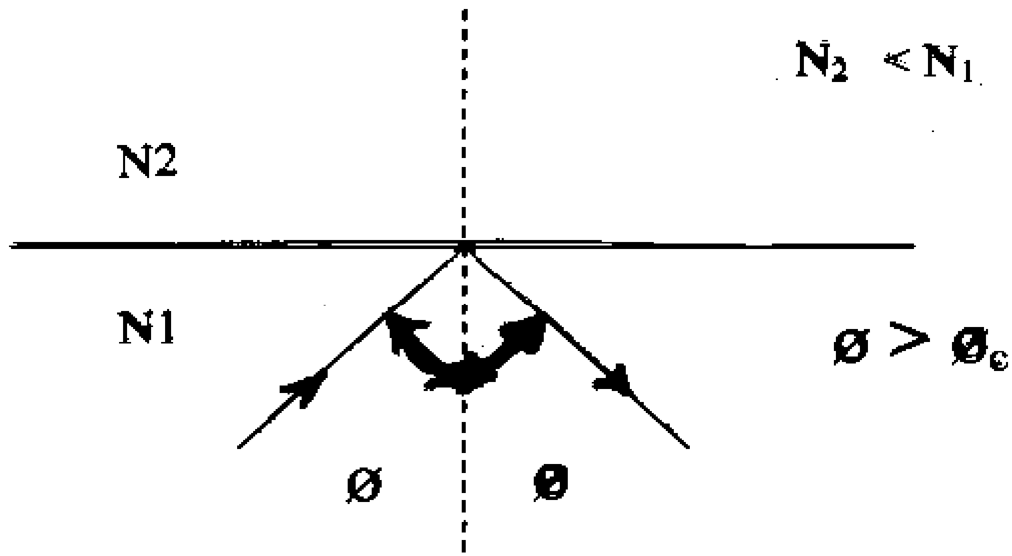


THREE MEDIA- CORE/ CLADDING/ AIR

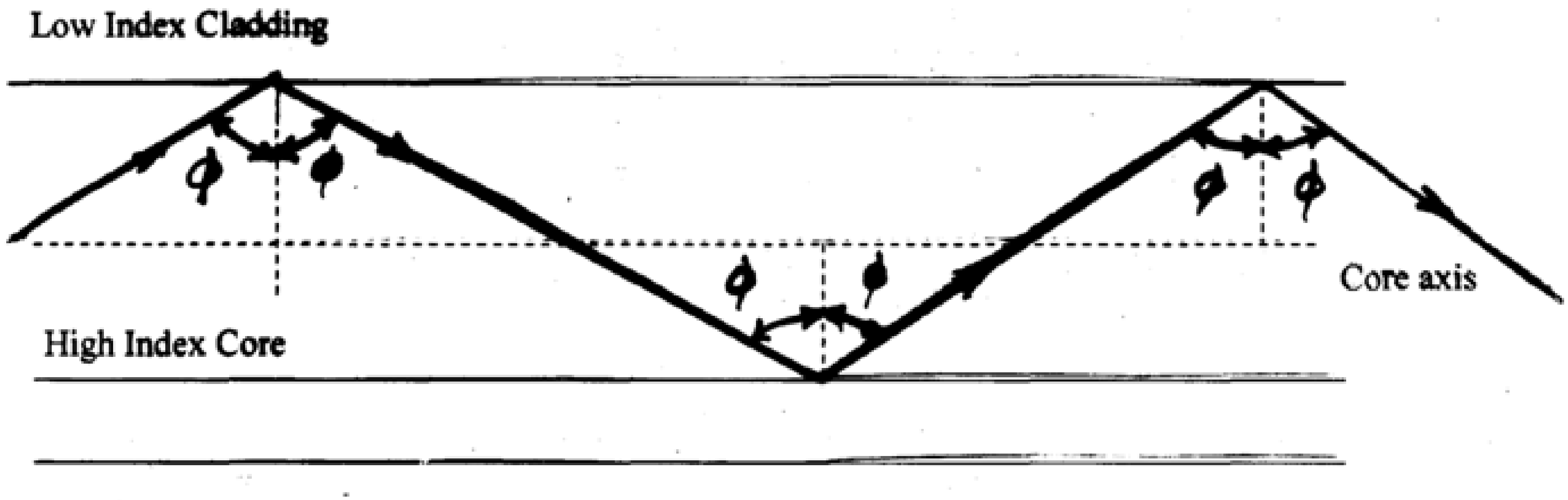
$\theta_1 < \theta_a$ (ACCEPANCE ANGLE)

$N_2 < N_1$

TOTAL INTERNAL REFLECTION (TIR)



- TIR OCCURS WHEN ANGLE OF INCIDENCE EXCEEDS THE CRITICAL ANGLE.
- LIGHT TRAVELS DOWN AN OPTICAL FIBER AT A SHALLOW ANGLE (LESS THAN $9O^0$ -ϕc)VIA A SERIES OF TOTAL INTERNAL REFLECTIONS



TRANSMISSION OF LIGHT RAY IN A PERFECT OPTICAL FIBER

IMPERFECTIONS AT THE CORE CLADDING INTERFACE WOULD RESULT IN LOSSES OF THE LIGHT RAY INTO THE CLADDING

$N_0 \ SIN\theta_1 = N_1 SIN \ \theta_2$---------1

INΔ ABC $\phi=\pi/2 - \theta_2$ OR $\theta_2 = (\pi/2 - \phi)$

WHERE $\phi > \phi_C$

EQUATION (1) BECOMES $N_0 \ SIN \ \theta_1 = N_1 SIN \ \theta_2 = N_1 SIN \ (\pi/2 - \phi)$

i.e. $N_0 \ SIN \ \theta_1 = N_1 \ COS \ \phi$

USING $SIN^2 \phi + COS^2 \phi = 1$

$N_0 \ SIN \ \theta_1 = N_1 \ (1 - SIN^2\phi)^{1/2}$

LIMITING CASE FOR TIR

$\boldsymbol{\phi = \phi_C, \ \theta_1 = \theta_a, \ SIN \ \phi_C = N_2/N_1}$

$N_0 \ SIN\theta_a = N_1 \ (1 - N_2^2/N_1^2)^{½} = (N_1^2 - N_2^2)^{½}$

$NA = N_0 \ SIN \ \theta_a = (N_1^2 - N_2^2)^{½} = \sin\theta_a$

(SINCE $N_0 = 1$ FOR AIR)

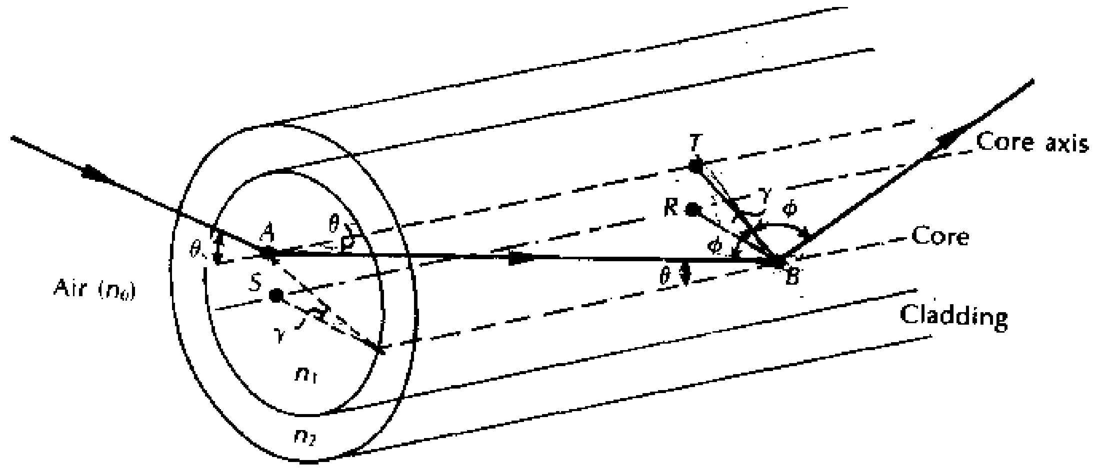
THE OPTICAL RAY WILL BE PROPAGATED ALONG THE FIBER FOR $0 \leq \theta_1 \leq \theta_a$

NA IS INDEPENDENT OF THE FIBER CORE DIA

LET $\Delta = N_1^{2-}N_2^2/2N_1^2$= RELATIVE REF. INDEX DIFF. BETWEEN CORE & CLADDING.

HENCE NA = $N_1 (2 \Delta)^{1/2}$

Skew Rays



The ray path within the fiber core for a skew ray incident at an angle θs to the normal at the air—core interface.

Y= Angle between the projection of the ray and radius of the fiber core at the point of reflection

- Plane BRS – Normal to core axis.

  Reflection at pt B at an angle Φ

  Cos γ Sin θ =cosΦ

  $=(1-\sin^2 \Phi)^{1/2}$ (A)

Skew Rays(Contd.)

Limiting Case

$\Phi = \Phi_c \qquad \sin\Phi_c = n_2/n_1$

From A $\sin\theta = \cos\Phi_c / \cos\gamma$

Using Snell's law at point A

no $\sin\theta_a = n_1 \sin\theta \quad [n_1 \sin\theta_1 = n_2 \sin\theta_2]$

where θa = max input axial angle for meridional rays

no $\sin\theta_{as} = n_1 \cos\Phi_c / \cos\gamma$

where θas =max. input angle (acceptance) for skew rays

no.$\sin\theta_{as} \cos\gamma = n_1 \cos\Phi_c = n1(1 - n_2^2/n_1^2)^{1/2}$

$= (n_1^2 - n_2^2)^{1/2} = NA$

$\sin\theta_{as} \cos\gamma = NA$

Skew Rays(Contd.)

$\sin\theta_{as} \cos\gamma = NA$ (skew Rays)

$\sin\theta_a = NA$ (Meridional Rays)

Skew rays are accepted at larger axial angles in a given fiber than meridional rays .

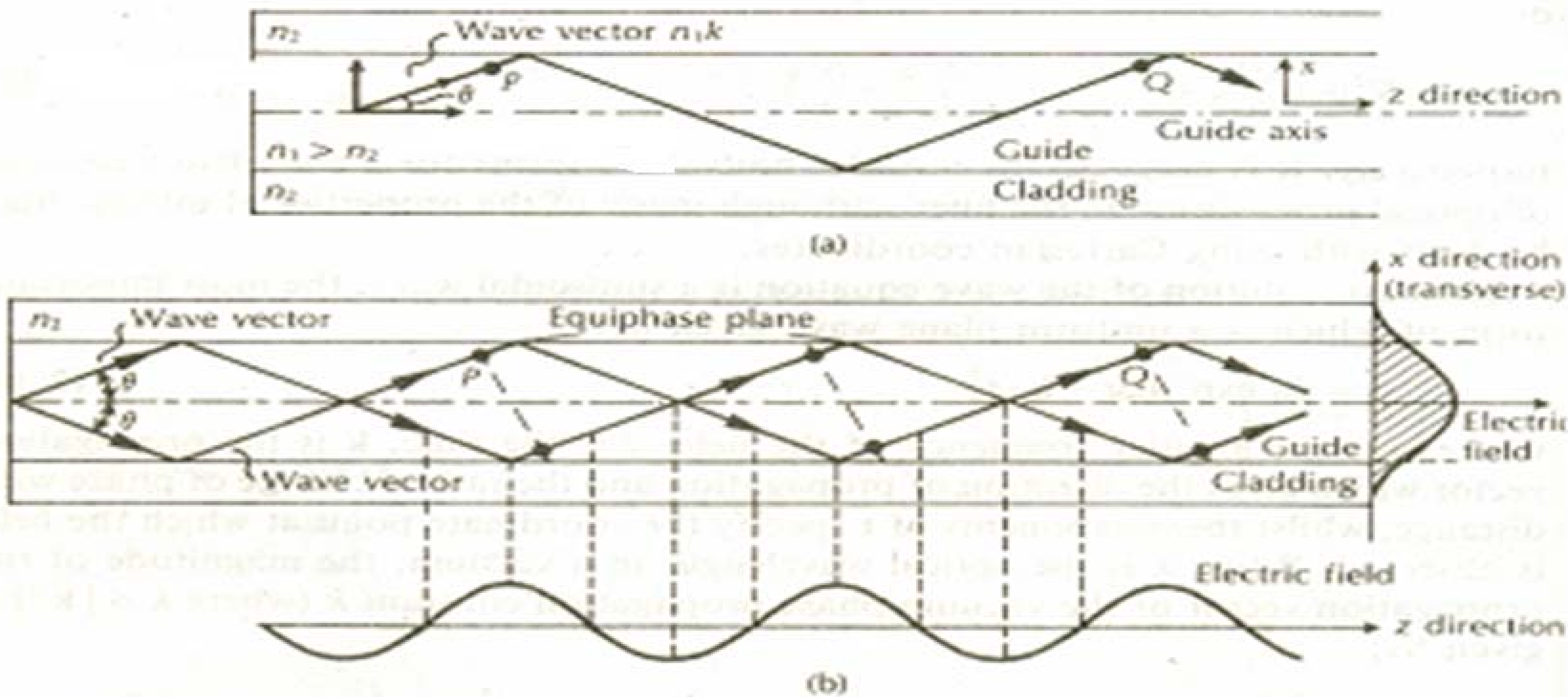
$\cos\gamma = 1$; $\theta_{as} = \theta_a$

Although θa is the maximum conical half angle for acceptance of meridional rays, it defines the minimum input angle for skew rays.

Thus skew rays tend to propagate in the angular region near the outer surface of the core.

Skew rays are complimentary to meridional rays and increase the light gathering capacity of the fiber.

MODES-Planar Guide



Picture The formation of a mode in a planar dielectric guide: (a) a plane wave propagating in the guide shown by its wave vector or equivalent ray – the wave vector is resolved into components in the z and x directions; (b) the interference of plane waves in the guide forming the lowest order mode ($m = 0$).

MODES (contd)

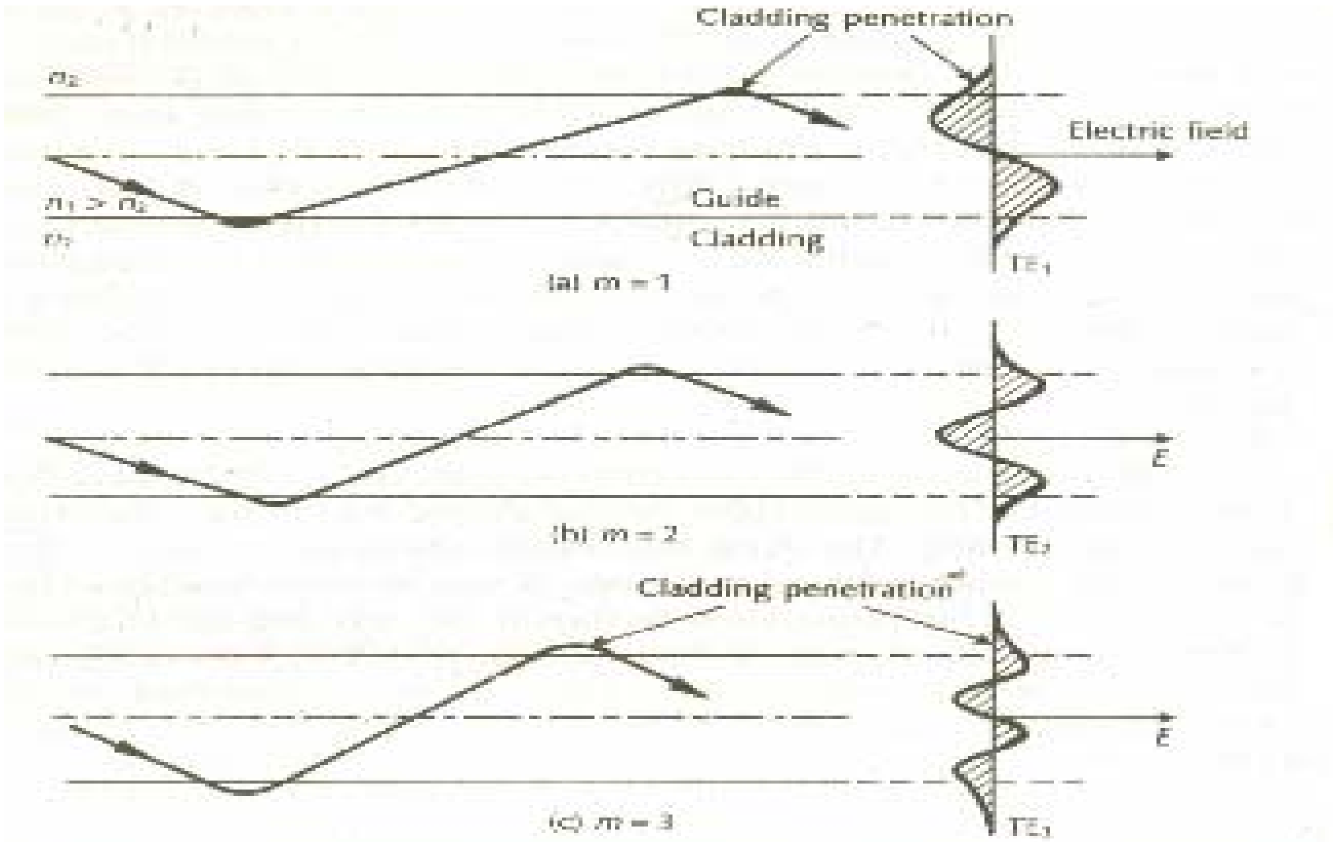


Figure Physical model showing the ray propagation and the corresponding transverse electric (TE) field patterns of three lower order models (m = 1, 2, 3) in the planar dielectric guide.

MODES (contd)

Mode: The stable field distribution in the X direction with only a periodic Z dependence is called a mode

- Each distinct value of θ corresponds to a mode
- **β= propagation constant= 2π / λ**
- **$e^{j(\omega t-\beta z)}$** ; factor describes a mode propagating in Z direction
- The integer m denotes the number of zeroes in the transverse field pattern
- m = mode number= order of the mode

MODES (contd)

TE Mode:

Electric field is perpendicular to the direction of propagation, $E_z = 0$(H_z is not 0)

TM Mode:

Magnetic field is perpendicular to the direction of propagation

So $H_z=0$(E_z is not 0)

•The field varies harmonically in guiding region (n_1) and decays exponentially outside this region.

•Lower order Modes: Field concentrated near centre(axis)

•Higher order modes: Field distributed more towards edges of the guide and penetrates farther into cladding.

V number= Value of fiber

- $V = \frac{2\pi a}{\lambda}(n1^2 - n2^2)^{1/2} = \frac{2\pi a}{\lambda}(NA) = \frac{2\pi a\, n1}{\lambda}(2\Delta)^{1/2}$

- V is a dimensionless parameter

- The number of guided modes depends on the value of V (a, Δ, λ)

$$M = \frac{V^2}{2}$$

- There is a cut off value of normalized frequency Vc for guided modes below which they cannot exist.

Note: most of the optical power is carried in the core region and not in the cladding.

MODES & MODE COUPLING

MODES: IN CYLINDERICAL WAVE GUIDES VARIOUS MODES OF PROPAGATION ARE REFERED TO TE $_{lm}$ or TM $_{lm}$ where l & m are integers.

. **MODE COUPLING**: wave guides are not perfect

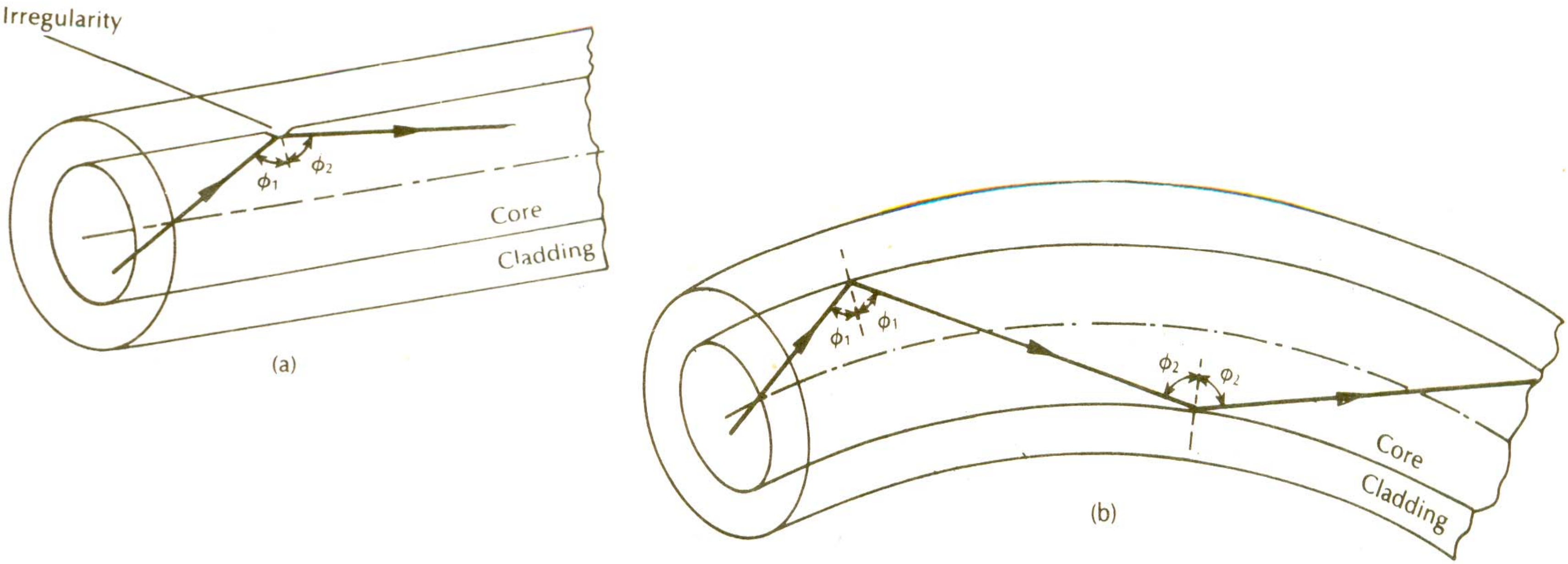
WAVE GUIDE IMPERFECTIONS: (a) fiber axis deviations from straightness.

(b) Variations in core dia

(c irregularities at the core cladding interface.

(d) Refractive index variation

Due to any /some of these disturbances, the energy travelling in one mode gets coupled to another mode.



Ray theory illustrations showing two of the possible fiber perturbations which give mode coupling: (a) irregularity at the core—cladding interface; (b) fiber bend.

- CHANGE OF ANGLE CORRESPONDS TO A CHANGE IN THE PROPAGATING MODE FOR THE LIGHT (MODE COUPLING) `

MODE- COUPLING(contd)

- **Thus individual modes do not propagate throughout the length of the fiber without large energy transfers to adjacent modes, even when the fiber is exceptionally good quality and is not strained or bent by its surroundings.**

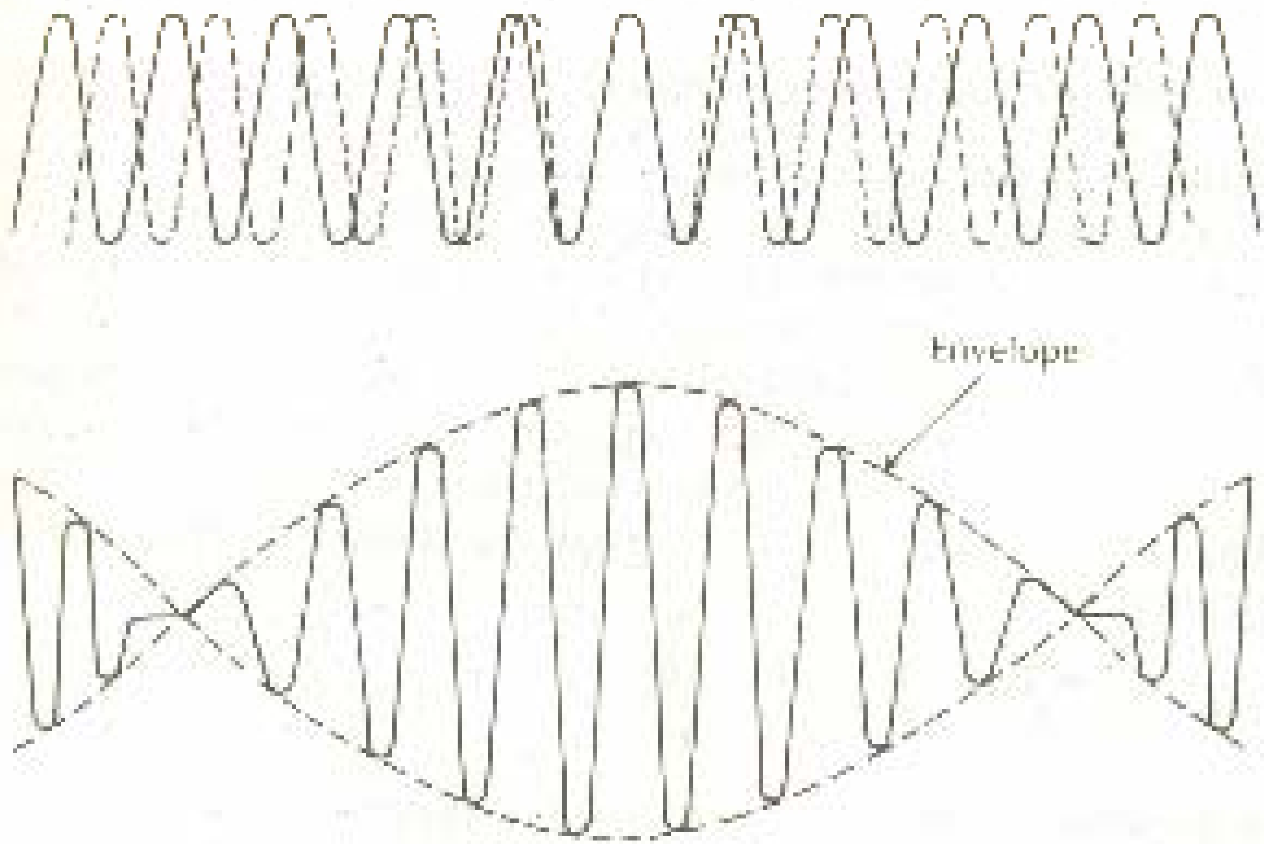
PHASE VELOCITY & GROUP VELOCITY

- WITHIN ALL EM WAVES, (PLANE OR OTHERWISE) THERE ARE POINTS OF CONSTANT PHASE.
- WAVE FRONT REFERS TO THE SURFACE FORMED BY CONSTANT PHASE POINTS.
- WAVE FRONT TRAVELS WITH A PHASE VELOCITY Vp

  $V_p = \omega / \beta$ ω - ANGULAR FREQ. OF THE WAVE

  β - PROPAGATION CONSTANT
- LIGHT IS GENERALLY COMPOSED OF A SUM OF PLANE WAVE COMPONENTS OF DIFFERENT FREQUENCIES.

Formation of wave packet



The formation of a wave packet from the combination of two waves with nearly equal frequencies. The envelope of the wave package or group of waves travels at a group velocity v_g.

GROUP INDEX(Vg)

$$v_g = \frac{d\omega}{d\beta} = \frac{d\omega / d\lambda}{d\beta / d\lambda} = \frac{d\omega}{d\lambda}\left[\frac{d\beta}{d\lambda}\right]^{-1}$$

$$= \frac{d\omega}{d\lambda}\left[\left\{\frac{d}{d\lambda}(n_1 \frac{2\pi}{\lambda})\right\}^{-1}\right] = \frac{d\omega}{d\lambda}\left[\frac{1}{2\Pi}\left\{\frac{d}{d\lambda}\left(\frac{n_1}{\lambda}\right)\right\}^{-1}\right]$$

GROUP INDEX(Vg)

$$= \frac{dw}{d\lambda}\left[\frac{1}{2\pi}\left\{\frac{\lambda.\frac{dn_1}{d\lambda} - n_1}{\lambda^2}\right\}^{-1}\right] = \frac{d\omega}{2\pi\lambda}\left[\frac{dn_1}{d\lambda}\frac{1}{\lambda} - \frac{n_1}{\lambda^2}\right]^{-1}$$

$$= \frac{\omega}{2\pi\lambda}\left[\frac{dn_1}{d\lambda}\frac{1}{\lambda} - \frac{n_1}{\lambda^2}\right]^{-1} = \frac{\frac{\omega}{2\pi\lambda}}{\frac{dn_1}{d\lambda}\frac{1}{\lambda} - \frac{n_1}{\lambda^2}}$$

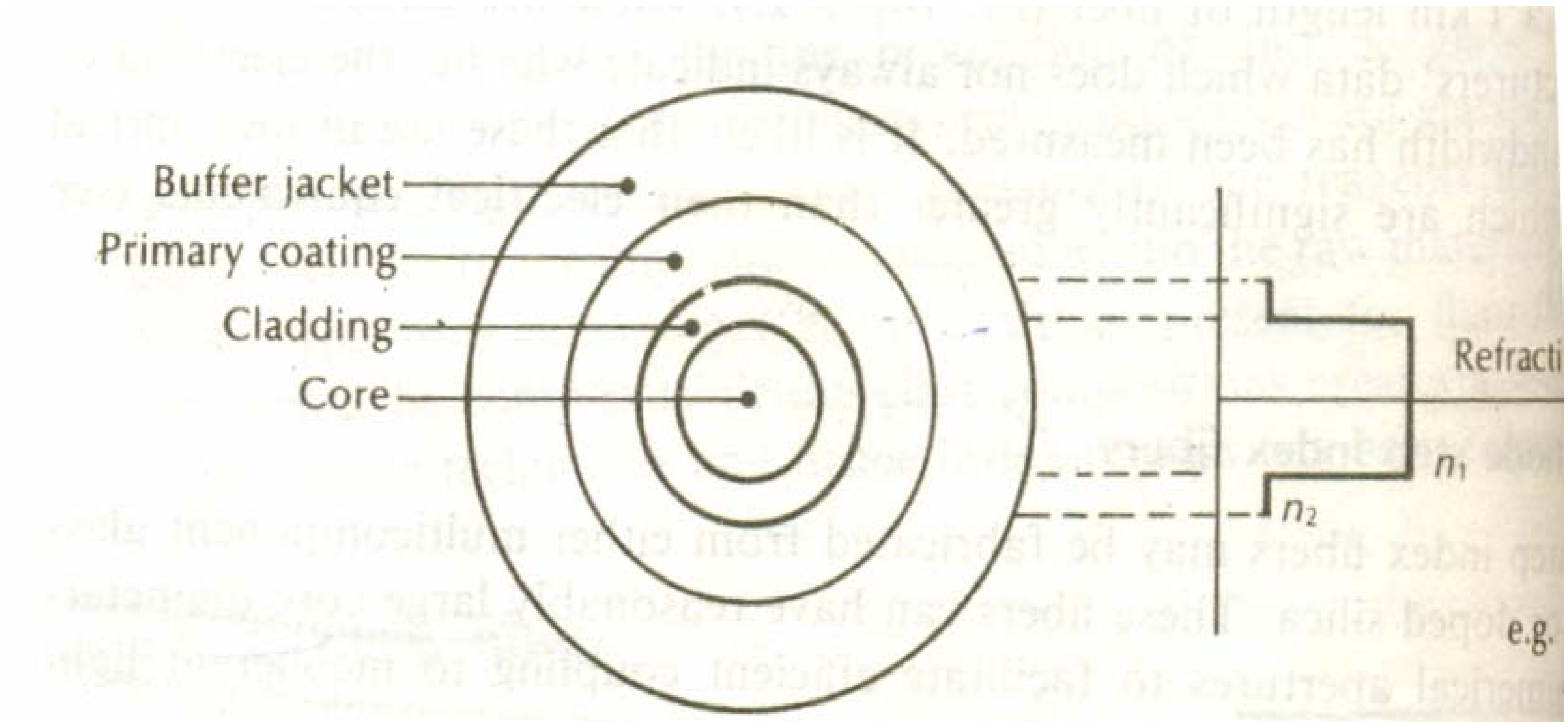
GROUP INDEX(Ng)

- Multiply numerator & denominator by λ²
- N_g - Group Index of the guide

$$\frac{\frac{\omega\lambda}{2\pi}}{\lambda\frac{dn_1}{d\lambda}-n_1}=\frac{-\frac{2\pi f\lambda}{2\pi}}{n_1-\lambda\frac{dn_1}{d\lambda}}$$

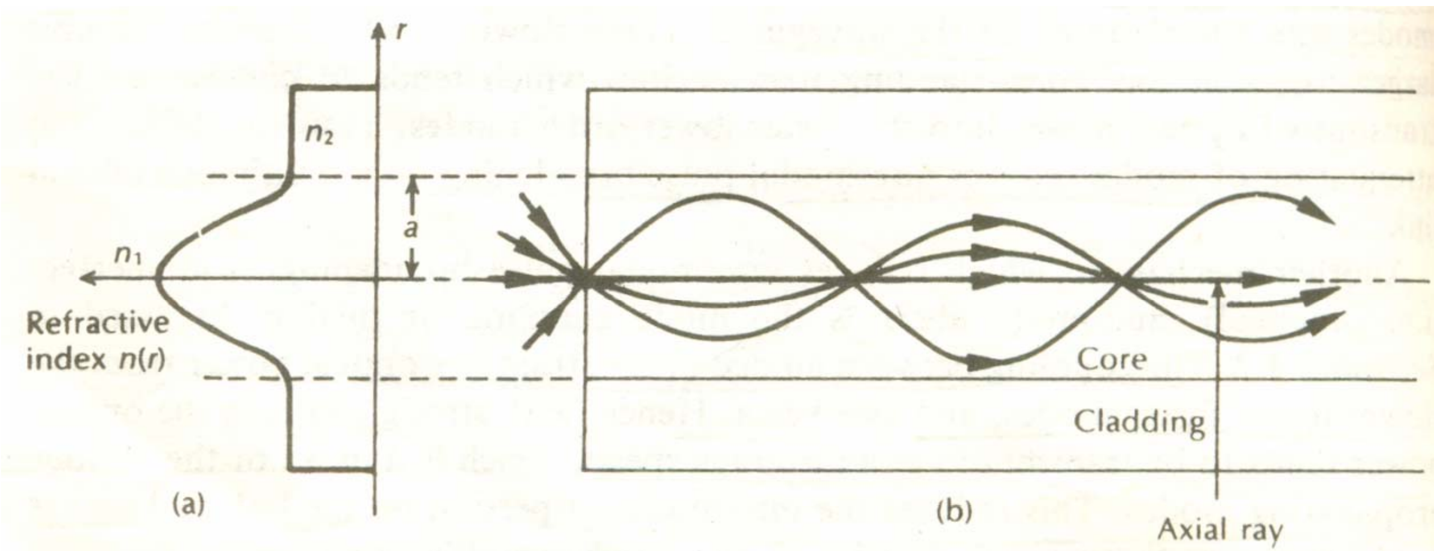
$$=\frac{c}{n_1-\lambda\frac{dn_1}{d\lambda}}=\frac{c}{N_g}$$

MULTIMODE STEP INDEX FIBERS



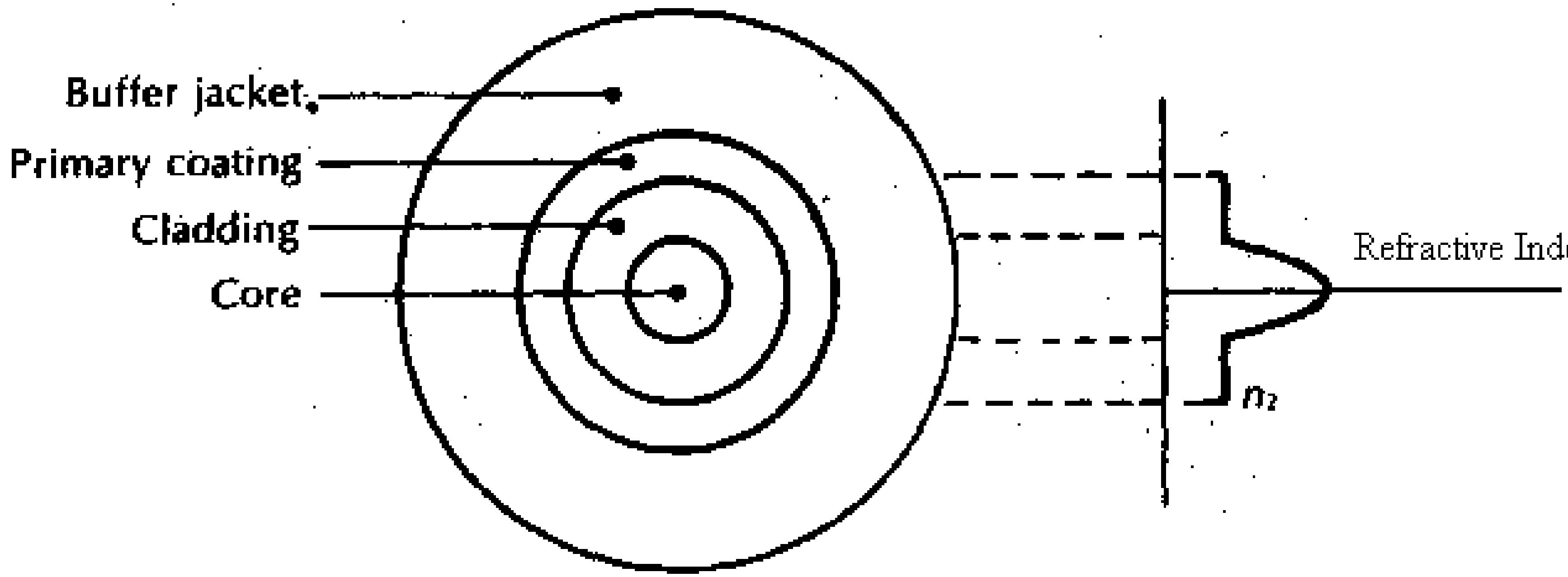
MULTIMODE GI FIBER(contd)

- The gradual decrease in ref index from the centre of the core ,creates many refractions of the rays .(High to low ref. index)



A multimode graded index fiber: (a) parabolic refractive index profile; (b) meridional ray paths within the fiber core.

GRADED INDEX FIBER (contd)



GRADED INDEX FIBERS

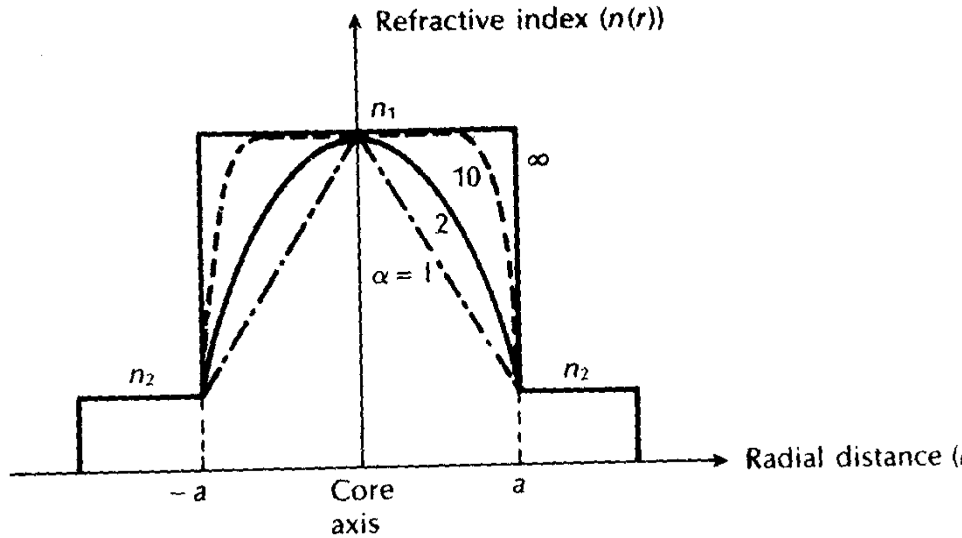
Max value of n_1 at the axis

Constant value of n_2 beyond core radius a.

$n(r) = n_1 (1-2\Delta (r/a)^{\alpha})^{1/2}$ r< a (core)

$n_1 (1-2\Delta)^{1/2} = n_2$ $r \geq a$ (cladding)

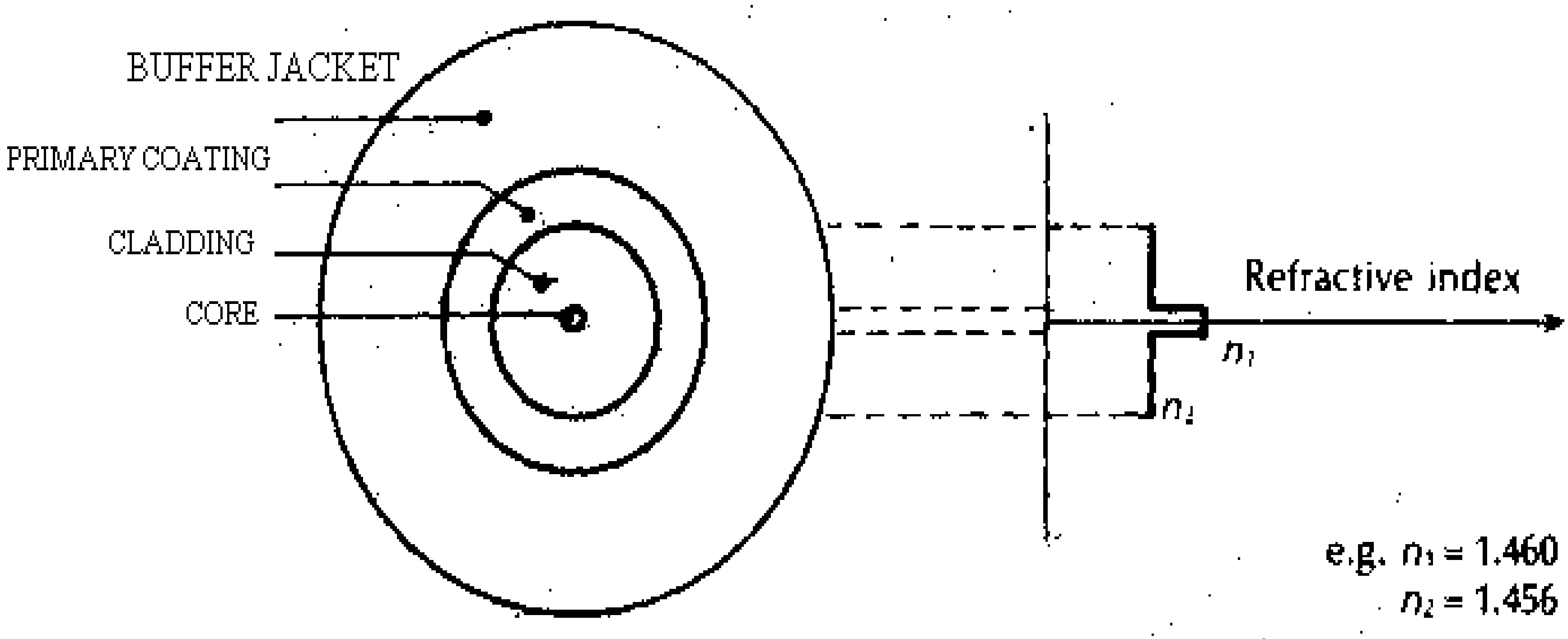
where α = profile parameter



Refractive index profile for diff values of α

Parabolic ref. index profile produces the best results for multi mode opt .propagation (α =2)

SINGLE MODE FIBERS



MULTIMODE STEP INDEX FIBERS

Material of fabrication-doped silica or multi component glass compounds

Doped silica fiber exhibit best performance.

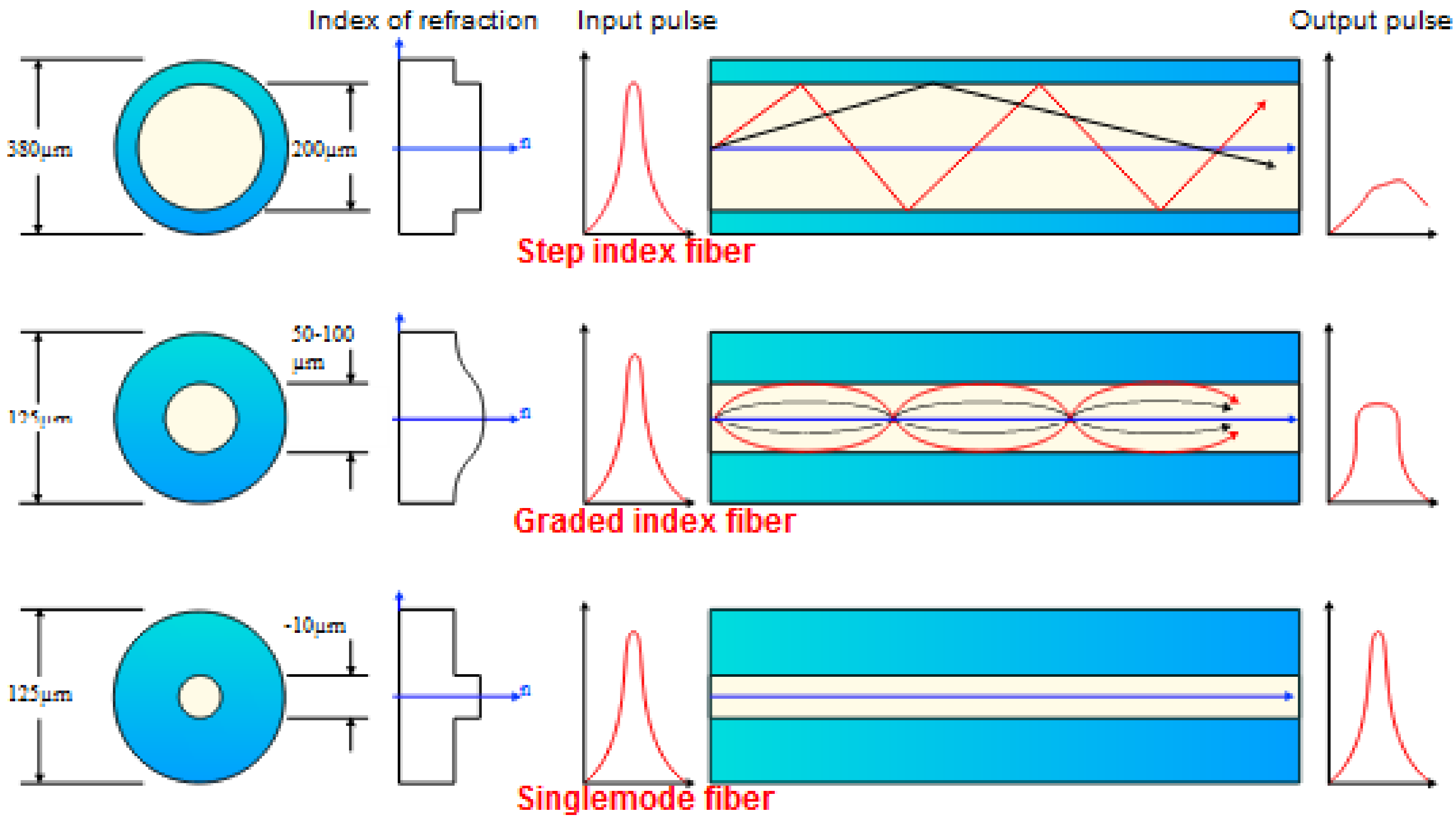
Structure: core DIA: 50 to 400 μm

Cladding DIA: 125 to 500μm

Buffer Jacket DIA: 250 to 1000μm

Numerical aperture: 0.16 to 0.5

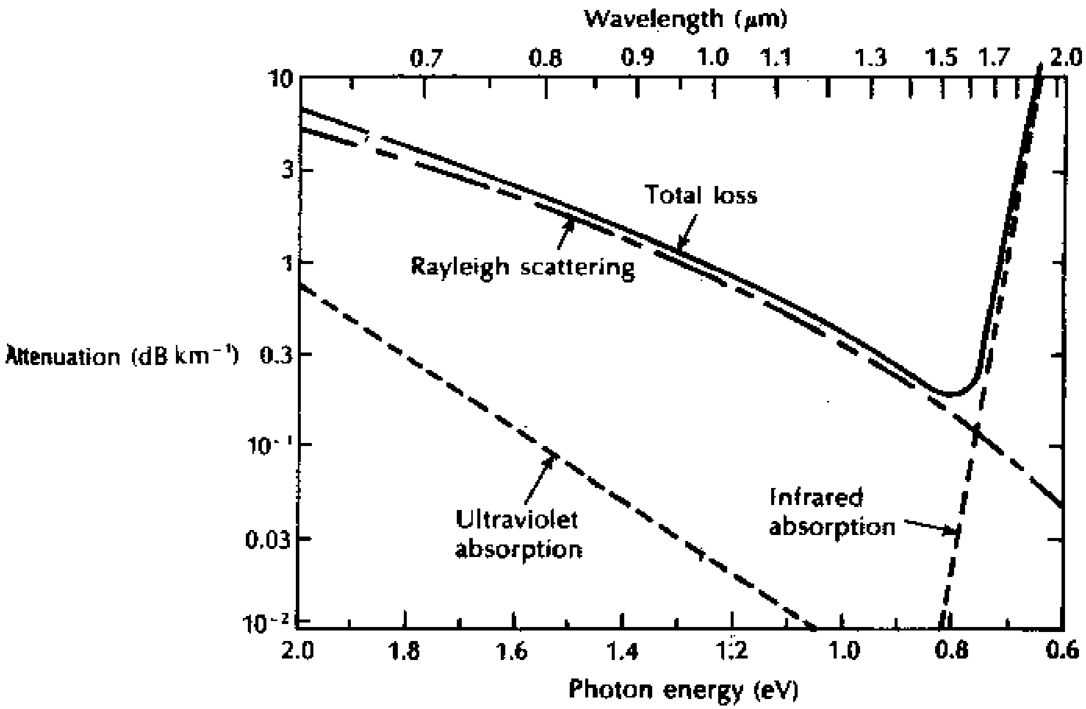
Review Of All Fiber Types



Material absorption Losses

- Material absorption is a loss mechanism related to material composition and fabrication process for the fiber.
- This results in dissipation of some of the transmitted optical power as heat in the wave guide.
- Absorption
  - Intrinsic (due to major components of glass)
  - Extrinsic (caused by impurities)

Material absorption Losses (contd.)



The attenuation spectra for the intrinsic loss mechanisms in pure GeO_2SiO_2 glass

Material absorption Losses (contd.)

- Attn. Spectra for intrinsic loss mechanism in pure GeO_2 - SiO_2 Glass
- Pure silicate glass has little intrinsic absorption, due to its basic material structure in the near infra-red region.
- Loss is due to stimulation of electron transitions within Glass!

Extrinsic Absorption

It is due to impurities (metal elements)

Impurities	Loss (due to 1 part in 10^9) in dB/Km
Cr^{3+}	1.6
Cu^{2+}	1.1
Fe^{2+}	0.68
Ni^{2+}	0.1

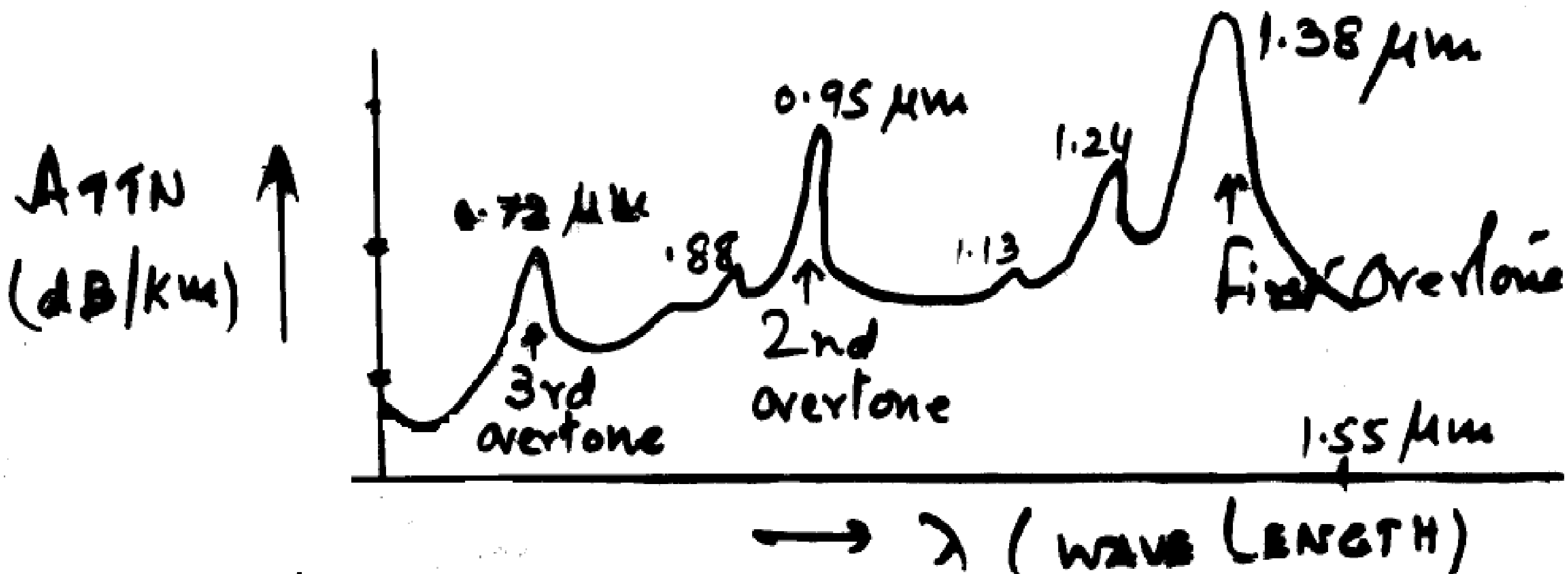
These transition element impurities can be reduced to acceptable levels (one part in 10^{10}) by glass refining techniques.

Another major extrinsic loss mechanism is due to water (oH ion) dissolved in glass .

At 0.95µm- 1.38µm, ATTN is 1-2 db/Km (1 ppm of OH)

Extrinsic Absorption (Contd.)

- Lowest ATTN for this fiber occurs at a wavelength of 1.55 μm and is about 0.2db/Km (Min possible is 0.18 db/Km.)



ABSORPTION SPECTRUM FOR OH GROUP IN SILICA

Linear Scattering

Two types of linear scattering

-**Rayleigh Scattering**

-MIE Scattering

Rayleigh Scattering

Dominant intrinsic loss mechanism between ultraviolet and infrared absorption regions.

It is due to changes in ref. index (inhomogeneties of a random nature)

The inhomogeneties are because of **density & composition variations** which are frozen into glass lattice on cooling.

Glass is composed of randomly connected network of molecules.

Rayleigh Scattering(contd)

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

(Rayleigh'Scattering Co-efficient)

p=average photo elastic coefficient

β_c = Isothermal compressibility at a fictive temp.

K= Boltzman's Constant

T_F= temp at which glass can reach a state of thermal equilibrium.

MIE Scattering

This results from non perfect cylindrical structure of the waveguide, and fiber imperfections, eg.

-Core, cladding interface irregularities

-Ref. index variation along fiber length

-Dia. fluctuations

-Strains & bubbles.

MIE Scattering(contd)

Scattering created is in the forward direction.

The inhomogenties can be reduced by

-**removing imperfections due to glass mfg. process.**

-**controlled extrusion & coating of fiber**.

- **Increasing the fiber guidance by increasing the relative ref. index difference**.

Note: There is no change of freq. on scattering with all linear processes.

-

TRANMISSION CHARACTERISTICS OF FIBERS

Attenuation (or loss)

Band width

Unit of attenuation: dB

$$dB = 10 \log_{10} P_i / P_o$$

where P_i = input opt. power into the fiber

P_o= output opt. power

By definition : $10^{dB/10} = P_i / P_o$

In OFC ,attenuation is generally expressed in decibels per unit length (dB/km)

TRANSMISSION CHARACHTERISTICS OF FIBERS

$$\therefore \alpha \text{ dB } .L = 10 \log_{10} P_i / P_o$$

where α is the signal attenuation per unit length

L is fiber length.

Note : OFC became specially attractive when transmission losses of fibers were reduced below those of competing metallic conductors. (< 5dB / km)

TRANSMISSION CHARACHTERISTICS OF FIBERS (contd)

- **BANDWIDTH**

-This is limited by the signal dispersion within the fiber, which determines the no of bits of information transmitted in a given time period.

Note : Today wideband fiber bandwidths of many tens of GHz over a number of Km are available

DISPERSION

DISPERSION MECHANISM CAUSES BROADENING OF THE TRANSMITTED LIGHT PULSES. (AS THEY TRAVEL ALONG THE CHANNEL)

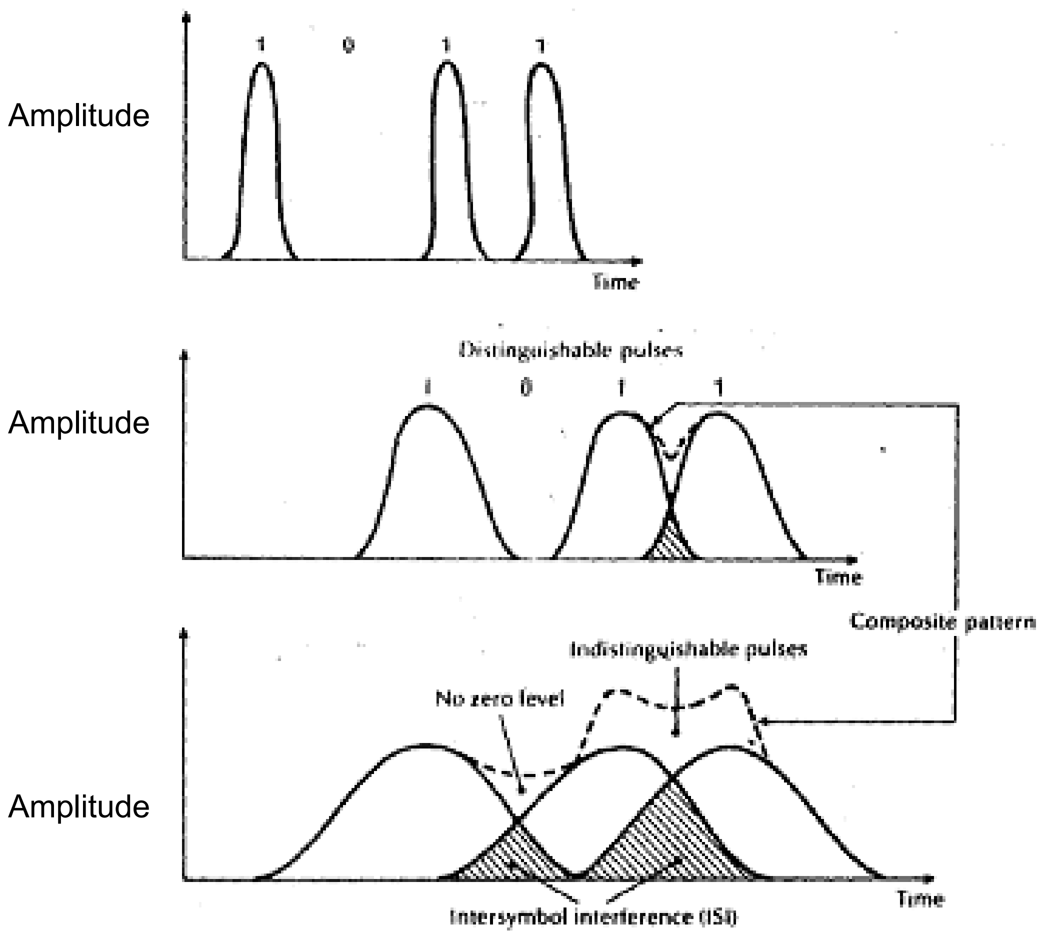
EACH PULSE BROADENS AND OVERLAPS WITH ITS NEIGHBOURS. THE EFFECT IS KNOWN AS

INTERSYMBOL INTERFERENCE (ISI)

ISI

- ISI RESULTS IN AN ERROR RATE WHICH IS A FUNCTION OF SIGNAL ATTENUATION AND SNR AT THE RECEIVER.
- SIGNAL DISPERSION LIMITS THE MAX. BANDWIDTH ATTAINABLE (TO THE POINT WHERE INDIVIDUAL SYMBOLS CAN NO LONGER BE DISTINGUISHED

• INTERSYMBOL INTERREFRENCE (ISI)



An illustration using the digital bit pattern 1011 of the broadening of light pulses as they are transmitted along a fiber: (a) fiber input; (b) fiber output at a distance L1;(c) fiber output at a distance L2> L1.

FOR NO OVERLAPPING OF LIGHT PULSES

DIGITAL BIT RATE, $B_T \leq 1/2\tau$

WHERE τ = INPUT PULSE DURATION

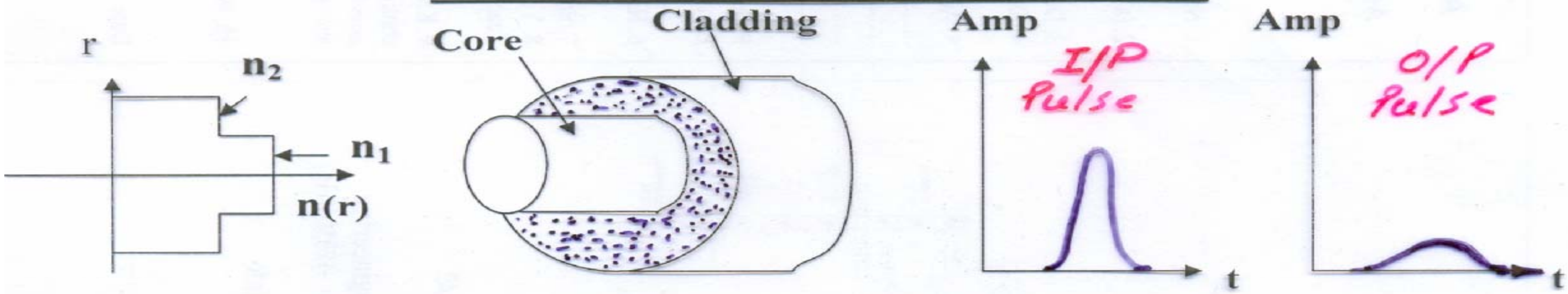
= PULSE BROADENING DUE TO DISPERSION

ALTERNATIVELY

$B_T = (1/4\sigma)/(1/\ 5\sigma)$

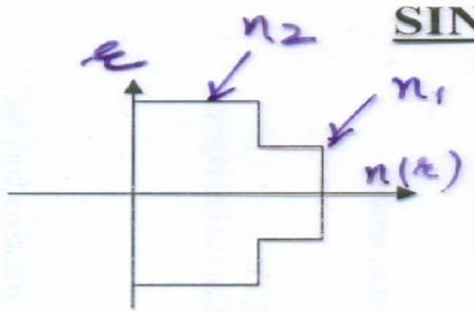
WHERE σ = RMS WIDTH OF GAUSSIAN SHAPE AT THE OUTPUT.

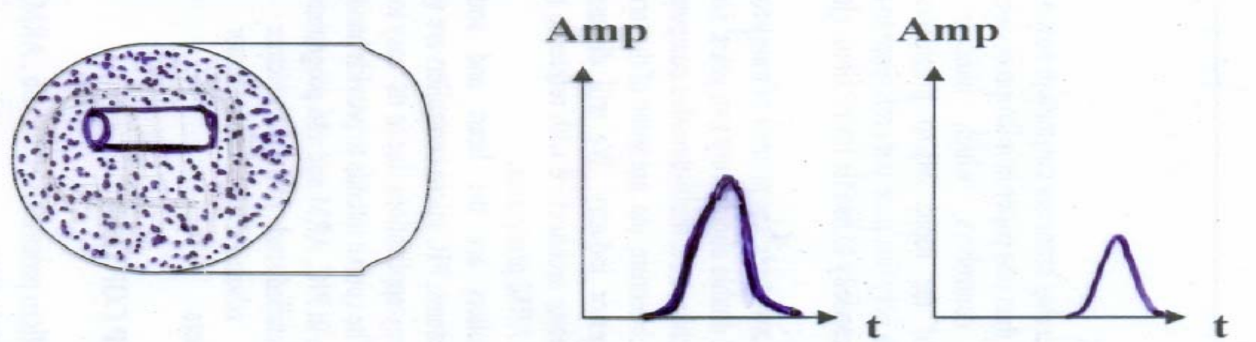
MULTIMODE STEP INDEX FIBER



MULTIMODE GRADED INDEX FIBER

SINGLE MODE STEP INDEX FIBER





SINGLE MODE FIBER GIVES MIN PULSE BROADENING & THUS YIELDS MAX TRANSMISSION BW

INTRAMODAL DISPERSION

OPTICAL SOURCES DO NOT EMIT JUST A SINGLE FREQ, BUT A BAND OF FREQUENCIES.

THIS RESULTS IN PROPAGATIQNAL DELAY DIFFERENCES BETWEEN THE DIFFERENT SPECTRAL COMPONENTS OF THE Tx SIGNAL.

THIS CAUSES **BROADENING OF EACH TRANSMITTED MODE (INTRAMODAL DISPERSION).**

THE INTRAMODAL DISPERSION MAY BE CAUSED BY **MATERIAL DISPERSION** AND **WAVE GUIDE DISPERSION.**

MATERIAL DISPERSION

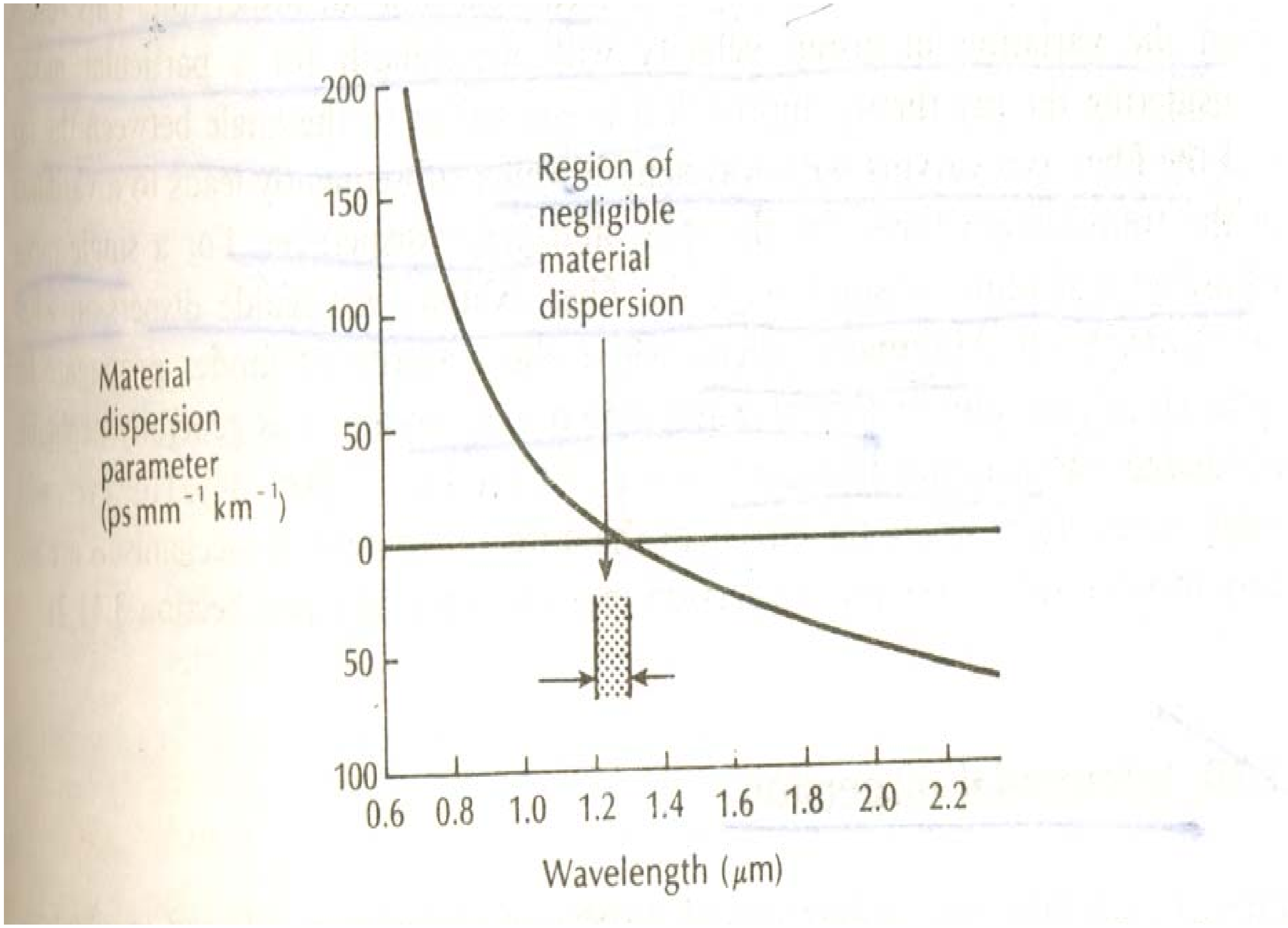
PULSE BROADENING RESULTS FROM DIFF.GROUP VELOCITIES OF VARIOUS SPECTRAL COMPONENTS LAUNCHED INTO OPTICAL FIBRE SOURCE.

PHASE VELOCITY OF WAVE VARIES NON-LINEARLY WITH WAVELENGTH.

A MATERIAL IS SAID TO EXHIBIT MATERIAL DISPERSION WHEN

$d^2n/ d\lambda^2 \neq 0$

- **0.1-0.2 ns / km in multimode fibers**



The material dispersion parameter for silica as a function of wavelength

.

WAVE GUIDE DISPERSION

THIS RESULTS FROM VARIATION IN GROUP VELOCITY WITH WAVELENGTH FOR A PARTICULAR MODE.

IT IS EQUIVALENT TO VARIATION OF ANGLE BETWEEN RAY AND FIBER AXIS WITH WAVELENGTH, RESULTING IN VARIATION IN TRANSMISSION TIMES FOR THE RAYS, AND HENCE DISPERSION.

SINGLE MODE FIBER EXHIBITS WAVEGUIDE DISPERSION WHEN $d^2\beta/d\lambda 2 \neq 0$

MULTIMODE FIBERS ARE NORMALLY FREE OF WAVEGUIDE DISPERSION.

INTERM0DAL / MODAL/ MODE DISPERSION

PULSE BROADENING RESULTS FROM THE PROPAGATION DELAY DIFFERENCES BETWEEN MODES WITHIN A MULTIMODE FIBER

.

DIFFERENT MODES IN A MULTIMODE FIBER TRAVEL ALONG THE CHANNEL AT DIFFERENT GROUP VELOCITIES.

<u>INTERM0DAL / MODAL/ MODE DISPERSION</u>

MULTIMODE STEP INDEX FIBERS EXHIBIT MAX INTERMODAL DISPERSION.

GRADED INDEX FIBERS EXHIBIT FAR LESS PULSE BROADENING THAN THE ABOVE CASE (TYPICALLY BY A FACTOR OF 100). **SO HIGHER BW IS AVAILABLE**.

SINGLE MODE STEP INDEX FIBERS EXHIBIT LEAST PULSE BROADENING AND HENCE THE GREATEST POSSIBLE BW.

REDUCING INTERMODAL DISPERSION

- BY ADOPTION OF AN OPTIMUM REF. INDEX PROFILE

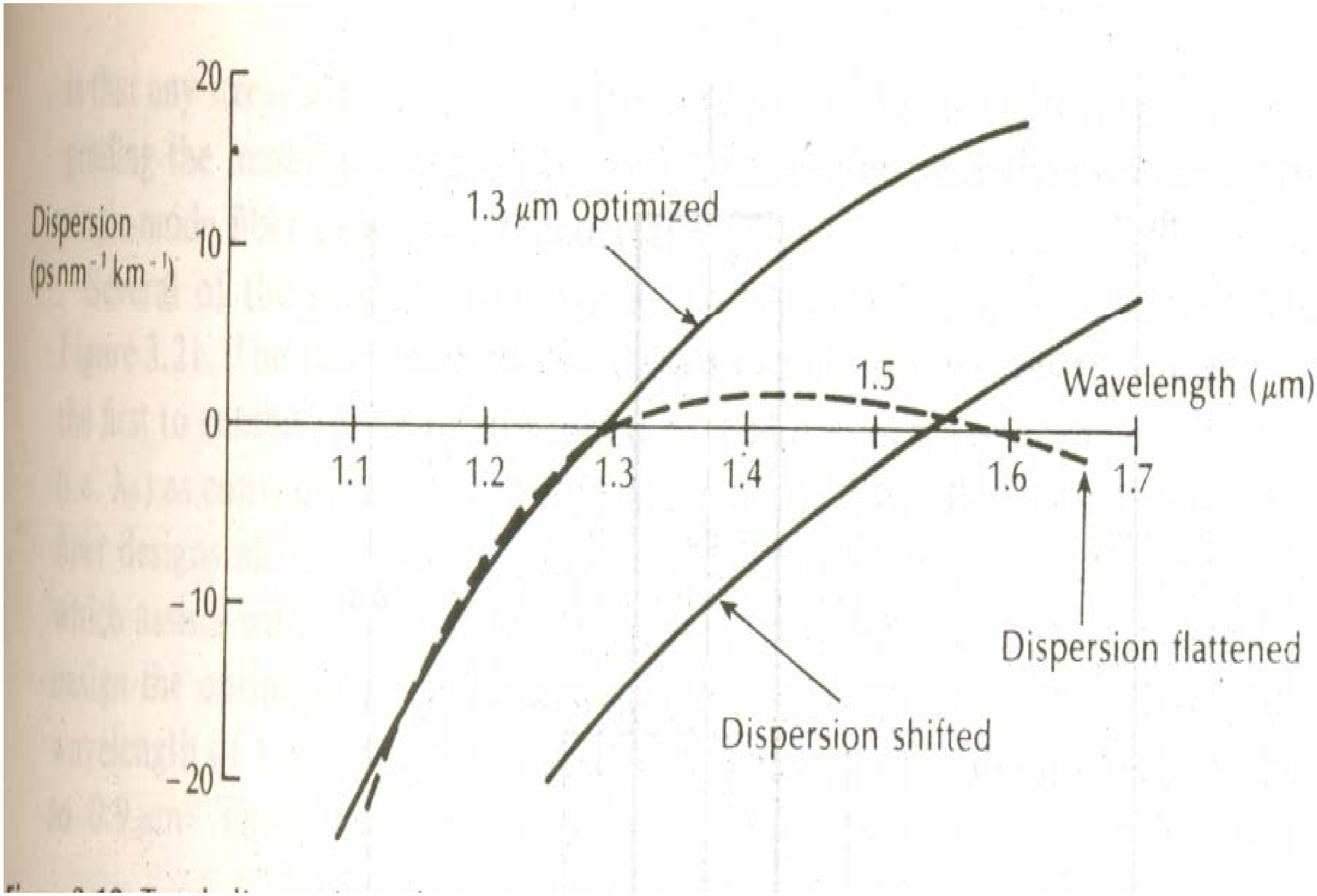
GRADING THE CORE REFRACTIVE INDEX TO FOLLOW A NEAR PARABOLIC PROFILE.

DISPERSION SHIFTED FIBERS

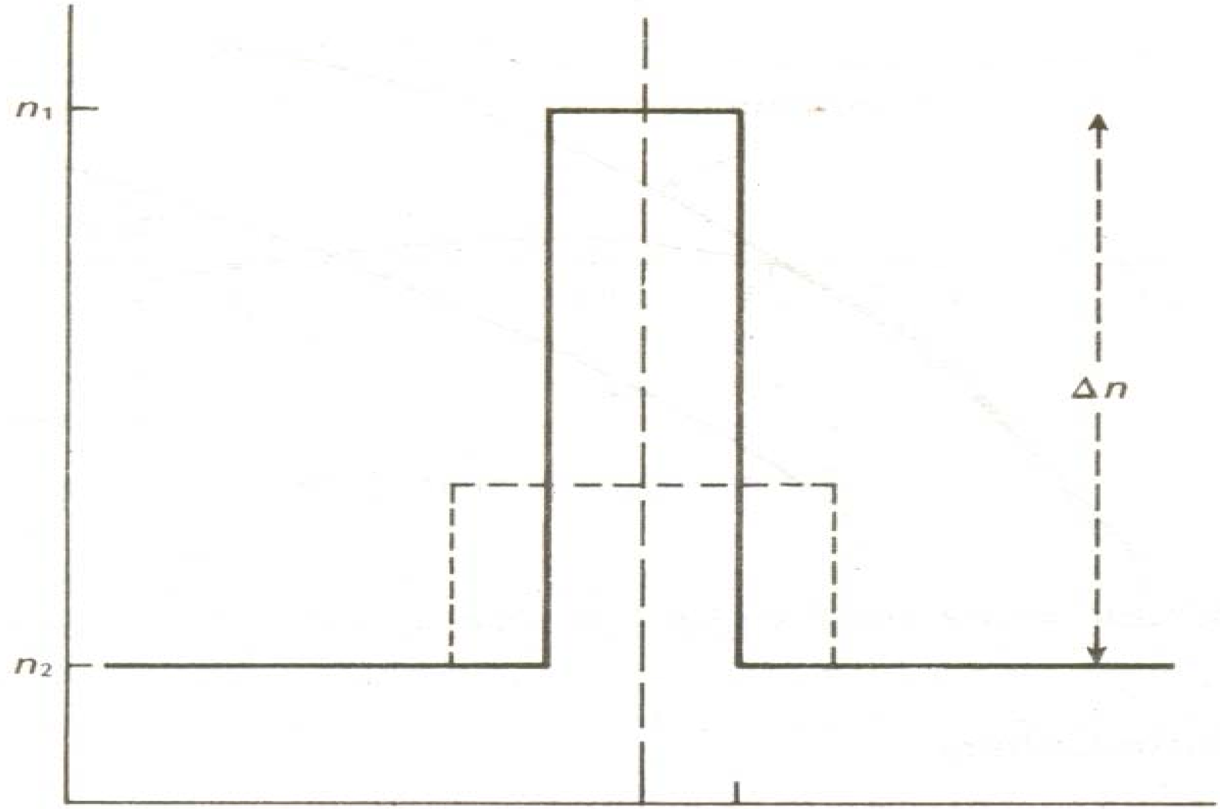
- Refractive Index profile can be modified in order to tune to zero dispersion wavelength point
- **Shift to a longer wavelength by reducing the core dia and increasing the fractional refractive index difference(fig)**
- **Higher concentration of the dopant causes a shift to longer wavelength**

DISPERSION SHIFTED FIBERS(contd)

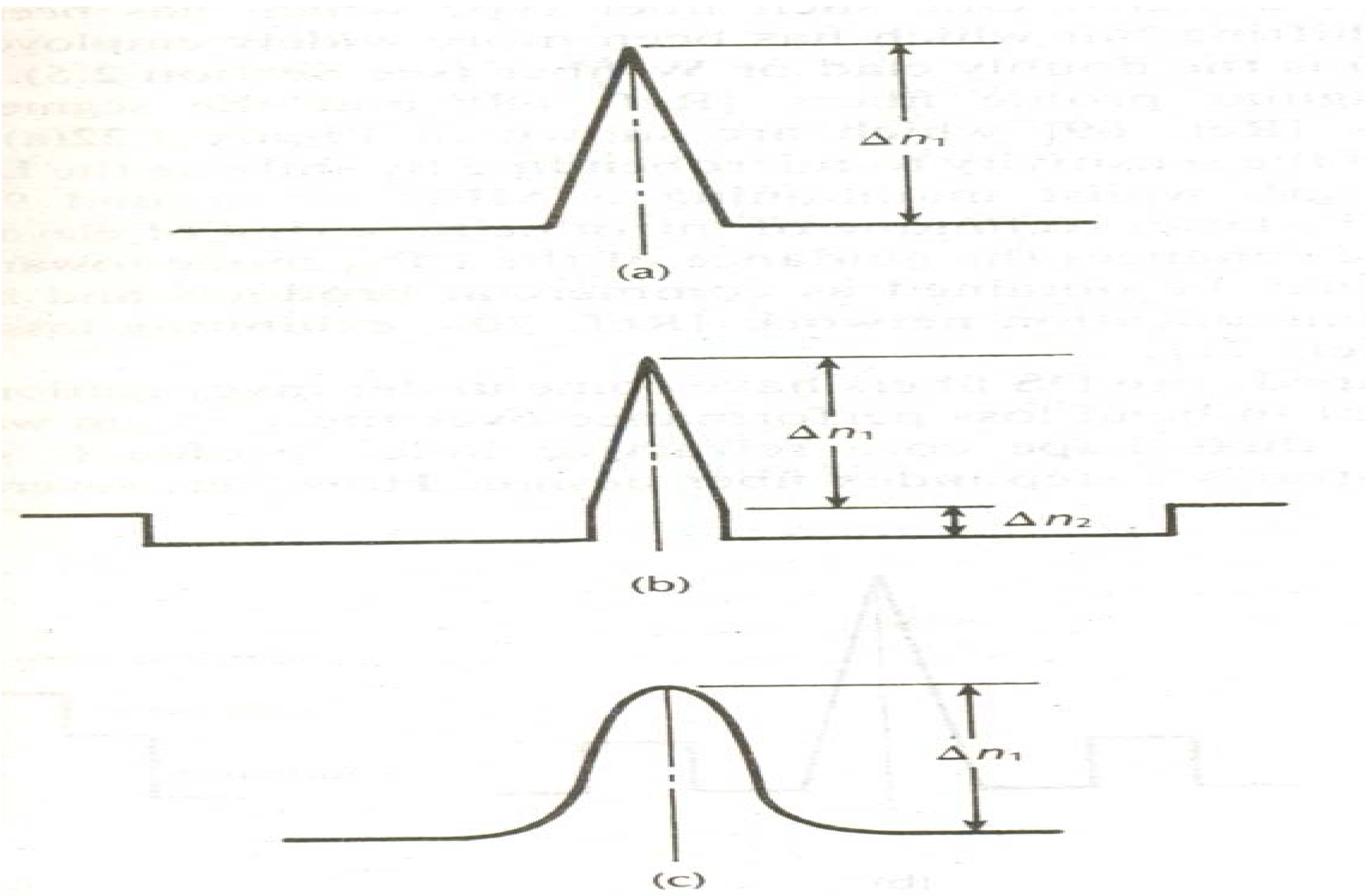
- **Increased dopant level however causes higher loss (2 dB / km).** This is overcome by using triangular profile. The loss is reduced to 0.24 dB / km at a wavelength of 1.56 µm (fig)
- The triangular profile is sensitive to bend induced losses. Remedy is to employ a triangular index profile combined with depressed cladding index or use a guassian refractive index profile. (fig)



Total dispersion characteristics for the various types of single – mode fiber .



Refractive index profile of a step index dispersion shifted fiber (solid) with a conventional nonshifted profile design (dashed)



Refractive index profiles for graded index dispersion shifted fibers:
a) triangular profile ;
b) depressed cladding triangular profile
c) Gaussian profile

Factors responsible for signal attenuation

- Material composition
- Preparation & purification technique
- Wave guide structure
- Curve& micro bending losses
- Mode coupling radiation losses.
- Losses due to leaky modes.
- Material scattering
  - -linear scattering
  - -non-linear scattering
- Connector losses
- Splice losses

NON-LINEAR SCATTERING LOSSES.

- Non linear scattering normally occurs at high power levels.
- Power is transfered either in the forward or backward direction to the same or other modes at a different frequency.

- Types of non linear scattering
- -Stimulated Brillouin scattering (SBS)
- -Stimulated Raman scattering (SRS)
- SBS
- It can be regarded as modulation of light thr ‘ thermal molecular vibrations (within the fiber) – USB/LSB

Brillouin scattering (SBS)-contd

- The incident photon produces a phonon of acoustic freq. as well as a scattered photon.
- This produces **an optical freq. shift which is max. in the backward direction** and zero in the forward direction.
- Threshold power (watts)P_B=

$$\mathbf{4.4*10^{-3}d^2\lambda^2\alpha_{db}V}$$

- α_{db} =fibre attenuation (db/km), v= source bandwidth (GHz)

Note: for single mode fiber ,$P_{B=10}$ mw, which is quite high value & can be avoided.

- **<u>STIMULATED RAMAN SCATTERING (SRS</u>)**
- Similar to SBS except that a high freq. optical phonon rather than an acoustic phonon is generated.
- It can occur both in the forward as well as backward direction.

THRESHOLD POWER, $P_R = 5.9\times10^{-2}\, d^2\, \lambda\, \alpha\, dB$ Watts

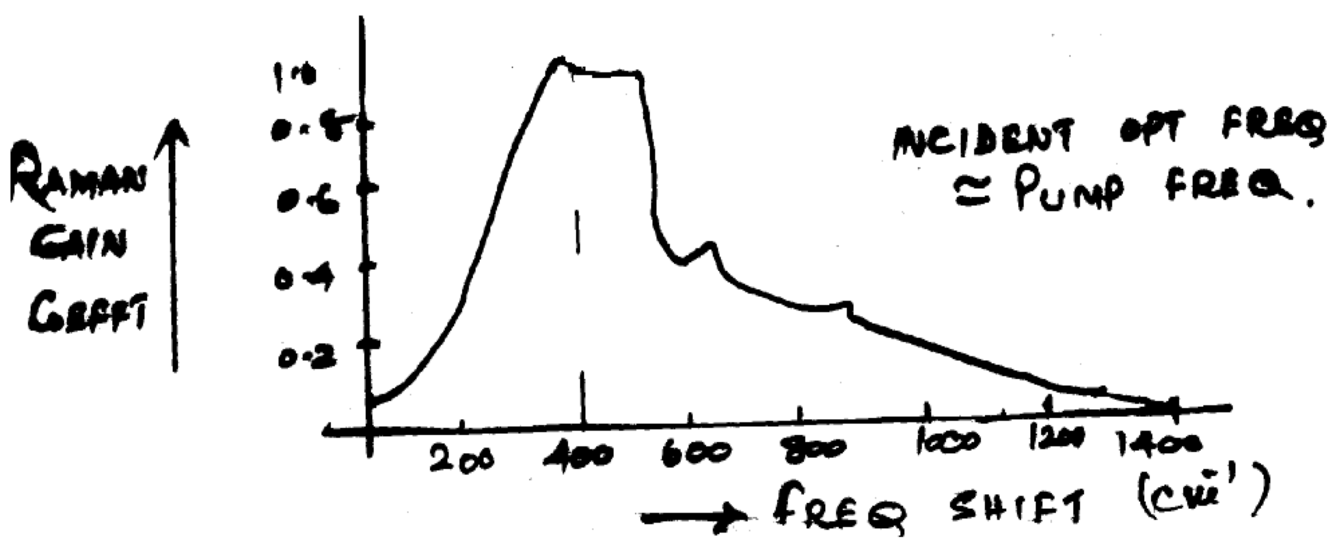
$$P_R > 3\, P_B$$

NOTE : SBS & SRS ARE NORMALLY NOT OBSERVED IN MULTIMODE FIBERS.

LINEAR SCATTERING PROCESS IS ELASTIC WHEREAS NON-LINEAR SCATTERING IS INELASTIC (FREQ. SHIFTS)

THE INELASTIC PROCESS RESULTS NOT ONLY IN SHIFT OF FREQ, BUT ALSO PROVIDES OPTICAL GAIN (AMPLICATION) AT THE SHIFTED FREQ.

RAMAN GAIN EXTENDS OVER A SUBSTANTIAL BAND WIDTH.



FIBER BEND LOSS

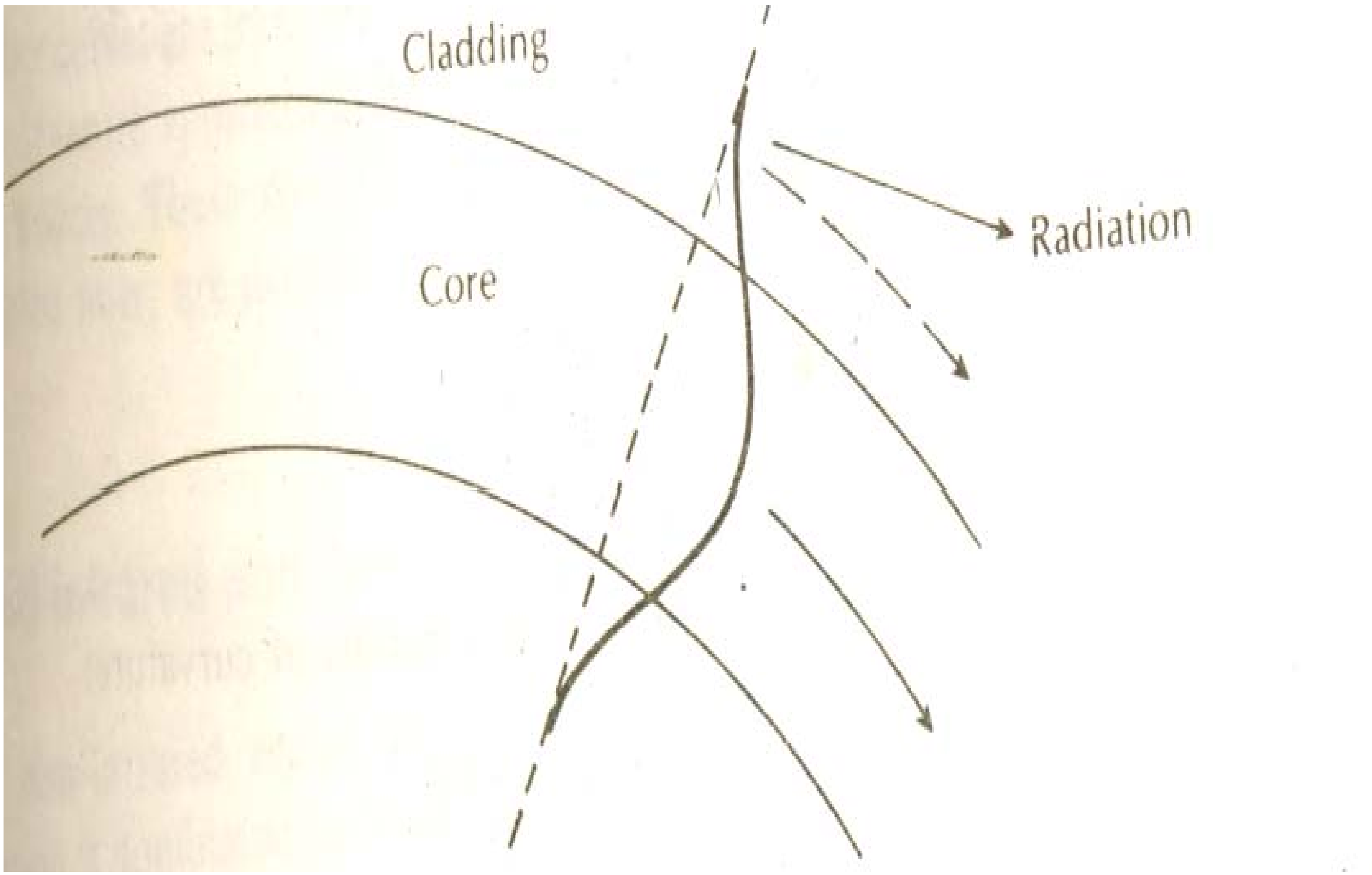
The losses at bends are due to the energy in the **short time field** ,at the bend exceeding the velocity of light in the cladding.

Guidance mechanism is slowed down.

This causes light energy to be radiated from the fiber.

Part of the mode in the cladding is required to travel faster than the velocity of light ,(in that medium)

FIBER BEND LOSS



FIBER BEND LOSS (Contd.)

Radiation .Attn. Coefficient. $\alpha_r = c_1 e - c_2 R$
where R is the Radius of curvature of bend

c_1, c_2 :constants.

Rc (critical rad. of curvature)=$3n_1^2 \lambda / 4\pi (n_1^2 - n_2^2)^{3/2}$
(for MM fiber)

Rc = $20\lambda/(n_1-n_2)^{3/2} [2.748- 0.996 \lambda / \lambda c]^{-3}$,

where λc=cut-off wave length for single mode fiber.

Note: **Sharp bends with R=Rc must be avoided**

OPT FIBERS & CABLES

- Opt. Fibers should have stable transmission characteristics over longer lengths
- Range of fibers should be available to suit different system applications
- Fibers may be converted into practical cables and should be easy to handle without any degradation or damage
- Ease of connecting and joining the cables in field

Preparation of Cables

-Scattering centres such as bubbles, strains and grain boundaries should be avoided

-Ref index is varied by suitable doping with another compatible material

-Glasses exhibit the best overall material characteristics for use in fabrication of low loss OFC

-Glass is processed in molten state

-Vapour-phase deposition method produces silica rich glasses(very high melting temp)

OPTICAL FIBRE STRUCTURES

a) **MULTI-MODE STEP INDEX FIBER**

b) MULTI-MODE GRADED INDEX FIBER

c) SINGLE-MODE STEP INDEX FIBER

d) PLASTIC CLAD SILICA FIBERS

e) ALL PLASTIC FIBERS

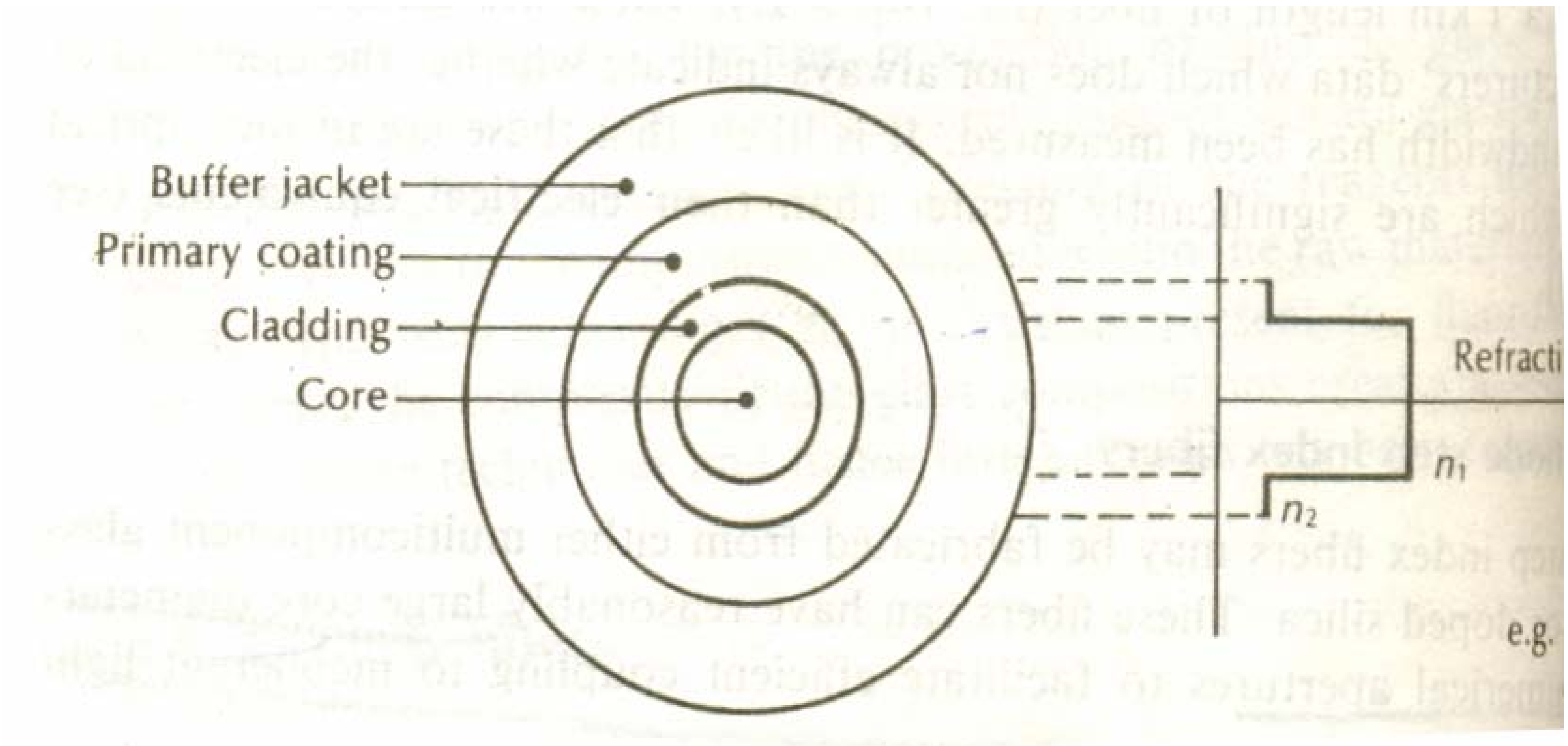
Three major wavelength regions

0.8 to 0.9 µm

1.3 µm

1.55 µm

MULTIMODE STEP INDEX FIBERS



MULTIMODE STEP INDEX FIBERS(contd)

Material– multicomponent glass compounds or doped silica

Attenuation :2.6 to 50 dB /km at 0.85 μm (λ)

The wide variation in attenuation is due to diff. preparation methods .

Attenuation is 40 db/km at 0.85 μm (λ) 0.4dB /km at 1.3μm (λ) for silica fibers.

BANDWIDTH: 6 to 50 MHZ km.

Applications: best suited for short haul, limited BW and low cost applications

MULTIMODE STEP INDEX FIBERS(contd)

- n1=1.48, n 2=1.45

- Core dia : : 50 to 400 μm
- Cladding dia : 125 to 500 μm
- Buffer jacket dia : 250 to 1000 μm
- NA : 0.16 to 0.5

MULITI MODE GRADED INDEX FIBERS

- MATERIAL FOR FABICATION :MULTICOMPONENT GLASS or DOPED SILICA
- **Materials used are of high purity** (than in SI fiber) to reduce fiber losses
- Hence these fibers exhibit better performance characteristics and lower attenuation .
- Core dia is normally smaller than that of step index fiber
- STRUCTURE : core dia: 30 to 100 μm

  : cladding dia: 100 to 150 μm

  : Buffer jacket dia : 250 to 1000 μm

  :Num aperture: 0.2 to 0.3

MULTI MODE GRADER INDEX FIBERS (contd)

Major groups available: (core –cladding dia)

50μm /125μm, 62.5μm / 125μm

85μm /125 μm 100μm / 125μm

Wave length range : (0.85-1.3 μm)

PERFORMANCE CHARACTERISTICS:

ATTENUATION: 2 to 10 db / km at 0.85μm (λ)

0.4db / km at 1.3 μm (λ)

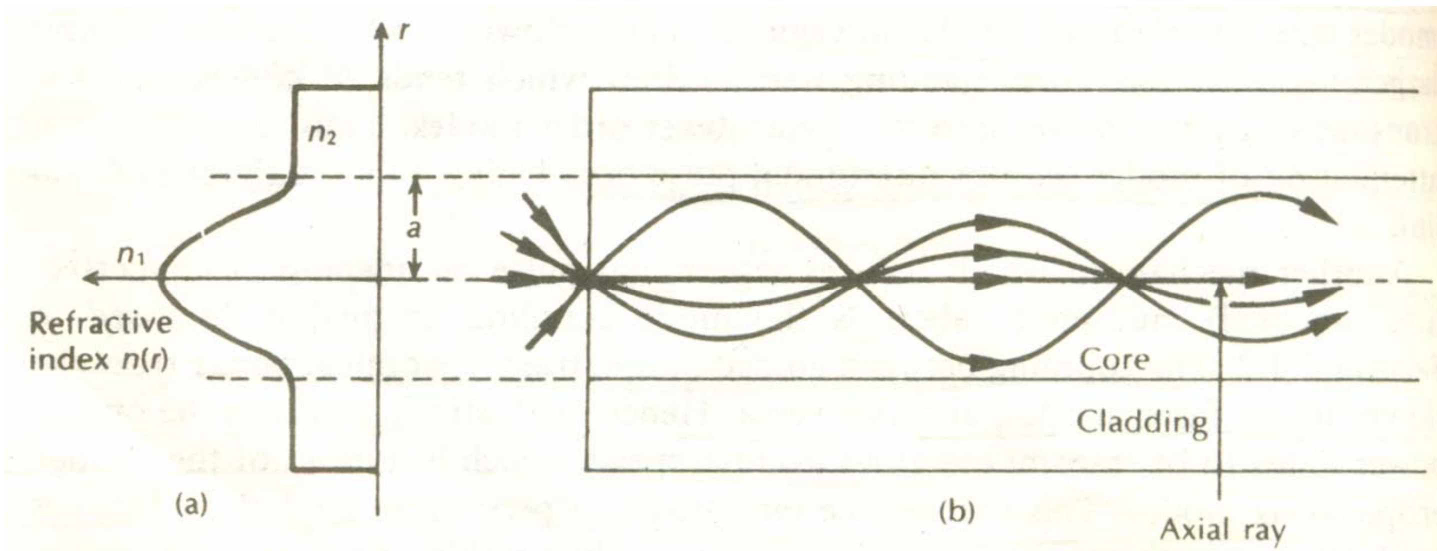
0.25 db / km at 1.55 μm (λ)

Bandwidth (BW): 300 MHz km to 3 GHz km

APPLICATION: best suited for medium haul, medium to high BW applications using LED & injection laser resp.

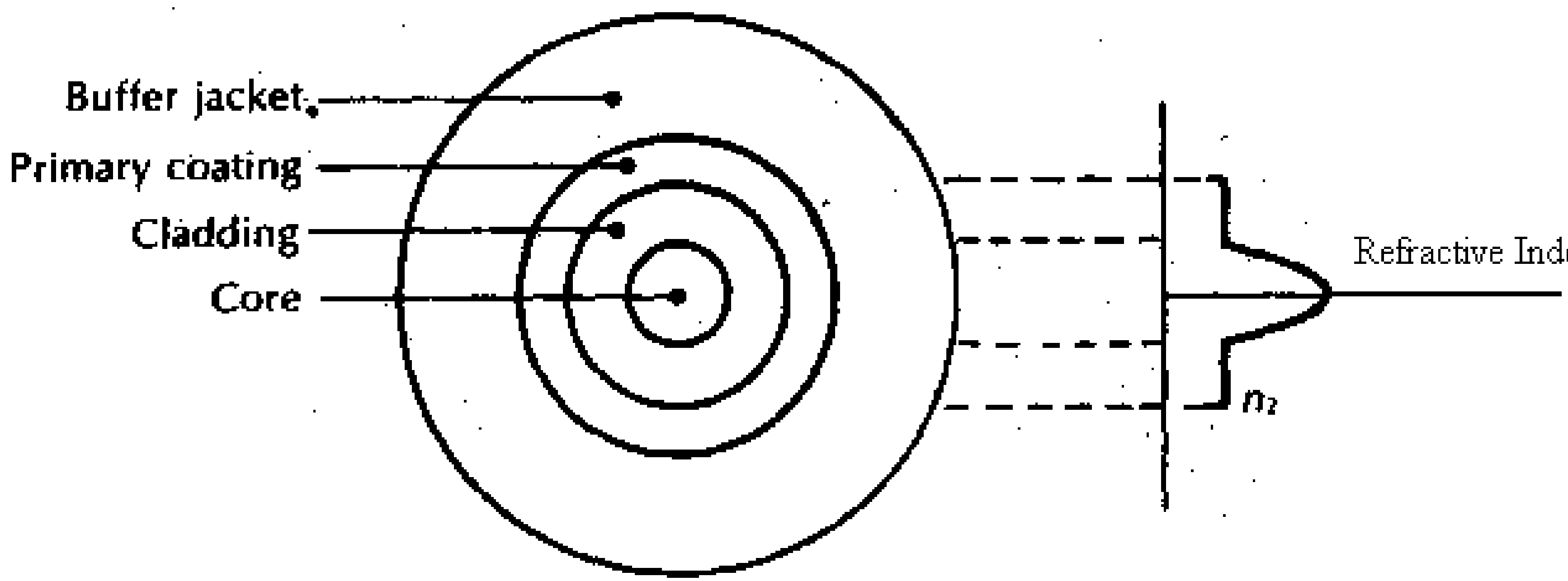
MULTIMODE GI FIBER(contd)

- The gradual decrease in ref index from the centre of the core ,creates many refractions of the rays .(High to low ref. index)



A multimode graded index fiber: (a) parabolic refractive index profile; (b) meridional ray paths within the fiber core.

GRADED INDEX FIBER (contd)



GRADED INDEX FIBER (contd)

MMGI fibers exhibit far less intermodal dispersion than MMSI fibers, due to their ref .index profile.

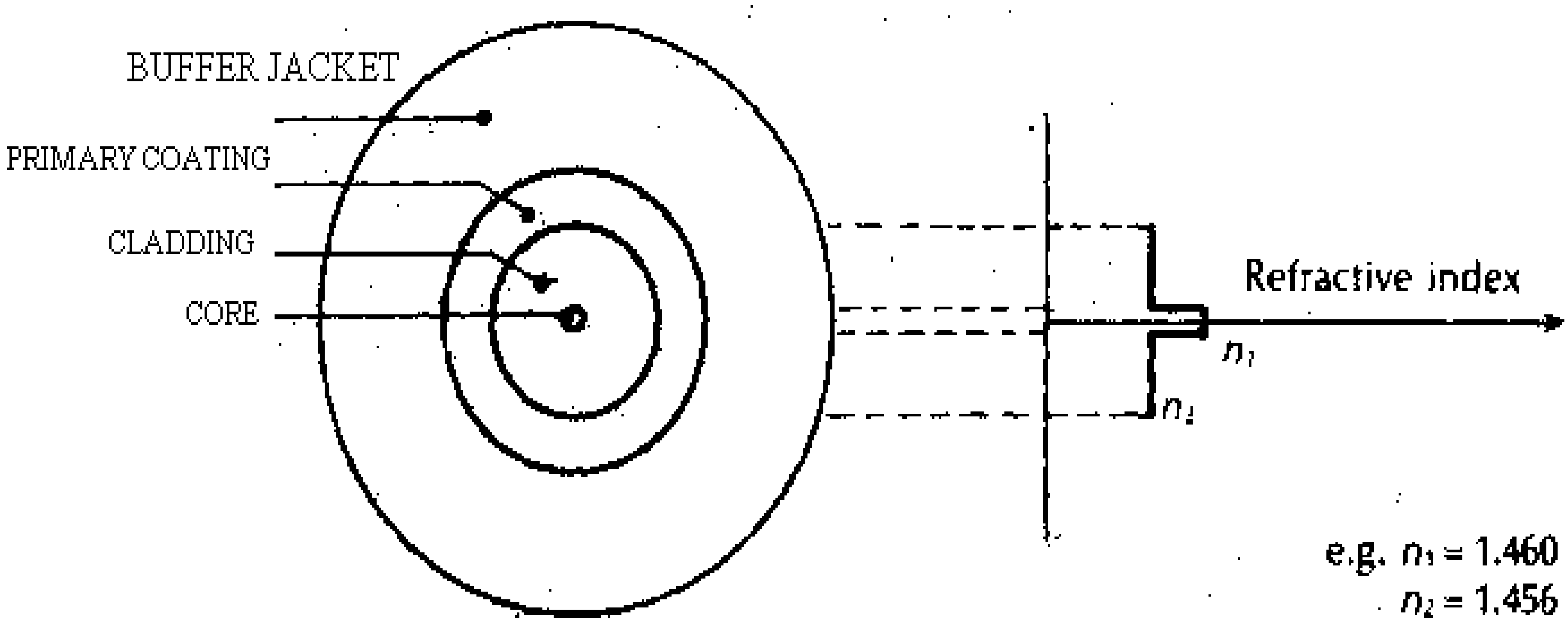
The diff. group velocities (of diff modes) tend to be normalizd by index grading.

Rays closer to the fiber axis have shorter paths when compared with rays travelling into the outer regions of the core

Nearer to axis, rays have lower velocity (travelling thr higher index) than more extreme rays. This compensates for shorter paths and reduces dispersion in the fiber.

Hence higher transmission BW^{s} than multimode step index fiber are available.

SINGLE MODE FIBERS



SINGLE MODE FIBERS

Commercially available single mode fibers are usually step index , as graded index type is expensive.

Material for fabrication: doped silica.

(in order to reduce attenuation)

Core dia is quite small . (**cladding dia must be at least 10 times the core dia. to avoid losses**(evanescent field)

Overall dia is similar to multimode fiber .

STRUCTURE: Core dia: 5 to 10 μm (typically 8.5 μm)

Cladding dia : 125 μm

Buffer jacket dia: 250 to 1000 μm

Num. Aperture: 0.08 TO O.15 (0.10 typically)

n1= 1.46, n 2= 1.456.

SINGLE MODE FIBER (contd)

Performance characteristics:

Attenuation: 2 to 5 db/km (0.85 μm λ)

0.35 db/km (1.3 μm λ)

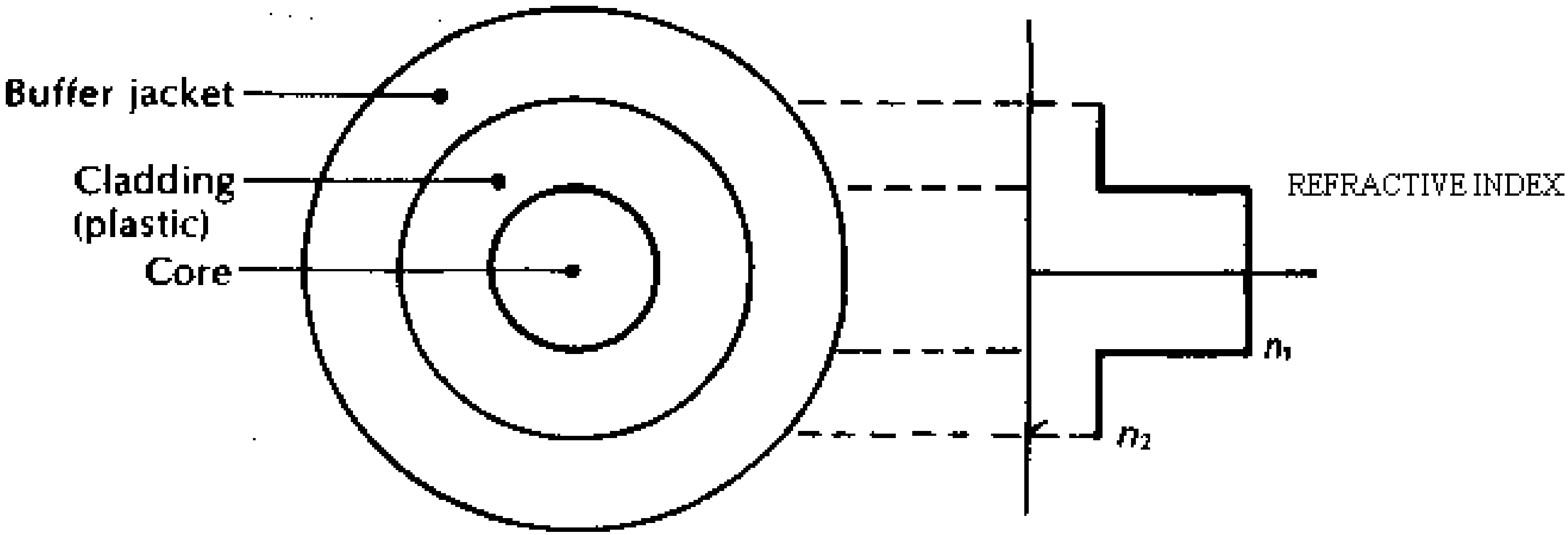
0.21 db/km (1.55 μm λ)

Band width : > 500 MHz km

Practical BW >10GHz km at 1.3 μm (λ)

Applications: **ideally suited for high BW, very long haul applications with injection laser source**.

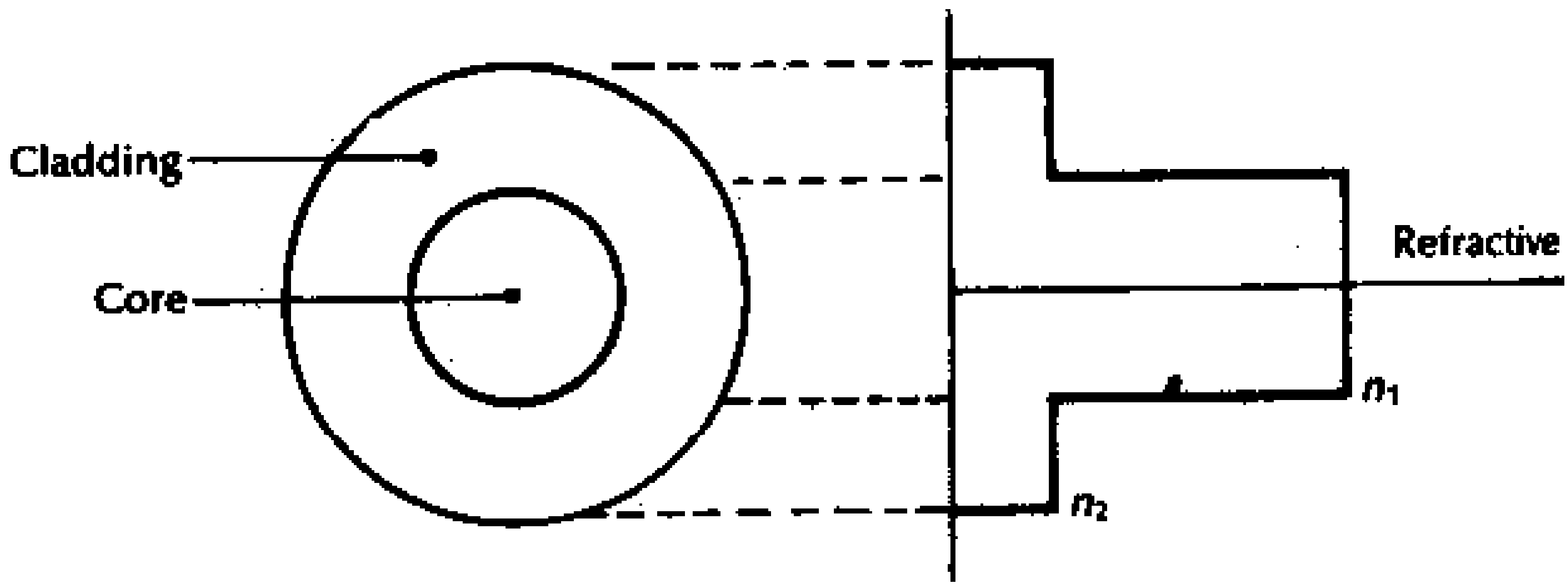
PLASTIC-CLAD FIBERS



Typical structure for a plastic-clad silica multimode

Step Index Fiber.

ALL PLASTIC FIBERS



Typical structure for an all-plastic fiber.

PLASTIC-CLAD & ALL PLASTIC FIBERS

Plastic- clad fibers:These are multimode and have a SI or GI profile.

- Construction: core - glass (silica or plastic clad silica-PCS)

  Cladding –plastic (silicone rubber)
- PCS fibers exhibit lower losses than silica clad silica fibers and so improved performance.
- Plastic clad fibers are generally cheaper than corresponding glass fibers.

PLASTIC-CLAD FIBERS (contd)

	Step index	graded index
Core dia	100 to 500 μm	50 to 100 μm
Cladding dia	300 to 800 μm	125 to 150 μm
Buffer jacket dia	500 to1000 μm	250 to 1000 μm
NA	0.2 to 0.5	0.2 to o.3
Attenuation	5 – 50 db/km	4 – 15 db / km.

ALL PLASTIC FIBERS

-These fibers are multi mode SI type with large core & cladding dia n_1=1.50, n_2=1.40

-**No need of buffer jacket** for fiber protection & strengthing

-Cheaper to produce ,easier to handle than silica based glass variety

Performance is restricted (in Infrared region) and

hence **limited use** in comm. applications.

- Core dia: 200 to 600μm, cladding dia 450-1000 μm
- NA:0.5 to 0.6 Attn. 50 to 1000 db/km.at 0.65 μm (λ)

- APPLICATION:These fibers can be used for short haul (in- house) low cost links.

FIBER JOINTS

Number of joints will depend on link length (BETWEEN REPEATERS)

Repeater station distance of 40 to 60 km is practical at data rate of 400 Mb/sec.

Advances in the field have resulted in achieving a distance of 100 km in practical systems at a data rate of upto10 G bits/sec

FIBER JOINTS:(Types)

1)FIBER SPLICES.

2)FIBER CONNECTORs (REMOVABLE)

FIBER JOINTS (contd)

Fiber splices :semipermanent /permanent joints (analogous to soldered joints)

Fiber Connectors: Removable/ demountable joints which allow easy fast manual coupling/decoupling of fibers (analogous to elect. plugs /sockets)

DIFF BETWEEN JOINTS &COUPLERS:

JOINTS: To **couple all the light** propagating in one fiber into an adjoining fiber.

COUPLERS: Branching devices that **split the light** from main fiber into two or more fibers **or couple the light** from branches to main fiber.

FIBER ALIGNMENT & JOINT LOSS

JOINT loss critically depends on alignment of two fibers.

Fresnel Reflection : even when two jointed fiber ends are smooth and perpendicular to fiber axis with 2 axes perfectly aligned **,a small portion of light is reflected back into the transmitting fiber** causing attenuation at the joint.

This is due to step changes in refractive index at jointed interface (GLASS-AIR- GLASS)

r= fraction of light reflected at a single interface=$(n_1\text{-}n/n_1+n)^2$

where n_1= ref index of core ,n= ref index of medium bet .fibers.

FRESNEL LOSS (db)= -10 $\log_{10}$ (1-r)

FIBER ALIGNMENT & JOINT LOSS (Contd)

FRESNEL Reflection can be reduced by using ***an index matching fluid*** in the gap between the jointed fibers.

INHERENT CONNECTION PROBLEMS:

a) Different core and/or cladding diameter

b) Different NA and/or ref. index difference

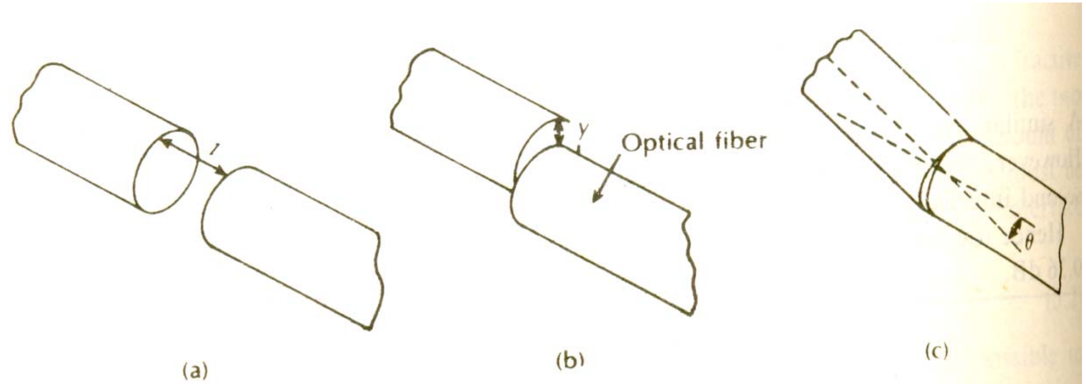
c) Different REF.INDEX profile

d) Fiber faults (ellipticity, concentricity)

MISALIGNMENT PROBLEM

- 3 dimensions of misalignment

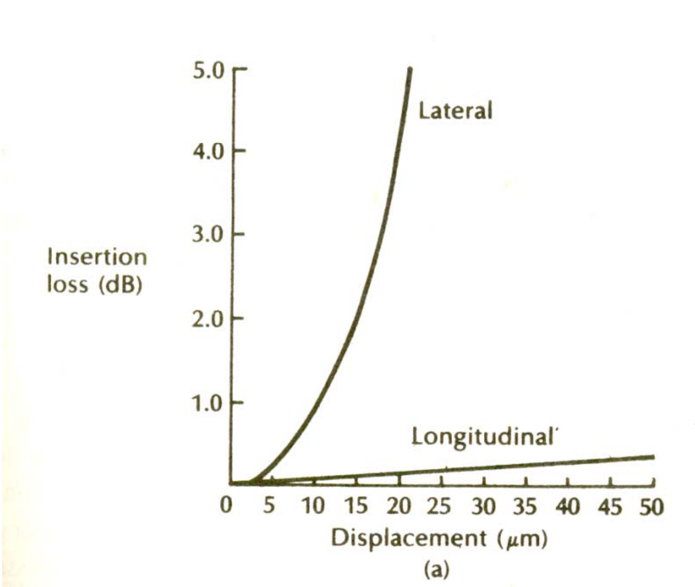
- -LONGITUDNAL
- -LATERAL
- -ANGULAR

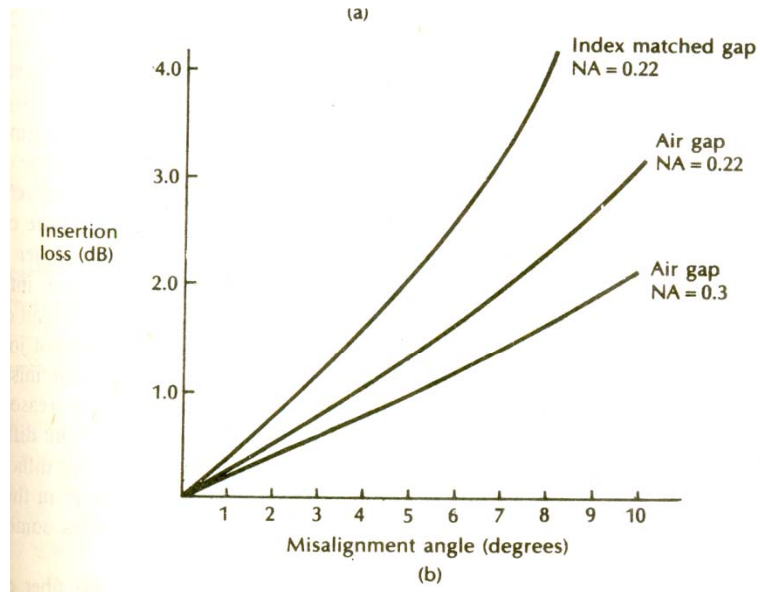


The three possible types of misalignment which may occur when joining compatible optical fibers (a) longitudinal misalignment; (b)lateral misalignment; (c) angular misalignment.

- Optical losses due to misalignment depend on fiber type, core dia and distribution of optical power between propagating modes.

MISALIGNMENT PROBLEM (contd)

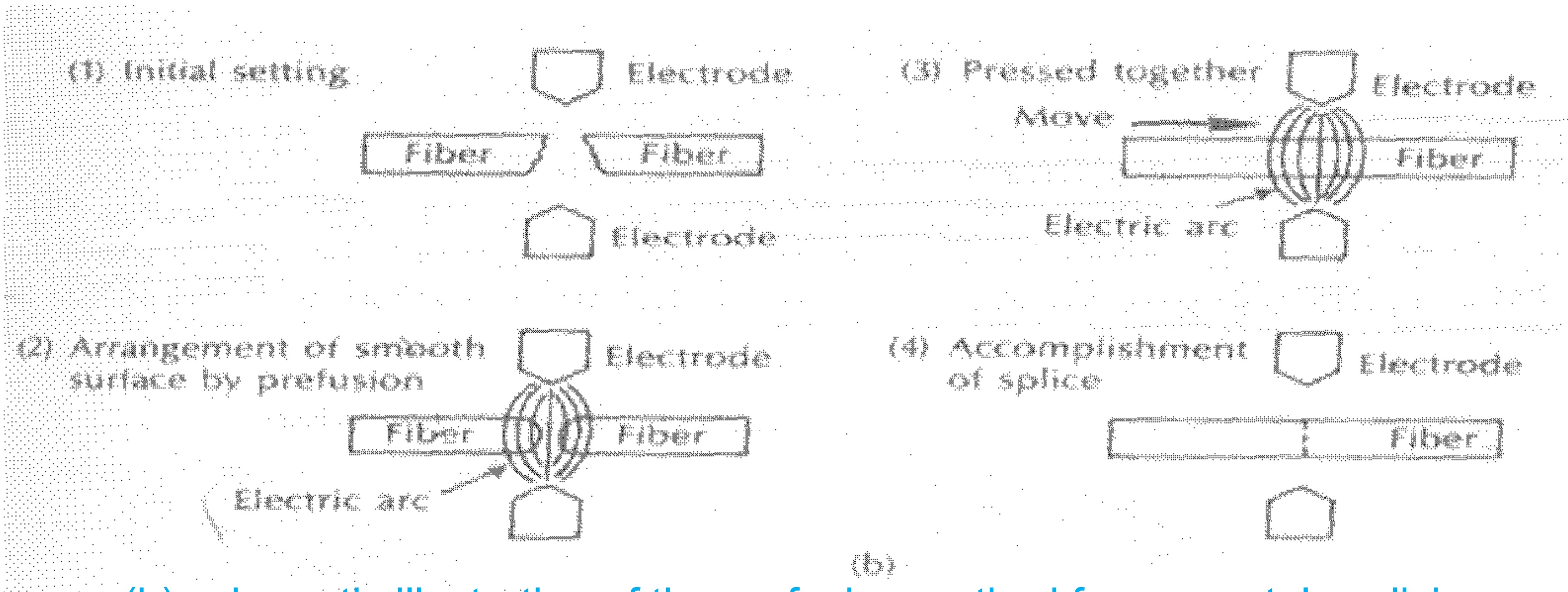




Insertion loss characteristics for jointed optical fibers with various types of misalignment: (a) insertion loss due to lateral and longitudinal misalignment for a 50 μm core diameter graded index fiber, (b) insertion loss due to angular misalignment for joints in two multimode step index fibers with numerical apertures of 0.22 and 0.3

Note**: lateral misalignment gives significantly more losses per unit displacement than longitudinal displacement**.

FUSION SPLICING(contd)



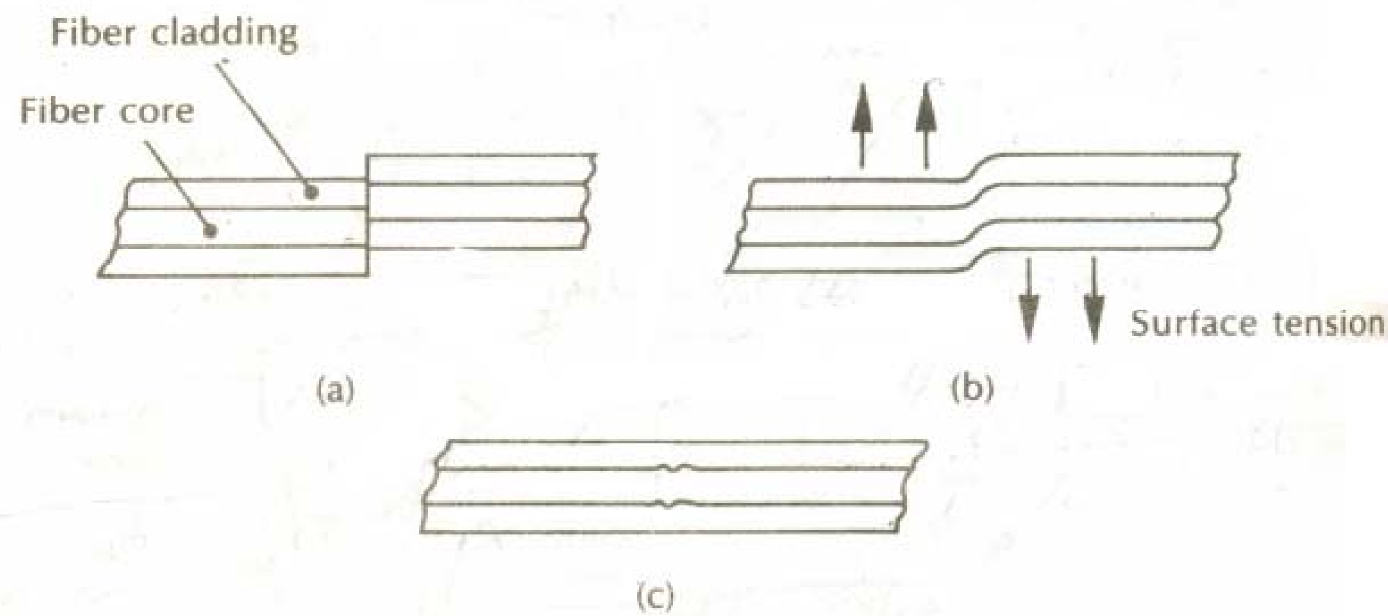
(b) schematic illustration of the perfusion method for accurately splicing optical fibers.

PREFUSION
METHOD FOR SPLICING FIBERS

- FLAME HEATING SOURCES: Argon, hydrogen, OXHYDRIC MICROBURNERS (O_2, H_2, ALCHOL VAPOUR)
- **Electric arc is the most widely used source**
- **Prefusion: This removes the requirement for fiber end preparation, an advantage in field environment.**
- AVG SPLICE LOSSES: 0.09 db.
- Disadvantage: tensile strength of fused fiber is down by 30 % (as compared to before fusion process) due to surface damage & changes in chemical composition

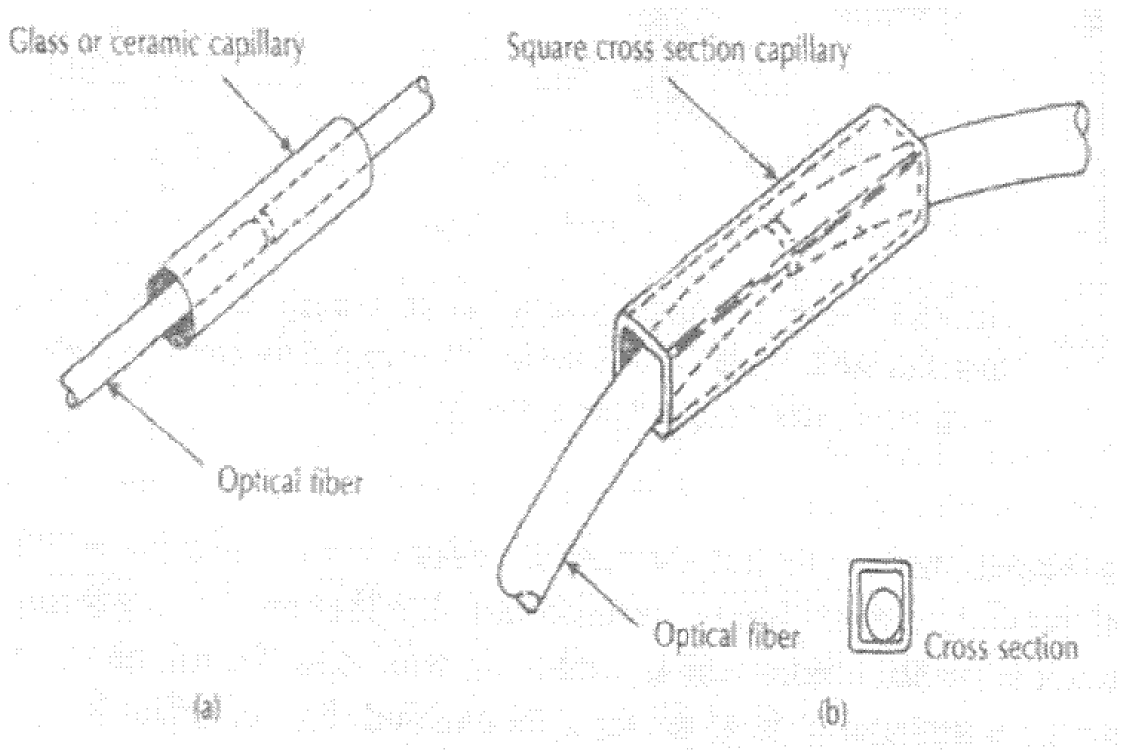
SELF ALIGNMENT

- Self alignment partially compensates for any lateral offset
- Lower splice Insertion losses may be achieved due to **self alignment process caused by surface tension effect** between the two fiber ends during fusing
- Mean splice losses of only 0.06 db have been obtained with single mode fiber fusion splicing machine



Self -alignment phenomenon which takes place during fusion splicing : (a) before fusion , (b) during fusion; (c) after fusion.

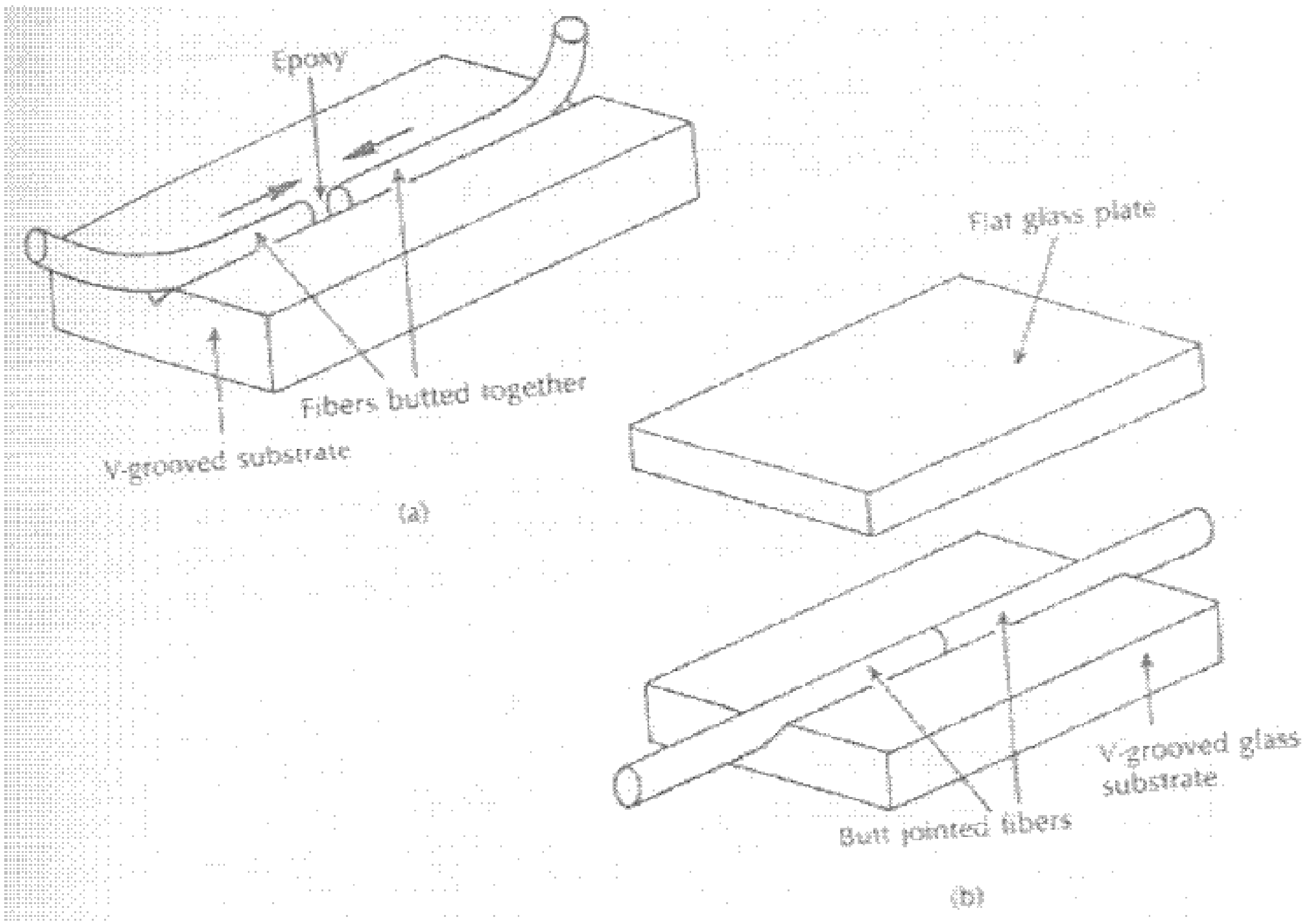
MECHANICAL SPLICES



Insertion loss:

0.1 dB - 0.5 dB 0.073 dB

MECH SPLICES(contd)
joint insertion loss- 0.1dB



FIBER CONNECTORS

REQUIREMENTS FOR OPTIMAL PERFORMENCE.

1) connector design must allow for repeated connection and disconnection, without problems of fiber alignment

2) Connector must protect the fiber ends from damage due to handling.

3) Performance should be independent of environment (insensitive to moisture and dust)

4) Adequate strength to cope with tensile load on the cable.

REQUIREMENTS FOR OPTIMAL PERFORMANCE-contd

5) Ease of fitment

6) Should be a low cost component.

Index matching fluid : Its use increases the light transmission thr the connection (at the joint) and keeps the dust away.

-But practically in field liquids attract dust (at the joint)

Insertion loss of commercially available connector is 0.2 to 0.3 dB

Types of fiber connector

- **1)butt jointed connector**
- **2)expanded beam connector.**

BUTT JOINTED CONNECTORS

These are most widely used connectors.

Types:

1)Cylinderical ferrule connector.

2)Capillary ferrule connector.

3)Biconical ferrule connector.

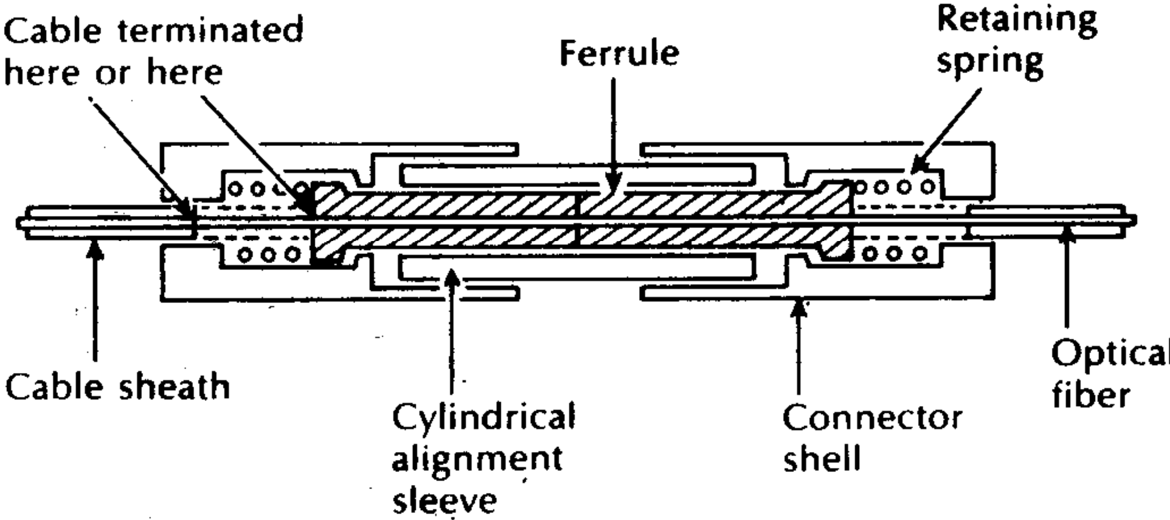
4)Double eccentric connector.

. **EXPANDED BEAM CONNECTOR**

1)Lens coupled expanded beam connectors.

A) using 2 microlenses. , B)using molded plastic lens connector assembly.

2) Using grin-rod lenses.



(a)

STRUCTURE OF BASIC FERRULE CONNECTOR.

- Simplest design
- The 2 ferrules are placed in an alignment sleeve.
- Retaining spring keeps ferrules in place.
- The 2 fibers to be connected are permanently bonded with epoxy resin.

STRUCTURE OF BASIC FERRULE CONNECTOR.(contd)

- The 2 fibers to be connected are permanently bonded with epoxy resin in metal plugs known as ferrules
- **NOTE**: polishing the fiber end face after insertion and bonding provides the best results. However it is time consuming and inconvenient in the field.

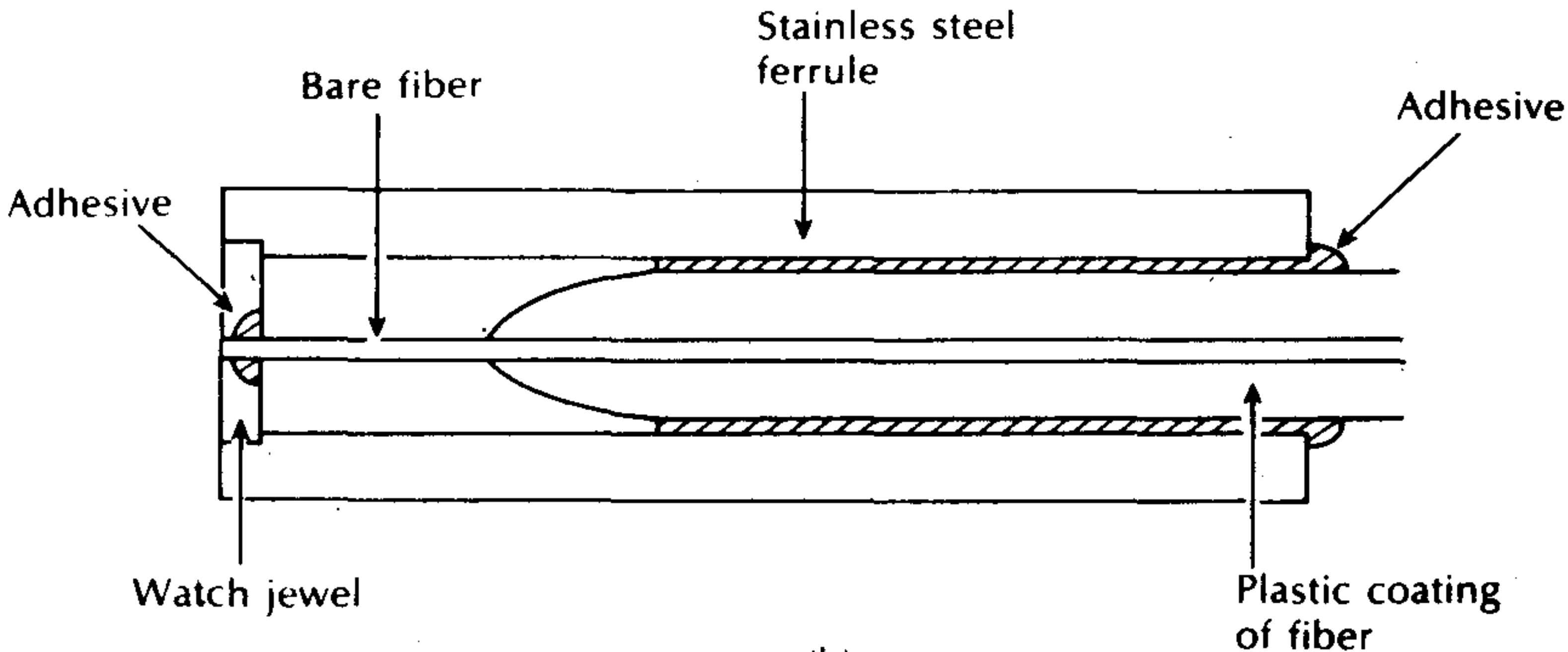
Cylindrical ferrule connectors

.

- Fiber ends to be jointed must be smooth and square. (perpendicular to fiber axis)

- Fiber alignment accuracy largely depends upon ferrule hole into which fiber is inserted.

- For this some ferrule connectors use a watch jewel in ferrule end face (jewelled connector) This allows close dia and tolerance requirements of ferrule end face hole to be obtained easily



(b)

(b) structure of a watch jewel connector ferrule

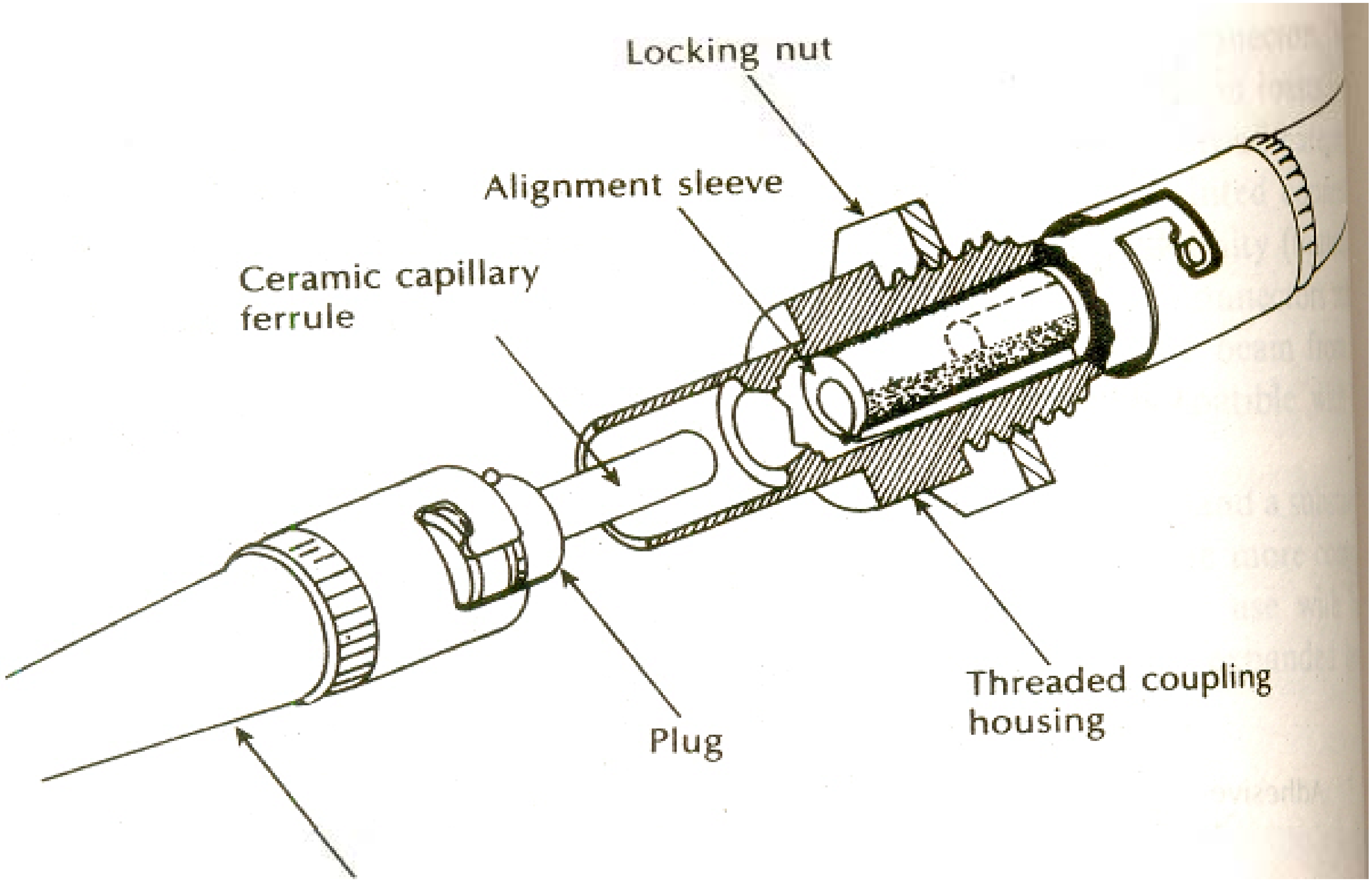
NOTE : FIBER IS CENTERED wrt. FERRULE THR' THE WATCH JEWEL HOLE.

Capillary Ferrules

- Manufactured from ceramic materials like “Alumina Porcelain”
- Capillary ferrules have a precision bore which is accurately centered in the ferrule .
- Ceramic materials posses outstanding thermal mechanical and chemical resistance characteristics in comparison to metals/plastics.

-Typ. loss 0.2 db(MM GI Fiber),0.3 db(SM Fiber)

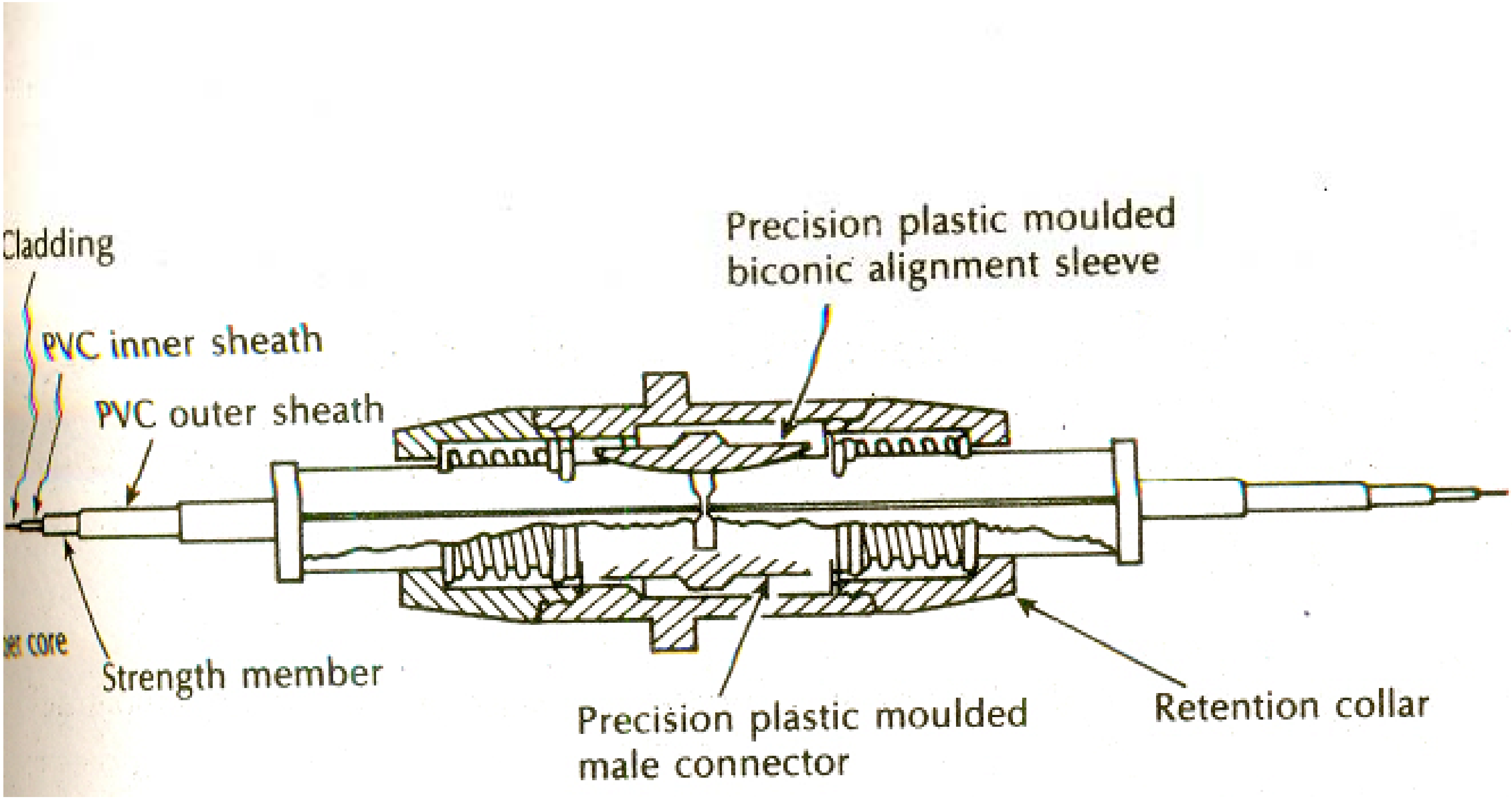
- Types : Straight Tip, D3/D4 Physical contact



ST Series multimode fiber connector using ceramic capillary ferrules

Biconical Ferrule Connector

- The plugs are transfer moulded directly on to the fiber, or cast around the fiber using a silicon loaded epoxy resin.
- After plug attachment, fiber end faces are polished before the plugs are inserted and aligned in biconical moulded centre sleeve
- Mean insertion Loss: 0.21 db (50 µm core dia GI fibers), 0.28dB -0.7 dB (with single mode fibers)



Cross section of the biconical connector

Double Ecentric Connectors

Allows close alignment of fiber axis being an active adjustable assembly.

Two eccentric cylinders are provided within the outer ring.

Opt. fiber is mounted in the inner cylinder eccentrically.

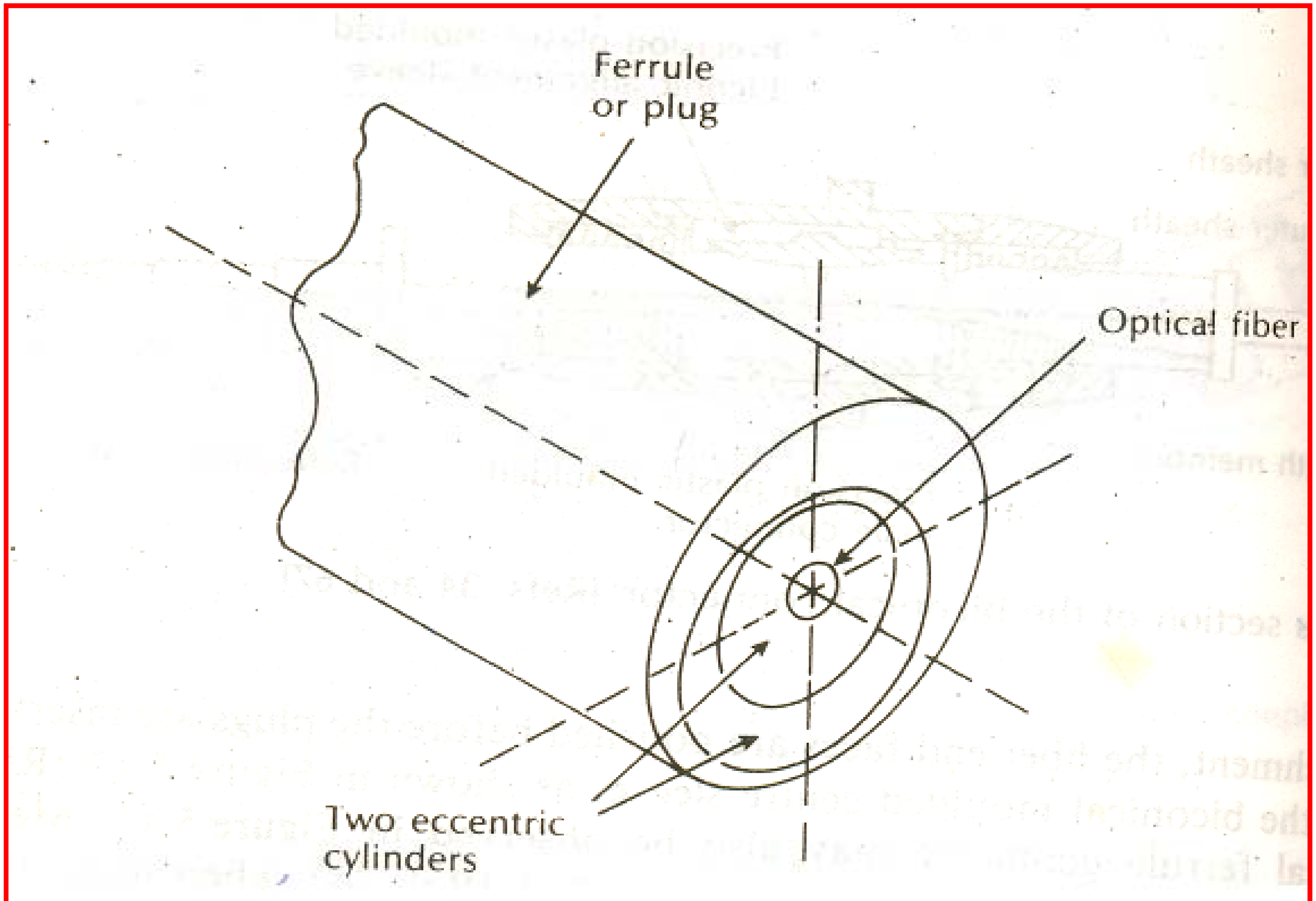
When two connectors halves are mated it is always possible thr' rotation of mechanism to make the fiber core axis coincide.

Inspection microscope can be used to ensure alignment of fiber axis

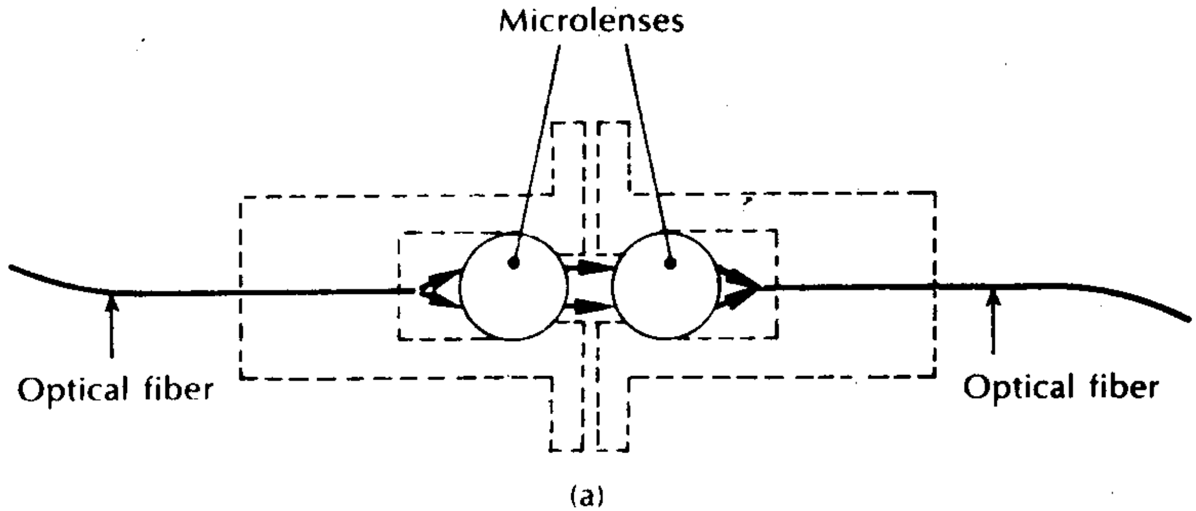
Mechanism can be locked for permanent alignment.

Insertion Loss 0.48 db (MMGI Fiber)
0.20 db (with use of Index matching fluid)
0.46 db (single mode fiber)

Double Ecentric Connectors

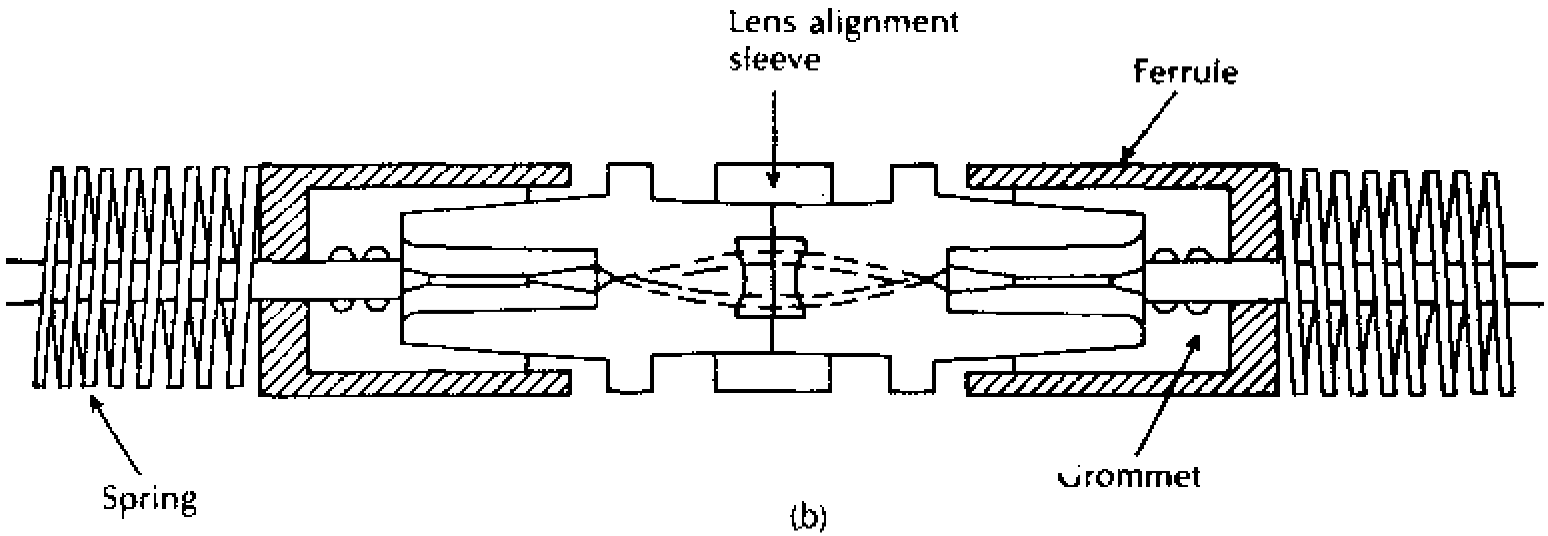


Lens Coupled Expanded Beam Connectors



Lens coupled expanded beam connectors: (a) schematic diagram of a connector with two microlenses making a 1: 1 image of the emitting fiber upon the receiving one

- Spherical micro lenses are used for beam expansion and reduction.
- Avg. Loss- 0.7db-1.0 db (lesser fig with the application of anti reflection coating)-(50μm core dia GI fiber)
- 0.7 dB loss with anti reflection coating with single mode fibers(8 μm core dia)



(b) moulded plastic lens connector assembly .

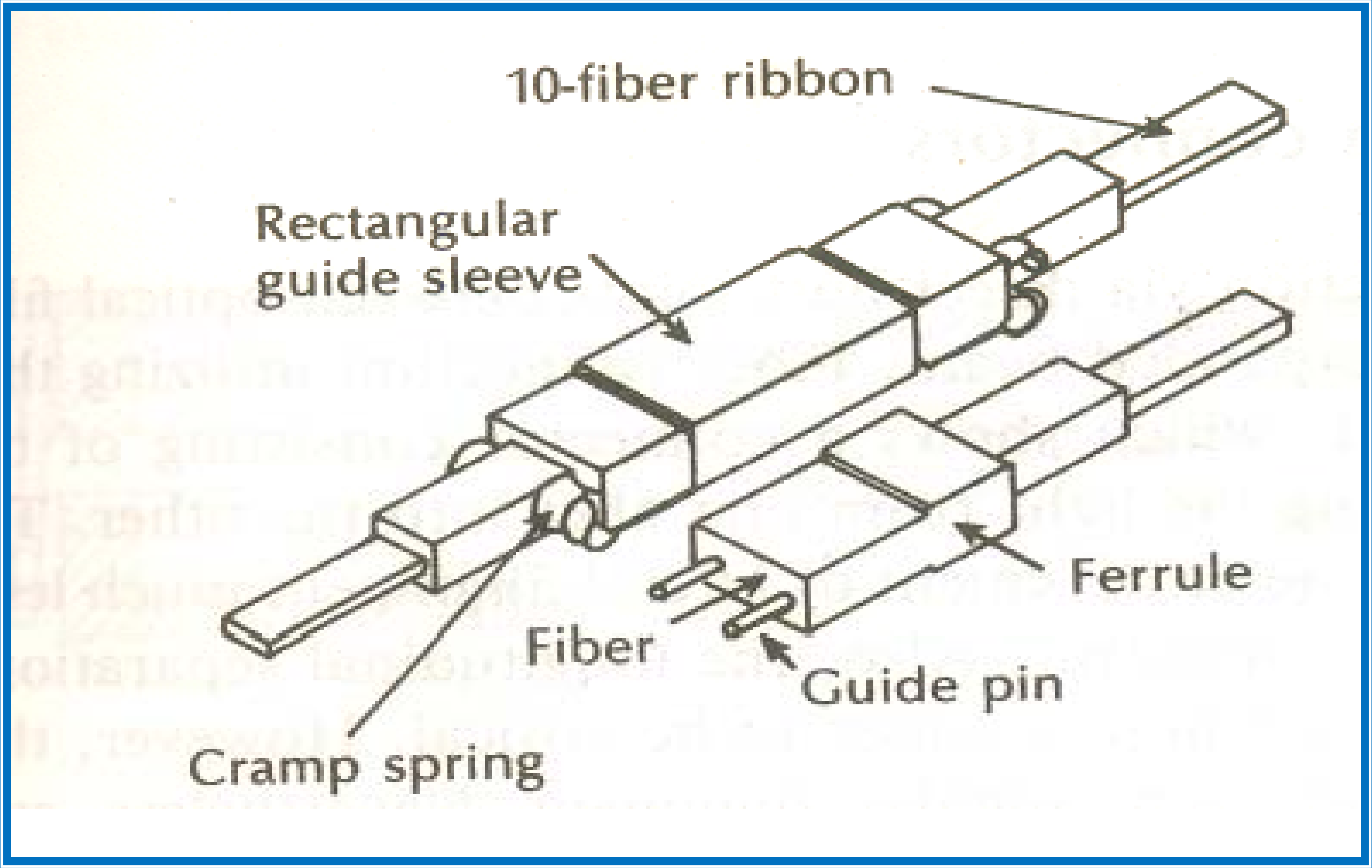
Moulded Spherical Lens (Expanded Beam Connector)

- Fiber is positioned approx. at the focal length of the lens.
- A lens alignment sleeve minimises effects of angular misalignment.
- AVG loss=0.7 db.

Single Mode Ten Fiber Connector

- Consist of 2 moulded ferrules with10 fiber ribbon cables which are accurately aligned by guide pins.
- Held in place by sleeve & spring

- Dimension- 6* 4 mm
- Avg. Loss - 0.43 dB


10-fiber ribbon
Rectangular guide sleeve
Ferrule
Fiber
Guide pin
Cramp spring

Grin –rod lenses (0.5 to 2mm dia)

Such lenses comprise a cylindrical glass rod typically 0.5 to 2mm in dia, which exhibits a parabolic ref. index profile with max at the axis. (similar to GI Fiber)

Grin –rod lens can produce a collimated output beam with divergent angle α (1^0 to 5^0) from a light source (Situated on /near opp. lens face)

Ref index variation is a wave length dependant parameter. Ref index varies with radius which causes all input rays to follow a sinusoidal path thr' lens medium.

Grin –rod lenses(contd)

One sinusoidal period –One full pitch

Grin rod lenses are manufactured with several pitch lengths: Three Major ones are:

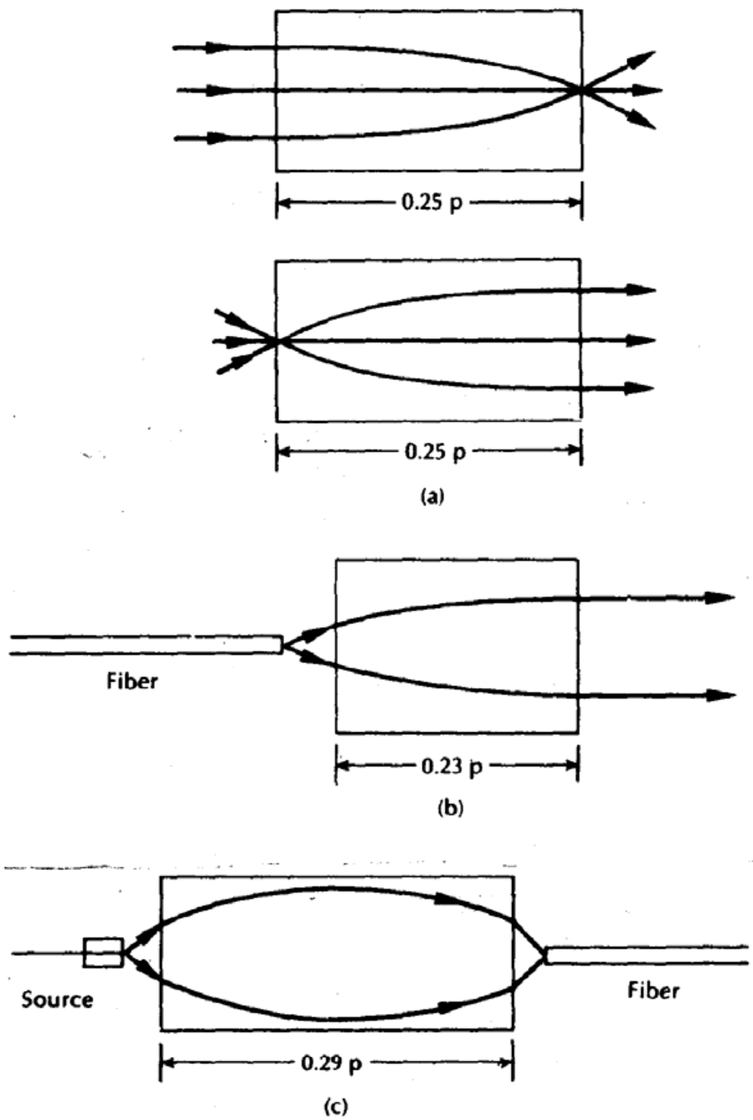
0.25 pitch (quarter pitch)

Produces a perfect collimated o/p beam when light emanates from a pt. source on opp. Lens face. (Focal pt coincident with lens faces)

0.23 Pitch: Focal pt. lies outside the lens when a collimated beam is projected on opp lens face.

0.29 Pitch : Both focal points lie just outside the lens end faces . Used for converting a divergent beam into a convergent beam.

Various Grin-rod lenses -operation



Operation of various GRIN-rod lenses:(a) the quarter pitch lens;(b) the 0.23 pitch lens; (c) the 0.29 pitch lens.

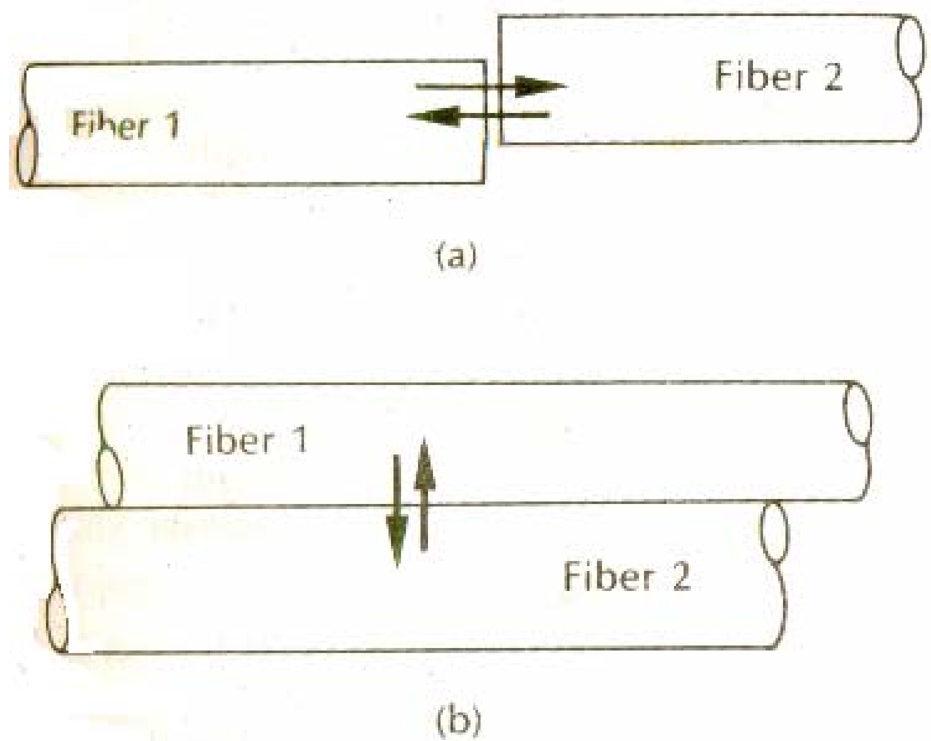
Fiber Couplers

Fiber Coupler is a device which distributes light from a main fiber into one or more branch fibers.

Power Transfer can take place either

-Through fiber core cross –section by butt-jointing the fibers (core interaction).

-Through surface interaction (normal to axis).



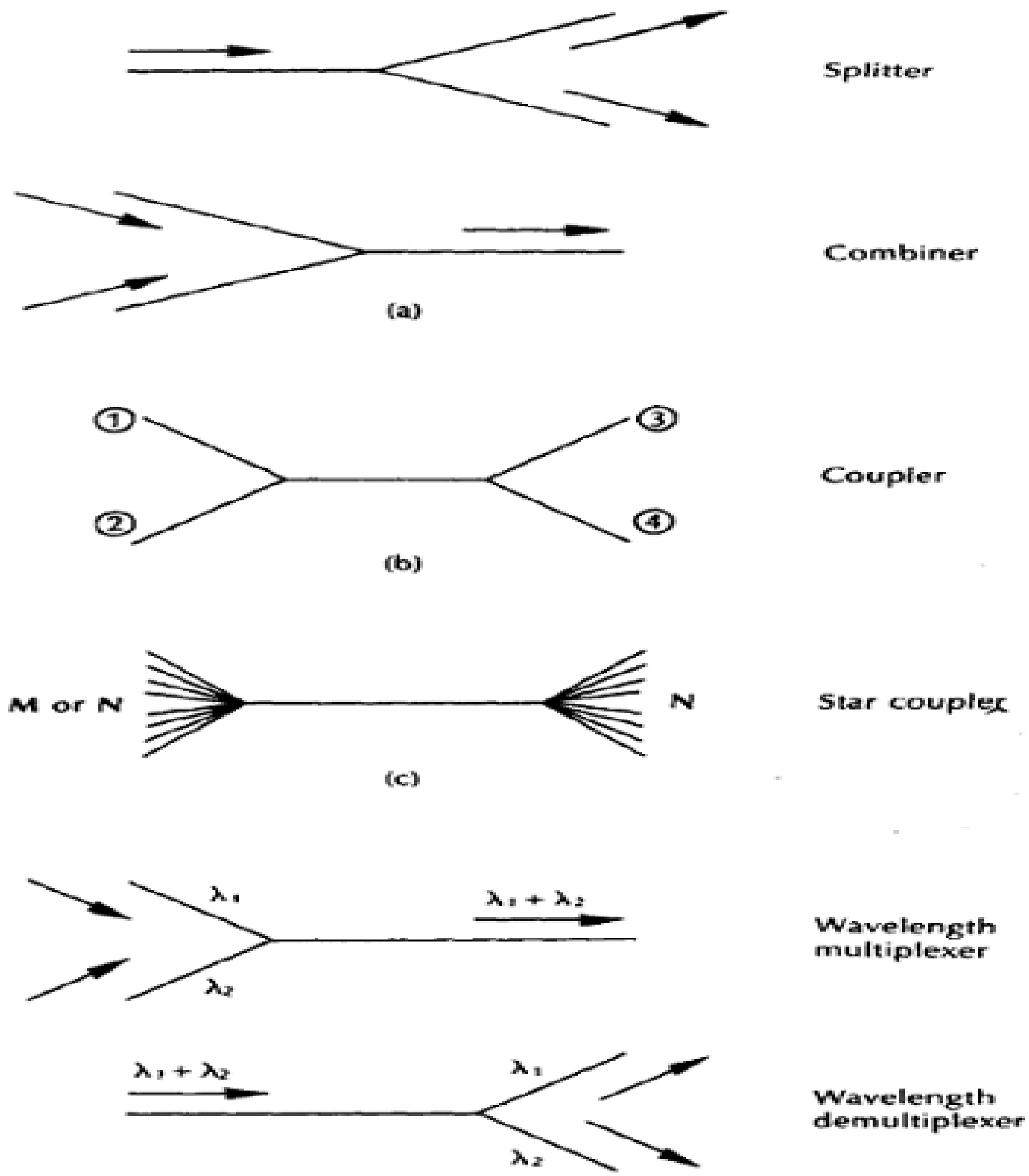
Classification of optical fiber couplers: (a) core interaction type; (b) surface interaction type.

Coupler Types & Functions

Coupler Type	Function
Three /Four port couplers	signal splitting, combining ,distribution
Star Couplers	Single I/P- multiple outputs.
Wave Length division multiplexing	Multiplexing
Wavelength division De-multiplexing	De-Multiplexing

Note :Ideal fiber couplers should distribute light among branch fibers with no scattering loss/noise etc. and should be insensitive to fiber modes & polarisation of light.

TYPES OF COUPLERS

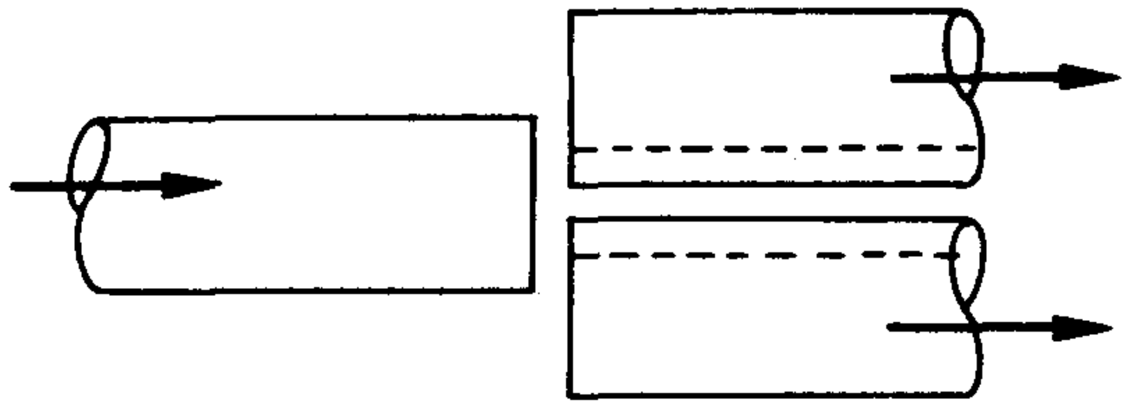


Optical fiber coupler types and functions: (a) three port couplers; (b) four port coupler; (C) star coupler; (d) wavelength division multiplexing and demultiplexing couplers.

- **<u>VARIOUS TYPES OF COUPLERS &THEIR FABRICATION.</u>**
- 3 PORT COUPLER-lateral offset method
- semitransparent mirror method.
- grin –rod lens based micro optic fiber couplers.
- 4 port coupler: fiber fused biconical taper coupler
- Micro bend type coupler.
- **<u>Star coupler</u>**
- 1)mixer rod method
- 2)fused biconical taper method.

- Note:1) The finite scattering loss at the coupler limits the number of terminals that can be connected.
- 2) generation of noise can cause problems in the specification of network performance.

Fabrication Of 3 port fiber coupler

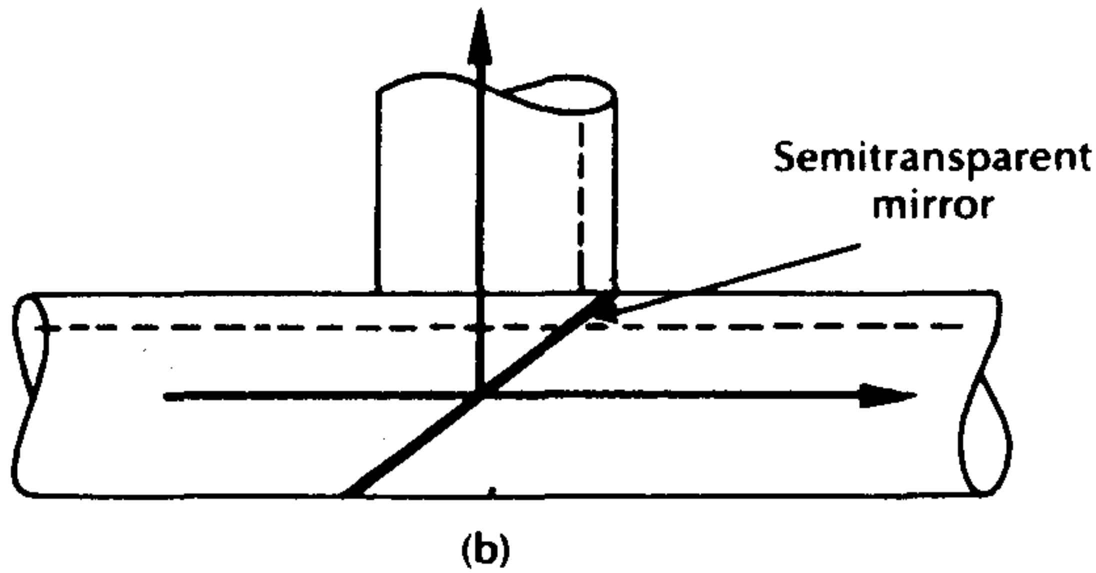


(a)

Fabrication techniques for three port fiber couplers: (a) the lateral offset method;

Lateral Offset Method

- Relies on overlapping of fiber end faces
- Coupling of light (between I/P & O/P fibers) depends on degree of overlap. Thus lateral offsets control the proportion of power transferred to o/p fibers
- Technique is bidirectional
- However losses are higher

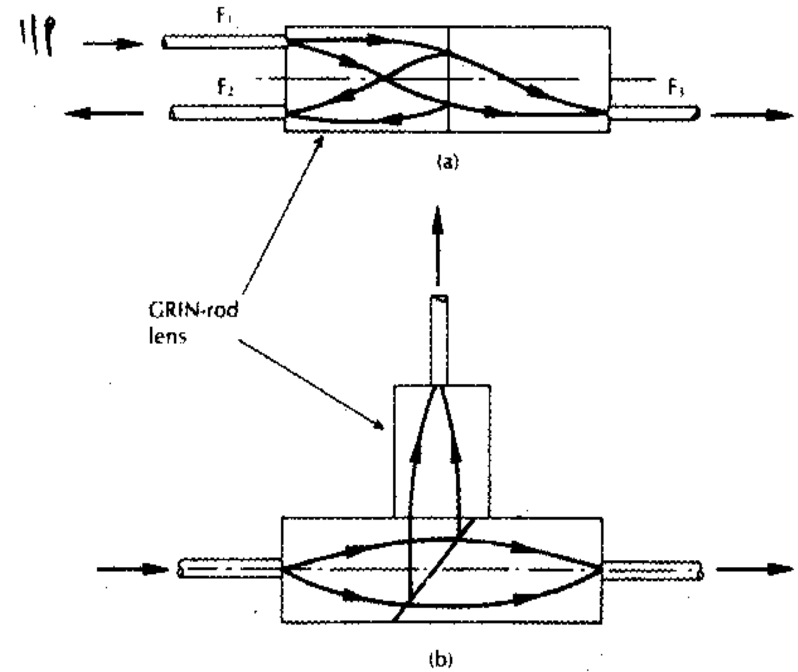


(b) **the semitransparent mirror method**.

- The partially reflecting mirror is a thin film beam splitter
- The i/p power can be split in any ratio between reflected & transmitted beams depending upon mirror properties.
- Typical excess Loss : 1 to 2 dB.

Grin –rod Lens based micro-optic fiber couplers.

- Consists of 2 quarter pitch lens with a semitransparent mirror in between.
- A portion of light incident on mirror is reflected back. (fiber F_2).
- The transmitted light goes to fiber F_3

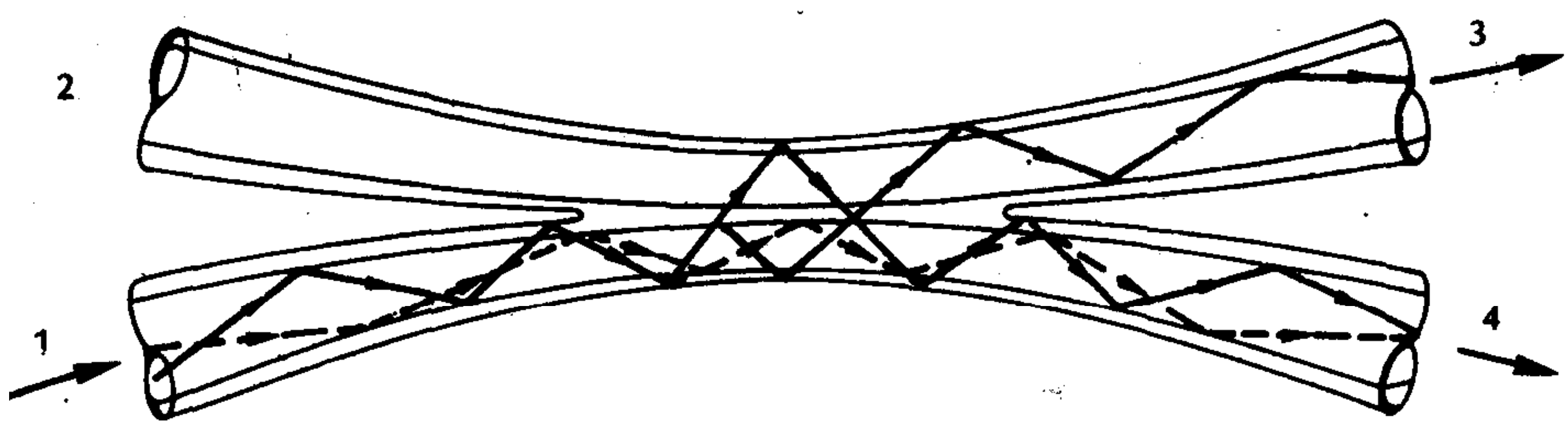


GRIN-rod lens based microoptic fiber couplers: (a) parallel surface type; (b) slant surface type.

- Note : Parallel surface type, is more attractive due to its ease of fabrication, compactness, simplicity and relatively low insertion loss.

FUSED BICONCICAL TAPER TECHNIQUE

Fibers are generally twisted together and spot fused under tension, so as to form an elongated biconical taper structure.



Structure and principle of operation for the fiber fused biconical taper coupler.

<u>FBT (contd</u>)

-3 port coupler is formed by removing one of the i/p fibers.

-Optical power launched propagates in the form of guided core modes.

-Higher order modes take part and only a portion of the total power gets coupled (lower order modes generally remain within the main fiber)

-When waist of taper is narrow, entire mode volume participates and a large portion of i/p power can be shared between o/p fibers.

Note: **coupling ratio obtained is mode dependent.**

Various loss parameters(4 port coupler)

Excess loss= $\frac{\text{Power I/P}}{\text{Power O/P}} = 10 \log_{10} \frac{P1}{P3 + P4}$ (dB)

Insertion loss (port 1 to port 4)=) $10\log_{10} P1/ P4$ (dB)

Cross talk= $10\log_{10} P2/ P1$ (dB)

This provides a measure of directional isolation where P2=backward scatter power (port 2)

Splitting ratio=P3/(P3 +P4)*100%

Losses in star coupler

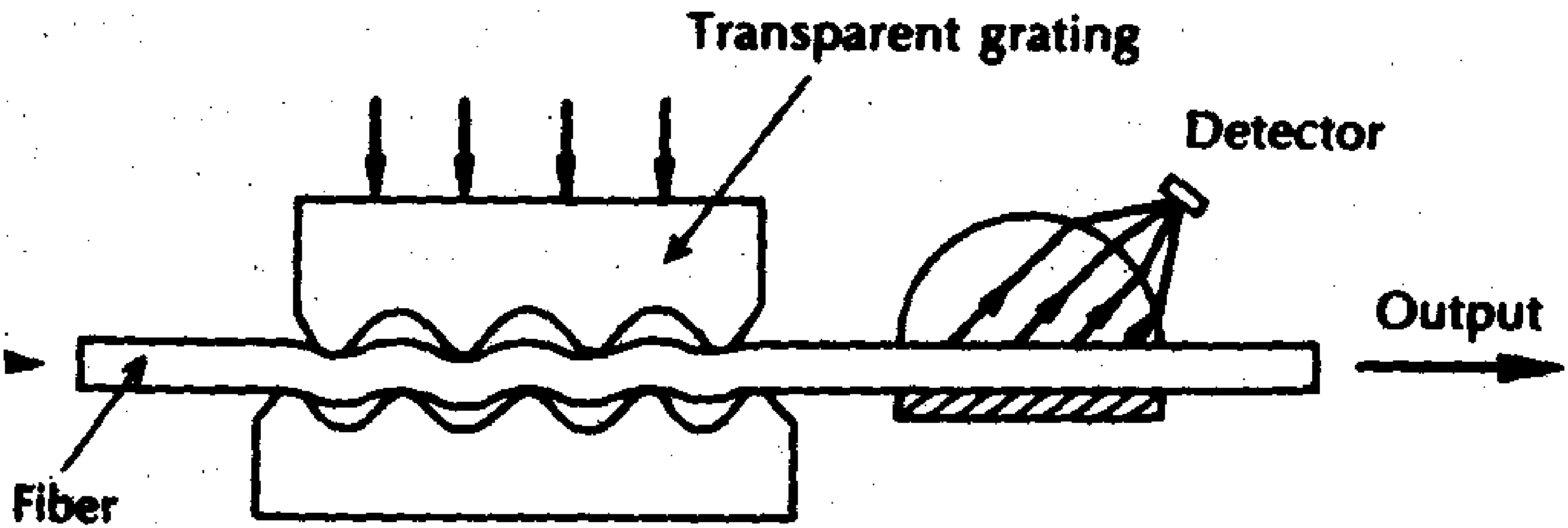
Splitting loss= $10\log_{10} N$ (dB)

Where N=total no. of ports (i/p+o/p)

Cross talk= $10\log_{10} P2/ P1$(dB)

Splitting ratio indicates the % age division of Optical Power between output ports.

TYPES OF COUPLERS- microbend type

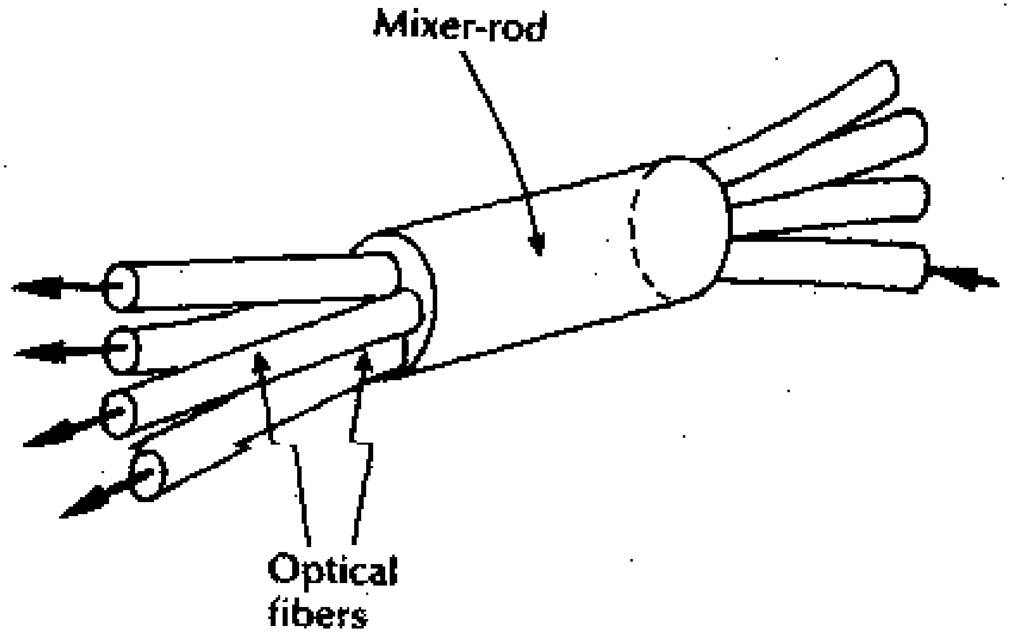


Schematic diagram of a microbend type coupler.

Microbend type Coupler

- A transparent mech grating is used to obtain mode coupling between guided and radiation modes
- **Variable coupling ratios can be obtained by altering the pressure on the fiber**
- Accordingly, low light levels can be extracted from the fiber with very little excess loss (0.05 db)

FIBER STAR COUPLERS- mixer rod technique

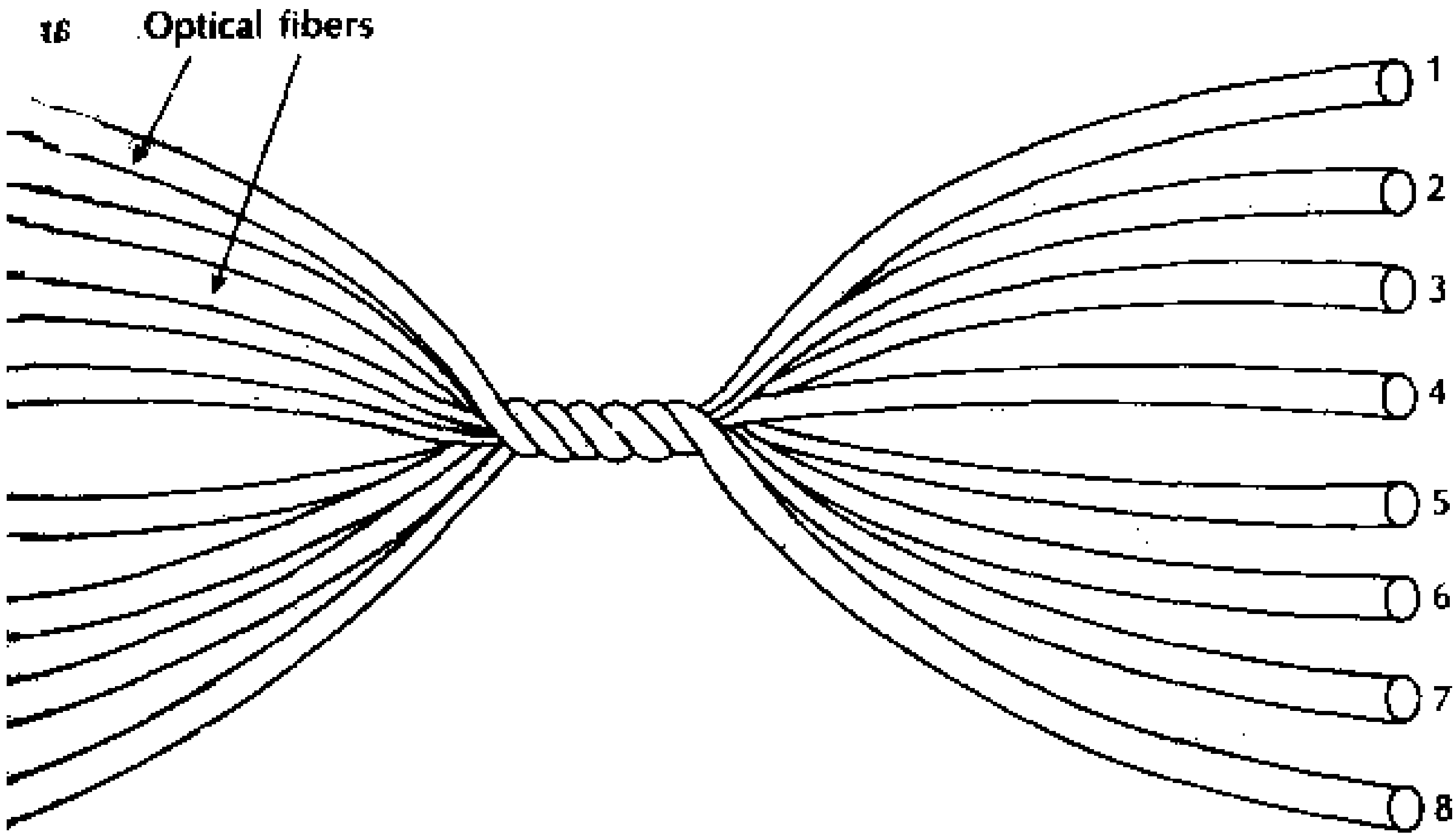


STAR COUPLER

- **Mixer rod method:** a thin platelet of glass is employed for mixing the light and dividing it among the outgoing fibers
- Typical loss for an 8*8 mixer-rod transmissive star coupler = 12.5 db
- **Fused biconical taper star coupler**

The fibers are bundled, twisted, heated and pulled to form the device

TYPES OF COUPLERS- biconical 8*8 port star



Fiber fused biconical taper 8 × 8 port star coupler.

STAR COUPLER

Splitting loss = 10 $\log_{10}$ N db

Excess loss = 10 $\log_{10}$ Pi / $\sum_{1}^{n}$ Pj db

Total loss = Splitting loss + Excess loss