KONGU ARTS AND SCIENCE COLLEGE

(An Autonomous Institution, Affiliated to Bharathiar University, Coimbatore)

ERODE – 638 107

CRITERION II: TEACHING, LEARNING AND EVALUATION

2.2 Catering to Student Diversity

2.2.1 Additional Information

STUDY MATERIALS FOR SLOW LEARNERS

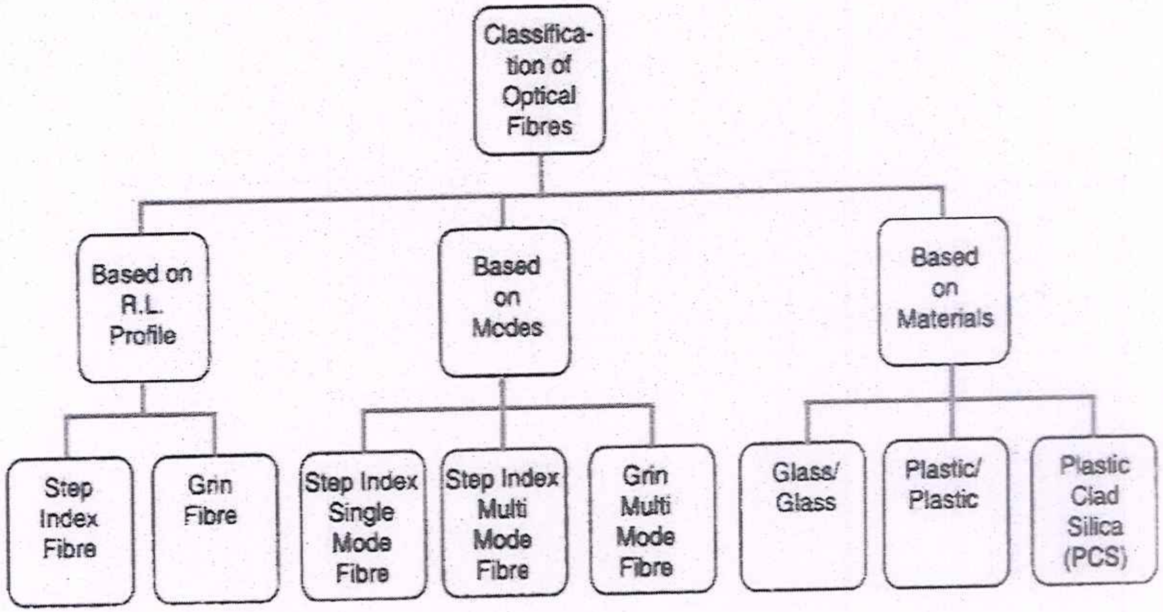
Course: Laser, Fiber Optics and Non-Linear Optics

FIBRE OPTICS (UNIT IV)

- R.CHITRA

B.Sc., Physics

Classification of optical fiber



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Classification based on refractive index profile

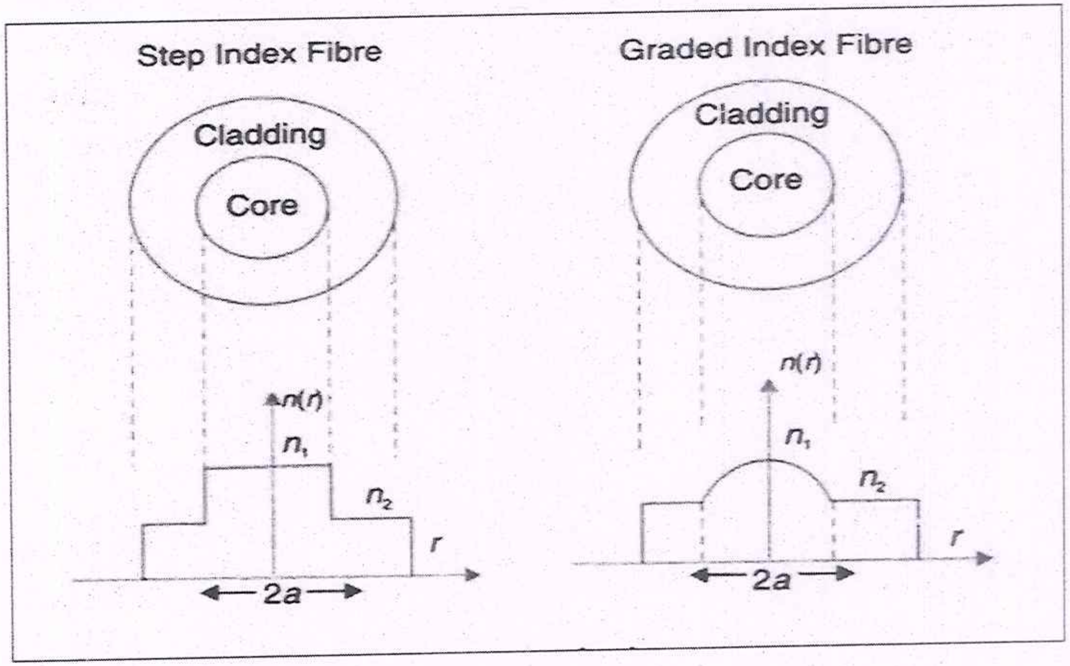
Step index fibres:

- The **refractive index of the core is constant** along the radial direction and sudden falls to a lower value at the cladding and core boundary

Graded index(GRIN) fibres:

- The refractive index of the core is not constant but varies smoothly over the diameter of the core
- It has a maximum value at the centre and decreases gradually towards the outer edge of the core.
- At the core-cladding interface the refractive index of the core matches with the refractive index of the cladding
- The refractive index of the cladding is constant.

Step index vs Graded index fibre



Classification based on mode of light propagation

On the basis of modes of light propagation,

(a) Single mode fibre (SMF)

(b) Multimode fibre (MMF)

Single mode fibre (SMF)

A single mode fibre has a smaller core diameter and can support only one mode of propagation.

Multimode fibre (MMF):

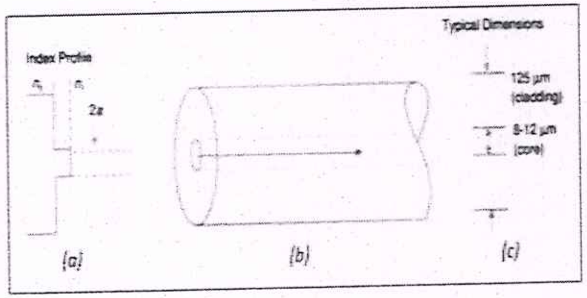
A multimode fibre has a larger core diameter and supports a number of modes.

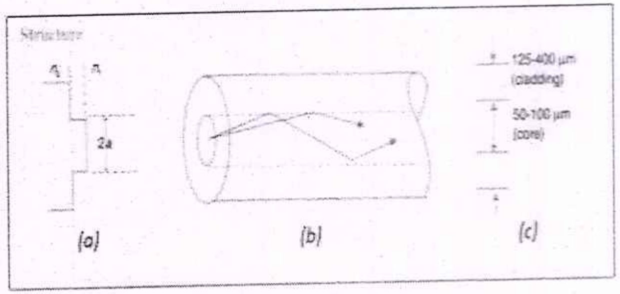
On the whole, the optical fibres are classified into 3 types

Single mode step-index (SMF) fibre

Multimode step-indx (MMF) fibre

Graded index (multimode) (GRIN) fibre





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Classification based on materials

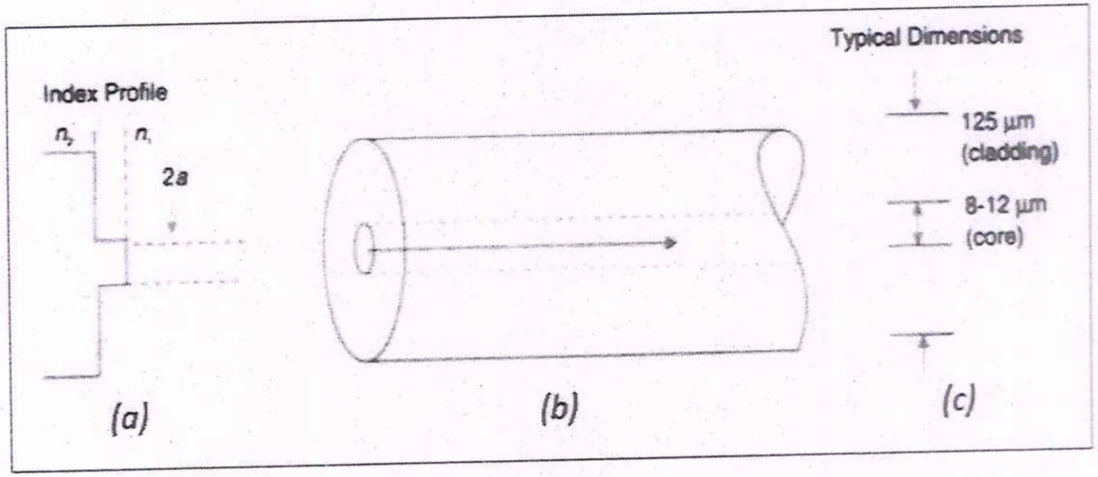
This classification deals with the materials used for core and cladding.

The optical fibres, under this consideration are classified in to three categories.

1. Glass/glass fibres (glass core glass cladding)
2. Plastic/plastic fibres (plastic core with plastic cladding)
3. PCS fibres (polymer clad silica)

The three types of fibre

- Single mode step index fiber structure



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Single Mode Step Index Fibre

Single Mode Step Index Fibre

- **Structure:** A single mode step index fibre has a very fine thin core of diameter of 8μm to 12μm
- It is usually made of germanium doped silicon. The core is surrounded by a thick cladding of lower refractive index.
- The cladding is composed of silica lightly doped with phosphorous oxide.
- The external diameter of the cladding is of the order of 125μm.
- The fibre is surrounded by an opaque protective sheath.
- The refractive index of the fibre changes suddenly at the core-cladding boundary.

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Single Mode Step Index Fibre contd...

- The variation of the refractive index of a step index fibre as a function of radial distance be mathematically represented as

$$n(r) = n_1 \; [r < a \;\; incide\ core]$$
$$= n_2 \; [r > a \;\; in\ cladding]$$

Propagation of light in SMF

- Light travels in SMF along a single path that is along the axis as shown in figure
- It is the zero order mode that is supported by a SMF
- Both Δ and N A are very small for single mode fibres
- This small value is obtained by reducing the fibre radius and by making Δ to be small
- The low N A means low acceptance angle
- Therefore, light coupling into the fibre becomes difficult
- Costly laser diodes are needed to launch light into SMDF

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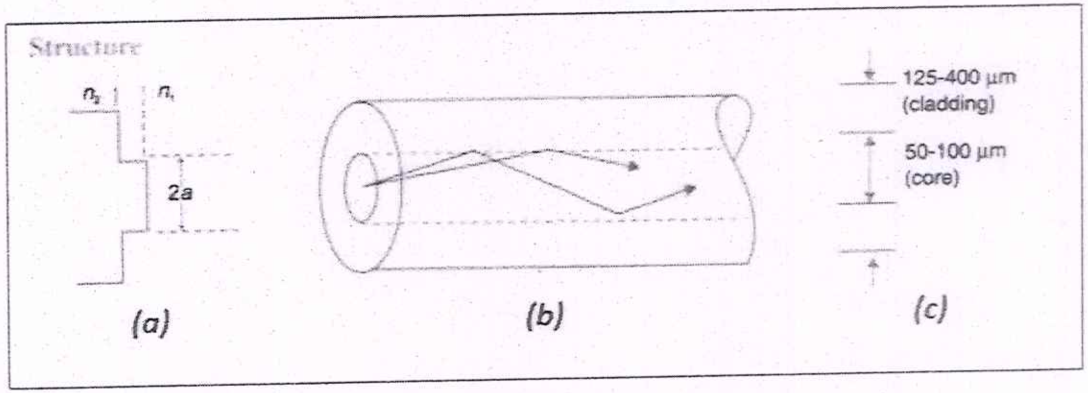
Multi mode step index fiber



The figure shows (a) its R.I. profile, (b) Ray paths (c) typical dimensions.

Multi mode step index fiber

Structure:

- A multimode step index fibre is very much similar to the single mode step index fibre except that its core is of larger diameter.
- The core diameter is of the order of 50 to 100μm, which is very large compared to the wavelength of light.
- The external diameter of cladding is about 150 to 250μm

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Propagation of light in MMF

- Multimode step index fibre allows finite number of guided modes.
- The direction of polarization, alignment of electric and magnetic fields will be different in rays of different modes.
- Many zigzag paths of propagation are permitted in a MMF.
- The path length along the axis of the fibre is shorter while the other zigzag paths are longer.
- The lower order modes reach the end of the fibre earlier while the high order modes reach after some time delay

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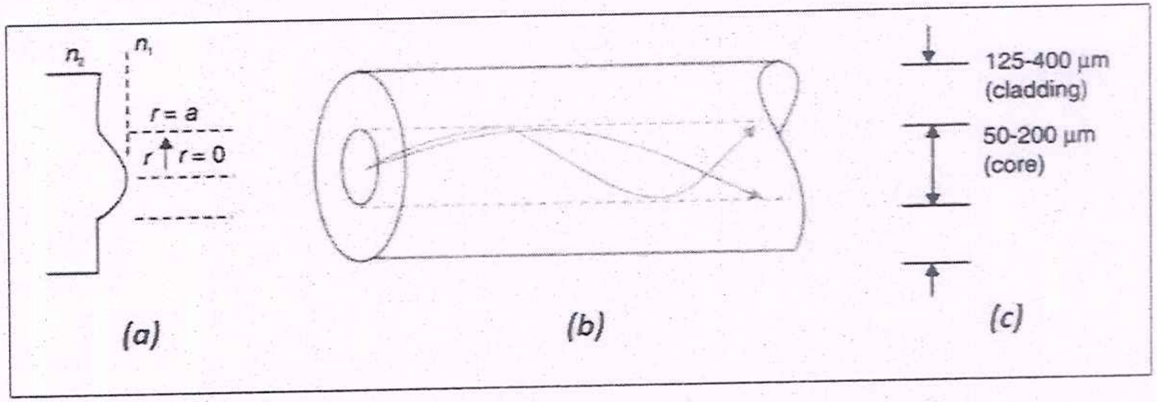
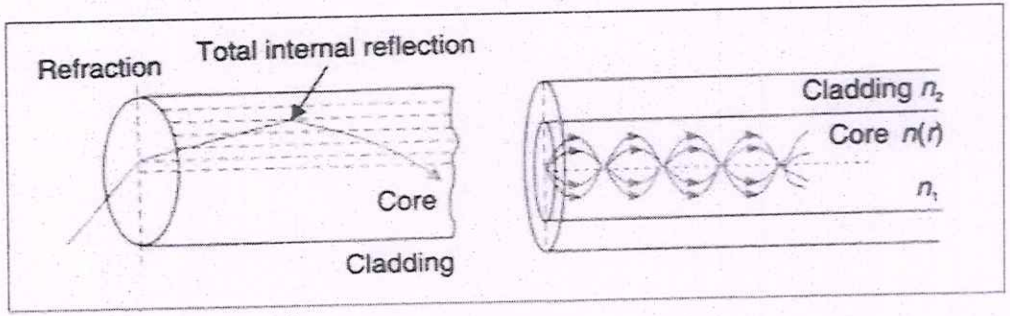
Graded index (grin) fiber





Graded index fiber

- A graded index fibre is multimode fibre with core consisting of concentric layers of different refractive indices
- Refractive index varies with distance from fibre axis
- High value at centre and falls off radially with distance from the axis
- Size is same as step index fibre
- Variation of refractive index of core with radius from centre is

$$n(r) = \begin{cases} n_1 \sqrt{1 - \left[2\Delta\left(\frac{r}{a}\right)^{\alpha}\right]}, & r < a \text{ inside core} \\ n_2, & r > a \text{ in cladding} \end{cases}$$

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Graded index (grin) fiber contd.,

- n_1 is the max refractive index at the core axis,
- a is the core radius
- α grading profile index no varies from 1 to ∞

Propagation of light in Graded index (grin) fiber

- When light travels from high refractive index to low refractive index region, it is bent away from the normal.
- The process continues till total internal reflection is met
- Continuous refraction is followed till core-clad interface
- All rays travelling through the fibre, irrespective of their modes of travel, almost with same optical length reach the end at the same time
- NA is given by

$$NA = \sqrt{n^2(r) - {n_2}^2} \approx n_1 (2\Delta)^{\frac{1}{2}} \sqrt{1 - \left(\frac{r}{a}\right)^2}$$

$$= n_1 \sqrt{2\Delta\left[1 - \left(\frac{r}{a}\right)^2\right]}$$

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Materials

Optical fibres are fabricated from glass or plastic which are transparent to optical frequencies.

Step index fibres are produced in three forms:

1. A glass core cladded with a glass having a slightly lower refractive index,
2. A silica glass core cladded with plastics and
3. A plastic core cladded with another plastic.

Generally the refractive index step is the smallest for all glass fibres, a little larger for the plastic clad Silica PCS (fibres) and the largest for all plastic construction.

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All Glass Fibres:

- The basic material of optical fibres is silica (SiO_2). It has a refractive index of 1.458 at λ=850nm.
- The materials of different refractive index are obtained by doping silica material with various oxides.
- If the silica is doped with Germania (GeO_2) or phosphorous pentoxide (P_2O_5), the refractive index of the material increases.
- Such materials are used as core materials and pure silica is used as cladding material in these cases.
- When pure silica is doped with boria (B_2O_3) or fluorine, its refractive index decreases.
- These materials are used for cladding when pure silica is used as core material.
- The examples for fibre compositions are

SiO_2 core – $B_2O_3.SiO_2$ cladding; $GeO_2.SiO_2$ core – SiO_2 cladding

All Plastic Fibres

- In these fibres, Perspex (PMMA) and polysterene are used for core. Their refractive indices are 1.49 and 1.59 respectively
- A fluorocarbon polymer or a silicone resin is used as a cladding material. A high refractive index difference is achieved between the core and the cladding materials
- Therefore, plastic fibres have large NA of the order of 0.6 and large acceptance angles up to 77°.
- The main advantages of the plastic fibres are low cost and higher mechanical flexibility. The mechanical flexibility allows the plastic fibres to have large cores, of diameters ranging from 110 to 1400μm
- They are temperature sensitive and exhibit very high loss. Therefore, they are used in low cost applications and at ordinary temperatures (below 80°C). Examples of plastic fibres compositions are

1. Polysterene core n_1=1.60 NA=0.60

   -Methyl methacrylate cladding n_2=1.49
2. Polymethyl methacrylate core n_1=1.49 NA=0.50

   -cladding made of its copolymer

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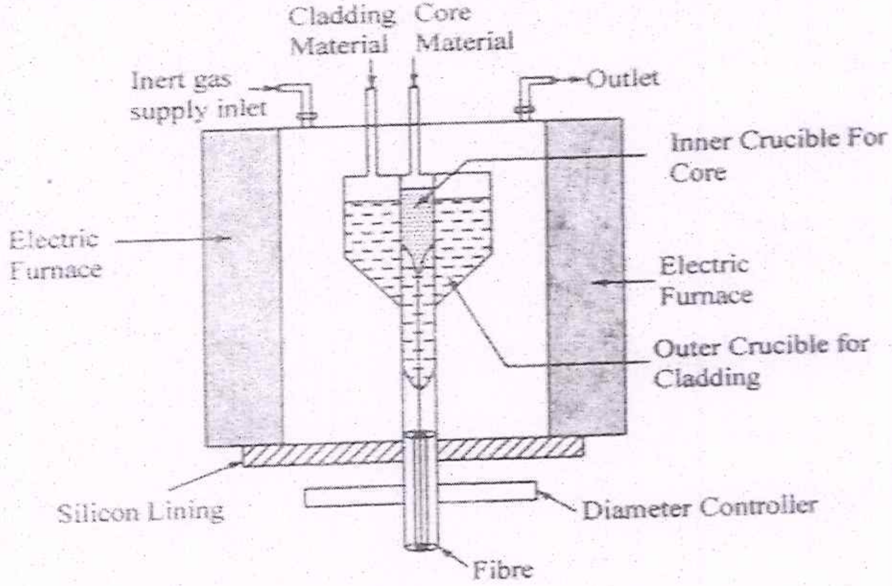
PCS Fibres:

- The plastic clad silica (PCS) fibres are composed of silica cores surrounded by a low refractive index transparent polymer as cladding.
- The core is made from high purity quartz.
- The cladding is made of a silicone resin having a refractive index of 1.405 or perfluoronated ethylene propylene (Teflon) having a refractive index of 1.338.
- Plastic claddings are used for step-index fibres only.
- The PCS fibres are less expensive but have high losses. Therefore, they are mainly used in short distance applications.

Fabrication

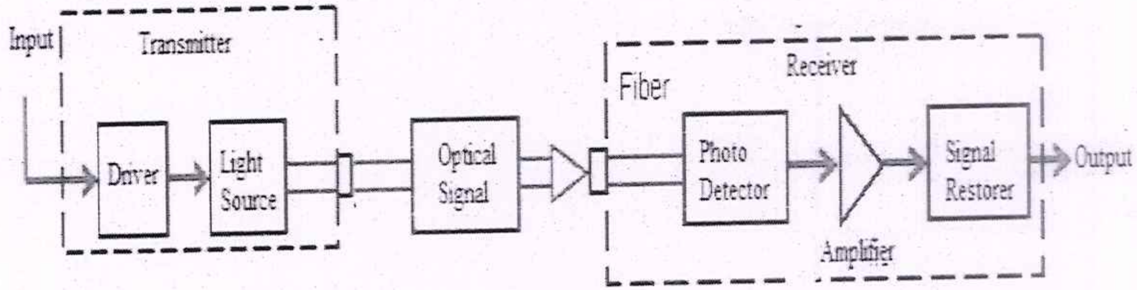
Double crucible method of fiber fabrication



- Consists of two concentric platinum crucibles having thin orifices at the bottom
- Raw material of core (glass) is placed in inner crucible and clad is placed in the outer crucible
- Double crucible arrangement is mounted vertically in a furnace
- The furnace is maintained at a suitable temperature to take the raw material into molten state
- Fibres are drawn through the orifices at the bottom
- As both core & clad materials are drawn simultaneously, optical fiber of required thickness is obtained with monitor
- Fiber is then coated with polymer and then passed through a plastic extrusion to form a plastic sheath over coating

Fibre Optic communication System

- **Transmitter**
- Transmitter section consists of light source with drive circuits
- Transducer (Driver) converts non-electrical message into electrical signal and is then fed to the light source
- **Light Source**
- LASERs or LEDs are usually used as light source here to convert digital pulses into optical pulses



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- Propagation Medium
- Optical fibre is a propagation medium.
- It acts as a waveguide and transmits optical pulses towards receiver by the principle of total internal reflection
- **Receiver**
- It consists of photo detector, amplifier and signal restorer
- Photo detector converts optical signal back into electrical signal
- Further signals are amplified
- These signals are decoded

- Working
- The light waves are modulated with the signal
- Digital modulation is achieved by varying intensity of light at a faster rate
- A pulse of light represents ‘1’ and absence is ‘0’.
- The transmitter feeds the analog or digitally modulated light wave to the channel known as ‘optical fiber link’
- Optical signal travelling through the optical fibre is directed into the photo detector at the end
- Photo detector converts light signal back into electrical signal
- Then the signals are amplified and decoded to obtain the message
- The output is again fed back to a suitable transducer to convert back into audio or video form

Applications

- **Local Area Network**
- Local Area Network (LAN)is a computer oriented multiuser communication system
- This operates over short distances of about 1 to 2 km.
- No. of channels are interconnected over a common channel
- Increases enormously the data handling efficiency
- **Long-haul communication**
- It is the important application of fibre optic communication
- This operates over long distances 10 km or more
- Telephone cables connecting various countries come under this category

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Fibre Losses

- The attenuation of an optical fiber measures the amount of light lost between input and output.
- Optical losses of a fiber are usually expressed in ***decibels per kilometer (dB/km)***. The expression is called the ***fiber's attenuation coefficient α*** and the expression is

$$\alpha = \frac{10}{L}\log\frac{P_i}{P_o}$$

- where Po is the optical power output, Pi is the power at the origin.

Different Mechanisms of Attenuation

Two Types

- **Intrinsic Attenuation**
  - Material absorption
  - Rayleigh scattering
- **Extrinsic Attenuation**

  Bending losses

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- **Material absorption**
- Due to imperfection and impurities in the fibre. This lead 3-5 % of attenuation
- Common impurity is (OH-) molecule which remains from manufacturing technique
- This results due to chemical reaction or humidity from the environment
- OH, Transition metals such as cu, Ni, Cr , Mn have electronic absorption in and near visible part of spectrum.
- Even pure glass absorbs light in specific wavelength region. Strong electronic absorption at UV wavelengths and vibrational absorption at IR wavelengths
- The absorption of light due to intrinsic or impurities cause transmission loss and can be controlled during manufacturing only

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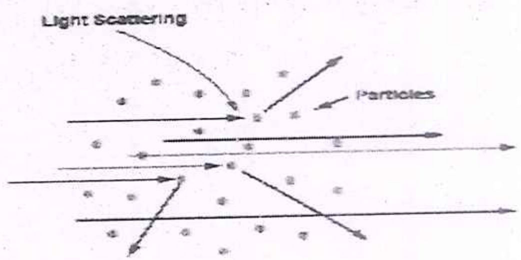
- Rayleigh Scattering
- Rayleigh scattering is the main type of linear scattering.
- It is caused by small-scale inhomogeneities that are produced in the fiber fabrication process.
- Examples of inhomogeneities are glass composition fluctuations and density fluctuations
- Rayleigh scattering accounts for about 96% of attenuation in optical fiber.
- As light travels in the core, it interacts with the silica molecules in the core.
- The local microscopic density variations in glass cause local variations in refractive index
- These variations occur while manufacturing fibre
- These small obstruction may also

scatter light



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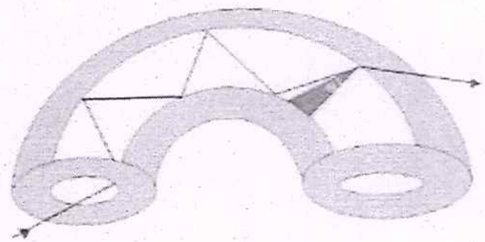
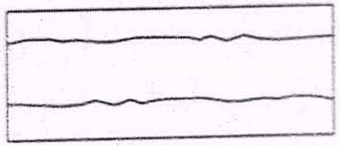
□ Macrobending Loss

- This loss occurs when radius of curvature of bend is greater than fibre diameter
- This situation arises when a fibre turns a corner
- At the corner, light radiation will not satisfy the condition for total internal reflection and hence light escapes out



- **Microbending Loss**
- Microbendings are the small-scale bends in the core-cladding interface.
- These are localized bends can develop during deployment of the fiber, or can be due to local mechanical stresses placed on the fiber, such as stresses induced by cabling the fiber or wrapping the fiber
- Microbending can also happen in the fiber manufacturing process.
- It is sharp but microscopic curvatures that create local axial displacement of a few microns and spatial wavelength displacement of a few millimeters.



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Fibre splicing

- The process of Joining two fibre is known as splicing
- It consists of fusing of two fibre ends and bonding them together in an alignment structure
- **Fusion Splicing**
- joining two fibres using heat is known as fusion splicing
- Goal is to fuse perfectly without light not scattering or reflected back by the splice
- Two cable ends of fibres are cleaved (cut) with a precision cleaver to make them perpendicular and placed inside the holder
- The splicer uses small motors to align end faces together and emits a small spark between the electrodes to burn off dust and moisture

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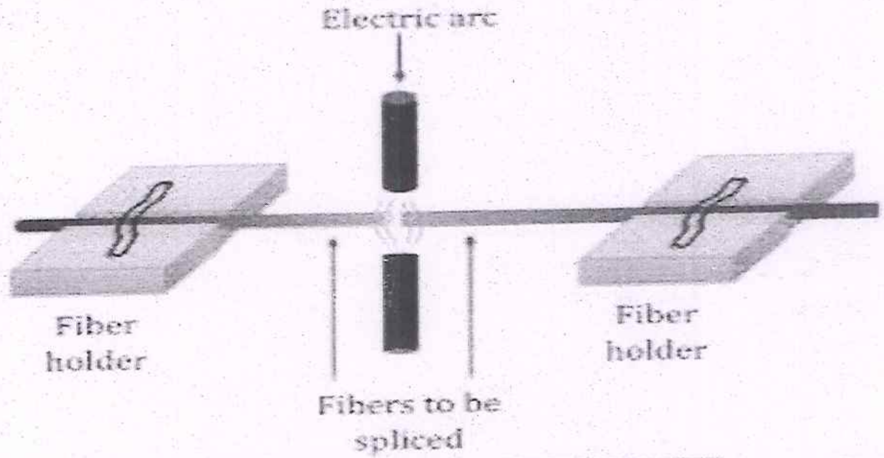
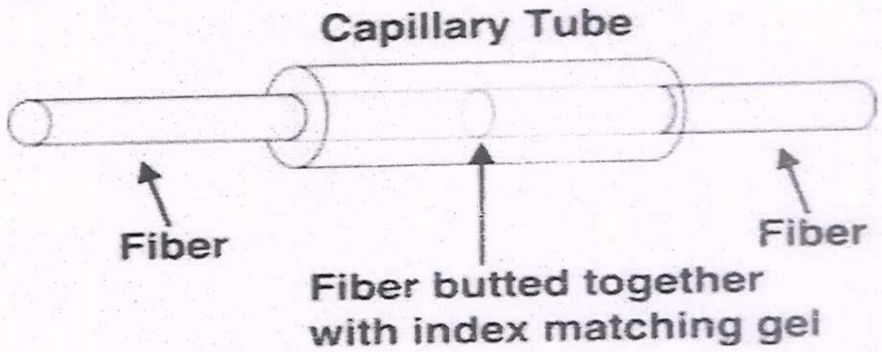
- Then the splicer generates a large spark that increases the temperature
- Temperature is maintained above melting point of fibre to join permanently

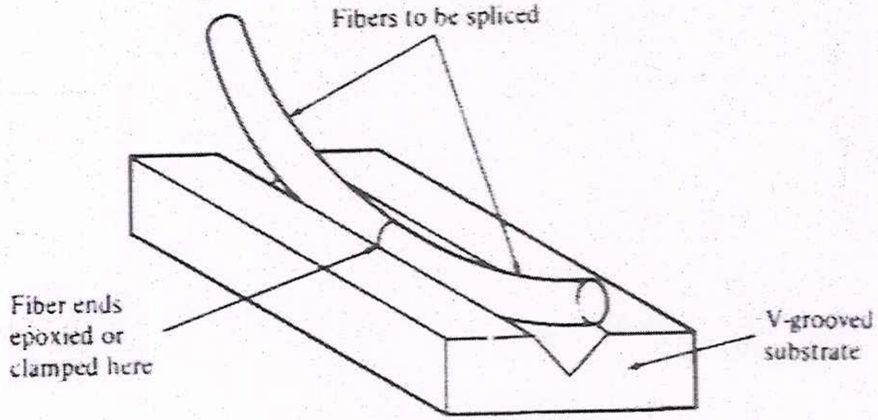


Fusion splicing of optical fiber

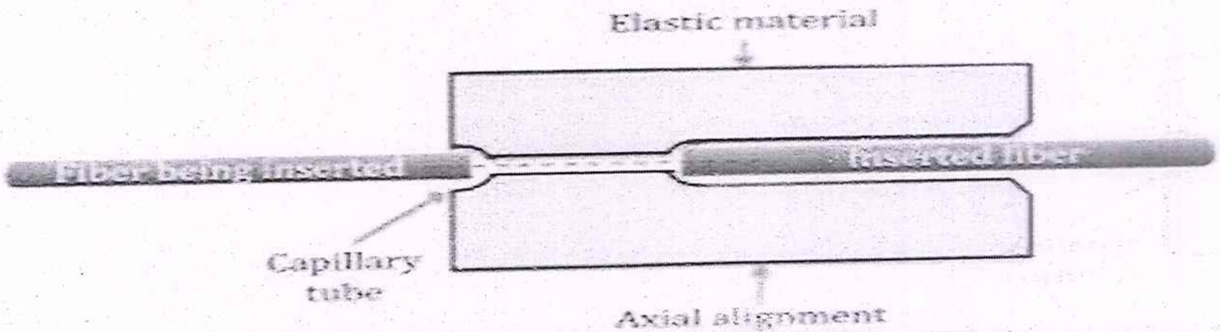
- Mechanical Splicing
- A mechanical splice is a junction of two or more optical fibers that are aligned and held in place by a self-contained assembly.
- The fibers are not permanently joined, just precisely ends are held together by index matching gel that enhances the transmission of light



- V-Groove splice technique
- Simplest mechanical splice
- Fibres to be joined are placed in the groove
- Angular alignment is well controlled
- Two fibre ends are epoxied permanently into position
- Misalignment would be negligible if two fibres have same core and cladding diameter



- **Elastomer splice technique**
- Elastomer is an elastic material usually made into a cylinder with an opening along its axis
- The groove is little smaller but accepts and centers it by expanding slightly when fibre is inserted
- The fibres are inserted from both ends of cylinder and touch near its midpoint
- The slice can be epoxied for permanent connection



Elastic-tube splicing of optical fiber

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Characteristics of Fibres:

Step index single mode fibre:

- It has a very small core diameter, typically of about 10μm.
- Its numerical apertures is very small
- It supports only one mode in which the entire light energy is concentrated.
- A single mode step index fibre is designed to have a V number between 0 and 2.4.
- Because of a single mode of propagation, loss due to intermodal dispersion does not exist.
- With careful choice of material, dimensions, and wavelength, the total dispersion can be made extremely small.
- The attenuation is least.
- The single mode fibres carry higher bandwidth than multimode fibres.
- It requires a monochromatic and coherent light source. Therefore, laser diodes are used along with single mode fibres.

Advantages:

- No degradation of signal
- Low dispersion makes the fibre suitable for use with high data rates.
- Single-mode fiber gives higher transmission rate and up to 50 times more distance than multimode.
- Highly suited for communications

- **Disadvantages:**

- Manufacturing and handling of SMF are more difficult.
- The fibre is costlier.
- Launching of light into fibre is difficult.
- Coupling is difficult.

- **Applications:**

- Used as under water cables

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Step-index multi-mode fibre:

- It has larger core diameter, typically ranging between 50-100μm.
- The numerical aperture is larger and it is of the order of 0.3
- Larger numerical aperture allows more number of modes, which causes larger dispersion.
- The dispersion is mostly intermodal & Attenuation is high.
- Incoherent sources like LEDs can be used as high sources with multimode fibres.
- **Advantages:**
- Easy to manufacture & less expensive
- LED or laser source can be used. Launching of light into fibre is easier.
- It is easier to couple multi-mode fibres with other fibres.
- **Disadvantages:**
- It has smaller bandwidth.
- Due to higher dispersion data rate is lower and transmission is less efficient.
- It is less suitable for long distance communications.
- **Applications:**
- Used in data links.

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- **Graded-index multi-mode fibre:**
- Core diameter is in the range of 50-100μm.
- Numerical aperture is smaller than that of step-index multimode fibre.
- The number of modes in a graded index fibre is about half that in a similar multimode step-index fibre.
- It has minimum attenuation.
- Intermodal dispersion is zero, but material dispersion is present.
- It has better bandwidth than multimode step-index fibre.
- **Advantages:**
- Either an LED or a laser can be used as the source of light with GRIN fibres.
- **Disadvantages:**
- The manufacture of graded index fibre is more complex. Hence, it is the most expensive fibre.
- Coupling fibre to the light source is difficult.
- **Applications:**
- Used in telephone links.

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Merits of Optical Fibre:

1. Cheaper:

- Optical fibres are made from silica (SiO_2) which is one of the most abundant materials on the earth.
- The overall cost of a fibre optic communication is lower than that of an equivalent cable communication system.

2. Smaller in size, lighter in weight, flexible and strong:

- The cross section of an optical fibre is about a few hundred microns.
- Optical fibres are quite lighter, flexible and strong.

3. Not hazardous:

- Accidents cannot occur with fibre links since fibre links are made of insulating materials.

4. Immune to EMI and RFI:

- In optical fibre, information is carried by photons.
- Photons are electrically neutral and cannot be disturbed by high voltage fields, lightening, etc.
- Therefore, fibres are immune to externally caused background noise generated through electromagnetic interference (EMI) and radiofrequency interference (RFI).

5. No cross talk:

- Light cannot couple into the fibre from sides.
- In view of these features, possibility of cross talk is minimized when optical fibre is used. Therefore, transmission is more secure and private.

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6. Wider bandwidth:

- Optical fibres have ability to carry large amounts of information.
- While a telephone cable composed of 900 pairs of wire can handle 10,000 calls, a 1mm optical fibre can transmit 50,000 calls.

7.Low loss per unit length:

- The transmission loss per unit length of an optical fibre is about 4dB/km. Therefore, longer cable-runs between repeaters are feasible.

Disadvantages:

- Installation and maintenance of optical fibres requires a new set of skills.
- They require specialized and costly equipment like optical time domain reflectometers etc.

Fibre Optic Sensor

- **Temperature Sensor**
- (a) Intensity Modulated Sensor
- Principle
- Temperature is sensed by the modulation of intensity of reflected light from a target(silicon)
- Depending on the temp, the amount of light absorbed by silicon varies
- **Construction**
- Fibre is coated with silicon at one end
- Silicon is coated with reflective coating at the back
- Silicon layer acts as the sensing element

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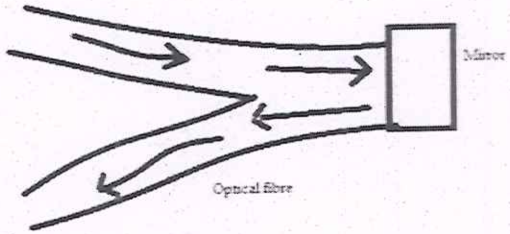
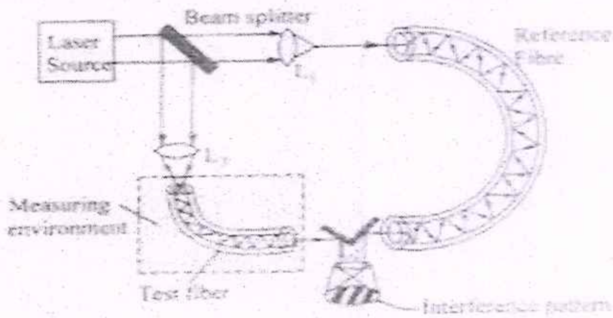
- Working
- Light is launched from one end of the fibre
- It passes through the fibre and then falls on silicon layer
- Silicon layer reflects the light back
- The reflected light emerges through another branch of multimode fibre and is collected by photodetector
- Absorption of light by silicon layer varies with temperature



- **(b)Phase Modulated sensor**
- **Principle**
- This sensor is based on phase variation resulting due to the variation of refractive index of the fibre under the influence of temperature
- **Construction**
- Laser produces light
- Beam splitter is to split the beam into 2 parts
- Then the light is passed through a sensing fibre and reference fibre
- Then light is detected by detector which measures the difference in phase of two light waves



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- Working
  - Light from source is divided into 2 parts by beam splitter
  - One part is passed through the sense fibre and other part is passed through the reference fibre
  - Light rays entering fibres are coherent and at same phase
  - When the sense fibre is heated, the temperature causes a change in refractive index
  - Therefore, light coming out of fibres will have phase difference
  - When they are superposed at the detector, interference pattern will be observed
  - When temperature increases, displacement in fringe pattern is observed
  - From displacement, magnitude of temperature can be determined

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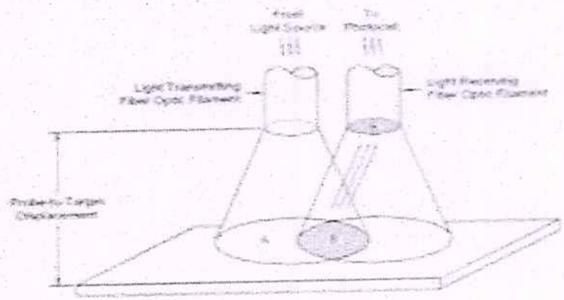
- **Displacement Sensor**
- **Principle**
- **Pair of fibre optic elements, one to carry light from a remote source to an object whose displacement is to be measured and other to receive light from the object and carry it back to remote photodetector**
- **Construction**
- **Two optical fibres are placed adjacent to each other**
- **One transmits light from a light source**
- **Other fibre receives light from the object under study and pass it on to a photodetector**



Working

- Light from the transmitting fibre element is incident on the object
- Receiver fibre element is placed near to the transmitting fibre
- Distance between the target object and fibre element is monitored
- Depending on the distance between object & fibre element, amount of reflected light is captured by the receiver, which in turn is carried to the detector
- With a proper calibration, we can obtain the displacement of the object in terms of the strength of the output signal of the photodetector

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