OPTICAL FIBERS/ FIBER OPTICS

(For students of Physics Hons, Sem – VI)

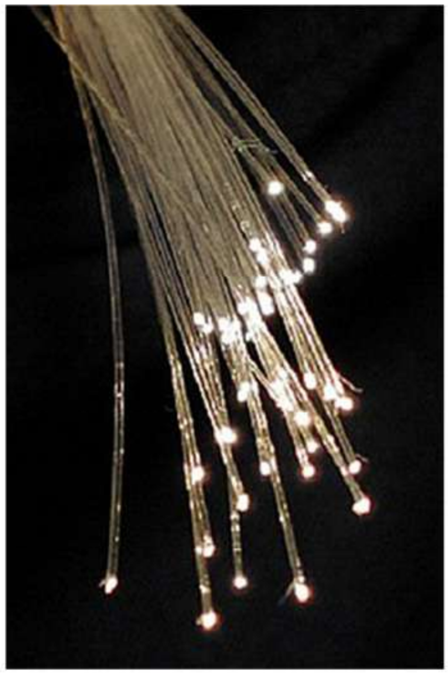

Fig. 01. A bundle of optical fibers [01]

A technology that uses glass (or plastic) threads (fibers) to transmit data. A fiber optic cable consists of a bundle of glass threads, each of which is capable of transmitting messages modulated onto light waves. [02]

An Introduction:

About 142 years ago ← The British Physicist John Tyndall provided the first experimental proof that light could be guided [03].

Employing the well-known optical phenomenon of total internal reflection, he demonstrated to the Royal Society that light could be guided along a curved stream of water.

1920's ← First glass fibers made.

1950's ← Concept of cladding brought forth.

↓

Guiding of light became practical with limited success.

1960 ← Invention of lasers by Maiman.

↓

Created a sensation in optical communication because of its high coherence property.

Why?

↓

Optical frequencies → of the order of 5×10^{14} Hz;

Frequencies employed in electrical communication system such as TV, radar and microwave links→ upto 10^{10}Hz.

↓

Theoretical increase of information capacity → 10^4 times higher in the optical range.

The barrier → Attenuation!!!

↑

Some of the best optical glasses, at that time, had attenuations of the order of several thousand dB/Km.

↓

Use of fiber for communication purposes made impractical.

What practically required?

↑

To a level of 20 dB/km or less.

- Research work went on.
- Enormous improvement in glass technology came in.
- As low as few tens of dB/km was indicated through measurements in pure silica.

↓

1966 → The first time suggestion by Charles Kao, and G. A. Hockman (Standard Telecommunications Laboratories in England) that optical fiber could be made with sufficiently low loss, suitable for relatively long distance communication.

By 1970 → Production of first fiber with loss under 20 dB/km, by workers at Corning glass.

By 1979 → Fiber loss brought down to just 0.2 dB/km near the 1.55 μm spectral region.

1982 → The world's longest optical fiber telephone cable was brought into service between London and Birmingham.

1984 → The world's first 140 Mbit/s single-mode optical fiber system was opened between Milton Keynes and Luton.

1985 → The first UK operational undersea optical fiber cable was laid, linking the Isle of Wight to the mainland across the Solent.

1986→ The first international optical fiber undersea link between the United Kingdom and Belgium was opened.

Revolution in the field of optical fiber communication brought in by the low loss fiber.

Some examples:

- 1977 → An optical communication system was installed in Chicago, which connected two telephone systems central offices and provided [03]
    - Analog data &
    - Digital data transmission; and
    - Audio &
    - Video services

in Chicago, Brownswick building. A 24-fiber optical cable less than 2.5 cm diameter in size was employed to carry 16,000 voice circuits to serve them.

- 1980's → Almost all the industrialized nations switched to fiber-optics communication.
    - More than 3 million kilometers of optical cables were laid, in U.S.A. alone, to replace electrical communication by optical fiber communication at various places across the country.

The demand for fiber rose to such a high level that the decade of 1980's is referred to as decade of glass.

Fiber optics communication → ← light wave communication.

⌂

PHOTONICS.

"PHOTONICS is the enabling technology for optical fiber communication to improve its performance and reduce its cost".

- Charles K. Kao, father of fiber optics.

Optical Fibers:

- ➔ Essentially light guides used in optical communications as waveguides.
- ➔ Transparent dielectrics.
- ➔ Able to guide visible and infrared light over long distances.

Made of mainly two parts:

Inner cylindrical material made of glass or plastic ← Core.

Cladding ← Envelops the inner core as a concentric cylinder.

← Also made of similar material but of lesser refractive index.

Material continuity → Between the core and the cladding.

The cladding → Enclosed in a polyurethane jacket (Fig. 02) → safeguards the fiber against

Chemical reaction with surroundings
Abrasion
Crushing.

Cable → Many fibers (as stated above), each one protected by individual jackets, grouped together (Fig. 03).

→ May consist of one to several hundred fibers.

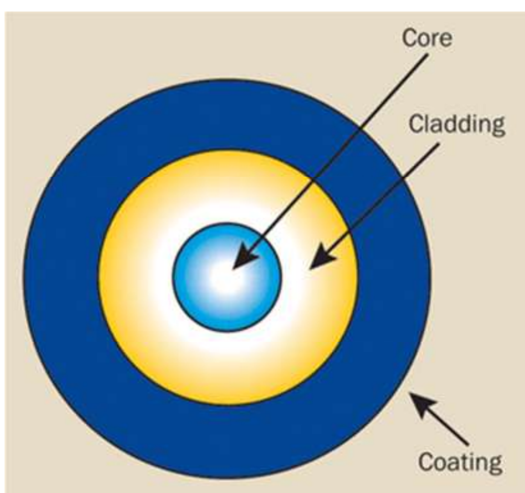

Fig. 02. [04]

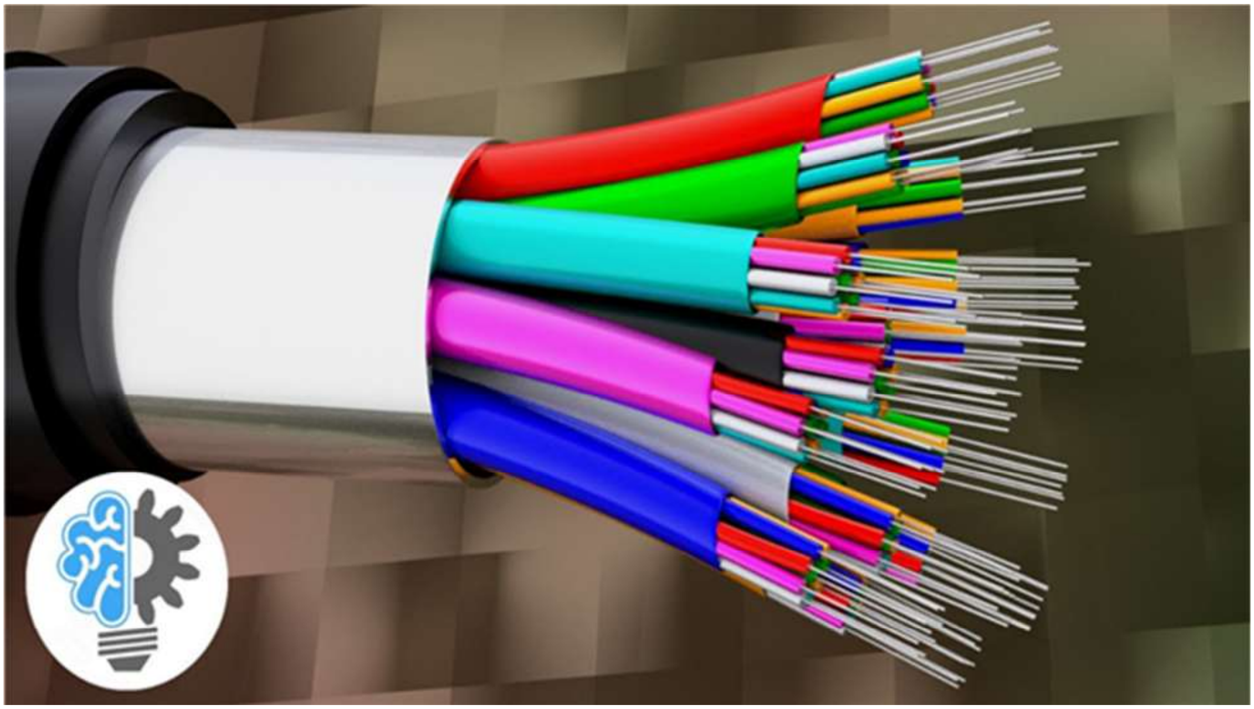

Fig. 03: Optical fiber cable.

What we do mean by 'Optical Fibers as Waveguides':

Defn.[03]:

"A waveguide is a tubular structure through which energy of some sort could be guided in the form of waves. Since light waves can be guided through a fiber, it is called lightguide. It is also called fiber wave waveguide or fiber lightguide."

Guiding Mechanism:

Let, in an optical fiber,

$\mu_{Cl} \rightarrow$ refractive index of the material of the cladding (we shall also denote it as n_2)

$\mu_{Co} \rightarrow$ refractive index of the material of the core (we shall also denote it as n_1)

$\mu_{Cl} < \mu_{Co}$, always.

The light signal is allowed to enter into the core. This can strike the interface of the core and cladding only at large angle of incidence, as could be seen from ray geometry in Fig. 4. The light signal undergoes reflection after reflection within the fiber core.

↑

Each reflection is a total internal reflection, it sustain its strength and confines itself completely within the core during propagation. ← Optical fiber functions as a waveguide.

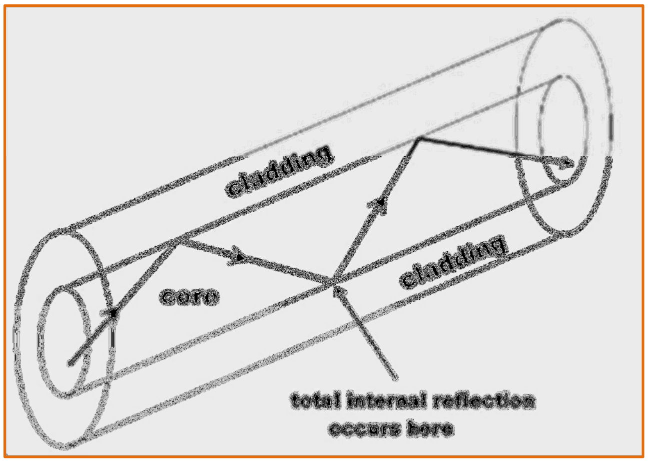

Fig. 04. [05]

What about the bending of the fiber?

Propagation of light continues to persist as long as the fiber is not bent too sharply. ← The light fails to undergo total internal reflection because of which the signal strength comes down drastically.

➔ Hence, care is taken to avoid very sharp bends in the signal carrying fiber.

[It may be noted that, for all analysis of signal propagation in the fiber, the wave property of light is primarily made use of.]

A recapitulation of Total Internal Reflection:

As per the Fig. 05(a) & Fig. 05(b) below, let

AO → incident ray travelling in the medium having refractive index n_1.

XX' → Boundary of the above medium separating the same from another medium of lower refractive index n_2.

θ_1 → angle of incidence, i.e., the angle made by the incident ray, with the normal to the boundary, at the point of incidence, in the medium having R.I. = n_1.

Refraction of the ray into the medium of refractive index n_2 → the ray (OA') bends away from the normal since $n_1 > n_2$.

Let

$\theta_2 \rightarrow$ angle of refraction, i.e., the angle made by the refracted ray, with the normal to the boundary, at the point of incidence/refraction, in the medium having R.I. = n_2.

➔ $\theta_2 > \theta_1$.

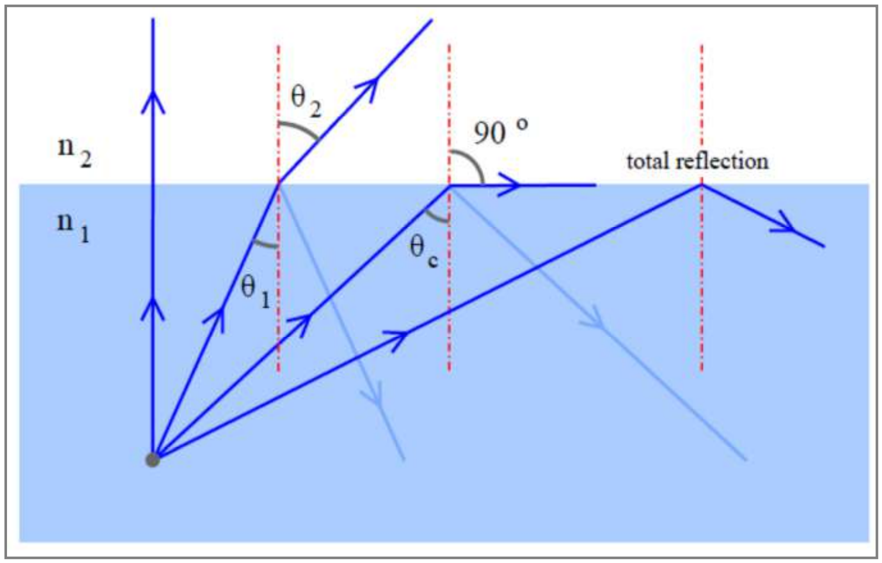

Fig. 05 (a)

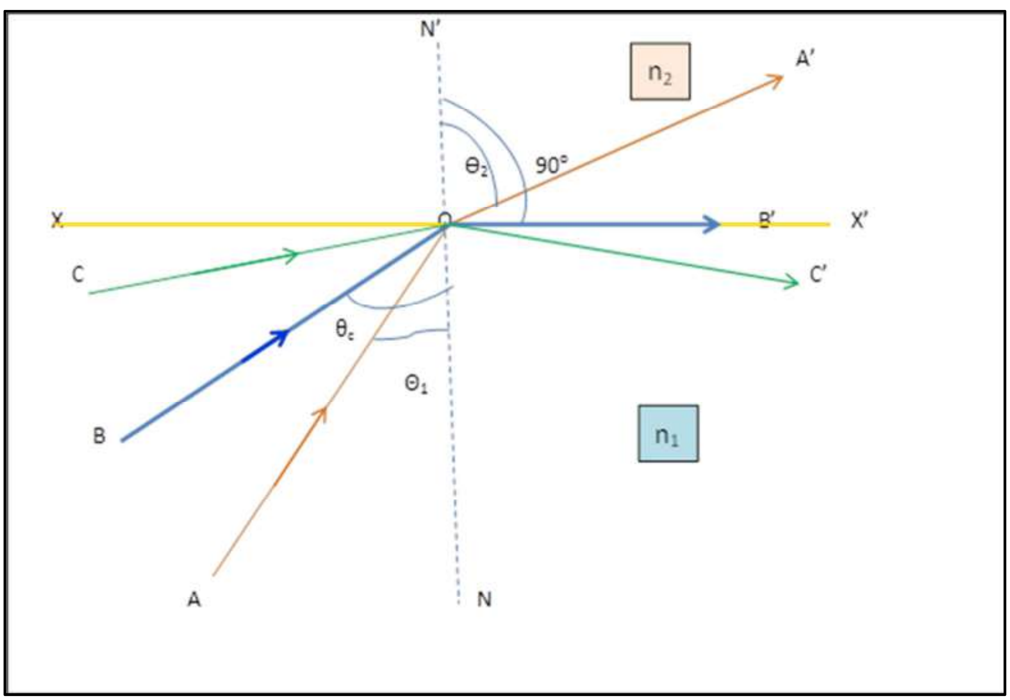

Fig. 05 (b)

Gradually increase θ_1. At certain value of θ_1, $\theta_2 = 90^o$. ← Refracted ray just grazes along the boundary of separation along OB'. ← The incident ray is along BO. ← $\theta_1 = \theta_c$, the critical angle of incidence.

$\theta_1 > \theta_c$ → the incident ray like CO always gets reflected back into the medium in which it is incident on the boundary. ← Total Internal Reflection.

Obeying Snell's law → $n_1 \sin \theta_1 = n_2 \sin \theta_2$.

For $\theta_1 = \theta_c$, $\theta_2 = 90^o$.

- ➔ $n_1 \sin \theta_c = n_2 \sin 90^o = n_2$ (since $\sin 90^o = 1$).
- ➔ $\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$.

Numerical Aperture, Acceptance Cone and Ray Propagation in the Fiber:

A special case be considered → a ray which suffers critical incidence at the core cladding interface.

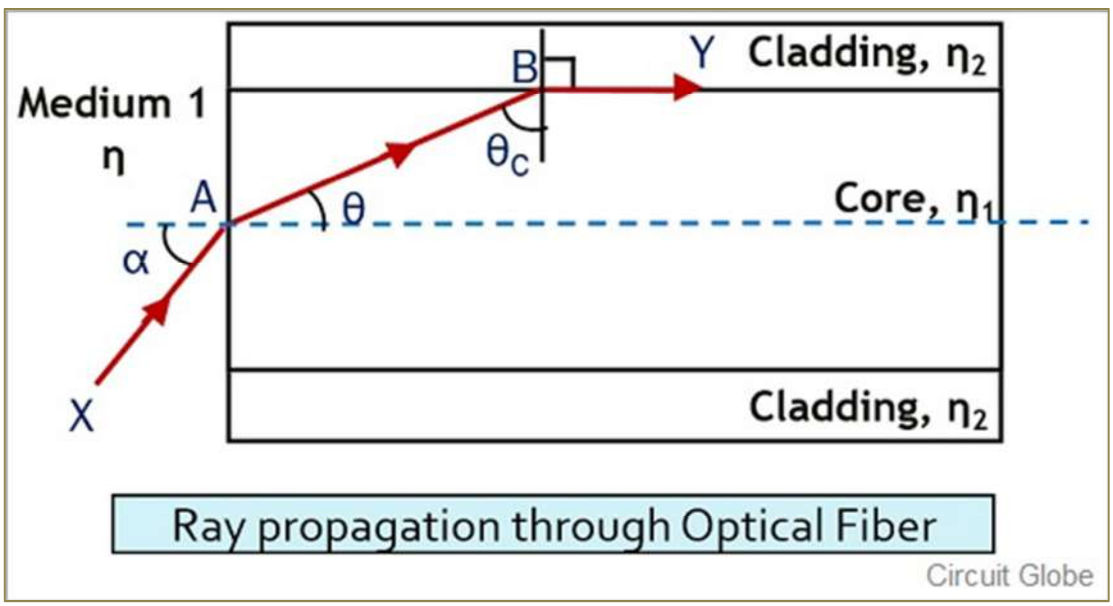

Fig. 06. Acceptance angle (α)

The ray XA enters into the core at an angle α to the fiber axis → refracted along AB at angle θ in the core → falls at critical angle of incidence, $\theta_c = 90^o - \theta$, at B on the interface between core and cladding → grazes along BY (having angle of refraction equal to 90^o).

Any ray which enters into the core, from the surrounding medium, at an angle of incidence less than α → suffers angle of refraction there less than θ → angle of incidence at the interface → $90^o - \theta$ ← greater than the θ_c →undergoes total internal reflection.

Any ray from the surrounding, having angle of incidence > α, at A → incident at the core cladding interface at an angle < θ_c → will be refracted into cladding region → will be lost ← it is the situation when angle of incident from surrounding to core > α.

Rotation of XA around the fiber axis, keeping α constant → describes a conical surface → Acceptance Cone (Fig. 07).

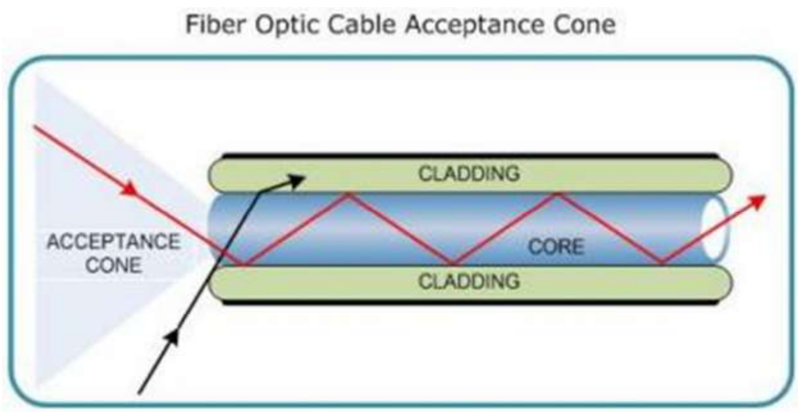

Fig. 07.

sin α → Numerical Aperture (N.A.) → representing the light-gathering capability of the optical fiber.

α → Acceptance cone half angle ← Waveguide acceptance angle.

Condition of Propagation:

Let

n_s → Refractive index of the surrounding medium

n_1 → Refractive index of the core material of the fiber

n_2 → refractive index of the material of the cladding

Consider refraction from surrounding into the core. For the ray XA

Apply Snell's law:

$n_s \sin\theta_s = n_1 \sin\theta_1$ …… (1) [Here α, as discussed above, has been replaced by θ_s, and θ by θ_1]

On the interface, at the point A, the angle of incidence θ_C (critical angle)

$\theta_c = 90^o - \theta_1$.

Again apply Snell's law:

$n_1 \sin(90^o - \theta_1) = n_2 \sin 90^0$

➔ $n_1 \cos\theta_1 = n_2$

➔ $\cos\theta_1 = \dfrac{n_2}{n_1}$ ….. (2).

Eq, (1) → $\sin\theta_s = \dfrac{n_1}{n_s}\sin\theta_1 = \dfrac{n_1}{n_s}\sqrt{1-\cos^2\theta_1}$ …… (3)

Put Eq (2) in Eq (3) →

$\sin\theta_s = \dfrac{n_1}{n_s}\sqrt{1-\dfrac{n_2^2}{n_1^2}} = = \dfrac{\sqrt{n_1^2 - n_2^2}}{n_s}$ ….. (4) ← Numerical aperture (N. A.)

If $n_s = 1$ (air)

$N.A. = \sin\theta_s = \sqrt{n_1^2 - n_2^2}$ …. (5)

Let θ_i → angle of incidence from surrounding medium into core. Then

If $\theta_i < \theta_s$, *i.e.*, *if* $\sin\theta_i < \sin\theta_s$, *i.e.*, *if* $\sin\theta_i < \sqrt{n_1^2 - n_2^2}$ ← allow the propagation.

Condition of propagation → $\sin\theta_i < N.A.$

Classification of fibers and their refractive index profiles:

Cladding ← Uniform refractive index.

Core material refractive index ↗ constant

↘ Vary in a particular way.

Refractive index profile → The curve representing the variation of refractive index w.r.t. the radial distance from the axis of the fiber.

Classification of fibers and their refractive index profiles:

Optical fiber

Single mode	Step index multimode	Graded index multimode

Single Mode Fiber

Core material ← uniform refractive index value (n_1)

Cladding ← Uniform refractive index (n_2)

$n_1 > n_2$.

- ➔ A step jump (increase) in the refractive index from cladding to core.
- ➔ The shape of the refractive index profile also so [Fig. 08].

The diameter of the

Core → 8 to 10 µm.

Cladding (external diameter) → 60 to 70 µm.

Narrow core → Guides just a single mode ← Single mode fiber.

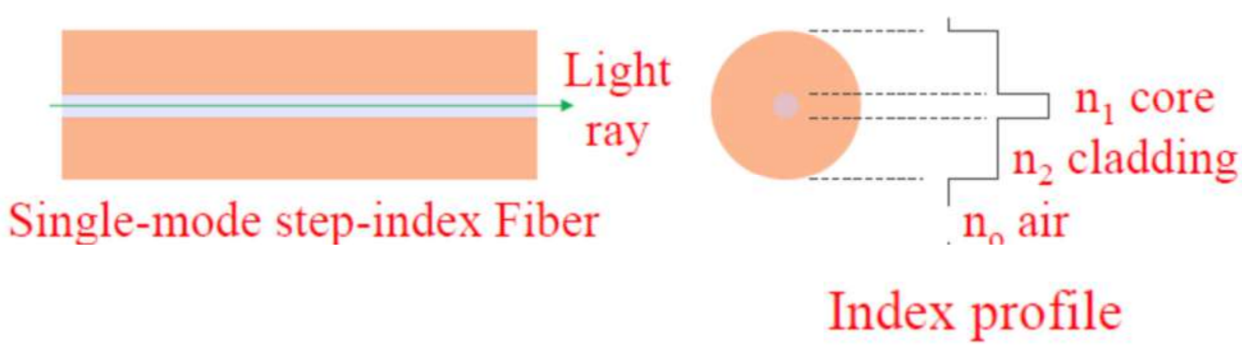

Fig. 08 [06].

- Most extensively used.
- Laser as the source of light.
- Particular application in submarine cable system.
- Very difficult to splice.

Step-index Multimode Fiber:

As for single mode fiber,

Core material ← uniform refractive index value (n_1)

Cladding ← Uniform refractive index (n_2)

$n_1 > n_2$.

- ➔ A step jump (increase) in the refractive index from cladding to core.
- ➔ The shape of the refractive index profile also so.

But

the diameter of the Core

→ much larger than that for single mode fiber so that it is able to support propagation of large number of modes (as shown in figure 09).

Cladding (external diameter) → as adequate for the corresponding core.

Core diameter → 50 to 250 µm.

Cladding (external diameter) → 100 to 250 µm.

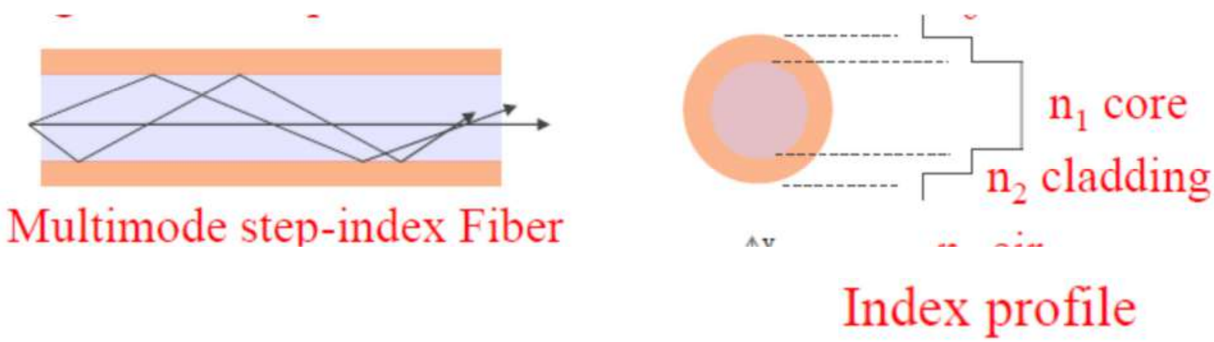

Fig. 09 [06].

- Refractive index profile → similar to that of a single mode fiber but with a larger plane region (signifying larger radius having constant refractive index) for the core.

- Accept a laser or LED as source of light.
- Least expensive.
- Application in data linking.

Graded-index Multimode Fiber (GRIN):

Geometry same as that of a step-index multimode fiber.

Core material ← Refractive index value decreases in radially outward direction from the axis, and becomes equal to that of the cladding at the core-cladding interface.

Cladding ← Uniform refractive index.

Core diameter → 50 to 250 μm.

Cladding (external diameter) → 100 to 250 μm.

Refractive index profile → As shown in Fig. 10.

Fig. 10.[Ref.: https://www.lehigh.edu/imi/teched/GlassProcess/Lectures/]

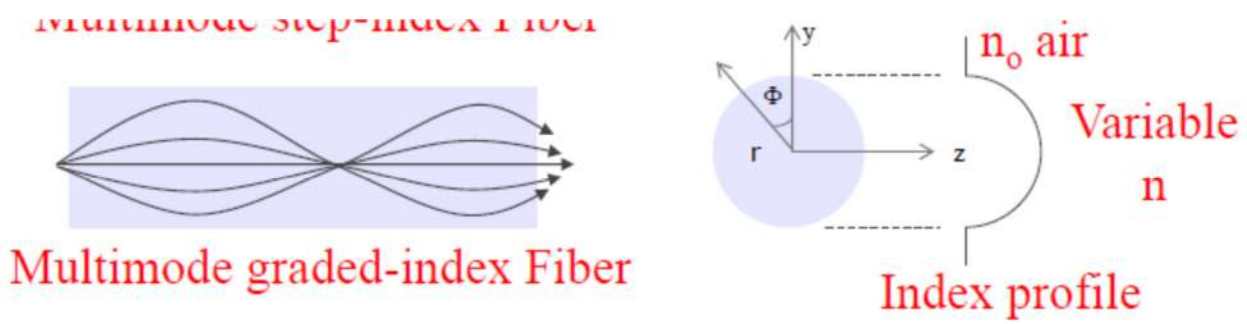

Fig. 10 [06].

- Accept a laser or LED as source of light.
- Most expensive.
- Splicing could be done with some difficulty.
- Application in telephone trunk between central offices.

Applications of Optical Fiber

Fiber optic cables find many uses in a wide variety of industries and applications.

Block diagram on the basics of communication system using optical fiber [03]:

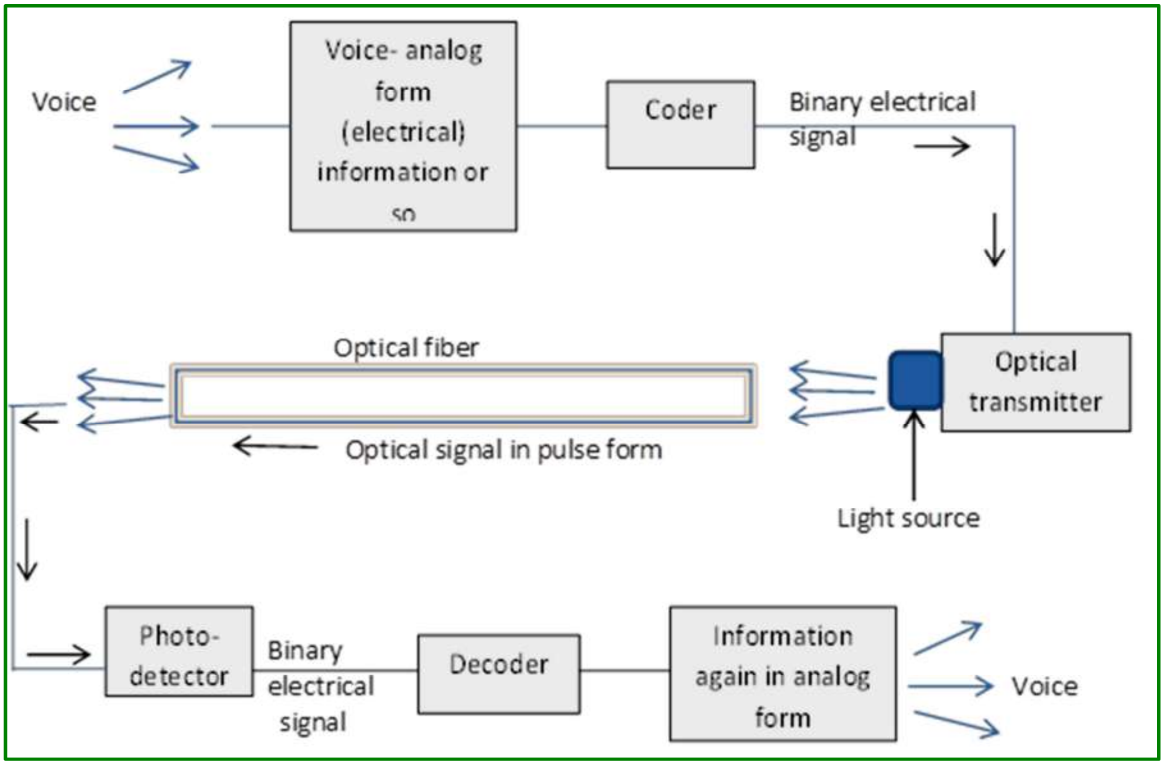

Fig. 11

Some uses of fiber optic cables include [07]:

- **Medical**
  - Laser for surgeries
  - Light guides
  - Imaging tools

- **Defense/Government**
  - Sound Navigation and Ranging (SONAR)
  - Hydrophones for seismic waves
  - Wiring in aircraft.
  - Field networking
  - Submarines and other vehicles.

- **Telecommunications**
  - Transmission & receiving purposes.

- **Data storage**
  - Data transmission

- **Networking**
  - Connecting users and servers; increasing speed and accuracy of data

transmission.

- **Industrial/Commercial**
  - Imaging in hard to reach areas.
  - Wiring in automobiles.

- **Broadcast**
  - CATV
  - HDTV
  - Internet

- **Research & Development.**

Advantages of Optical Fiber Cable / Communications:

We quote some of the advantages [08] in the following. For details, one must go through the ref. concerned.

- “Optical Fiber Cables can run massive distances like 40 KM or much more (Single Mode Fiber Cables) without having to repeat the signal anywhere in-between.”

- “Its normally enough to replace the optics (active components) at either end in order to upgrade the fiber communication to support higher bandwidths. There is no need to change all the underlying cabling.”

- “Multiple cores are built into each optical fiber cable(like 6/12/24 cores) and hence each optical cable can support multiple individual connections (3/6/12).”

- “Optical Fiber Cables are not affected by EMI – Electromagnetic Interference as they carry light, and hence can be used even for the most demanding industrial applications.”

- “They can also be used in lightning prone areas as they do not carry the electrical signals as such to affect switch ports, etc during a lightning.”

- “The danger of ignition during a fire is much less with optical fiber cables.”

- “Trouble shooting an Optical Fiber Network is possible with equipments like the OTDR Tester (Optical Time Domain Reflectometer). Using this, one could measure the optical power loss and locate the faults caused due to fiber breaks, connectors or splicing.”

- “Wire tapping with Optical Fiber Cables is more difficult.”

Limitations of Optical Fiber Cable Networks:

We quote some of the disadvantages [08]. For details, one must go through the ref. concerned.

- "Optical Fiber cables have limited bend radius (about 30 mm). So, if they are bent more, it might lead to some signal loss. But recently, bend resistant fibers have been introduced which have higher tolerance to bending."
- "By bending the normal optical fiber cables, some leakage of signal could be induced and that can be used for hacking the information in them. So, even though doing that might be difficult, they are not totally tamper proof."
- "There are outdoor fiber cables but they need to be shielded well. This shielding makes them less agile/ flexible to run in all the places and it increases the cost of cables as well."
- "Each Core of the Optical Fiber cable needs to be spliced in order to complete the connection to the network/optical switch. Both the splicing equipment and the cost of installation (for splicing) per core is quite high."

Attenuation:

Definition: Attenuation [09] in fiber optics, also known as transmission loss, is the reduction in intensity of the light beam (or signal) with respect to distance travelled through a transmission medium.

Unit: Attenuation coefficients in fiber optics usually use units of dB/km through the medium due to the relatively high quality of transparency of modern optical transmission media.

Expression: Quantitatively, the attenuation in fiber optics may be expressed using the equation:

$$Attenuation\,(dB) = 10 \times \log_{10}\left(\frac{Input \quad \text{int}\,ensity\,(W_i)}{Output \quad \text{int}\,ensity\,(W_o)}\right)$$

The transmission medium is typically a fiber of silica glass that confines the incident light beam to the inside. When transmitted through a large distance, the attenuation becomes an important factor.

Two main depending factors:

- **Light scattering:**

  Caused by rough and irregular surfaces (even molecular level irregularities), reflecting light in many random directions instead of required total internal reflection. The scattering is from internal surfaces as well as from interfaces. It is wavelength dependent. The diffuse reflection [Fig. 12]:

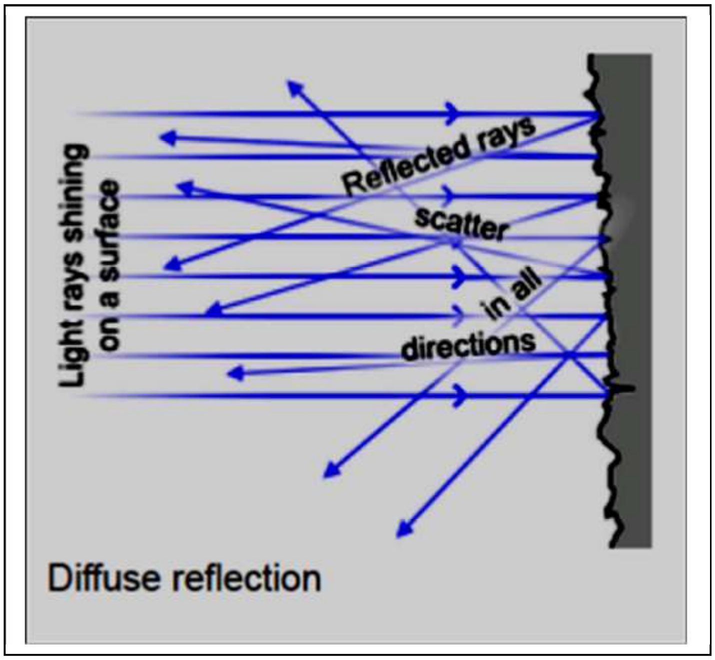

Fig. 12

- **Light absorption:**

  Signal loss can occur due to selective absorption of specific wavelengths. Electronic level as well as molecular level may come into account.

- **Connection loss:**

  Caused by misalignment between to fibers [05]. To be taken care of properly to minimize the lateral offset of the core, tilt, angular mismatch, etc.

Fiber optic endoscope

“In **endoscopy**. **Fibre-optic endoscopes** are pliable, highly maneuverable instruments that allow access to channels in the body that older, semirigid instruments cannot access at all or can access only at great discomfort to the patient.” [10]

“An **endoscope** can consist of: a rigid or flexible tube. a light delivery system to illuminate the organ or object under inspection. The light source is normally outside the body and the light is typically directed via an **optical fiber** system.”

Fiberscope [11]

➔ flexible optical fiber bundle with an eyepiece on one end and a lens on the other that is used to examine and inspect
- small,
- difficult-to-reach places

such as the insides of machines, locks, and the human body.

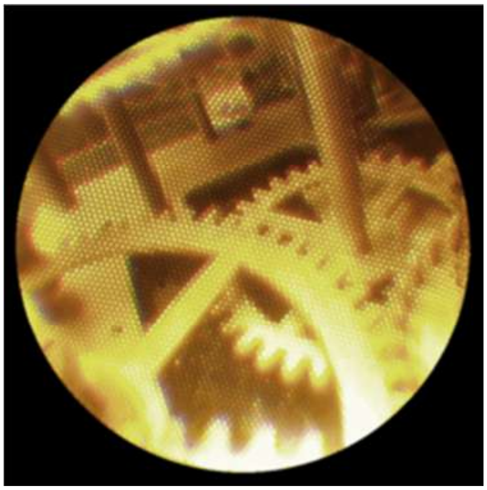

Fig. 13
A low quality fiberscope observing the inside of an antique clock mechanism. It is important to note how individual fibers are discernable, as each fiber only relays one part of the image.

Brief History

1930 → Heinrich Lamm, a German medical student, became the first person to put together a bundle of optical fibers to carry an image.

➔ The discoveries led to the invention of endoscopes and fiberscopes.

1960s → the endoscope was upgraded with glass fiber, a flexible material that allowed light to transmit, even when bent.

➔ This provided users with the capability of real-time observation but it did not provide them with the ability to take photographs.

1964 → the fiberscope, the first gastro camera, was invented. It was the first time an endoscope had a camera that could take pictures, leading to more careful observations, and more accurate diagnoses.

Components & Optics

Fiberscopes work by utilizing the science of fiber-optic bundles, which consist of numerous fiber-optic cables. Fiber-optic cables are made of optically pure glass and are as thin as a human's hair. The three main components of a fiber-optic cable are:

- ➔ Science of fiber optic bundles utilized.
- ➔ Bundles consist of numerous fiber optic cables
- ➔ Glass used in the core: optically pure & as thin as human's hair.

Different types of fiber-optic bundles in a fiberscope:

- illumination bundle – designed to carry light and illuminate the area in front of the lens
- imaging bundle – Continuous strand of flexible glass fibers designed to carry an image from the lens to the eyepiece

Functioning

- Eyepiece → Magnifies the image carried back by the imaging bundle so that human eye can view it.
- Imaging bundle → Transmit the image to the eyepiece.
- Distal lens →The combination of micro lenses that take images and focus them into the small imaging bundle.
- Illumination system → A Fiber optic light guide that relays light from the source to the target area
- Articulation system → The ability of the user to control the movement of the bending section of the fiberscope that is directly attached to the distal lens.
- Fiberscope body →The control section that is designed to help aide one hand operation.
- Insertion tube → Most of the length of the fiberscope, made to be durable and flexible. This protects the optical fiber bundle and the articulation cables.
- Bending section →The most flexible part of the fiberscope, it connects the insertion tube to the distal viewing section.
- Distal section → Where the ending points of both the illumination and imaging fiber bundle are.

Medical applications as Endoscopy (having a very low risk of causing infection and blood loss.) involves:

- Arthroscopy ← Joints
- Bronchoscopy ← Lungs
- Colonoscopy ← Colon
- Cystoscopy ← Bladder
- Enteroscopy ← Small Intestine
- Hysteroscopy ← Uterus
- Laparoscopy ← Abdomen/Pelvis
- Laryngoscopy ← Larynx (voice box)
- Upper Gastrointestinal Endoscopy← Esophagus and upper intestinal tract
  etc.

Other applications

- Checking the position of pins.
- Inside of machines.
- Surveillance.

A link for YouTube video What is Fiber Optics? | Mocomi Kids is als given in Ref. [12].

References:

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[12] Link: https://youtu.be/o5t6evogJbg

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