OPTICAL COMMUNICATION (EEC-701)
UNIT – 1

Introduction: Block diagram of optical fiber communication system. Advantages of optical fiber communication.

Optical fiber waveguides: structure of optical wave guide, light propagation in optical fiber using ray theory, acceptance angle, numerical aperture, skew rays, wave theory for optical propagation, modes in a planar and cylindrical guide, mode volume, single mode fibers, cutoff wavelength, mode field diameter, effective refractive index and group and mode delay factor for single mode fiber.

Communication may be defined as the transfer of information from one point to another. Within the communication system the information transfer is frequently achieved by superimposing or modulating the information transfer on to an electromagnetic wave which acts as a carrier for the information signal. This modulated signal is then transmitted to the required destination where it is received and the original information signal is obtained by demodulation.

The use of visible light to carry the information is called optical communication and the light travels through a optical fiber cable.

Optical Fiber Communication:

- Wavelength → 1.7µm to 0.8µm
- Frequency → 10^{14} to 10^{15} Hz
- Attenuation → 0.2 dB/km

1.1 Block Diagram of Optical Communication System: The optical fiber communication system is similar in basic concepts, the block diagram is shown:

The block diagram represents the information source provides an electrical signal to a transmitter comprising an electrical signal to a transmitter comprising an electrical signal which derives an optical source to give modulation of light wave carrier. The optical sources (LED or LASER) which provide the optical conversion used to convey the light travels through fiber cable in a particular manner. At the receiver end a optical detector exists, it can be a PIN or APD photodiode, it converts light energy to electrical signal. Electrical receiver receives the signal and converts it into a message format. This is the working of a optical fiber communication system.

1.1.1 Advantages: Optical fiber communication offers a number of advantages over other communication systems because it has very low attenuation:

a) Enormous potential bandwidth: The optical fiber communication offers frequency in the range of 10^{13} to 10^{16} Hz which yields a far greater potential transmission bandwidth. At present, the bandwidth available to fiber system is not fully utilized but modulation over three hundred kilometer without repeaters is possible.

b) Small size and weight: Fiber cables have very small diameter, just like a hair, rather than when it cover with jackets for protection still they are very light and small diameter.

c) Electrical Isolation: Optical fibers are fabricated from glass or sometimes a plastic polymer, they are electrical insulators and they do not exhibit earth loop.

d) Immunity to interface and cross talk: Optical fiber form a dielectric waveguide and are therefore free from electromagnetic interference (EMI), radio frequency interference (RFI) or switching transients electromagnetic pulses.

e) Signal Security: The light from optical fiber does not radiate significantly and therefore they provide a high degree of signal security.

f) Low transmission loss: The attenuation in optical fiber cable is very low (around 0.2 dB/km) as compare to other communication channels.

g) Ruggedness and flexibility: Optical fibers are manufactured with very high tensile strength. The fiber may bent to quite small radii or twisted without damage.
h) System reliability and ease of maintenance: It reduces the requirement of intermediate repeaters or live amplifiers to boost the transmitted signal strength. The reliability is high due to predicted life time of 20 years to 30 years.

1.1.2 Disadvantages:
   a) Optical cables can be handle with a skilled hand, the perfect joining of cable is most important otherwise signal lost in between the cable.
   b) The detection of faulty area is very hard because these cable situated under Mud.
   c) The whole establishment of optical cables is very expensive.
   d) Bending loss occurs, so cable must be properly aligned.

1.2 Optical Fiber Waveguide: The light travels in cable, which have a transparent core with a refractive index $\eta_1$ surrounded by transparent cladding of slightly lower refractive index $\eta_2$. The cladding supports the waveguide structure and reducing the radiation loss into the surrounding air.

Refractive Index = ratio of speed of light in a vacuum to that in matter (speed $v$)

$$\eta = \frac{c}{v}$$

Typically the value of light in a vacuum of refractiveindexes of

- $\eta=1$, for air
- $\eta=1.33$, for water
- $\eta=1.5$, for glass
- $\eta=2.42$, for diamond

1.2.1 Ray theory transmission:
   1.2.1.1 Reflection and refraction: When a light ray encounters a boundary separation of two different media, either the ray reflected back into the first medium; it’s called Reflection, or it will bent towards second medium called Refraction. Refraction affects the refractive index of the medium. The relationship at the interface is known as Snell’s Law.

$$\eta_1 \sin i = \eta_2 \sin r$$

or,

$$\eta_1 \cos i = \eta_2 \cos r$$

1.2.1.2 Total Internal Reflection: As $\eta_1$ is greater than $\eta_2$, the angle of refraction is always greater than the angle of incidence. Thus when angle of refraction is $90^0$ and refracted emerges parallel to axis, the angle is called critical angle. The critical angle is given by,

$$\sin \phi_c = \frac{\eta_2}{\eta_1}$$

At angles of incidence greater than the critical angle the light is reflected back into the originating dielectric medium that is called total internal Reflection. This is the mechanism by which light at a sufficient shallow angle (less than $90^0 - \phi_c$) may be considered to propagate down an optical fiber with low loss.
1.2.1.3 Numerical Aperture and Acceptance Angle: As per the diagram a meridional ray A enters at the critical angle $\phi_c$ within the fiber at the core cladding interface. The ray enters the fiber core at an angle $\theta_a$ to the fiber axis and refracted at the air – core interface at critical angle. Hence any ray which are incident into the fiber core at an angle greater than $\theta_a$ will be transmitted to the core cladding interface at an angle less than $\phi_c$ and will not be totally reflected, This $\theta_a$ is called ‘Acceptance Angle’.

‘Numerical Aperture’ (NA) is relationship between acceptance angle and refractive indexes. Fig shows a light ray incident on the fiber core at an angle $\theta_a$ to the fiber axis which is less than the acceptance angle for the fiber. The ray enters to the fiber from medium (air) of refractive index number.

As snell’s Law,
$$\eta_0 \sin \theta_a = \eta_1 \sin \theta$$  \hspace{1cm} (1)

Consider the right angle triangle, then
$$\phi = \frac{\pi}{2} - \theta$$  \hspace{1cm} (2)

where $\phi$ is greater than the critical angle at core cladding interface. Hence,
$$\eta_0 \sin \theta_a = \eta_1 \cos \phi$$  \hspace{1cm} (3)

$$\eta_0 \sin \theta_a = \eta_1 (1-\sin^2 \phi)^{1/2}$$

When the limiting case for TIR is considered, $\phi$ becomes equal to critical angle, so
$$\sin \phi_c = \eta_2 / \eta_1$$

so the limiting case will be,
$$\eta_0 \sin \theta_a = (\eta_1^2 - \eta_2^2)^{1/2}$$  \hspace{1cm} (4)

This equation serves as a basic for the definition of Numerical Aperture, so
$$\text{NA} = \eta_0 \sin \theta_a = (\eta_1^2 - \eta_2^2)^{1/2}$$

The NA may also be given in the terms of relative refractive index difference between core and cladding.
$$\Delta = \frac{\eta_1^2 - \eta_2^2}{2 \eta_1^2} \approx \frac{\eta_1 - \eta_2}{\eta_1} \text{ for } \Delta \ll 1$$
Hence,

\[ \text{NA} = \eta_1 (2\Delta)^{1/2} \]

1.2.1.4 Skew Rays: Skew rays are the rays which does not follow the fiber axis. These rays are not easy to visualize, only the direction can be predicted in helical path of direction change of \(2\gamma\) at each reflection. \(\gamma\) is the angle between the projection of the ray in the two dimension and the radii of the fiber core at the point of reflection.

When the light input to the fiber is non uniform, rays will therefore tend to have a smoothing effect on the distribution of light as it is transmitted, giving more information output.

\[ \text{NA in case of skew rays,} \]

\[ \text{NA} = \eta_0 \sin \theta \text{as} \cos \gamma = (\eta_1^2 - \eta_2^2)^{1/2} \]

1.2.2 Optical Fiber Modes:

Modes: In a planar guide, TE\((E_2 = 0)\) and TM\((H_2 = 0)\) modes are obtained within the dielectric cylinder. Thus two integers, \(l\) and \(m\) are necessary in order to specify the modes, the single integer \((m)\) required for the planar guide, for cylindrical waveguide we refer TE\(_{lm}\) and TM\(_{ln}\) modes.

Modes in Fiber: There are two fiber modes exists. First is

a) Single mode Fiber
b) Multi mode Fiber

The optical fiber is a dielectric waveguide that operates at optical frequencies. The fiber waveguide is normally cylindrical in form. Single mode fiber sustains only one mode of propagation, whereas multimode fibers contain many hundreds of modes. The diameter of core of SMF is comparatively very small from MMF.

A disadvantage of MMF is that they suffer from intermodal dispersion but it can be reduced.

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**SINGLE MODE FIBER**

**MULTI MODE FIBER**

1.2.3 Mode Theory for Circular Waveguide: In optical fibers, the core cladding boundary conditions lead to a coupling between the electric and magnetic field components. This gives rise to hybrid modes, which means optical waveguide analysis is more complex than metallic waveguide analysis. Fibers are constructed so that the difference in the core and cladding indexes of refraction is very small, i.e \(\eta_1 - \eta_2 \ll 1\).

The field components are called linearly polarized (LP) modes and labeled as \(\text{LP}_{jm}\) where \(j \& m\) are integers designating mode solutions.

Figure shows a electric field distribution for several of the lower order guided modes in a symmetrical slab waveguide.
The core of this waveguide is a dielectric slab of index $\eta_1$ that is sandwiched between two dielectric layers which have refractive indexes $\eta_2 < \eta_1$. Fig shows the field patterns of several of the lower order transverse electric (TE) modes. The order of a mode is equal to the ray congruence or same corresponding to this mode makes with the plane of the waveguide. The plot shows that the electric fields of the guided modes are not completely confined to the central dielectric slab. The field varies harmonically in the guiding region of the refractive index $\eta_1$ and decay exponentially outside of the region. For low order modes the fields are tightly concentrated near the center of the slab, will little penetration into the cladding region. On the other hand, for higher order modes the fields are distributed more towards the edges of the guide and penetrate faster into the cladding region.

**Mode Coupling:** As the core and cladding modes propagates along the fiber; mode coupling occurs between the cladding and higher order core modes. This coupling occurs because the electric fields of the guided core modes are not completely confined to the core but expend partially into the cladding.

### No of modes in a fiber with cut off conditions:

- **SMF,** $V = \frac{2\pi a}{\lambda} (\eta_1^2 - \eta_2^2)^{1/2} = \frac{2\pi a}{\lambda} \text{NA}$; ideally its $V \leq 2.405$
- **MMF,** $M = \frac{1}{2} \left( \frac{2\pi a}{\lambda} \right)^2 (\eta_1^2 - \eta_2^2) = \frac{V^2}{2}$

\[
\frac{P_{\text{clad}}}{P} = \frac{4}{M}
\]

**Power:**

- $P = \text{total optical power}$
- $P_{\text{clad}} = \text{avg optical power residing in cladding}$

### 1.2.4 Step Index Fiber and Graded Index Fiber:

#### 1.2.4.1 Step Index Fiber:

The optical fiber with a core of constant refractive index $\eta_1$ and a cladding of a slightly lower refractive index $\eta_2$ is known as step index fiber. This is because the refractive index profile for this type of fiber makes a step change at the core cladding interface.

The refractive index profile,

\[
\eta(r) = \begin{cases} 
\eta_1, & r < a \ (\text{core}) \\
\eta_2, & r \geq a \ (\text{cladding})
\end{cases}
\]

The figure shows a multimode step index fiber (a) and a single mode index fiber (b). The core diameter of SMF is around 2 to 10 µm. The modes in step index fiber is,

\[
M_s = \frac{\nu^2}{2}
\]

#### 1.2.4.2 Graded Index Fiber:

Graded index fiber do not have a constant refractive index in the core but a decreasing core index $\eta(r)$ with radial distance from a maximum value of $\eta_1$ at the axis to a constant value $\eta_2$ beyond the core radius $a$ in the cladding.

The refractive index profile,

\[
\eta(r) = \begin{cases} 
\eta_1 (1 - 2\Delta(r/a)^2)^{1/2}, & r < a \ (\text{core}) \\
\eta_1 (1 - 2\Delta)^{1/2}, & r \geq a \ (\text{cladding})
\end{cases}
\]

where $\Delta = \text{relative refractive index difference}$
\[ \alpha = \text{profile parameter} ; \quad \text{when} \quad \alpha = \infty , \text{step index profile} \]

\[ \alpha = 1 , \text{triangular profile} \]

\[ \alpha = 2 , \text{parabolic profile} \]

“The graded index profile results best near \( \alpha = 2 \) in multimode optical propagation.” The multimode graded index fiber exhibits for less inter modal dispersion than multimode step index fiber.

Number of modes for graded index fibers is:

\[ N_g \approx \left( \frac{\alpha}{\alpha + 2} \right) \left( \frac{\nu^2}{2} \right) \]

1.2.4.3 Single Mode Fibers: Single mode fibers have only relatively recently emerged as a viable optical communication medium they have quickly become the dominant and most widely used fiber type within telecommunications. The advantages of single mode fibers are:

1. They currently exhibit the greatest transmission bandwidths and lowest losses of the fiber transmission media.
2. They have superior transmission quality over other fiber types because absence of modal noise.
3. They offer a upgrade capability for future wide bandwidth services using faster Transmitter or receiver.
4. They are compatible with the developing integrated optics technology.

1.2.5 Cut off Wavelength:

\[ \lambda_c = \left( \frac{2\pi n_1}{V_c} \right) (2\Delta)^{1/2} \]

(1)

where \( V_c \rightarrow \text{cut off normalized frequency} \)

\( \lambda_c \rightarrow \text{cut off wavelength} \)

so dividing this equation with the reference equation, we get

\[ \frac{\lambda_c}{\lambda} = \frac{V}{V_c} \]

(2)

\[ \lambda_c = \frac{V\lambda}{V_c} = \frac{V\lambda}{2405} \]

1.2.6 Mode Field diameter and Spot Size: Many losses occur including jointing, micro bend, dispersion and width of radiation pattern. Therefore, Mode field diameter is a parameter for characterizing single mode fiber properties which takes into account the wavelength dependent field penetration into the field cladding.
1.2.7 Effective Refractive Index: The rate of change of phase of the fundamental LP_{01} mode propagating along a straight fiber is determined by the phase propagation constant $\beta$. It is directly related to the wavelength of the LP_{01} mode $\lambda_{01}$ by the factor $2\pi$.

$$\beta \lambda_{01} = 2\pi$$  \hspace{1cm} (1)

Sometimes it is defined by a phase index or normalized phase change coefficient, $\eta_{\text{eff}}$:

$$\eta_{\text{eff}} = \frac{\beta}{k}$$  \hspace{1cm} (2)

Hence, the wavelength of the fundamental mode $\lambda_{01}$ is smaller than the vacuum wavelength $\lambda$ by the factor $1/\eta_{\text{eff}}$, where

$$\lambda_{01} = \frac{\lambda}{\eta_{\text{eff}}}$$

The effective refractive index can be considered as an average over the refractive index of this medium.

1.2.8 Group Delay and Mode Delay factor: The transmit time or group delay $\tau_g$ for a light pulse propagating along a unit length of fiber is the inverse of the group velocity, $V_g$, hence

$$\tau_g = \frac{1}{V_g} = \frac{dB}{dW} = \frac{1}{c} \frac{dB}{dR}$$  \hspace{1cm} (1)

The group index of a uniform plane wave propagation in a homogenous medium has been determined,

$$N_{ge} = \frac{c}{V_g} \text{ for single mode fiber}$$  \hspace{1cm} (2)

so,

$$\tau_g = \frac{N_{ge}}{c}$$  \hspace{1cm} (3)

The effective group index may be written in terms of effective refractive index,

$$N_{ge} = n_{\text{eff}} - \lambda \frac{dn_{\text{eff}}}{d\lambda}$$  \hspace{1cm} (4)

1.2.9 Fiber Material and Fabrication Techniques: A optical fiber material, must satisfy three conditions:

a) It must be possible to make long, flexible fiber from the material.

b) The material must be transparent at a particular optical wavelength in order for the fiber to guide light efficiently.

c) Physically compatible materials that have slightly different refractive indexes for the core and cladding.

These requirements can be satisfied by

a) Glass
b) Plastics
c) Photonic Crystal Fibers

1.2.9.1 Glass Fiber: Glass is made by fusing mixtures of metal oxides, sulfides or solenoids. The resulting material is a randomly connected molecular network rather than a well defined ordered structure as found in crystalline material.
When glass is heated up from room temperature, it remains a hard solid up to several hundred degrees. As the temperature increases further, the glass gradually begins to soften until at very high temperature it becomes viscous liquid. An extended temperature range in which the glass becomes fluid enough to free itself fairly quickly of gas bubbles. The most common fiber material built by glass is silica (SiO₂), which has refractive index of 1.458 at 850nm and slightly similar refractive index materials are B₂O₃, GeO₂ or P₂O₅ are added to silica.

E.g. 1) GeO₂ - SiO₂ – core, SiO₂ – cladding
2) P₂O₅ - SiO₂ – core, SiO₂ – cladding
3) SiO₂ – core, B₂O₃ - SiO₂ – cladding

Active Glass Fiber: Some glass material (atomic no 57.71) resulting new optical and magnetic properties. These new properties allow the material to perform amplification, attenuation and phase retardation on light passing through it. Doping can be carried out for silica, tellurite and halide glasses.

1.2.9.2 Plastic Optical Fibers: For high speed services and high bandwidth, graded index polymer (plastics) optical fiber [OF] designed. The core of these fibers is either polymethacrylate or a perfluronated polymer. These polymers are referred to as PMMA POF and PFPOF. They offer greater optical signal attenuations than a glass fiber. They are tough and durable.

COMPARISON BETWEEN PMMA & PF POLYMER OPTICAL FIBER:

<table>
<thead>
<tr>
<th>CHARACTERISTICS</th>
<th>PMMA POF</th>
<th>PF POF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Diameter</td>
<td>0.4 mm</td>
<td>0.125 – 0.30 mm</td>
</tr>
<tr>
<td>Cladding Diameter</td>
<td>1.0 mm</td>
<td>0.25 – 0.60 mm</td>
</tr>
<tr>
<td>Numerical Aperture</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td>Attenuation</td>
<td>150 dB/km at 650 nm</td>
<td>&lt;40 dB/km at 650 nm</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>2.5 Gb/s over 200 m</td>
<td>2.5Gb/s over 550 nm</td>
</tr>
</tbody>
</table>

1.2.9.3 Photonic Crystal Fibers: Photonic crystal fibers are basically hollow from center, so it is also called holey fiber initially. The difference between PCF structure and that of a conventional fiber is that the cladding and air hole in core. The air hole runs along the entire length of the fiber. The size and spacing of the holes in the microstructure and the refractive index of its constituent material determine the light guiding characteristics of PCF. The basic PCFs are index guiding PCF and the photonic band gap fiber.

a) Index Guiding PCF: This fiber has a solid core that is surrounded by a cladding region which contains air holes running along the length of the fiber. The hole has a diameter d and pitches Λ. The core and cladding material are same but the air gap has lower refractive index of each cladding. E.g. SiO₂ is cladding having 1.45 refractive index but air has refractive index 1. But practically, core can be made of pure silica. It gives more advantages like low losses, ability to transmit high optical power levels and many more.

b) Photonic Band gap fiber: The structure of index guiding PCF and photonic band gap fiber are same. The fiber has a hollow core that is surrounded by a cladding region which contains air holes running along the fiber length.

c) But the functional principle is analogous to the role of a periodic crystalline lattice in a semiconductor, which blocks electrons from occupying a band gap region. The hollow core acts as a defect in the photonic band gap structure, which creates a region in which the light can propagate.

1.2.10 Fiber Fabrication: The basic techniques for fabrication of all glass optical waveguide are:

1.2.10.1 Outside Vapor Phase Oxidation: In this method, a layer of SiO₂ particles called ‘soot’ is deposited from a burner into a rotating graphite or ceramic mandrel. The glass soot adheres to this bait rod and layer by layer porous glass preform is built up. By
property controlling the constituents of the metal halide vapor stream during the deposition process, the glass compositions and dimensions desired for the core and cladding can be incorporated into the perform. When the deposition process is completed, the mandrel is removed and the porous tube is then vitrified in a dry atmosphere at a high temperature (above 1400°) to a clear perform and it is mounted in a fiber – drawing tower and made into a fiber.

1.2.10.2 Vapor Phase Axial Deposition (VAD): It is nearly like OVPO method. In this method, SiO$_2$ particles are formed in the same way. As these particles emerge from the torches, they are deposited onto the end of surface of a silica glass rod which acts as a seed. A porous perform is grown in the axial direction by moving the rod upward. When it moves upward, it is transformed into a solid, transparent rod perform by zone melting with the carbon ring heater. Any fiber, step index or graded index, can be made by this VAD method.

Advantages:
1) The preform has no central hole.
2) The preform can be fabricated in continuous lengths which can effect process costs and product yields.
3) The deposition chamber and zone melting ring heater are tightly connected to each other in the same enclosure allows the clean environment.

1.2.10.3 Modified Chemical Vapor Deposition (MCVD): The MCVD was widely adopted to produce very low loss graded index fibers. The glass vapor particles arising from the reaction of the constituent metal halide gases and oxygen flow through the inside of a revolving silica tube. As SiO$_2$ particles are deposited, they are sintered to a clear glass layer by a oxy hydroxide torch which travels back and forth along the tube. When the desired thickness of glass has been deposited, the vapor flow is shut off and the tube is heated strongly to cause it to collapse into a solid rod perform.

1.2.10.4 Plasma Activated Chemical Vapor Deposition: In PCVD, a non isothermal microwave plasma operating at low pressure initiates the chemical reaction. With the silica tube held at temperatures in the range of 1000 – 1200°C to reduce mechanical stresses in the growing glass films, a moving microwave resonator operating at 2.45 GHz generates plasma inside the tube to activate the chemical reaction. This process deposits clear glass material directly on the tube wall, there is no soot formation.