CHARACTERISTICS OF LIGHT
The search for a medium for transmission of light over long distances led the scientist to investigate glass which was already in use for laboratory optical experimentations. But, it was found that laboratory-used glass, either in the form of prisms or lenses, had a very high loss figure of about 1000 dB/Km. However, investigations also showed that this high loss was not an intrinsic characteristic of glass but was due to the impurities that were present in the glass. In other words, the high loss of optical energy was not due to glass molecules but was caused by the impurities in it that remained in it during its manufacture. So, with the best possible manufacturing technology scientists prepared purified glass which was then found to have a loss figure of only 20 dB/Km. Although in modern days this loss is in no way small, but in early times it was very much comparable to the other available alternatives for wide band communication medium like the coaxial cables. Gradually, technologies improved and highly purified glass started to be manufactured which had very low attenuation. So, let us just have a glimpse of this improvement in the manufacture of glass in the last fifty years. A “History of Attenuation” graph is shown in the figure 2.1 below.

![Fig. 2.1: History of Attenuation graph in the manufacture of glass](image)

The above figure shows the loss profiles of manufactured glass with the best possible available technologies in the early 1970s, 80s and 90s. As is seen, it can be clearly concluded that manufacture of purified glass has drastically improved due to which the loss figures have become negligibly small in comparison to other alternatives. In the 1970s, manufactures glass had a loss profile which showed a minimum loss at around wavelength of 800 nm (0.8µm). By the time this study of
glass was going on, LASERs also were invented which used a semiconductor material named Gallium Arsenide (GaAs) for emission of light. GaAs intrinsically is capable of emitting light of wavelength 800nm. So, coincidently we had glass which had minimum loss at the wavelength that was emitted by LASERs, and so it proved to be great combination. So initial optical communications were started at 800nm wavelength region and hence it is called as the “First Window” of optical communication.

As technology improved, glass was further purified and it showed a region of minimum loss at 1300nm and 1550nm regions in the 1980s as shown in figure 2.1. There was no minimum in the 800nm window and hence GaAs LASERs could not be used as sources. But in this course of time the semiconductor material technology had also improved simultaneously and we had sources available which could emit light both in 1300nm and the 1550nm regions. So, optical communications were now shifted to these regions and were called as the “Second Window” and “Third Window” of optical communication. The 1300nm window not only has low loss but also can support high data rates. But today, most of the optical transmission take place in the 1550nm window because though the 1300nm window had high bandwidth, it also had higher loss which significantly affected the performance of the communication system since distances became considerable large. The 1550nm window allows the installation of optical amplifiers at regular distance intervals that can amplify the light in the optical domain without converting it into electrical signal. This leads to a more reliable communication and hence today most optical communications lie in the third window.

Let us now look into the advantages of optical communication:

ADVANTAGES OF OPTICAL COMMUNICATION

- Optical Communication provides an ultra-high bandwidth for communication of the order of Terahertz (THz). This advantage meets the first requirement of a high quality reliable communication system.

- The loss figure of optical communication is very low, about 0.2 dB/Km. So this system has high SNR values. This advantage provides a reliable communication system. No other medium today, can provide such low loss figures as optical medium.

- Optical communication systems have very low or even negligible electromagnetic interference (EMI).

- Optical Communication provides high security data transmission. This is because optical signal travels through optical fibers which do not allow leakage of light energy. So tapping of transmitted information is very difficult in optical communication.
- Optical communication systems have very low manufacturing cost. Whatever cost is incurred is only due to the technology. This is because optical medium—glass is made from silica, which is freely abundant in nature. So, the only cost is in moulding it to a form of optical medium like optical fibre. The cost per voice channel of an optical fibre is also very much smaller than cost per voice channel of any other medium like coaxial cable though the two may have comparable costs per kilometre. This is because the bandwidth of optical fibre is almost 1000 times larger than a coaxial cable. So, cost per channel of an optical fiber would be one thousandth of that in a coaxial cable.

- Applications where space and weight are constraints, optical fiber serves adequately because optical fibers have low weight and low volume compared to other media.

The only flaw, if at all to be pointed out, is that optical communication is a point-to-point communication technology. We already saw that satellite communication technology in this regard is advantageous in that it is a broadcast type of technology. But in modern scenario where optical fibres are reaching to every home, atleast in an urban area, information can be broadcasted to every home in a very short time. Thus we see that optical communication has a lot of advantages over any other mode of communication, which make it the most desirable option for communication today. These advantages were precisely the reasons behind the rapid developments in the field of optical communication that revolutionized itself almost every 10 years and is still in a fast pace of developments. Today, most of the networks are composed of optical fibers using the optical networking technology. New developments to increase the capacity of an optical communication system have also taken place such as wavelength division multiplexing (WDM) technology.

Let us now look deeper into this new domain of communication with more detailed prospective. But before going into the details, let us revise some basic characteristics of light.

**CHARACTERISTICS OF LIGHT**

We know that light is a form of electromagnetic radiation. We are also familiar with the propagation of light in the form of rays which help us to prove different laws like laws of reflection, Snell’s law, interference, diffraction, etc. We are well acquainted with phenomena like photonic emission, photo-electricity which define a particle nature for light in the form of photons. So basically, the nature of light depends on the context of which we talk about. So, in this course we first treat light in the context of the Ray Model and study different phenomena based on the ray model of light. Proceeding further, when we find the ray model is inadequate in explaining some phenomena, we depart from the ray model and then adopt a higher model for light which is the wave-model where light is treated as an electromagnetic
wave. And in those situations where we find even the wave-model inadequate in explain certain phenomena like interaction light with matter, we adopt the quantum model of light where light will be treated as a photons. So, in this course, we will treat light in the following three models:

- Ray Model
- Wave Model
- Quantum Model

**CHARACTERIZATION OF A LIGHT SOURCE**

A very elementary question that may now come to the reader’s mind is how to characterise or describe a light source? A source of light can be characterized by the following factors:

**Intensity of the light:** Intensity of light is defined as the power per unit solid angle. So for a given power of the source, if the emitted light is scattered into a very wide solid angle then the source has low intensity. If the emitted light is confined to very narrow cone, the source appears to be very bright because its intensity increases. This happens in case of a LASER whose light appears to be much brighter and travels long distance than a normal 60W bulb though the power of the LASER is much smaller than 60W. The intensity of the source is indicative of how focussed is the emitted light.

**Wavelength of Light (λ):** The second characteristic on which a source is characterized is the wavelength of the emitted light. The wavelength of light is indicative of the colour of the light and so many a times it is also called as the colour of the source. The visible light lies within a wavelength range of 400nm to 700nm. If we look into figure 2.1, we find that glass which appears so transparent to us in daily life is not actually that transparent to wavelengths of 400nm to 700nm. In fact, it is much more transparent to lights of wavelengths 1300nm and 1550nm, which lie in the infrared region. Since these regions are not in the visible range, colour does not have any meaning, yet we may retain the colour as one of the characteristic to categorize light. Depending on the desired loss performance of the optical communication system λ can be chosen either 1300nm or 1550nm. So, the choice of wavelength of transmission has a direct relation to the SNR of the transmission.

**Spectral Width of Source (Δλ):** It is basically the wavelength range over which the emission takes place. In other words, it is the range of wavelengths emitted by the source. Thus the spectral width may be considered to be indicative of the purity of the colour of the light source. That is, if we have a source with a wide spectral width, say for example if it emits all the wavelengths ranging from blue to red, we get a light from the source which will look like white light. If we reduce the
spectral width to near red, we would get a sharp red colour light. If we reduce it to near blue, we would get a blue coloured light and so on. Thus reducing the spectral width increases the purity of the colour. Spectral width is a very important parameter of a source because we would later discover that spectral width of a source is related to the data rate upto which a source can be used as a transmitter of optical signal. Smaller the value of ∆λ more will be the purity of the source and also higher would be the data rate of the source. In other words, higher will be the bandwidth of the communication system. So, the choice of ∆λ has a direct relation to the bandwidth of the transmission.

The above three characteristic treat light as sources of energy. Nowhere does the wave nature of light is to be noticed. However, when we move on to discuss the propagation of light in an optical fibre, this notion of light as an energy source is inadequate and we have to treat light as an electromagnetic wave. Under this adoption, if the dimensions of the medium of propagation are very large compared to the wavelength of the light, light can be considered as a transverse electromagnetic (TEM) wave. This means that the direction of electric field, direction of magnetic field and the direction of propagation of light are mutually perpendicular to one another according to the right hand thumb rule as shown in figure 2.2 (a) & (b).

Fig. 2.2 (a): TEM nature of Light

Fig. 2.2 (b): TEM nature of Light
The electric and magnetic fields of light are hence related to each other through the medium parameter $\eta$ which is called the intrinsic impedance of the medium. That is,

$$\frac{|E|}{|H|} = \eta \text{ (intrinsic impedance of medium)} = \sqrt{\frac{\mu}{\varepsilon}} \quad ---- (2.1)$$

Where,

- $|E|$ = magnitude of electric field $E$.
- $|H|$ = magnitude of magnetic field $H$.
- $\mu$ = Permeability of the medium.
- $\varepsilon$ = Permittivity of the medium.

So, if the electric field is known completely, the magnitude of magnetic field can be determined using the above relation and its direction would be perpendicular to the direction of electric field. Thus with the knowledge of electric field the magnetic field can also be determined. The behaviour of the electric field as a function of time is called the **polarization of light**. Polarization is one of the very important parameters of any electromagnetic wave. It is a quantity which illustrates the vector nature of light unlike other quantities like intensity, wavelength and spectral width which show scalar nature of light. It shows that light is made up of varying electric and magnetic fields which are vector quantities. If we look at the locus of the tip of the electric field vector with respect to time, this locus gives the polarization of the wave. There may be different shapes that the tip of the electric field vector can trace with respect to time. Based on these shapes there are different types of polarization which are called as the states of polarization, viz.

- Linear Polarization
- Elliptical Polarization
- Circular Polarization
- Random Polarization

Linear and circular polarizations are special cases of elliptical polarization as we would very soon see. In general, the tip of the electric field vector traces out an ellipse and the light is then said to be elliptically polarized. This kind of polarization is shown in figure 2.3. From the figure we can clearly see that the electric field vector $\mathbf{E}$ traces out an ellipse with respect to time and so the light is said to be elliptically polarized. In general, it can be said that light is elliptically polarized. However, in some special cases, this ellipse can degenerate into a circle or a straight line and the light is then said to be circularly polarized or linearly polarized respectively. When the major axis and the minor axis of the ellipse become equal to each other, the locus of $\mathbf{E}$ would be a circle and it is then said to be circularly polarized. When either of the
major axis or the minor axis of the ellipse becomes zero, the locus of $E$ would be a straight line and the light is then said to be linearly polarized.

So, in general, we can say that light which is transverse electromagnetic in nature has three states of polarization, linear, circular or elliptical. If the light does not have a systematic behaviour with respect to time, i.e., if the electric field orients itself randomly as a function of time (which may happen in case of a light from a source with large value of $\Delta \lambda$) the light is said to be randomly polarized. In this type of polarization either the amplitude or direction of $E$ or both varies randomly with respect to time. Incoherent lights in general do not have any definite state of polarization and are said to be randomly polarized.

So, polarization is another very important characteristic that categorizes different sources of light. It represents and illustrates the vector nature of light.

**RAY-MODEL OF LIGHT**

With the above background of information, let us now move on to discuss the simplest possible model of light, the ray-model. Fundamentally, we have two main aspects of the ray nature of light.

![Fig. 2.4: Spherical and Plane Wave-Fronts](image)
Light rays actually are fictitious lines which in reality represent the direction of propagation of what are called as phase-fronts of light as shown in figure 2.4. Phase-fronts are nothing but constant phase surfaces in which the phase difference between any two points is zero. In reality they represent the spatial nature of propagation of a wave and hence are also called as wave-fronts. These phase-fronts may be either spherical or planar in nature and accordingly, we get two aspects of ray nature of light. A line drawn perpendicular to a phase front at every point gives the direction of propagation of light energy at that point and is conventionally called as a light-ray. So, light-rays are actually imaginary lines that determine the direction of propagation of light energy. In other words, what we actually have is not light ray but the direction of propagation of phase-fronts of light energy that are represented by directed line segments called light rays.

If we have an isotropic source of light situated at finite distance, as in figure 2.4(a), we get spherical phase-fronts because the light source would emit light in all directions and light waves would travel spherically outwards from the source of light. If we now draw lines perpendicular to these phase-fronts at any point, these lines would give the direction of flow of light energy at that point and the line drawn would then be called a light ray. Due to their spherical nature, the light waves can be called as spherical waves.

If the same source is now placed at a very large distance from the point of observation (ideally at infinity) the wave-fronts would appear almost planar and parallel to each other as shown in figure 2.4 (b). So the light rays too would now not look divergent, but appear parallel to each other because they are perpendicular to the phase fronts at every point. The light waves now can be called plane waves.

In the subsequent sections, when we discuss the propagation of light in an optical fiber, first we proceed treating light as a ray and then observe the fidelity of our explanation by considering the wave-fronts and refine our discussion if required.

**WAVE-MODEL OF LIGHT**

With the “Ray-Model” being clear to us, let us move on to discuss the wave nature of light. The “Wave-Model” of light introduces light as an electromagnetic wave. If light is treated as an electromagnetic wave then light must be expressible in terms of the generalized wave function, which is given as:

\[ \psi(x, t) = Ae^{j(\omega t - \beta x)} \]  

\[ (2.2) \]

Where, \(A=\) Amplitude of the wave.
\(\omega=\) Angular Frequency of the wave (radian/second)
\(\beta=\) Phase Constant (Radian/metre)
The wave function is a generalized function of space \((x)\) and time \((t)\). The term \((\omega t - \beta x)\) is the phase function of \(\psi(x,t)\). Thus the phase of the wave is a function of space and time. If we now freeze space, i.e. take \(x=\text{constant}\) or in other words observe at a particular point, we see that there is a sinusoidal variation of the wave amplitude as a function of time having an angular frequency of \(\omega\) rad/s. If we freeze time, i.e. take \(t=\text{constant}\) or in other words observe the whole wave simultaneously, we see that the amplitude of the wave has a sinusoidal variation with a phase constant \(\beta\) rad/m. So these two phenomena together constitute a wave phenomenon represented by the generalized wave equation.

The phase constant \(\beta\) is defined as the phase change per unit distance. The wavelength \((\lambda)\) of a wave is the distance between two consecutive points on the wave which are in the same phase. The phase difference between two points in the same phase is either zero or an integral multiple of \(2\pi\). Thus the wavelength of a wave is measured between two points that have a phase difference of \(2\pi\). Hence the phase constant \(\beta\) can be calculated as:

\[
\beta = \frac{2\pi}{\lambda} \quad \text{(2.3)}
\]

So, if we know the wavelength \((\lambda)\) of a wave in a medium, we can calculate the phase constant of the wave in that medium and vice-versa. One basic question that may come to the reader’s mind is that, once the frequency of light \((f)\) is known, the wavelength \((\lambda)\) can be readily calculated from the relation:

\[
\lambda = \frac{c}{f} \quad \text{(2.4)}
\]

Where, \(c = \text{velocity of light}\), then what is so special about \(\beta\)? But the reader should note at this point that velocity of light is a medium dependent parameter. It is \(c\) \((3 \times 10^8 \text{ m/s})\) in vacuum, but is different in different media. In the same medium too, the velocity of light may vary if the medium is made bound. Thus the velocity of light is a medium dependent parameter. So, the wavelength of light is not always given by equation (2.4) but can be found from:

\[
\lambda_{\text{(medium)}} = \frac{\text{velocity of light in the medium}}{\text{frequency of light}} \quad \text{(2.5)}
\]

And

\[
\beta_{\text{(medium)}} = \frac{2\pi}{\lambda_{\text{(medium)}}} \quad \text{(2.6)}
\]

Once the frequency of light is known, we may calculate the value of \(\beta_{\text{(medium)}}\) and then from equation (2.6), we can calculate the value of \(\lambda_{\text{(medium)}}\) and then find the velocity of light from equation (2.5).

Treating light as an electromagnetic wave, let us now define an important optical parameter of a medium called the refractive index of the medium. Refractive
index of a medium is defined as the ratio of the velocity of light in vacuum to the velocity of light in that medium. It is denoted by \( n \). Since refractive index is a ratio of two velocities, it is a pure number and has no unit.

Refractive index of medium \( n_{\text{(medium)}} \) = \( \frac{\text{Velocity of light in vacuum (c)}}{\text{Velocity of light in the medium (v)}} \) -- (2.7)

For most media, \( n_{\text{(medium)}} < 1 \), i.e. the velocity of light reduces from its value in vacuum. In fact, light travels fastest in vacuum and in any other medium it slows down. For example, the refractive index of material glass is about 1.5, i.e. light travels 1.5 times faster in vacuum than in glass. Similarly the refractive index of water is 1.33. In other words, refractive index of a medium indicates the factor by which the speed of light reduces in the medium. As we study further, we would encounter another type of refractive index, called the effective refractive index which is denoted by \( n_{\text{eff}} \) and is given by,

\[
\text{Effective refractive index} = n_{\text{eff}} = \frac{c}{v'}
\]  

Where \( v' \) is not the necessarily the velocity of light in an unbound medium but is a generalized velocity of light in a bound medium like optical fibres, optical waveguides, etc. and it is structure or size dependent velocity. For example, the actual refractive index of glass in unbound form is 1.5. But if glass is made in the form of a bound medium (say an optical fiber) its refractive index changes because the velocity of light in it changes. The refractive index of this particular bound form or structure of glass is then the effective refractive index of this structure of glass and would change again if we alter this form.

We have already seen that in general, whenever we discuss issues related to light, conventionally, we discuss them in terms of the wavelength of light rather than frequency. This was precisely the reasons for defining the three windows of optical communication in terms of wavelengths and not in terms of frequencies. We have also come across the quantity called the spectral width of the source of light which is the range of wavelengths that are emitted by a source of light. In general, wavelength of light is given by the relation (2.5). That is,

\[
\lambda = \frac{v}{f}
\]  

Where, \( \lambda \) = wavelength of light in a medium.  
\( v \) = velocity of light in the medium.  
\( f \) = frequency of the light under study.

The spectral width can be calculated from (2.8) as,

\[
\Delta \lambda = -\frac{v}{f^2} \Delta f
\]  

\[\text{(2.9)}\]
Or, $\Delta \lambda = \left( \frac{v}{f} \right) \left( \frac{\Delta f}{f} \right)$

The quantity $(v/f)$ is the wavelength and so, the above relation (2.9) can be rewritten as,

$$\frac{\Delta \lambda}{\lambda} = - \frac{\Delta f}{f} \quad \text{---------- (2.10)}$$

Let us now take a small example. Let us assume an operating wavelength $(\lambda)$ of about 1000 nm and an optical window of operation $(\Delta \lambda)$ of about 1000 nm, then from the relation (2.10), we find the value of bandwidth $(\Delta f)$ of our assumed optical communication system to be about $3 \times 10^{13}$ Hz. Though this is a very crude and small example, but yet it gives the reader an idea about the enormous bandwidth that optical communication can provide. Thus an optical communication system is really a very wideband system compared to a conventional microwave communication system.

With this basis of knowledge about the characteristics of light, let us now look into the very basic component of an optical communication system, the optical fiber. Constructionally, an optical fiber is a solid cylindrical glass rod called the core, through which light in the form of optical signals propagates. This rod is surrounded by another coaxial cylindrical shell made of glass of lower refractive index called the cladding. This basic arrangement that guides light over long distances is shown in figure 2.5.

![Fig. 2.5: Constructional Details of an Optical Fiber](image)

The diameter of the cladding is of the order of 125 µm and the diameter of the core is even smaller than that. Thus it is a very fine and brittle glass rod that we are dealing with. In order to provide mechanical strength to this core-cladding arrangement, other coaxial surrounding called the buffer coating and jacketing layers are provided. They do not play any role in the propagation of light through the optical fiber, but are present solely for providing mechanical strength and support to the fiber.

The light energy in the form of optical signals propagates inside the core-cladding arrangement and throughout the length of the fiber by a phenomenon called the Total Internal Reflection of light. This phenomenon occurs only when the refractive index of core is greater than the refractive index of cladding and so the
cladding is made from glass of lower refractive index. By multiple total internal reflections at the core-cladding interface the light propagates throughout the fiber over very long distances with low attenuation.