FIBER OPTIC TRAINER

INTRODUCTION TO FIBER OPTICS

Communication may be broadly defined as the transfer of information from one point to another. Before fiber optics came along, the primary means of real time data communication was electrical in nature. It was accomplished by using copper wire or by modulating information on to an electro - magnetic wave that acts as a carrier for the information signal. All these methods have one problem in common the communication had to be over a straight - line path. Fiber optics provides an alternatives means of sending information over significant distance using light energy. Light as utilized for communication has major advantages because it can be modulated at significant higher frequencies than electrical signals. That is till 1870, when **IRISH PHYSICIST JOHN TYNDALL** carried out a simple experiment. He filled a container with water and shone light into it. In the dark room he pulled the bung from the opposite end of the container. The light shone out, of course but in which direction ?

The light followed the curved path of water. The light was guided and a new science was born. This was due to a property of light called **REFRACTION.**

THEORY OF FIBER OPTICS

How Optical Fiber Works ?

The principal of operation of optical fiber lies in the behavior of light. It is a widely held view that light always travels in a straight line and at constant speed. But that's not necessarily true as shown by **TYNDALL'S** experiment. To understand the propagation of light within an optical fiber it is necessary to take into account reflective index of the dielectric medium. Reflective index of a medium is defined as the ratio of velocity of light in vacuum to velocity of light in medium.

$$\text{Refractive Index} = \frac{\text{Velocity of Light in Vacuum}}{\text{Velocity of Light in Medium}}$$

Since, the velocity of light in any solid, transparent material is less than in vacuum, the reflective index of such material is always greater than 1. A ray of light travels slowly in an optically dense medium than one that is less dense. Now, the direction that the light approaches the boundary between the two materials is very important. When a ray is incident on the interface between two dielectrics of differing reflective indices, refraction occurs. It may be observed that ray approaching the interface is propagating in a dielectric of refractive index n_1 and is at an angle ϕ_1 to the normal at the surface of the interface. If the di - electric on the other side of interface has refractive index n_2 which is less than n_1, then the refraction is such that the ray path in this lower index medium is at an angle ϕ_2 to the normal where ϕ_2 is greater than ϕ_1.

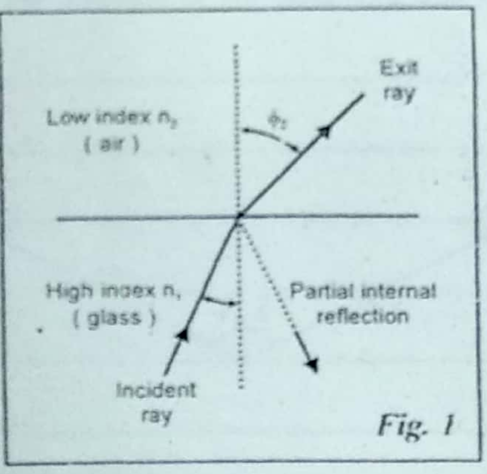


Fig. 1

The angle of incidence ϕ_1 and refraction ϕ_2 are related to each other and to refractive indices of dielectrics by **SNELL'S LAW OF REFRACTION** which states that :

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

$$\frac{\sin \phi_1}{\sin \phi_2} = \frac{n_2}{n_1}$$

Total Internal Reflection :

Since, the angle of refraction is always greater than the angle of incidence. Thus when the angle of refraction is 90^0 and the refracted ray emerges parallel to the interface between the dielectrics the angle of incidence must be less than 90^0. This is the limiting case of refraction and this angle of incidence is known as critical angle ϕ_c. The value of critical angle is given by :

$$\sin \phi_c = n_2 / n_1$$

At angles of incidence greater than the critical angle the light is reflected back into the originating dielectric medium. This behaviour of light is termed as **"TOTAL INTERNAL REFLECTION"**. Here, Angle of Incidence = Angle of Reflection.

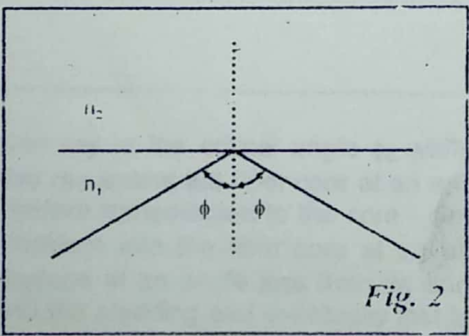


Fig. 2

This is the mechanism by which light may be considered to propagate down to an optical fiber with low loss. Figure 3 below illustrates the transmission of a light ray in an optical fiber via a series of total internal reflection at the interface of the silica core and slightly lower refractive index silica cladding.

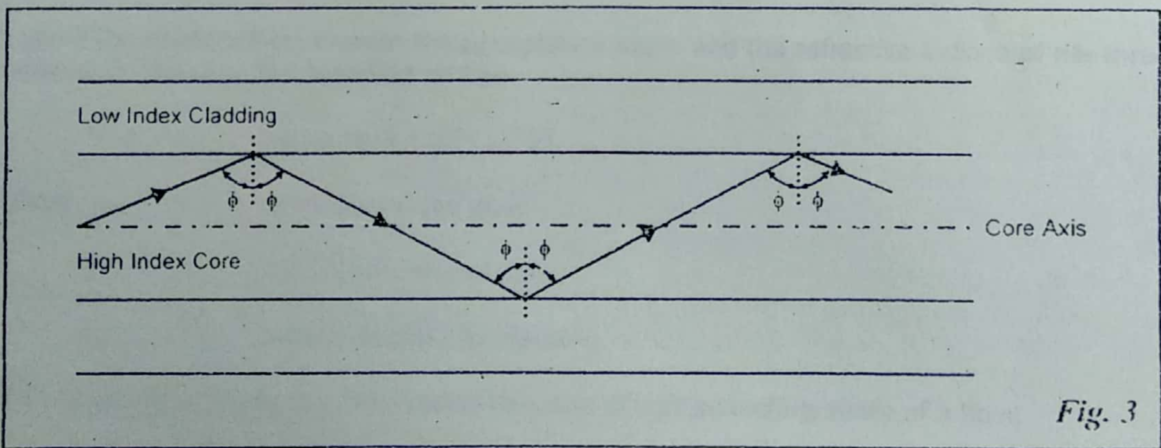


Fig. 3

The light ray shown in figure is known as meridian ray as it passes through the axis of the fiber core. It is generally used when illustrating the fundamental transmission properties of optical fiber.

Acceptance Angle :

Since, only rays with an angle greater than critical angle at the core cladding interface are transmitted by total internal reflection, it is clear that not all rays entering the fiber core will continue to be propagated down the length.

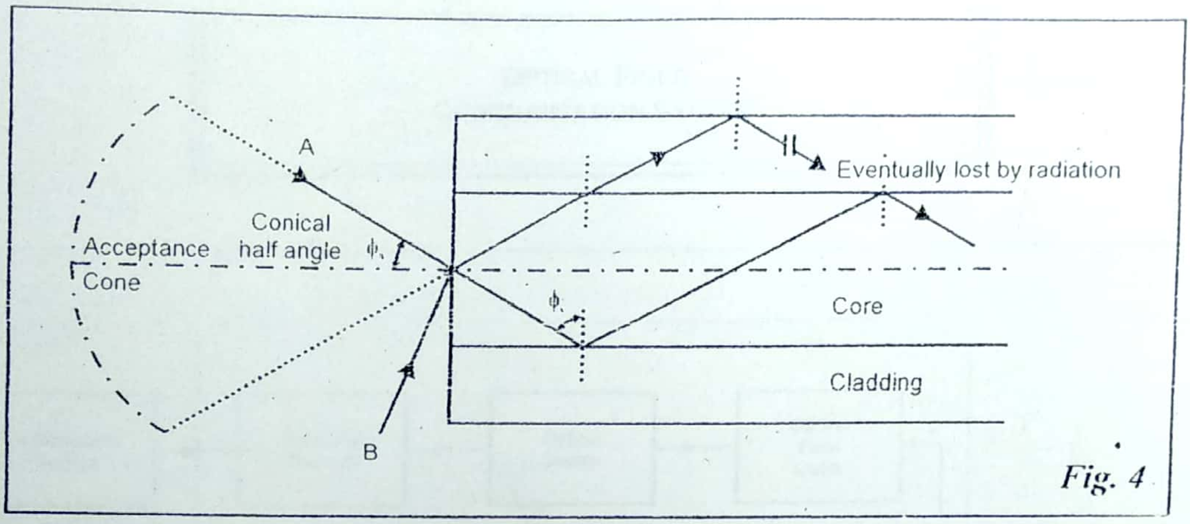


Fig. 4

Figure 4 illustrates a meridian ray at the critical angle ϕ_c within the fiber at core cladding interface. It may be observed that this ray enters the fiber core at an angle θa to the fiber axis and is refracted at the air - core interface before transmission to the core - cladding interface at the critical angle. Hence, any ray which are incident into the fiber core at an angle greater than θa will be transmitted to the core cladding interface at an angle less than θc and will not be totally internally reflected instead will be refracted into the cladding and eventually lost by radiation. Thus, for rays to be transmitted by total internal reflection within the fiber core they must be incident on the fiber core within an acceptance cone defined by conical half angle θa. Hence, θa is the maximum angle to the axis at which light may enter the fiber in order to be propagated and is referred to as the acceptance angle for the fiber.

Numerical Aperture :

It gives the relationship between the acceptance angle and the refractive indices of the three media involved viz the core, the cladding and air.

$$N.A = n_0 \sin \theta a = (n_1^2 - n_2^2)^{1/2}$$

Where, n_0 = refractive index of air

n_1 = refractive index of core

n_2 = refractive index of cladding

The numerical aperture is a very useful measure of light collecting ability of a fiber.

OPTICAL FIBER COMMUNICATION SYSTEM

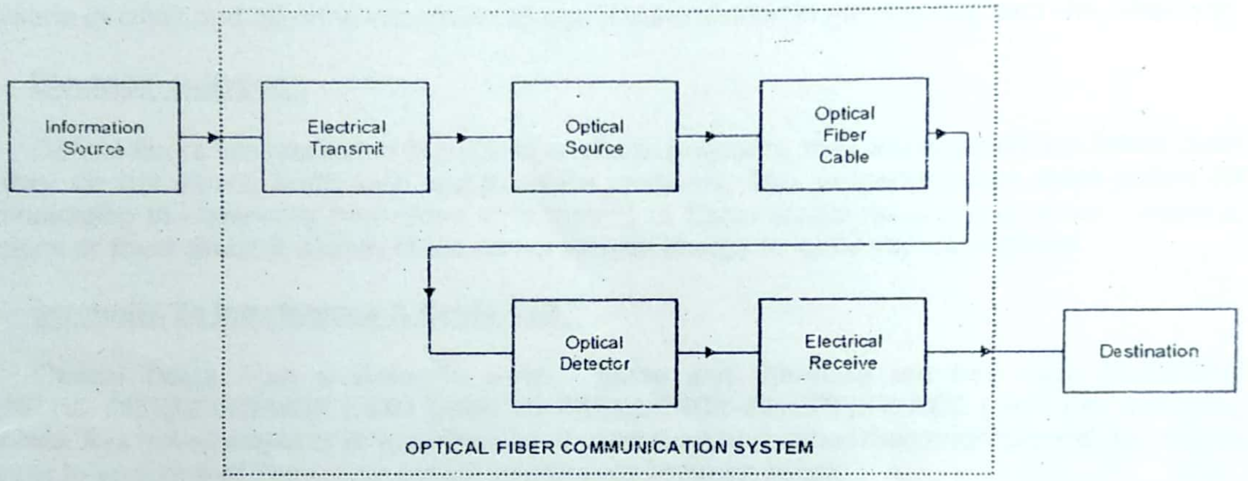


Fig. 5

Here the information source provides an amplified electrical signal to a transmitter comprising an electrical stage that drives an optical source to give conversion may be either a semiconductor laser or LED. The transmission medium consists of modulation of light wave carrier. The optical source, which provides an electrical to optical conversion, an optical fiber cable and the receiver, consists of an optical detector that drives a further electrical stage and hence provides demodulation of optical carrier. This electrical signal amplified and applied to the destination e.g. speaker. Photo diodes (p - i - n or avalanche) and in some instances phototransistors and photo conductors are utilized for detection of optical signal and optical to electrical conversion. The optical carrier may be modulated using an analog or digital information signal. Analog modulation involves the variation of light emitted from the optical source in continuous manner. In digital modulation however, discrete changes in the light intensity are obtained (i.e. ON - OFF pulses). Although the often simpler to implement, analog modulation with an optical fiber communication system is less efficient, requiring a far higher signal to noise ratio at the receiver than digital modulation. Also, linearity needed for analog modulation is not provided by semiconductor optical sources especially at high modulation frequencies.

<u>Advantages of Fiber Optic System.</u>

a. <u>Enormous Potential Band Width :</u>

The optical carrier frequency in the range 10^{13} to 10^{16} Hz (generally near infrared around 10^{14} or 10^{15} GHz) yields a far greater potential transmission BW then metallic cable system. (i.e. coaxial cable BW up to 500 MHz) or even millimeter wave radio system, (i.e. system currently operating with modulation BW of 700 MHz). At present the BW available to fiber system is not fully utilized by modulation at several GHz over hundred km and hundred of MHz over 300 km with intervening electronics (repeaters) is possible. There fore, the information carrying capacity of optical fiber system has proved far superior to best copper cable available, by comparison losses in coaxial cable system restrict. A much enhanced BW utilization for an optical fiber can be achieved by transmitting several optical signals each at different center wavelengths in parallel on the same fiber. This wavelength division multiplexed operation particularly with dense packing of the optical wavelength or (fine frequency spacing) offers potential information carrying capacity.

b. **Small Size & Weight :**

Optical fibers have very small diameter. Hence, when they are covered with protective coatings they are far smaller & lighter. This is a tremendous boon towards the alleviation of duct congestion in cities and allowing expansion of signal transmission in mobiles e.g. aircrafts, ships etc.

c. **Electrical Isolation :**

Optical fibers are fabricated from glass or plastic polymers, they are electrical insulators there fore they do not exhibit earth loop and interface problems. This property makes them suited for communication in electrically hazardous environment as fibers create no arcing or spark hazard at abrasions or short circuit & usually fibers do not contain energy to ignite vapors or gases.

d. **Immunity To Interference & Cross Talk :**

Optical fibers from a dielectric wave - guide and therefore are free from **ELECTRO MAGNETIC INTERFERENCE (EMI), RADIO FREQUENCY INTERFERENCE (RFI)** or switching transients. It is not susceptible to lighting striker if used overhead rather than underground. Mcre over it is easy to ensure that there is no optical interference between fibers.

e. **Signal Security :**

The light from optical fibers does not radiated significantly and therefore they provide a high degree of signal security. A transmitted optical signal cannot be obtained from a fiber in a non - invasive manner (i.e. without drawing optical power from the fiber). In theory, any attempt to acquire a massage signal transmitted optically may be detected. This feature is obviously attractive for military & banking.

f. **Low Transmission Loss :**

Optical fibers result in low attenuation or transmission loss in comparison with the best copper conductor. It facilitates the implementation of communication links with extremely wide repeater spacing thus reducing both system cost and complexity. This quality along with already proven modulation BW capability of fiber cable, it is used in long haul telecommunication applications.

g. **Potential Low Cost :**

The glass that generally provides optical fiber transmission medium is made from sand not a scarce resource. In comparison with copper conductors, optical fiber offers low cost line communication.

CHARACTERISTICS OF OPTICAL FIBER

The Optic Fiber :

The simplest fiber optic cable consists of two concentric layers of transparent materials. The inner portion (the core) transports the light, the outer covering (the cladding) must have a lower refractive index than the core so the two are made of different materials.

To provide mechanical protection for the cladding an additional plastic layers, the **PRIMARY BUFFER** is added. Some constructions of optic fiber have additional layers of buffer that are then referred to as **SECONDARY BUFFER**. It is very important to note that the whole fiber - **CORE, CLADDING & PRIMARY BUFFER** is solid and the light is confined to the core by the TIR due to the difference in the refractive index of the core compared so that of cladding.

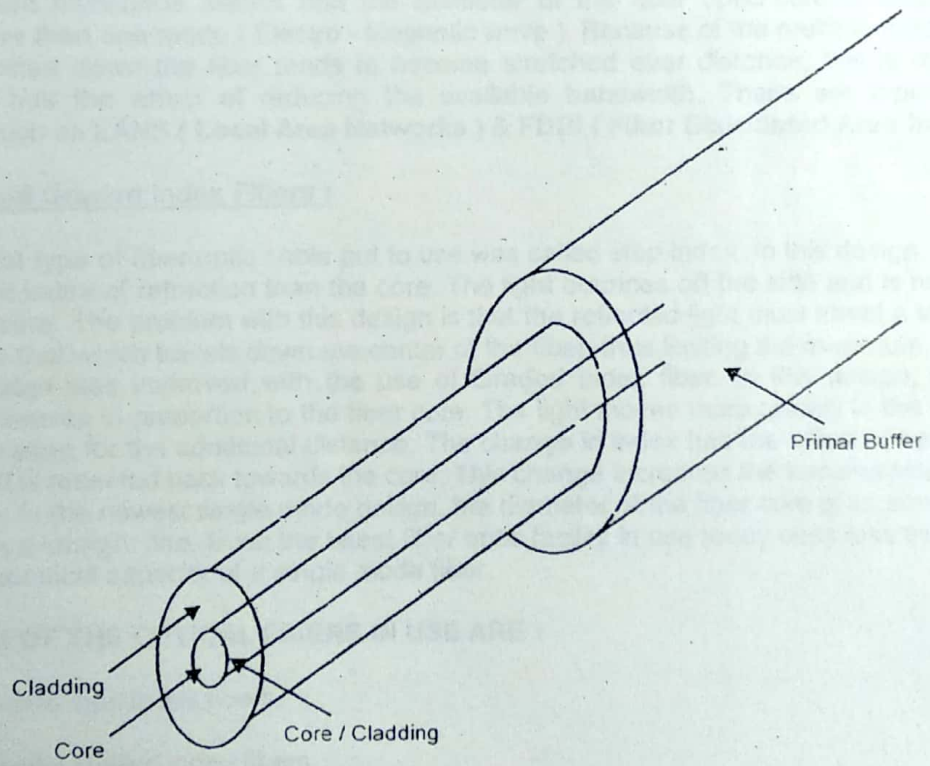


Fig. 6

Single Mode v/s Multi Mode :

As we have already seen that there are particular angles of propagation defined by cone of acceptance, which can be transmitted down the optic fiber. At these angles, the electromagnetic wave that is the light can set a number of complete patterns across the fiber. The number of complete patterns called MODES depends on the dimensions of the optic fiber core. There are essentially two different types of fiber optic transmission schemes in use viz :

1. Single Mode.
2. Multi Mode.

Single Mode :

As the name suggest the single mode cable is able to propagate only one mode (electro - magnetic wave). This is used in long distance and / or, high - speed communication. It is beneficial over long distance since it completely eliminates a problem known as **INTERMODAL DISPERSION** associated with multimode cables. All our long distance telephone conversations are now carried by a single mode optic fiber system over at least some part of the route.

Multi - Mode :

The term multimode means that the diameter of the fiber optic core is large enough to propagate more than one mode (Electro - Magnetic wave). Because of the multiple modes the pulse that is transmitted down the fiber tends to become stretched over distance, this is referred to as dispersion & has the effect of reducing the available bandwidth. These are typically used in applications such as **LANS (Local Area Networks)** & **FDDI (Fiber Distributed Area interface).**

Step Index And Graded Index Fibers :

The first type of fiber optic cable put to use was called step index. In this design, the cladding has a different index of refraction than the core. The light bounces off the side and is reflected back into the fiber core. The problem with this design is that the reflected light must travel a slightly longer distance, than that which travels down the center of the fiber, thus limiting the maximum transmission rate. This design was improved with the use of Graded index fiber. In this design, the index of refraction decreases in proportion to the fiber core. The light moves more quickly in the outer portion thus compensating for the additional distance. The change in index has the effect of bending due to which the light is reflected back towards the core. This change increases the transmission capacity by a factor or so. In the newest single mode design, the diameter of the fiber core is so small that all the light travels in a straight line. Even the latest fiber optic facility in use today uses less than 5% of the maximum theoretical capacity of a single mode fiber.

SOME OF THE OPTICAL FIBERS IN USE ARE :

1. Multimode step index fibers.
2. Multimode graded index fibers.
3. Single mode step index fibers.
4. Plastic - clad fibers.
5. All plastic fibers.

Dimensions of fiber optic cables are written as a ratio e.g. a cable with cladding diameter of 125 microns and fiber core diameter of 62.5 or 50 microns will be referred to as 62.5 / 125 or 50 / 125 fibers.

Choices of Operating Frequency :

Once we had the laser and the new optic fiber available, every thing was in place for a significant upsurge in communications. This resulted in two driving forces, one towards the ability to send more data faster and secondly, to send the data to greater distances without being re - amplified.

More Data Faster :

As the transmission rate of data is increased, the required bandwidth increases and this can be best accommodated by increasing the carrier frequency. This premise has stood us in good stead over many years. The speech and poor quality music transmission on the medium frequency, AM radio, gave way to the higher frequency of FM radios, which accommodate the increased bandwidth necessary for improved music quality. When television required even higher data rates, we responded by moving to even higher frequencies. These previous experience rather suggested that the light used for fiber optic communications should be the highest frequency possible. But there was a surprise in store.

Lower Frequencies Mean Lower Losses :

The first experiments used visible light of different colours (frequencies). As the losses were measured, we found that the higher frequencies caused more losses.

The losses actually increased by the 4th power of the frequency. This means that trebling of the frequencies would result in the losses increasing by 3^4 or 81 times. We therefore have two conflicting influences :

HIGH FREQUENCY = HIGH DATA RATES

LOW FREQUENCY = LONG RANGES

At the moment, long distance communication is more important than achieving the ultimate in data transmission rates. Therefore in most real installations, we tend to go for the relatively low frequencies of infrared light that is just below the visible spectrum.

Fiber Windows :

We now have an infrared range between 800 nm - 1700 nm with one part of it around 1380 nm so that equipment from different manufactures could be compatible.

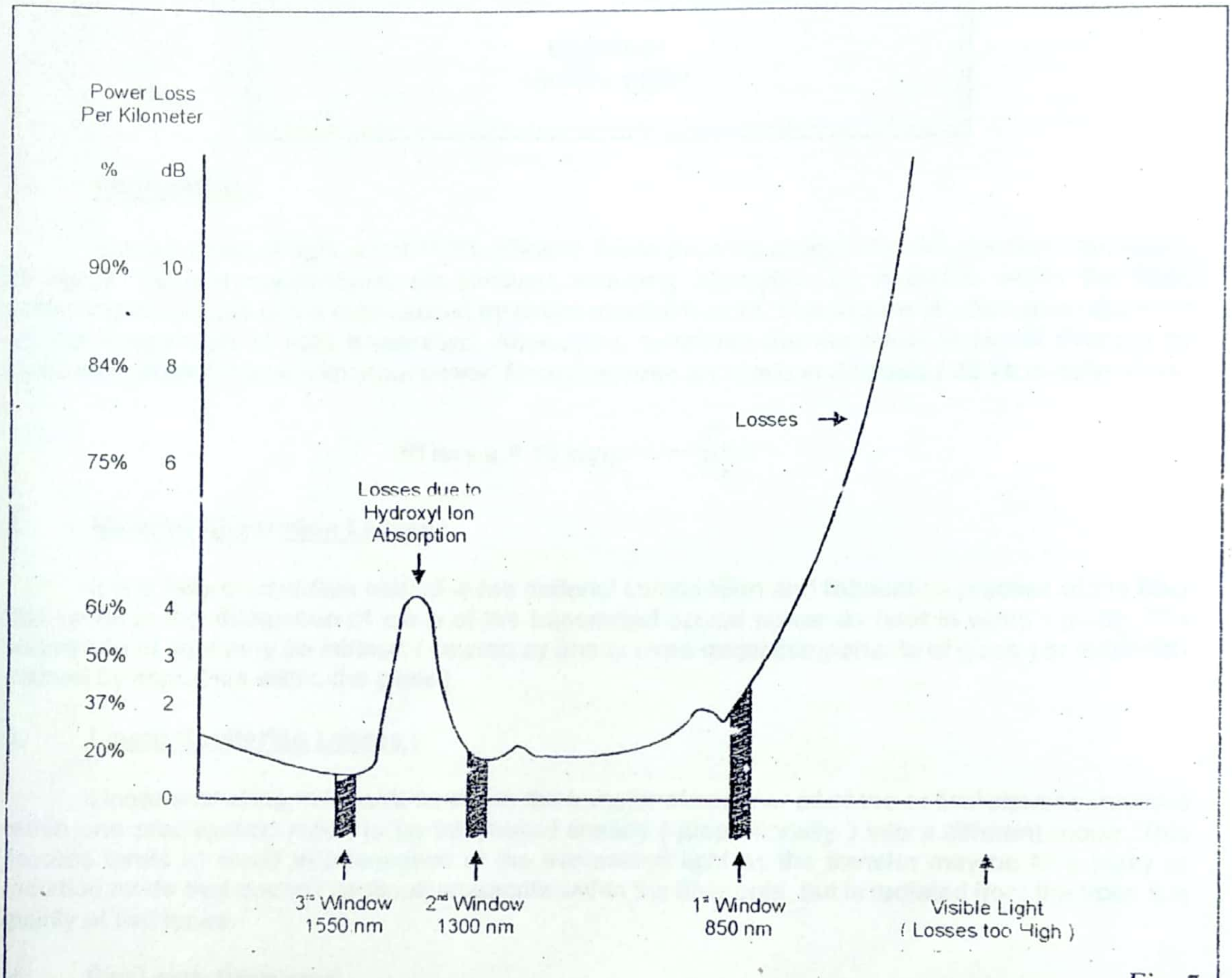


Fig. 7

This has resulted in three standard wavelengths called windows. The windows were really the result of looking at the available light sources. Some wavelengths of LED and laser light are easier and less expensive than others to produce. The design and manufacture of the optic fiber is then optimized for these frequencies.

Note :

The infrared light is very dangerous to eyes, it can cause irreversible damages and since it is invisible care should be taken to ensure that the optic fiber is not live.

LOSSES IN OPTICAL FIBER

1. **Attenuation :**

Transmission of light is not 100% efficient. Some photons of light are lost, causing attenuation of signal. Several mechanisms are involved, including absorption by materials within the fiber, scattering of light out of the core caused by environmental factors. The degree of attenuation depends on the wavelength of light transmitted. Attenuation measures the reduction in signal strength by comparing output power with input power. Measurements are made in decibels (db) It is defined as :

$$\text{dB loss } \alpha = 10 \log_{10} \frac{P_i}{P_o}$$

2. **Material Absorption Losses :**

It is a loss mechanism related to the material composition and fabrication process of the fiber that result in the dissipation of some of the transmitted optical power as heat in wave - guide. The absorption of light may be intrinsic (caused by one or more major components of glass) or extrinsic (caused by impurities within the glass).

3. **Linear Scattering Losses :**

Linear scattering mechanisms cause the transfer of some or all of the optical power contained within one propagation mode to be transferred linearly (proportionally) into a different mode. This process tends to result in attenuation of the transmitted light as the transfer may be to a leaky or radiation mode that doesn't continue propagate within the fiber core, but is radiated from the fiber. It is mainly of two types.

- ✓ Ray Leigh Scattering.
- ✓ Mie Scattering.

✓ **Ray Leigh Scattering :**

When the infrared light strikes a very-very small place where the materials in the glass are imperfectly mixed. This gives rise to localized changes in the refractive index resulting in the light being scattered in all directions. Some of the light leaves the optic fiber, some continues in the correct direction and some is returned towards the light source. This is called back **SCATTER.**

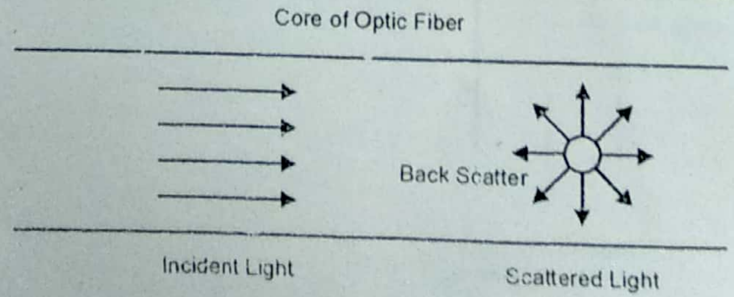


Fig. 8

1. **Mie Scattering :**

These results from the non - perfect cylindrical structure of the wave - guide. It may be caused by the imperfections such as irregularities in the core cladding interface core, cladding refractive index difference along the fiber length, diameter fluctuations, strains & bubbles. The scattering created by such in homogeneities is mainly in the forward direction.

2. **Non Linear Scattering :**

Optical wave - guide does not behave linearly, several non - linear effects occur, which in the case of scattering cause disproportionate attenuation usually at high optical power level. This non - linear scattering causes the optical power from one mode to be transferred in either the forward or backward direction to the same, or other modes at different frequency. It depends critically upon the optical power density within the fiber and hence only becomes significant above threshold power levels.

3. **Micro - Bending and Macro - Bending :**

A problem that often occurs in cabling of the optical fiber is the meandering of the fiber core axis on a microscopic scale with in the cable form. This phenomenon, known as micro bending resulting from small lateral forces exerted on the fiber during the cabling process and it causes losses due to radiation in both multimode and single mode fiber.

Macro Bends :

The light propagates down the optic fiber solely because the incident angle exceeds the critical angle. If a sharp bend occurs, the normal and the critical angle move round with the fiber. The incident ray continues in a straight line and it finds itself approaching the core - cladding boundary at an angle less than the critical angle and much of light is able to escape.

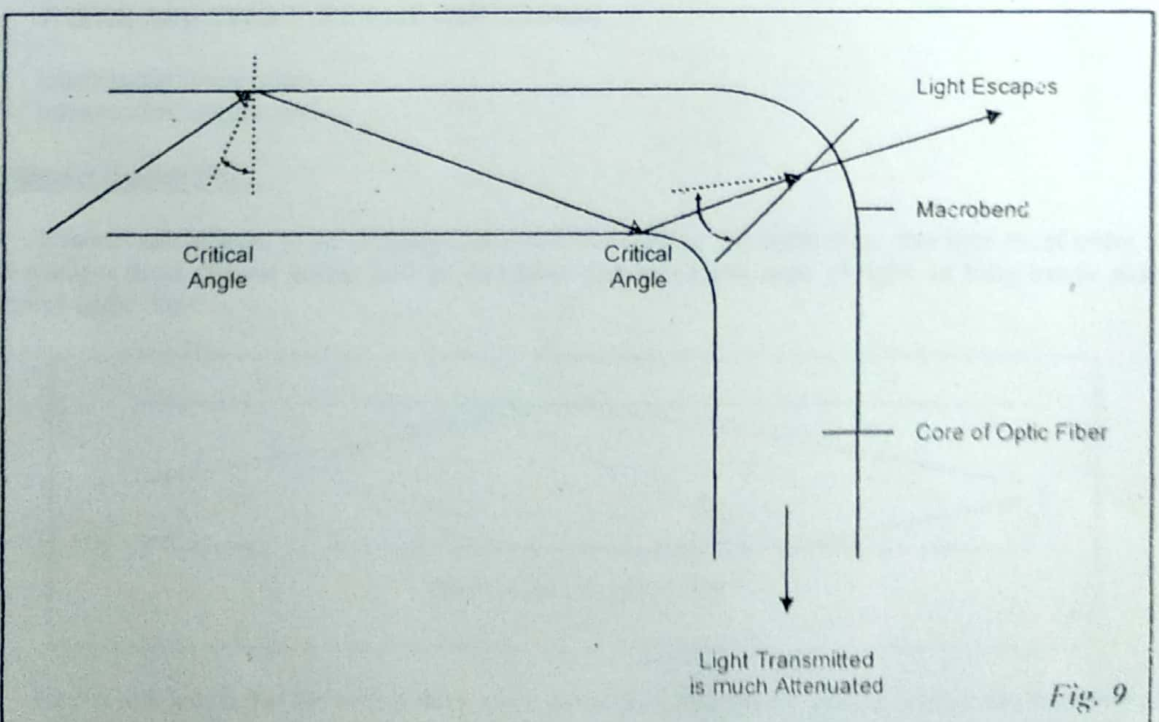


Fig. 9

Dispersion :

When an electrical pulse energies a laser, it launches a short flash or light along the optic fiber. The light spreads out, this effects is called **'Dispersion'** in fig. 10 the light pulse shown before and after it has traveled through the cable.

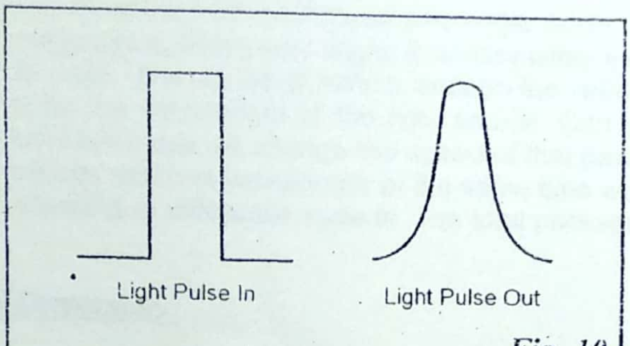


Fig. 10

It is going to limit how fast we can send data - how many bits per second we can transmit through a fiber optic link. In fact it is the main limit to the data transmission rate for long distance communication system.

If we send flashes of laser light down a long link in which dispersion is a problem, the flashes will merge at the far end and the ON / OFF states will not be distinguished by the receiver. Over a given transmission path, there are only two remedies. Firstly, we could reduce the transmission rate so that even allowing for the spreading effect of the dispersion, the ON - OFF states are still clearly separated. This is not a very exciting solution and would clash with one of the main reasons for using optic fiber.

THERE ARE TWO TYPES OF DISPERSION :

1. Intermodal dispersion.
2. Intramodal dispersion.

Inter Modal Dispersion :

You will recall that, to be propagated down the core of the optic fiber, the light must enter at an angle greater than critical angle. Let us consider just two such rays of light as they travel along a section of optic fiber.

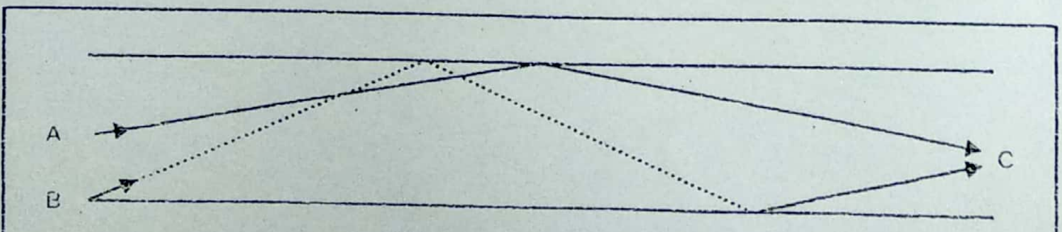


Fig. 11

Ray A will reach the far end before ray B since it is traveling a shorter distance. Assuming that rays A and B are part of the same pulse of light and start at the same time, we can now see how the spreading of the pulses can occur. Each and every ray being propagated at its own angle will arrive at slightly different times at the far end. This spreading effect will occur all along the fiber so it is also important to appreciate that the longer the optic fiber, the greater the dispersion. Transmission rates that are actually possible on an optic fiber therefore depend on its length. In practice, there are only particular angles of propagation that can be transmitted down the fiber.

Intra Modal Dispersion :

This form of dispersion occurs in both multimode and single mode optic fibers. It is only really significant in single mode usage since, being very slight; it is completely swamped by the intermodal dispersion in the multimode case. The cause is simple enough-the refractive index of material is determined to some extent by the wavelength of the light source. Can you see how this causes dispersion ? A change in refractive index will change the speed of that particular wavelength of light. Now if your light source produces different wavelength at the same time we will have components of the transmitted light pulse traveling at difference speeds. The total package of light will spread out - hence the dispersion.

The Cure For Inter Modal Dispersion :

A large core diameter means many modes and severe intermodal dispersion. The cure for this type of dispersion is quite simple. Reduce the core size; the number of modes decreases and the intermodal dispersion is reduced. We can do better than just reducing the intermodal dispersion, we can completely eliminate it. Simply make the core so small that only one mode is propagated. A single ray cannot possibly go at two different speeds so intermodal dispersion cannot occur. In practice the core is reduced to about 9 mm. The optic fiber that now carries only a single mode is now referred to as a 'single mode fiber'. Single mode fiber is used for all long distance and / or high - speed communications. All long distance telephone conversations are now carried by single mode fiber optic systems over at least some parts of the route. The larger core optic fibers for short and medium distances carry many modes are called 'Multimode'.

The Cure for Intra Modal Dispersion :

The cure is apparently so simple i.e. use a light source that emits only one wavelength of light. Unfortunately, it has not yet been invented. The light sources in current use are the LED and the laser. Study fig.12 and decide which of the two would cause the lesser amount of Intramodal Dispersion.

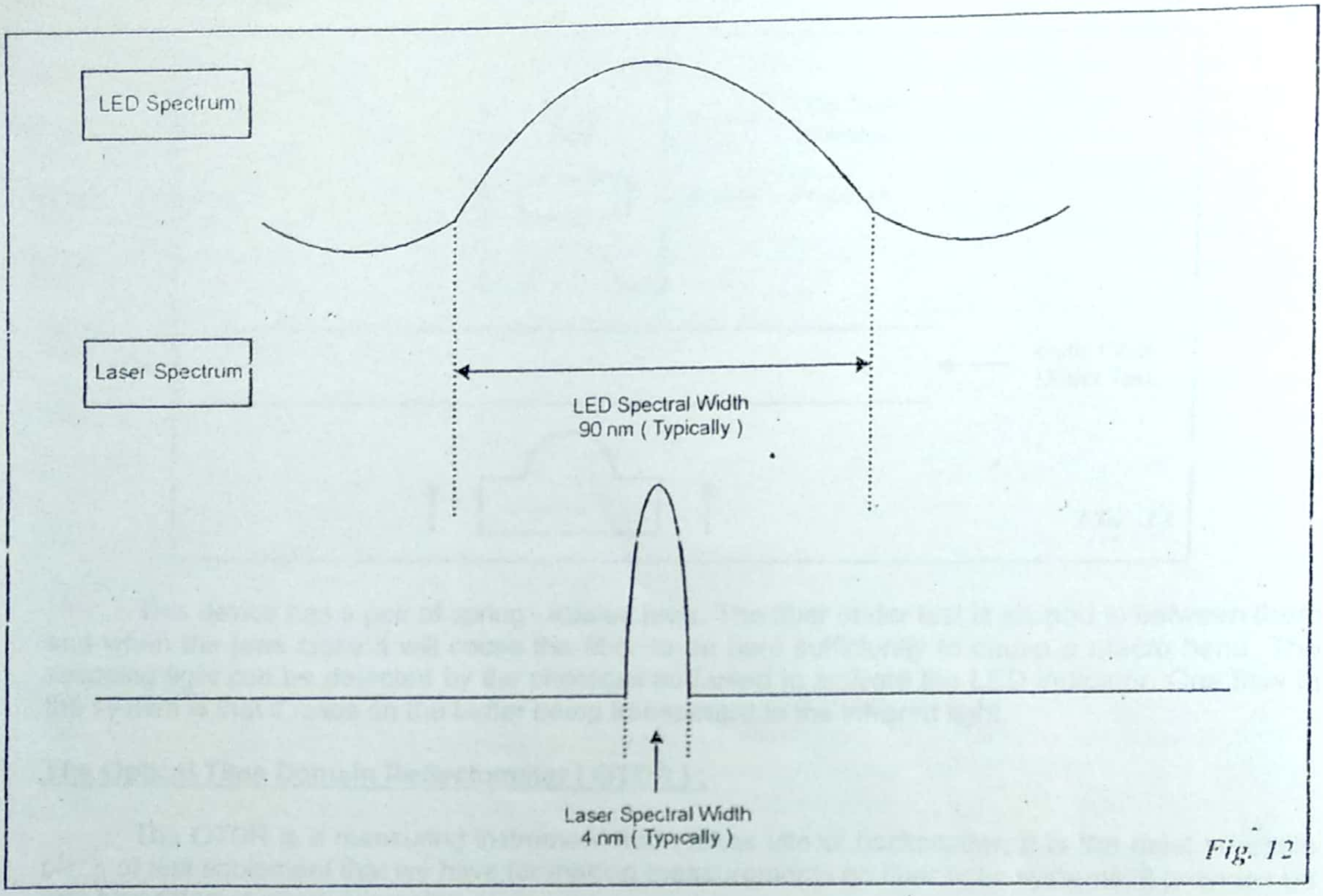


Fig. 12

The laser would cause less intramodal dispersion because its light is more concentrated around the central wavelength. The spread of wavelength measured between the points where the power output falls to half of the peak power is called the spectral width. Some lasers have spectral widths as low as 0.1nm. The low spectral width together with its high power and fast switching makes the laser first choice for long distance communications using single mode optic fiber. Also there are some losses due to coupling in between the fibers and at LED and photo detector ends.

Applications of Macro Bends :

1. A Live Fiber Detector :

WHY LONG DISTANCE FIBER OPTIC SYSTEMS EMPLOY POWERFUL LASERS OPERATING IN THE INFRARED REGION OF THE SPECTRUM ? The infrared light has two properties that are very significant to the engineers and technicians working on the system. We have various pieces of test equipment that can be used to check the system. The 'live' fiber detector is able to find which fibers are carrying data in most day to day checks, but read the instruction manual first to ensure that the instrument is suitable for the type of optic fiber you are checking.

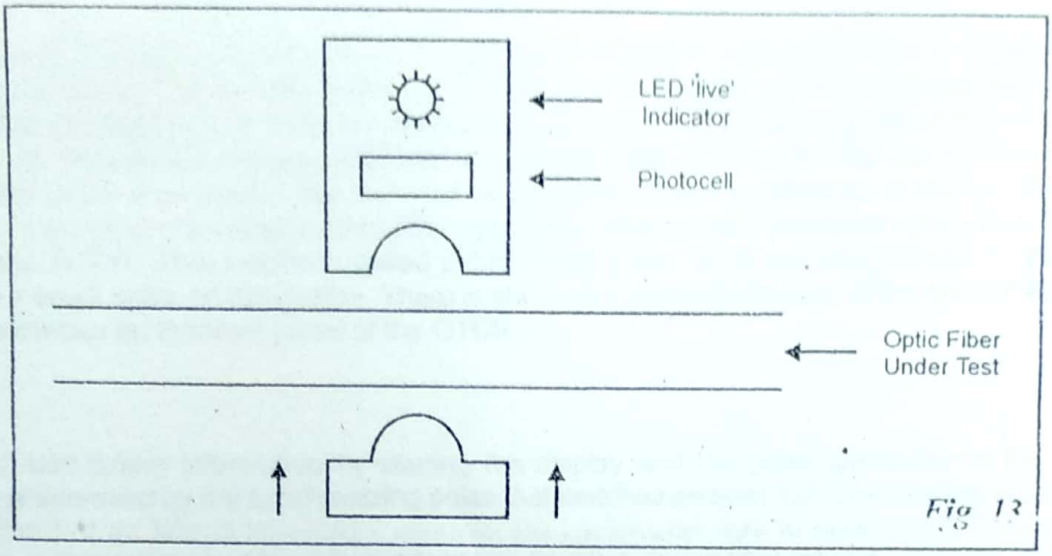


Fig. 13

This device has a pair of spring - loaded jaws. The fiber under test is slipped in between them and when the jaws close it will cause the fiber to be bent sufficiently to cause a macro bend. The escaping light can be detected by the photocell and used to activate the LED indicator. One flaw in the system is that it relies on the buffer being transparent to the infrared light.

The Optical Time Domain Reflectometer (OTDR) :

The OTDR is a measuring instrument that makes use of backscatter. It is the most versatile piece of test equipment that we have for making measurements on fiber optic systems. It provides us with two different measurements :

1. It can measure the magnitude of any losses that occur along optic fiber.
2. It can measure distance analog the optic fiber.

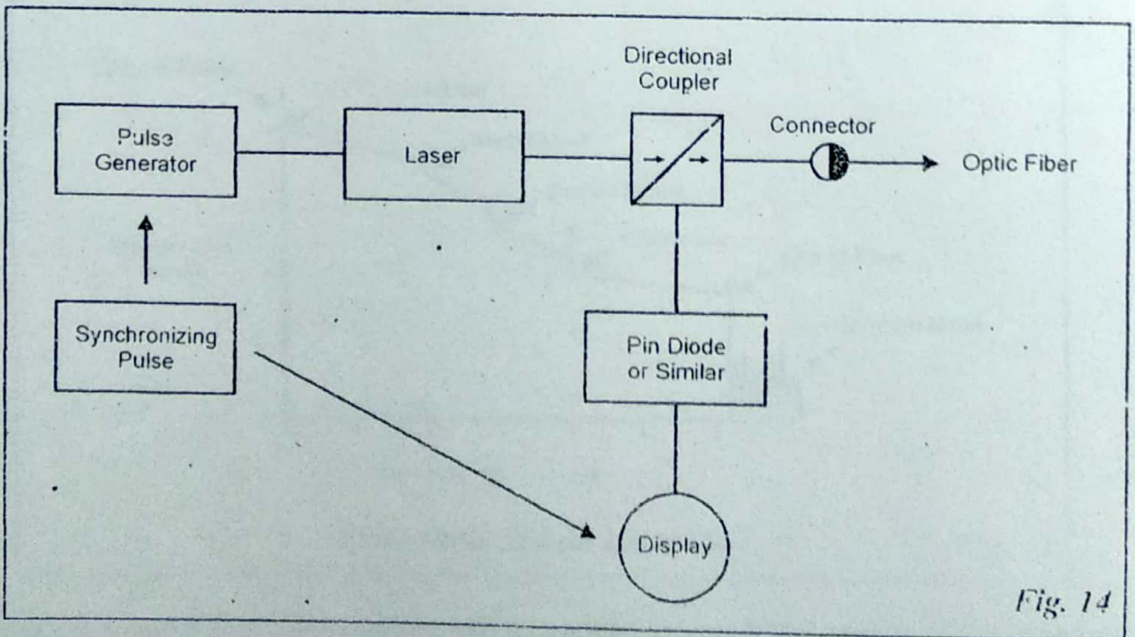


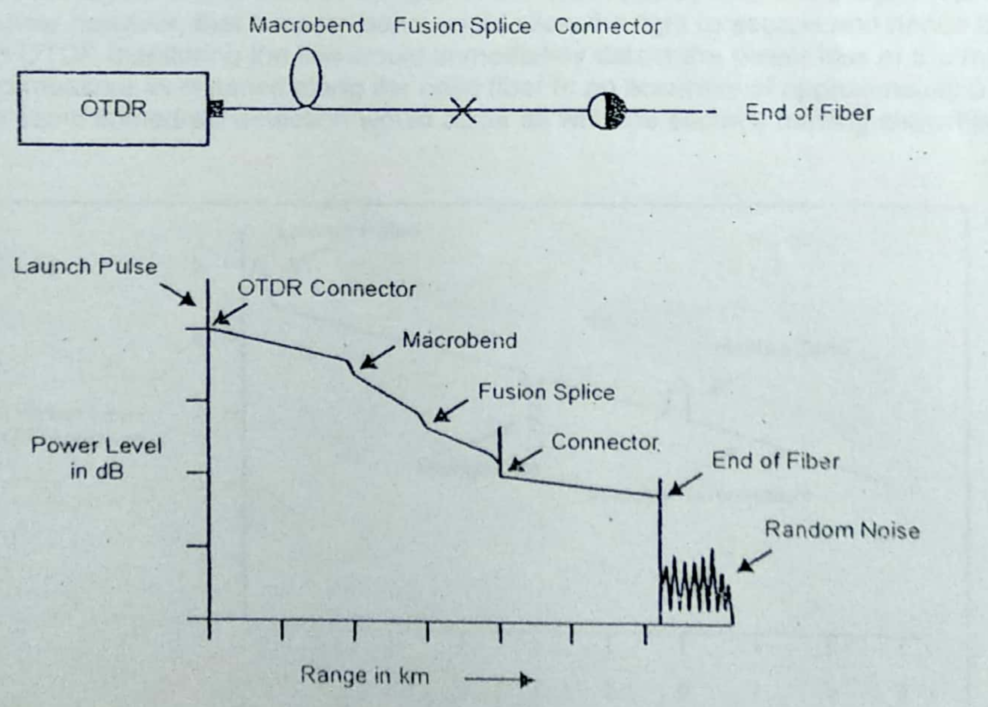
Fig. 14

Losses :

As the light moves along the optic fiber, the light intensity is attenuated by the losses in the optic fiber and so the reflections returned to the OTDR receiver become weaker. Measurement of the amplitude of the returned signals tells us the optic fiber loss in db / km. If a macro bend has occurred, it would show up as a drop in the signal level at a particular point. If the optic fiber has been cut, as it has to be when fitting a connector, the end face of the glass causes a reflection of energy. It is also usual for this to occur at the extreme end of the optic fiber. This cause a localized increase in energy returned to the OTDR. This reflection called a FRESNEL (the 'S' is not pronounced) reflection shown up as a small spike on the display. There is always a Fresnel Reflection at the start of the fiber due to the connector on the front panel of the OTDR.

Distance :

We obtain timing information by starting the display and the pulse generator at the same instant. This is achieved by the synchronizing pulse that switches on both the laser and the receiver at the same instant. If we known how long it takes for the backscatter light to return to the OTDR then we only have to know how fast the infrared light has traveled. Some light returns after say, 500ns, it follows that it has traveled to a total of 100 meters. This represents 50 meters out along the optic fiber and 50 meters back. You will remember that the actual speed of propagation is determined by the refractive index of the core of the optic fiber. Speed of propagation = speed of light in free space / refractive index of the core (the refractive index of the optic fiber being tested must be punched in to the OTDR otherwise all the distance will be miscalculated. The value of the refractive index is quoted by the manufacturer). The synchronizing pulse simply provides a start to the generator and to the display circuits to allows them to determine the travel - time of the laser light and the backscatter.



Fiber Optic System Under Test *Fig. 15*

Fig. 15 shows FO system together with its appearance on OTDR screen. Notice that both the macro bends and fusion splices are shown as a sudden loss of power at a particular point. Indeed, it is not possible to distinguish between macro bed and a fusion splice just by observing the OTDR display. It just shows a localized loss. The loss may show up as a vertical drop or by a sloping line depending upon the speed at which the screen being scanned on the OTDR. The connector has a similar loss but also has a Fresnel reflection. Typical value of losses :

Fusion splices 0.05db.

Connector 0.2 db.

Macro bend : 0 more than 8 dB depending on the severity of the macro bend.

Applications Of Backscatter :

1. Distributive Temperature Sensing (DTS) :

The amount of backscatter occurring in an optic fiber is dependent upon the manufacture of the optic fiber, the optic window used, and also upon the temperature of optic fiber. Now we find a characteristic of the optic fiber that depends on the temperature, it is but a small step away from using the effect to measure temperatures. This new technique is called Distributive Temperature Sensing (DTS). Basically it is an optic fiber connected to equipment operating just like an OTDR that is then passed through the areas to be measured. If it is passed through a refrigerator (minimum temperature of - 190^{0}c or - 310^0 F). See fig.16. e.g. the trace on the OTDR will show the backscatter level falling to a level dependent upon the temperature in the refrigerator. Similarly, a heated area (maximum temperature 460^0 C or 860^0 F) would return a higher level of backscatter.

2. Security :

You will recall that one of the advantages of the fiber optic system is the high level of security offered. We know however, that a macro bend would allow the light to escape and hence the data to be copied. An OTDR monitoring the line would immediately detect the power loss of the macro bend and be able to measure its distance along the optic fiber to an accuracy of approximately 0.1meters (4 inches) the same immediate detection would occur as with the security matting shown in fig. 17 a, b, c.

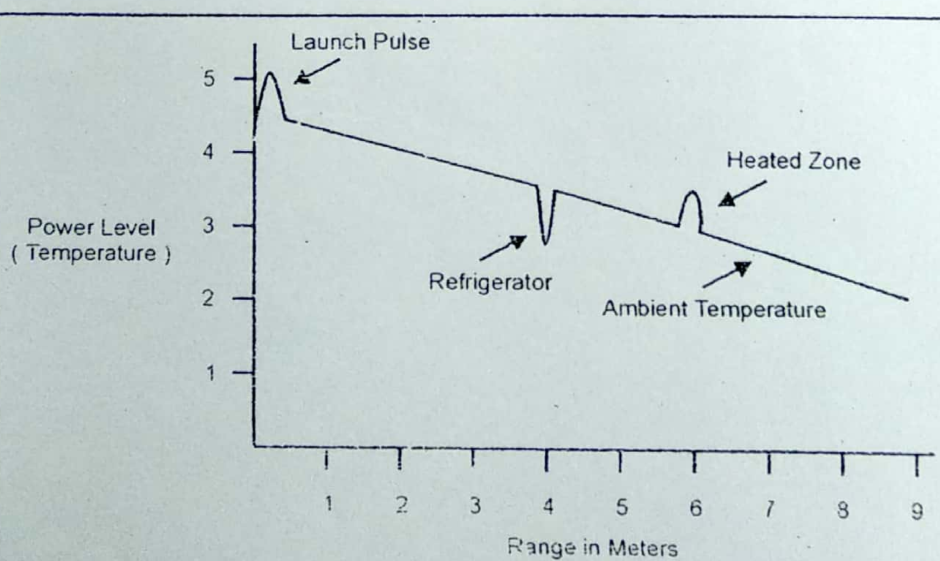


Fig. 16

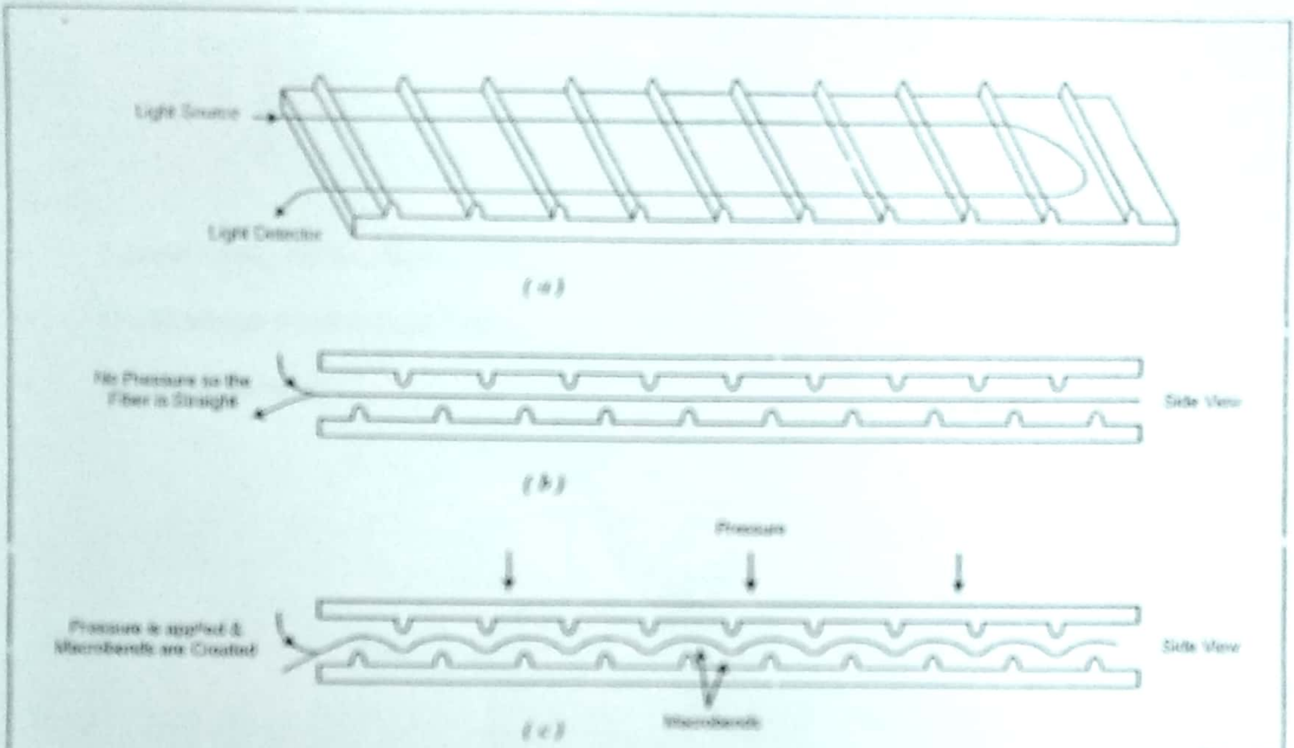

Light Source
Light Detector
(a)
No Pressure so the Fiber is Straight
Side View
(b)
Pressure
Side View
(c)

Fig. 17