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Study of Dispersion management of Optical fiber

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Introduction

1.1Overview of Optical fiber communication:

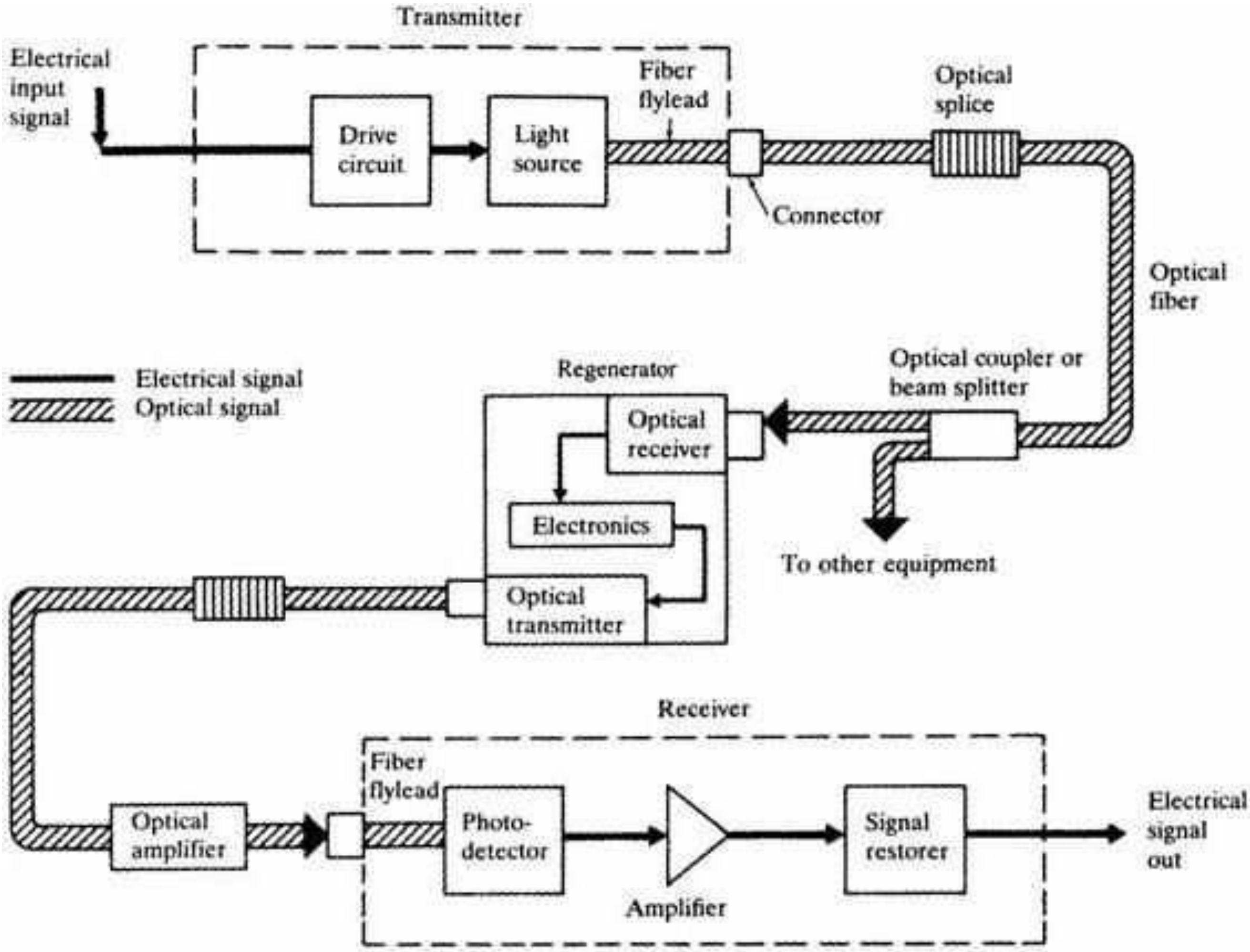

Fig 1.1 : Overview of Optical fiber communication

1.2 History of optical fiber :

Fiber optics, though used extensively in the modern world, is a fairly simple and old technology. Guiding of light by refraction, the principle that makes fiber optics possible, was first demonstrated by Daniel Colladon and Jacques Babinet in Paris in the early 1840s. John Tyndall included a demonstration of it in his public lectures in London a dozen years later. Tyndall also wrote about the property of total internal reflection in an introductory book about the nature of light in 1870: "When the light passes from air into water, the refracted ray is bent towards the perpendicular... When the ray passes from water to air it is bent from the perpendicular... If the angle which the ray in water encloses with the perpendicular to the surface be greater than 48 degrees, the ray will not quit the water at all.It will be totally reflected at the surface.The angle which marks the limit where total reflection begins is called the limiting angle of the medium. For water this angle is 48°27', for flint glass it is 38°41', while for diamond it is 23°42'. Unpigmented human hairs have also been shown to act as an optical fiber.

Practical applications, such as close internal illumination during dentistry, appeared early in the twentieth century. Image transmission through tubes was demonstrated independently by the radio experimenter Clarence Hansell and the television pioneer John Logie Baird in the 1920s. The principle was first used for internal medical examinations by Heinrich Lamm in the following decade. Modern optical fibers, where the glass fiber is coated with a transparent cladding to offer a more suitable refractive index, appeared later in the decade. Development then focused on fiber bundles for image transmission. Harold Hopkins and Narinder Singh Kapany at Imperial College in London achieved low-loss light transmission through a 75 cm long bundle which combined several thousand fibers. Their article titled "A flexible fiber scope, using static scanning" was published in the journal Nature in 1954. The first fiber optic semi-flexible gastro scope was patented by Basil Hirschowitz, C. Wilbur Peters, and Lawrence E. Curtiss, researchers at the University of Michigan, in 1956. In the process of developing the gastro scope, Curtiss produced the first glass-clad fibers; previous optical fibers had relied on air or impractical oils and waxes as the low-index cladding material.

A variety of other image transmission applications soon followed.

In 1880 Alexander Graham Bell and Sumner Tainter invented the 'Photophone' at the Volta Laboratory in Washington, D.C. to transmit voice signals over an optical beam. It was an advanced form of telecommunications, but subject to atmospheric interferences and impractical until the secure transport of light that would be offered by fiber-optical systems. In the late 19th and early 20th centuries, light was guided through bent glass rods to illuminate body cavities. Jun-ichi Nishizawa, a Japanese scientist at Tohoku University, also proposed the use of optical fibers for communications in 1963, as stated in his book published in 2004 in India. Nishizawa invented other technologies that contributed to the development of optical fiber communications, such as the graded-index optical fiber as a channel for transmitting light from semiconductor lasers. Charles K. Kao and George A. Hockham of the British company Standard Telephones and Cables (STC) were the first to promote the idea that the attenuation in optical fibers could be reduced below 20 decibels per kilometer (dB/km), making fibers a practical communication medium. They proposed that the attenuation in fibers available at the time was caused by impurities that could be removed, rather than by fundamental physical effects such as scattering. They correctly and systematically theorized the light-loss properties for optical fiber, and pointed out the right material to use for such fibers — silica glass with high purity. This discovery earned Kao the Nobel Prize in Physics in 2009.

NASA used fiber optics in the television cameras sent to the moon. At the time, the use in the cameras was classified confidential, and only those with the right security clearance or those accompanied by someone with the right security clearance were permitted to handle the cameras.

The crucial attenuation limit of 20 dB/km was first achieved in 1970, by researchers Robert D. Maurer, Donald Keck, Peter C. Schultz, and Frank Zimar working for American glass maker Corning Glass Works, now Corning Incorporated. They demonstrated a fiber with 17 dB/km attenuation by doping silica glass with titanium. A few years later they produced a fiber with only 4 dB/km attenuation using germanium dioxide as the core do pant. Such low attenuation ushered in optical fiber telecommunication. In 1981, General Electric produced fused quartz ingots that could be drawn into fiber optic strands 25 miles (40 km) long.

Attenuation in modern optical cables is far less than in electrical copper cables, leading to long-haul fiber connections with repeater distances of 70–150 kilometers (43–93 mi). The erbium-doped fiber amplifier, which reduced the cost of long-distance fiber systems by reducing or eliminating optical-electrical-optical repeaters, was co-developed by teams led by David N. Payne of the University of Southampton and Emmanuel Desurvire at Bell Labs in 1986. Robust modern optical fiber uses glass for both core and sheath, and is therefore less prone to aging. It was invented by Gerhard Bernsee of Schott Glass in Germany in 1973.

1.3 Working Principe of optical fiber:

An optical fiber is a cylindrical dielectric waveguide (no conducting waveguide) that transmits light along its axis, by the process of total internal reflection. The fiber consists of a core surrounded by a cladding layer, both of which are made of dielectric materials. To confine the optical signal in the core, the refractive index of the core must be greater than that of the cladding. The boundary between the core and cladding may either be abrupt, in step-index fiber, or gradual, in graded-index fiber.

Index of refraction (Refractive index)

The index of refraction is a way of measuring the speed of light in a material. Light travels fastest in a vacuum, such as outer space. The speed of light in a vacuum is about 300,000 kilometers (186,000 miles) per second. Index of refraction is calculated by dividing the speed of light in a vacuum by the speed of light in some other medium. The index of refraction of a vacuum is therefore 1, by definition. The typical value for the cladding of an optical fiber is 1.52. The core value is typically 1.62. The larger the index of refraction, the slower light travels in that medium. From this information, a good rule of thumb is that signal using optical fiber for communication will travel at around 200 million meters per second. Or to put it another way, to travel 1000 kilometers in fiber, the signal will take 5 milliseconds to propagate. Thus a phone call carried by fiber between Sydney and New York, a 12000 kilometer distance, means that there is an absolute minimum delay of 60 milliseconds (or around 1/16 of a second) between when one caller speaks to when the other hears. (Of course the fiber in this case will probably travel a longer route, and there will be additional delays due to communication equipment switching and the process of encoding and decoding the voice onto the fiber).

Total internal reflection:

When light traveling in an optically dense medium hits a boundary at a steep angle (larger than the "critical angle" for the boundary), the light will be completely reflected. This is called total internal reflection. This effect is used in optical fibers to confine light in the core. Light travels along the fiber bouncing back and forth off of the boundary. Because the light must strike the boundary with an angle greater than the critical angle, only light that enters the fiber within a certain range of angles can travel down the fiber without leaking out. This range of angles is called the acceptance cone of the fiber. The size of this acceptance cone is a function of the refractive index difference between the fiber's core and cladding.

In simpler terms, there is a maximum angle from the fiber axis at which light may enter the fiber so that it will propagate, or travel, in the core of the fiber. The sine of this maximum angle is the numerical aperture (NA) of the fiber. Fiber with a larger NA requires less precision to splice and work with than fiber with a smaller NA. Single-mode fiber has a small NA.

1.4 Advantages of Optical fiber:

Let us see the advantages of optical fiber communication over conventional communication system.

1. **Enormous Bandwidths:**
The information carrying capacity of a transmission system is directly proportional to the carrier frequency of the transmitted signals. The optical carrier frequency is in the range of 1014 Hz while the radio frequency is about 106 Hz. Thus the optical fibres have enormous transmission bandwidths and high data rate. Using wavelength division multiplexing operation, the data rate or information carrying capacity of optical fibres is enhanced to many orders of magnitude.

2**. Low transmission loss:**
Due to the usage of ultra low loss fibres and the erbium doped silica fibres as optical amplifiers, one can achieve almost loss less transmission. Hence for long distance communication fibres of 0.002 dB/km are used. Thus the repeater spacing is more than 100 km.

3. **Immunity to cross talk:**
Since optical fibres are dielectric wave guides, they are free from any electromagnetic interference (EMI) and radio frequency interference (RFI). Since optical interference among different fibres is not possible, cross talk is negligible even many fibres are cabled together.

4**. Electrical Isolation:**
Optical fibres are made from silica which is an electrical insulator. Therefore they do not pick up any electromagnetic wave or any high current lightening. It is also suitable in explosive environment.

5. **Small size and weight**
The size of the fiber ranges from 10 micrometres to 50 micrometres which is very small. The space occupied by the fiber cable is negligibly small compared to conventional electrical cables. Optical fibers are light in weight. These advantages make them to use in aircrafts and satellites more effectively.

6. **Signal security:**
The transmitted signal through the fibre does not radiate. Unlike in copper cables, a transmitted signal cannot be drawn from a fiber without tampering it. Thus, the optical fiber communication provides 100% signal security.

7. **Ruggedness and flexibility:**
The fibre cable can be easily bend or twisted without damaging it. Further the fiber cables are superior than the copper cables in terms of handling, installation, stroage, transportation, maintenance, strength and durability.

8. **Low cost and availability:**
Since the fibres are made of silica which is available in abundance. Hence, there is no shortage of material and optical fibers offer the potential for low cost communication.

9. **Reliability:**
The optical fibres are made from silicon glass which does not undergo any chemical reaction or corrosion. Its quality is not affected by external radiation. Further due to its negligible attenuation and dispersion, optical fiber communication has high reliability. All the above factors also tend to reduce the expenditure on its maintenance.

1.5 Types of Optical Fiber:

Understanding the characteristics of different fiber types aides in understanding the applications for which they are used. Operating a fiber optic system properly relies on knowing what type of fiber is being used and why. There are two basic types of fiber: multimode fiber and single-mode fiber. Multimode fiber is best designed for short transmission distances, and is suited for use in LAN systems and video surveillance. Single-mode fiber is best designed for longer transmission distances, making it suitable for long-distance telephony and multichannel television broadcast systems. Be describe that different types of optical fiber:

1. Multi mode fiber
2. Single mode fiber

1.5.1 Multimode Fiber:

The first to be manufactured and commercialized, simply refers to the fact that numerous modes or light rays are carried simultaneously through the waveguide. Modes result from the fact that light will only propagate in the fiber core at discrete angles within the cone of acceptance. This fiber type has a much larger core diameter, compared to single-mode fiber, allowing for the larger number of modes, and multimode fiber is easier to couple than single-mode optical fiber. Multimode fiber may be categorized as step-index or graded-index fiber. Multimode Step-index Fiber shows how the principle of total internal reflection applies to multimode step-index fiber. Because the core's index of refraction is higher than the cladding's index of refraction, the light that enters at less than the critical angle is guided along the fiber.

Total Internal Reflection in Multimode Step-index fiber

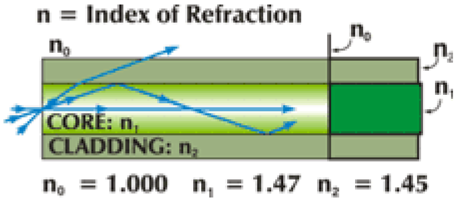

Fig 1.5.1 : Multimode Step-index fiber

Three different light waves travel down the fiber. One mode travels straight down the center of the core. A second mode travels at a steep angle and bounces back and forth by total internal reflection. The third mode exceeds the critical angle and refracts into the cladding. Intuitively, it can be seen that the second mode travels a longer distance than the first mode, causing the two modes to arrive at separate times. This disparity between arrival times of the different light rays is known as dispersion, and the result is a muddied signal at the receiving end. For a more detailed discussion of dispersion, see "Dispersion in Fiber Optic Systems" however, it is important to note that high dispersion is an unavoidable characteristic of multimode step-index fiber. Multimode Graded- index Fiber Graded-index refers to the fact that the refractive index of the core gradually decreases farther from the center of the core. The increased refraction in the center of the core slows the speed of some light rays, allowing all the light rays to reach the receiving end at approximately the same time, reducing dispersion.

Multimode Graded-index Fiber

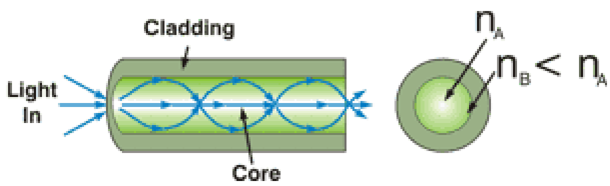

Fig 1.5.2 : Multimode Step-index fiber

The principle of multimode graded-index fiber. The core's central refractive index, nA, is greater than that of the outer core's refractive index, nB. As discussed earlier, the core's refractive index is parabolic, being higher at the center.The light rays no longer follow straight lines; they follow a serpentine path being gradually bent back toward the center by the continuously declining refractive index. This reduces the arrival time disparity because all modes arrive at about the same time. The modes traveling in a straight line are in a higher refractive index, so they travel slower than the serpentine modes. These travel farther but move faster in the lower refractive index of the outer core region.

1.5.2 Single-mode Fiber:

Single-mode fiber allows for a higher capacity to transmit information because it can retain the fidelity of each light pulse over longer distances, and it exhibits no dispersion caused by multiple modes. Single-mode fiber also enjoys lower fiber attenuation than multimode fiber. Thus, more information can be transmitted per unit of time. Like multimode fiber, early single-mode fiber was generally characterized as step-index fiber meaning the refractive index of the fiber core is a step above that of the cladding rather than graduated as it is in graded-index fiber. Modern single-mode fibers have evolved into more complex designs such as matched clad, depressed clad and other exotic structures.

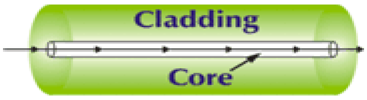

Fig 1.5.3 : Single-mode fiber

Single-mode fiber has disadvantages. The smaller core diameter makes coupling light into the core more difficult. The tolerances for single-mode connectors and splices are also much more demanding. Single-mode fiber has gone through a continuing evolution for several decades now. As a result, there are three basic classes of single-mode fiber used in modern telecommunications systems. The oldest and most widely deployed type is non dispersion-shifted fiber (NDSF). These fibers were initially intended for use near 1310 nm. Later, 1550 nm systems made NDSF fiber undesirable due to its very high dispersion at the 1550 nm wavelength. To address this short coming, fiber manufacturers developed, dispersion-shifted fiber(DSF), that moved the zero-dispersion point to the 1550 nm region. Years later, scientists would discover that while DSF worked extremely well with a single 1550 nm wavelength, it exhibits serious nonlinearities when multiple, closely-spaced wavelengths in the 1550 nm were transmitted in DWDM systems. Recently, to address the problem of nonlinearities, a new class of fibers were introduced. These are classified as non zero-dispersion-shifted fibers (NZ-DSF). The fiber is available in both positive and negative dispersion varieties and is rapidly becoming the fiber of choice in new fiber deployment. For more information on this loss mechanism, see the article "Fiber Dispersion."

Chapter-02

Optical Source

02.01Optical source:

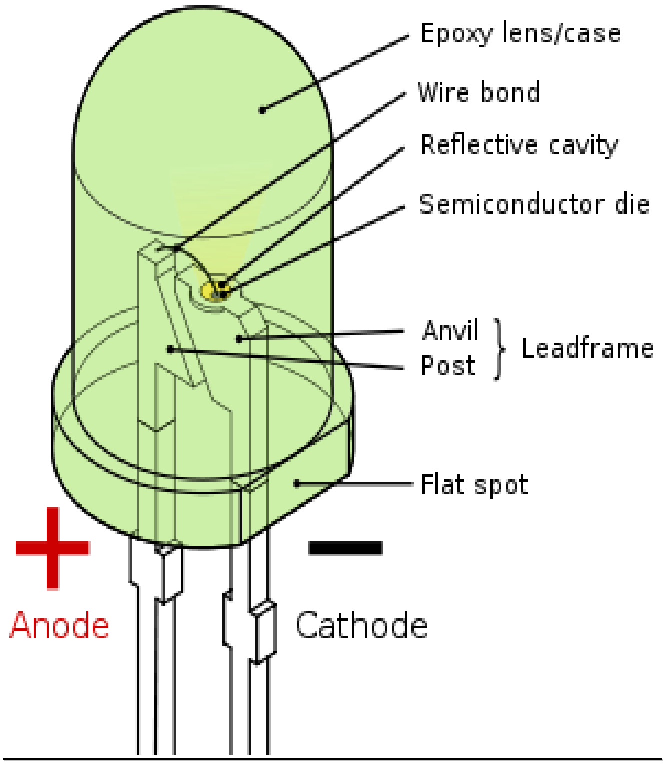

Fig 2.1 : light-emitting diode

A light-emitting diode (LED) is a semiconductor light source. LEDs are used as indicator lamps in many devices and are increasingly used for other lighting. Introduced as a practical electronic component in 1962, early LEDs emitted low-intensity red light, but modern versions are available across the visible, ultraviolet and infrared wavelengths, with very high brightness.

When a light-emitting diode is forward biased (switched on), electrons are able to recombine with electron holes within the device, releasing energy in the form of photons. This effect is called electroluminescence and the color of the light (corresponding to the energy of the photon) is determined by the energy gap of the semiconductor. LEDs are often small in area (less than 1 mm^2), and integrated optical components may be used to shape its radiation pattern. LEDs present many advantages over incandescent light sources including lower energy consumption, longer lifetime, improved robustness, smaller size, and faster switching. LEDs powerful enough for room lighting are relatively expensive and require more precise current and heat management than compact fluorescent lamp sources of comparable output.

Light-emitting diodes are used in applications as diverse as replacements for aviation lighting, automotive lighting (particularly brake lamps, turn signals and indicators) as well as in traffic signals. LEDs have allowed new text, video displays, and sensors to be developed, while their high switching rates are also useful in advanced communications technology. Infrared LEDs are also used in the remote control units of many commercial products including televisions, DVD players, and other domestic appliances.

Lighting

2.2 Priciple of LED :

With the development of high efficiency and high power LEDs it has become possible to use LEDs in lighting and illumination. Replacement light have been made, as well as dedicated fixtures and LED lamps. LEDs are used as street lights and in other architectural lighting where color changing is used. The mechanical robustness and long lifetime is used in automotive lighting on cars, motorcycles and on bicycle lights.

LED street lights are employed on poles and in parking garages. In 2007, the Italian village Torraca was the first place to convert its entire illumination system to LEDs.[104]

LEDs are used in aviation lighting. Airbus has used LED lighting in their Airbus since 2007, and Boeing plans its use in the 787. LEDs are also being used now in airport and heliport lighting. LED airport fixtures currently include medium-intensity runway lights, runway centerline lights, taxiway centerline & edge lights, guidance signs and obstruction lighting.

LEDs are also suitable for backlighting for LCD televisions and lightweight laptop displays and light source for DLP projectors (See LED TV). RGB LEDs raise the color gamut by as much as 45%. Screens for TV and computer displays can be made thinner using LEDs for backlighting.[105]

LEDs are used increasingly in aquarium lights. Particularly for reef aquariums, LED lights provide an efficient light source with less heat output to help maintain optimal aquarium temperatures. LED-based aquarium fixtures also have the advantage of being manually adjustable to emit a specific color-spectrum for ideal coloration of corals, fish, and invertebrates while optimizing photo synthetically active radiation (PAR) which raises growth and sustainability of photosynthetic life such as corals, anemones, clams, and microalgae. These fixtures can be electronically programmed to simulate various lighting conditions throughout the day, reflecting phases of the sun and moon for a dynamic reef experience. LED fixtures typically cost up to five times as much as similarly rated fluorescent or high-intensity discharge lighting designed for reef aquariums and are not as high output to date.

The lack of IR/heat radiation makes LEDs ideal for stage lights using banks of RGB LEDs that can easily change color and decrease heating from traditional stage lighting, as well as medical lighting where IR-radiation can be harmful. In energy conservation, LEDs lower heat output also means air conditioning(cooling) systems have less heat to dispose of, reducing carbon dioxide emissions.

LEDs are small, durable and need little power, so they are used in hand held devices such as flashlights. LED strobe lights or flashes operate at a safe, low voltage, instead of the 250+ volts commonly found in xenon flash lamp-based lighting. This is especially useful in cameras on mobile, where space is at a premium and bulky voltage-raising circuitry is undesirable.

LEDs are used for infrared illumination in night vision uses including security. A ring of LEDs around a video camera, aimed forward into a retro reflective background, allows chroma keying in video productions.

LED's are now used commonly in all market areas from commercial to home use: standard lighting and AV installations, stage and theatrical, architectural and public spaces, wherever artificial light is used.

In many countries incandescent lighting for homes and offices is no longer available and building regulations insist on new premises being fitted out at day one with LED fixtures and fittings.

Increasingly the adaptability of color LED's are finding uses in medical and educational applications such as mood enhancement and new technologies, such as AmBX, for the control of color LED's have been developed to exploit LED versatility. NASA has even sponsored research for the use of LEDs to promote health for astronauts.

2.3 Laser:

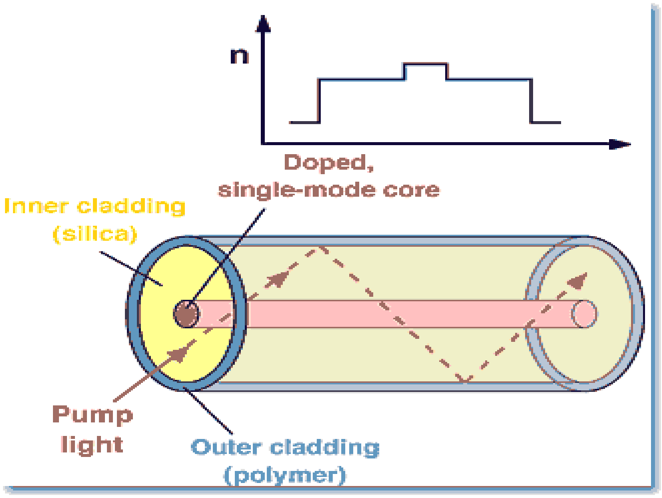

Fig 2.3 : LASER

A laser is a device that emits light (electromagnetic radiation) through a process of optical amplification based on the stimulated emission of photons. The term "laser" originated as an acronym for Light Amplification by Stimulated Emission of Radiation.[1][2] The emitted laser light is notable for its high degree of spatial and temporal coherence, unattainable using other technologies.

Spatial coherence typically is expressed through the output being a narrow beam which is diffraction-limited, often a so-called "pencil beam." Laser beams can be focused to very tiny spots, achieving a very high irradiance. Or they can be launched into a beam of very low divergence in order to concentrate their power at a large distance.

Temporal (or longitudinal) coherence implies a polarized wave at a single frequency whose phase is correlated over a relatively large distance (the coherence length) along the beam.[3] A beam produced by a thermal or other incoherent light source has an instantaneous amplitude and phase which vary randomly with respect to time and position, and thus a very short coherence length.

Most so-called "single wavelength" lasers actually produce radiation in several modes having slightly different frequencies (wavelengths), often not in a single polarization. And although temporal coherence implies monochromaticity, there are even lasers that emit a broad spectrum of light, or emit different wavelengths of light simultaneously. There are some lasers which are not single spatial mode and consequently their light beams diverge more than required by the diffraction limit. However all such devices are classified as "lasers" based on their method of producing that light: stimulated emission. Lasers are employed in applications where light of the required spatial or temporal coherence could not be produced using simpler technologies.

2.4 Princile of LASER:

Solid-state lasers or laser amplifiers where the light is guided due to the total internal reflection in a single mode optical fiber are instead called fiber lasers. Guiding of light allows extremely long gain regions providing good cooling conditions; fibers have high surface area to volume ratio which allows efficient cooling. In addition, the fiber's wave guiding properties tend to reduce thermal distortion of the beam. Erbium and ytterbium ions are common active species in such lasers.

Quite often, the fiber laser is designed as a double-clad fiber. This type of fiber consists of a fiber core, an inner cladding and an outer cladding. The index of the three concentric layers is chosen so that the fiber core acts as a single-mode fiber for the laser emission while the outer cladding acts as a highly multimode core for the pump laser. This lets the pump propagate a large amount of power into and through the active inner core region, while still having a high numerical aperture (NA) to have easy launching conditions.Pump light can be used more efficiently by creating a fiber disk laser, or a stack of such lasers.Fiber lasers have a fundamental limit in that the intensity of the light in the fiber cannot be so high that optical nonlinearities induced by the local electric field strength can become dominant and prevent laser operation and/or lead to the material destruction of the fiber. This effect is called photo darkening. In bulk laser materials, the cooling is not so efficient, and it is difficult to separate the effects of photo darkening from the thermal effects, but the experiments in fibers show that the photo darkening can be attributed to the formation of long-living color centers.

Chapter -03

Optical Receiver

3.1Optical Receiver:

The PIN photodiodes

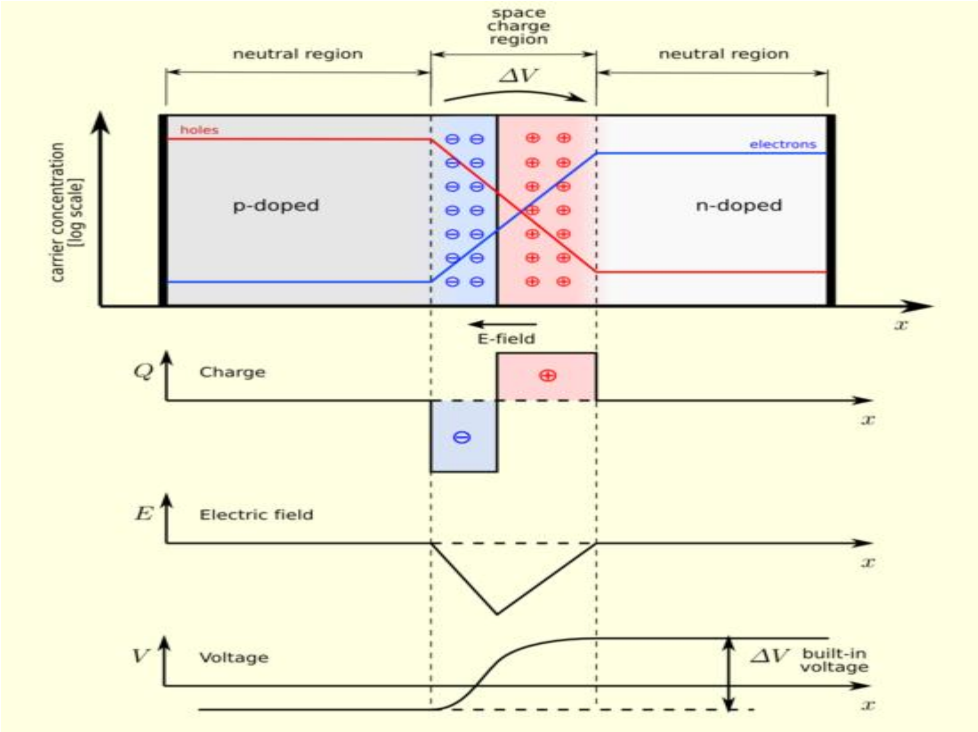

Fig 3.2 : photodiode

A photodiode is a type of photo detector capable of converting light into either current or voltage, depending upon the mode of operation.[1] The common, traditional solar cell used to generate electric solar power is a large area photodiode.

Photodiodes are similar to regular semiconductor diodes except that they may be either exposed (to detect vacuum UV or X-rays) or packaged with a window or optical fiber connection to allow light to reach the sensitive part of the device. Many diodes designed for use specifically as a photodiode use a PIN junction rather than a p-n junction, to increase the speed of response. A photodiode is designed to operate in reverse bias.

Principle of operation:

A photodiode is a p-n junction or PIN structure. When a photon of sufficient energy strikes the diode, it excites an electron, thereby creating a free electron (and a positively charged electron hole). This mechanism is also known as the inner photoelectric effect. If the absorption occurs in the junction's depletion region, or one diffusion length away from it, these carriers are swept from the junction by the built-in field of the depletion region. Thus holes move toward the anode, and electrons toward the cathode, and a photocurrent is produced. This photocurrent is the sum of both the dark current (without light) and the light current, so the dark current must be minimized to enhance the sensitivity of the device.[3]

Applications:

P-N photodiodes are used in similar applications to other photo detectors, such as photoconductors, charge-coupled devices, and photomultiplier tubes. They may be used to generate an output which is dependent upon the illumination (analog; for measurement and the like), or to change the state of circuitry (digital; either for control and switching, or digital signal processing).

Photodiodes are used in consumer electronics devices such as compact disc players, smoke detectors, and the receivers for infrared remote control devices used to control equipment from televisions to air conditioners. For many applications either photodiodes or photoconductors may be used. Either type of photo sensor may be used for light measurement, as in camera light meters, or to respond to light levels, as in switching on street lighting after dark.

Photo sensors of all types may be used to respond to incident light, or to a source of light which is part of the same circuit or system. A photodiode is often combined into a single component with an emitter of light, usually a light-emitting diode (LED), either to detect the presence of a mechanical obstruction to the beam (slotted optical switch), or to couple two digital or analog circuits while maintaining extremely high electrical isolation between them, often for safety (photo coupler).

Photodiodes are often used for accurate measurement of light intensity in science and industry. They generally have a more linear response than photoconductors.

They are also widely used in various medical applications, such as detectors for computed tomography (coupled with scintillates), instruments to analyze samples (immunoassay), and pulse oximeters.

PIN diodes are much faster and more sensitive than p-n junction diodes, and hence are often used for optical communications and in lighting regulation.

P-N photodiodes are not used to measure extremely low light intensities. Instead, if high sensitivity is needed, avalanche photodiodes, intensified charge-coupled devices or photomultiplier tubes are used for applications such as astronomy, spectroscopy, night vision equipment and laser range finding.

3.2 Avalanche photodiode (APD):

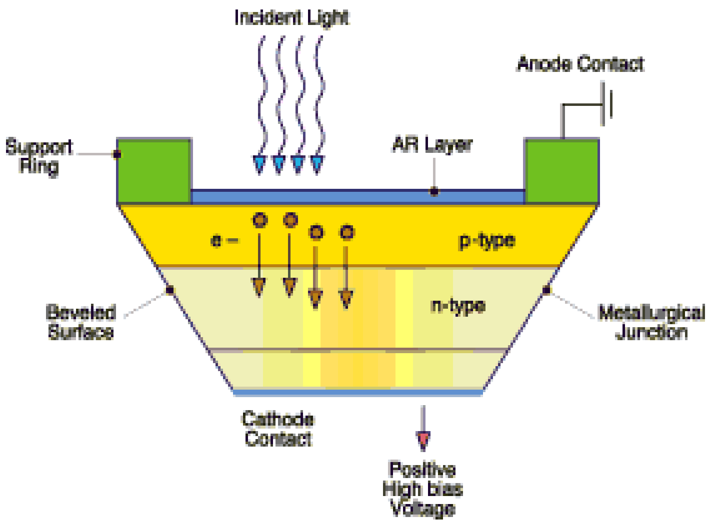

Fig 3.2.1: avalanche photodiode

An avalanche photodiode (APD) is a highly sensitive semiconductor electronic device that exploits the photoelectric effect to convert light to electricity. APDs can be thought of as photo detectors that provide a built-in first stage of gain through avalanche multiplication. From a functional standpoint, they can be regarded as the semiconductor analog to photomultipliers. By applying a high reverse bias voltage (typically 100-200 V in silicon), APDs show an internal current gain effect (around 100) due to impact ionization (avalanche effect). However, some silicon APDs employ alternative doping and beveling techniques compared to traditional APDs that allow greater voltage to be applied (> 1500 V) before breakdown is reached and hence a greater operating gain (> 1000). In general, the higher the reverse voltage the higher the gain. Among the various expressions for the APD multiplication factor (M), an instructive expression is given by the formula

$$M = \frac{1}{1 - \int_0^L \alpha(x)\, dx}$$

where L is the space charge boundary for electrons and α is the multiplication coefficient for electrons (and holes). This coefficient has a strong dependence on the applied electric field strength, temperature, and doping profile. Since APD gain varies strongly with the applied reverse bias and temperature, it is necessary to control the reverse voltage to keep a stable gain. Avalanche photodiodes therefore are more sensitive compared to other semiconductor photodiodes.

If very high gain is needed (10^5 to 10^6), certain APDs (single-photon avalanche diodes) can be operated with a reverse voltage above the APD's breakdown voltage. In this case, the APD needs to have its signal current limited and quickly diminished. Active and passive current quenching techniques have been used for this purpose. APDs that operate in this high-gain regime are in Geiger mode. This mode is particularly useful for single photon detection provided that the dark count event rate is sufficiently low.

A typical application for APDs is laser rangefinders and long range fiber optic telecommunication. New applications include positron emission tomography and particle physics. APD arrays are becoming commercially available.

APD applicability and usefulness depends on many parameters. Two of the larger factors are: quantum efficiency, which indicates how well incident optical photons are absorbed and then used to generate primary charge carriers; and total leakage current, which is the sum of the dark current and photocurrent and noise. Electronic dark noise components are series and parallel noise. Series noise, which is the effect of shot noise, is basically proportional to the APD capacitance while the parallel noise is associated with the fluctuations of the APD bulk and surface dark currents. Another noise source is the excess noise factor, F. It describes the statistical noise that is inherent with the stochastic APD multiplication process.

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Chapter-04

Transmission channel

4.1 Attenuation in Transmission Lines:

Every transmission line will have some loss, because of the resistance of the conductors and because power is consumed in the dielectric used for insulating the conductors. Power lost in a transmission line is not directly proportional to the line length, but varies logarithmically with the length. For this reason line losses are expressed in terms of decibels per unit length, since the decibel is a logarithmic unit. Calculations are very simple because the total loss in a line is found by multiplying the decibel loss per unit length by the total length of the line. The power lost in a matched line is called matched-line loss. It is usually expressed in decibels per 100 feet. It is necessary to specify the frequency for which the loss applies, because the loss varies with frequency. Conductor and dielectric losses increase with frequency, but not in the same way. The relative amount of each type of loss depends also on the construction on the line, so there is no specific relationship between loss and frequency valid for all types of lines. Actual loss values for practical lines can be found in the following table, expressed in

$$\frac{dB}{100\text{m}}$$

Cable Type	144 MHz	1.2 GHz	2.4 GHz	5.8 GHz
RG-58	20.3	69.2	105.6	169.2
RG-213	9.2	33.1	49.9	93.8
LMR-400	4.9	15.7	22.3	35.4
3/8" LDF	4.3	13.8	19.4	26.6

.

The power lost in a given line is minimum when the line is terminated in a resistance equal to its characteristic impedance. On non-matched lines there is an additional loss that increases with the increase of the SWR. This is because the effective values of both current and voltage become greater on lines with standing waves. This increase raises the ohmic losses (I2R) in the conductors and the losses in the dielectric (E2/R). The total loss in a line, including matched-line and the additional loss due to standing waves may be calculated as follows

Total Loss (db)=10log $\alpha 2 - \rho\, 2/\alpha(1-\rho\, 2\,)$ *Where* , $\alpha = 10ML/10$ = matched-line loss ratio

ρ = SWR −1

4.2Attenuation of optical fiber:

In electrical engineering and telecommunications, attenuation affects the propagation of waves and signals in electrical circuits, in optical fibers, as well as in air (radio waves).

Attenuation coefficient:

Attenuation coefficients are used to quantify different media according to how strongly the transmitted ultrasound amplitude decreases as a function of frequency. The attenuation coefficient (α) can be used to determine total attenuation in dB in the medium using the following formula:

$$\text{Attenuation} = \alpha[\text{dB}/(\text{MHz cm})] \cdot \ell[\text{cm}] \cdot \text{f}[\text{MHz}]$$

As this equation shows, besides the medium length and attenuation coefficient, attenuation is also linearly dependent on the frequency of the incident ultrasound beam. Attenuation coefficients vary widely for different media. In biomedical ultrasound imaging however, biological materials and water are the most commonly used media. The attenuation coefficients of common biological materials at a frequency of 1 MHz are listed below:

Material	$\alpha(\text{dB}/(\text{MHz} \cdot \text{cm}))$
Blood	0.2
Bone, cortical	6.9
Bone, trabecular	9.94
Brain	0.6
Breast	0.75
Cardiac	0.52
Connective tissue	1.57
Dentin	80

Enamel	120
Fat	0.48
Liver	0.5
Marrow	0.5
Muscle	1.09
Tendon	4.7
Soft tissue (average)	0.54
Water	0.0022

There are two general ways of acoustic energy losses: absorption and scattering, for instance light scattering. Ultrasound propagation through homogeneous media is associated only with absorption and can be characterized with absorption coefficient only. Propagation through heterogeneous media requires taking into account scattering.

Optical Fiber Loss Mechanisms

Absorption

Absorption is uniform. The same amount of the same material always absorbs the same fraction of light at the same wavelength. If you have three blocks of the same type of glass, each 1-centimeter thick, all three will absorb the same fraction of the light passing through them.

Absorption also is cumulative, so it depends on the total amount of material the light passes through. If the absorption is 1% per centimeter, it absorbs 1% of the light in the first centimeter, and 1% of the remaining light the next centimeter, and so on.

Intrinsic Material Absorption

Intrinsic absorption is caused by interaction of the propagating light wave with one more more major components of glass that constitute the fiber's material composition. These looses represent a fundamental minimum to the attainable loss and can be overcome only by changing the fiber material.

An example of such an interaction is the infrared absorption band **o**f SiO_2 shown in the above figure. However, in the wavelength regions of interest to optical communication (0.8-0.9um and 1.2-1.5um), infrared absorption tails make negligible contributions.

Extrinsic Impurity Ions Absorption

Extrinsic impurity ions absorption is caused by the presence of minute quantity of metallic ions (such as Fe^{2+}, Cu^{2+}, Cr^{3+}) and the OH^- ion from water dissolved in glass. The attenuation from these impurity ions is shown in the following table.

Impurity Ion	Loss due to 1ppm of impurity (dB/km)	Absorption Peak Wavelength (um)
Fe^{2+}	0.68	1.1
Fe^{2+}	0.15	0.4
Cu^{2+}	1.1	0.85
Cr^{3+}	1.6	0.625
V^{4+}	2.7	0.725
OH^-	1.0	0.95
OH^-	2.0	1.24
OH^-	4.0	1.38

From the table above, we can see that 1 part per million (ppm) of Fe^{2+} would lead to a loss of 0.68 dB/km at 1.1um. This shows the necessity of ultrapure fibers. Luckily, losses due to the metallic ions can be reduced to very low by refining the glass mixture to an impurity level below 1 par per billion (ppb).

The OH^- ion from water vapor in the glass leads to absorption peaks at 0.72um, 0.88um, 0.95um, 1.13um, 1.24um and 1.38um. The broad peaks at 1.24um and 1.38um in the first figure cure are due to OH^- ion. The good news is OH^- ion absorption band is narrow enough that ultrapure fibers can achieve losses less than 0.2 dB/km at 1.55um.

With new manufacturing techniques, we can reduce the OH^- ion content to below 1 part per billion (ppb). The results are ultra-low-loss fibers which have a wider low-loss window in silica glass fibers shown in the following figure. This improvement enables the use of WDM technology in fiber optic networks, which dramatically increased the capacity of fiber optic systems.

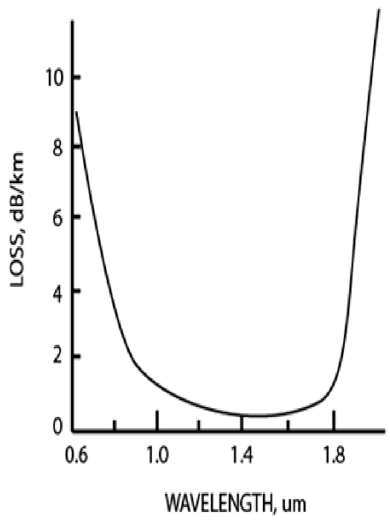

Fig 4.2.1 : Rayleigh Scattering

Hydrogen Effects

When fused silica glass fiber is exposed to hydrogen gas, attenuation of the fiber also increases. The hydrogen can interact with the glass to produce hydroxyl ions and their losses. Hydrogen can also infiltrate the fiber and produce its own losses near 1.2um and 1.6um.

The fibers can come into contact with hydrogen which is produced by corrosion of steel-cable strength members or by certain bacteria. The way to solve this problem is to add a coating to the fiber that is impermeable to hydrogen

Scattering

Scattering losses occur when a wave interacts with a particle in a way that removes energy in the directional propagating wave and transfers it to other directions. The light isn't absorbed, just sent in another direction. However, the distinction between scattering and absorption doesn't matter much because the light is lost from the fiber in either case.

There are two main types of scattering: linear scattering and nonlinear scattering.

For linear scattering, the amount of light power that is transferred from a wave is proportional to the power in the wave. It is characterized by having no change in frequency in the scattered wave.

On the other hand, nonlinear scattering is accompanied by a frequency shift of the scattered light. Nonlinear scattering is caused by high values of electric field within the fiber (modest to high amount of optical power). Nonlinear scattering causes significant power to be scattered in the forward, backward, or sideways directions.

Rayleigh Scattering (Linear Scattering)

Rayleigh scattering (named after the British physicist Lord Rayleigh) is the main type of linear scattering. It is caused by small-scale (small compared with the wavelength of the light wave) in homogeneities that are produced in the fiber fabrication process. Examples of in homogeneities are glass composition fluctuations (which results in minute refractive index change) and density fluctuations (fundamental and not improvable). Rayleigh scattering accounts for about 96% of attenuation in optical fiber.As light travels in the core, it interacts with the silica molecules in the core. These elastic collisions between the light wave and the silica molecules result in Rayleigh scattering. If the scattered light maintains an angle that supports forward travel within the core, no attenuation occurs. If the light is scattered at an angle that does not support continued forward travel, the light is diverted out of the core and attenuation occurs. Depending on the incident angle, some portion of the light propagates forward and the other part deviates out of the propagation path and escapes from the fiber core. Some scattered light is reflected back toward the light source. This is a property that is used in an OTDR (Optical Time Domain Reflect meter) to test fibers.

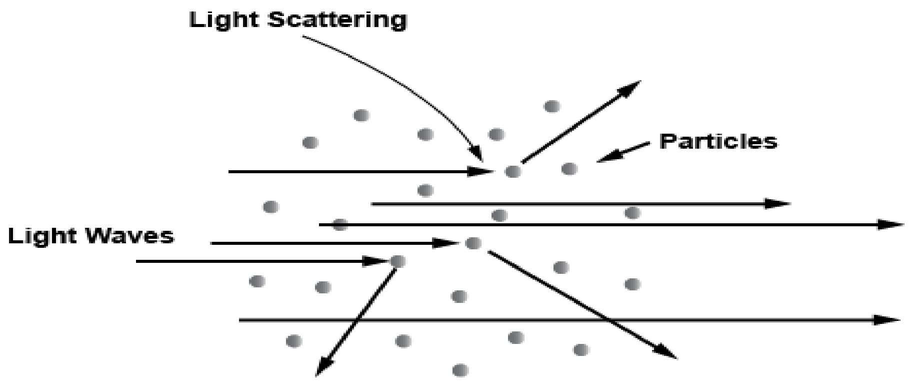

Fig 4.2.2 : Scattering

Rayleigh scattering describes the elastic scattering of light by particles which are much smaller than the wavelength of light. The intensity of the scattered radiation is given by

$$I = I_0 \left(\frac{1+\cos^2\theta}{2R^2}\right)\left(\frac{2\pi}{\lambda}\right)^4\left(\frac{n^2-1}{n^2+2}\right)^2\left(\frac{d}{2}\right)^6,$$

where *R* is the distance between the particle and the observer, θ is the scattering angle, *n* is the refractive index of the particle, and *d* is the diameter of the particle.

The size of a scattering particle is parameterized by the ratio *x* of its characteristic dimension *r* and wavelength λ:

$$x = \frac{2\pi r}{\lambda}.$$

Rayleigh scattering can be defined as scattering in the small size parameter regime $x \ll 1$. Scattering from larger particles is explained by the Mie scattering for an arbitrary size parameter *x*. For small *x* the Mie theory reduces to the Rayleigh approximation.

It can be seen from the above equation that Rayleigh scattering is strongly dependent upon the size of the particle and the wavelengths. The intensity of the Rayleigh scattered radiation increases rapidly as the ratio of particle size to wavelength increases. Furthermore, the intensity of Rayleigh scattered radiation is identical in the forward and reverse directions. The Rayleigh scattering model breaks down when the particle size becomes larger than around 10% of the wavelength of the incident radiation. In the case of particles with dimensions greater than this, Mie's scattering model can be used to find the intensity of the scattered radiation.

Rayleigh scattering depends not on the specific type of material but on the size of the particles relative to the wavelength of light. The loss due to Rayleigh scattering is proportional to λ^{-4} and obviously decreases rapidly with increase in wavelength (see the first figure above – Loss vs.. Wavelength). Short wavelengths are scattered more than longer wavelengths. Any wavelength that is below 800nm is unusable for optical communication because attenuation due to Rayleigh scattering is too high.

The attenuation coefficient due to Rayleigh scattering in (pure) fused silica is given by the following approximate formula $\alpha(\lambda)=\alpha_0\left(\frac{\lambda_0}{\lambda}\right)^4$

where

α_0 = 1.7 dB/km at λ_0 = 0.85um

The above formula predicts the Rayleigh scattering loss to be 0.31 dB/km at 1.3um and 0.15 dB/km at 1.55um wavelengths.

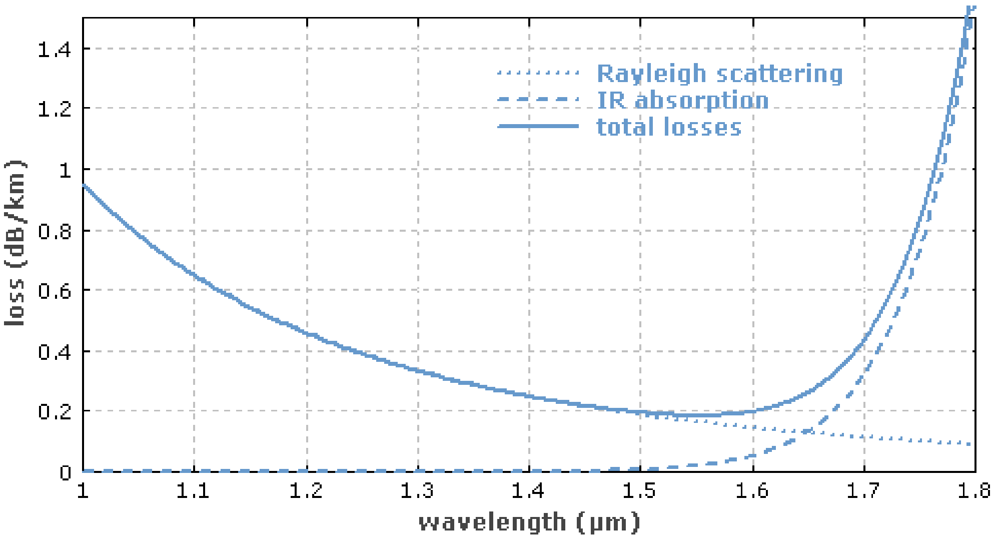

Fig 4.2.3 : attenuation coefficient wavelengths

Intrinsic Losses of Silica Fiber

From the figure above (you can also refer to the first figure in this tutorial), we can see that the fundamental loss limits for a silica-based glass fibers are the Rayleigh scattering at short wavelengths and the material absorption (the infrared absorption) properties of silica (SiO_2) at long wavelengths. A theoretical attenuation minimum for silica fibers can be predicted at a wavelength of 1550nm where the two curves cross. This has been one reason for laser sources and receivers that work in this portion of the spectrum.

Mie Scattering (Linear Scattering)

Mie scattering is named after German physicist Gustav Mie. This theory describes scattering of electromagnetic radiation by particles that are comparable in size to a wavelength (larger than 10% of wavelength).

For particles much larger, and much smaller than the wavelength of scattered light there are simple and excellent approximations that suffice.

For glass fibers, Mie scattering occurs in in homogeneities such as core-cladding refractive index variations over the length of the fiber, impurities at the core-cladding interface, strains or bubbles in the fiber, or diameter fluctuations.

Mie scattering can be reduced by carefully removing imperfections from the glass material, carefully controlling the quality and cleanliness of the manufacturing process.

In commercial fibers, the effects of Mie scattering are insignificant. Optical fibers are manufactured with very few large defects. (larger than 10% of wavelength)

Here is an interactive Mie Scattering calculator on the web developed by Scott Prahl.

Brillouin Scattering (Nonlinear Scattering)

Brillouin scattering is caused by the nonlinearity of a medium. In glass fibers, Brillouin scattering shows as a modulation of the light by the thermal energy in the material.

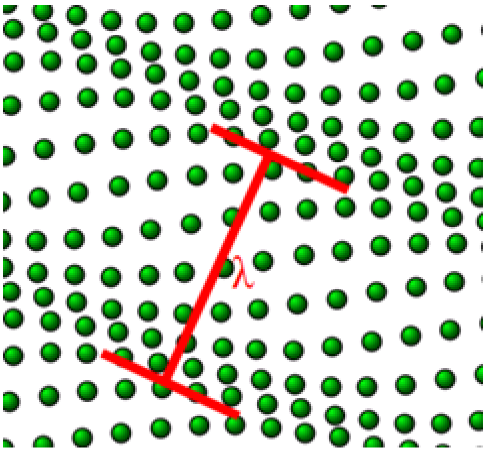

Fig 4.2.4 : Nonlinear Scattering

An incident photon can be converted into a scattered photon of slightly lower energy, usually propagating in the backward direction, and a phonon (vibrational energy). This coupling of optical fields and acoustic waves occurs via electrostriction.

The frequency of the reflected beam is slightly lower than that of the incident beam; the frequency difference $v_B$corresponds to the frequency of emitted phonons. This is called Brillouin Frequency Shift. This phenomenon has been used for fiber optic sensor applications.

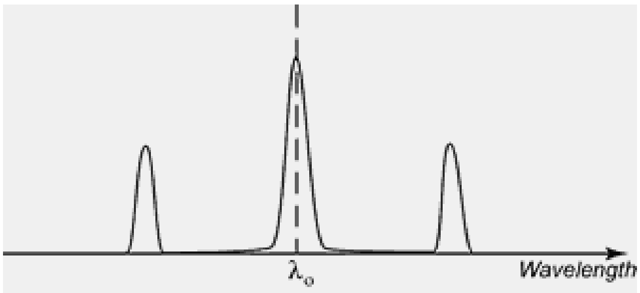

Fig 4.2.5 : Brillouin scattering wavelength

Brillouin scattering can occur spontaneously even at low optical powers. This is different than Stimulated Brillouin Scattering which requires optical power to meet a threshold high enough to happen.

Above a certain threshold power, stimulated Brillouin scattering can reflect most of the power of an incident beam. The optical power level at which stimulated Brillouin scattering becomes significant in a single mode fiber is given by the empirical formula below.

$$P_B = (17.6 \times 10^{-3})\, a'^2 \lambda'^2 \alpha \Delta\nu'$$

where

P_B = Stimulated Brillouin Scattering Optical Power Level Threshold (watts)

a' = Fiber radius (um)

λ' = Light source wavelength (um)

α = Fiber loss (dB/km)

∆v' = Light source linewidth (GHz)

Stimulated Raman Scattering (Nonlinear Scattering)

Stimulated Raman scattering is a nonlinear response of glass fibers to the optical intensity of light. This is caused by vibrations of the crystal (or glass) lattice. Stimulated Raman scattering produces a high-frequency optical phonon, as compared to Brillouin scattering, which produces a low-frequency acoustical phonon, and a scattered photon.

When two laser beams with different wavelengths (and normally with the same polarization direction) propagate together through a Raman-active medium, the longer wavelength beam can experience optical amplification at the expense of the shorter wavelength beam. This phenomenon has been used for Raman amplifiers and Raman lasers.

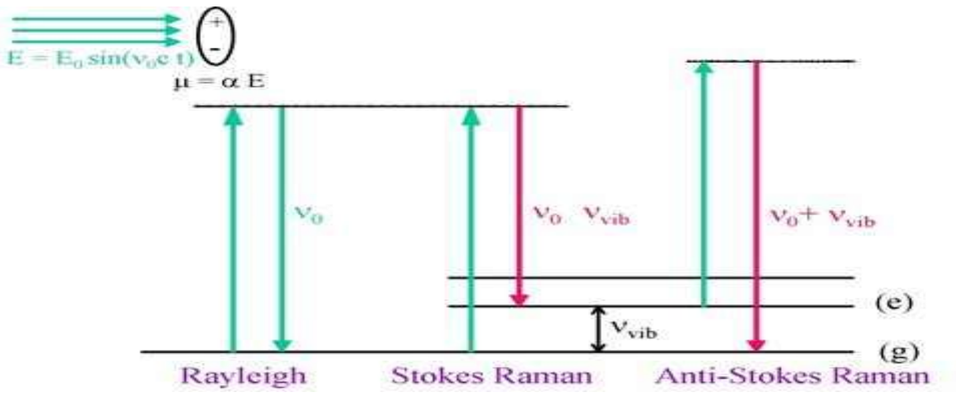

Fig 4.2.6 : **Stimulated Raman Scattering**

In Stimulated Raman scattering, the scattering is predominately in the forward direction, hence the power is not lost to the receiver.

Stimulated Raman Scattering also requires optical power to be higher than a threshold to happen. The formula below gives the threshold $P_R = (23.6 \times 10^{-2})a'^2\lambda'\alpha$

where

P_R = Stimulated Raman Scattering Optical Power Level Threshold (watts)

a' = Fiber radius (um)

λ' = Light source wavelength (um)

α = Fiber loss (dB/km)

Macro bending Loss

Macro bending happens when the fiber is bent into a large radius of curvature relative to the fiber diameter (large bends). These bends become a great source of power loss when the radius of curvature is less than several centimeters.

Macro bend may be found in a splice tray or a fiber cable that has been bent. Macro bend won't cause significant radiation loss if it has large enough radius.

However, when fibers are bent below a certain radius, radiation causes big light power loss as shown in the figure below.

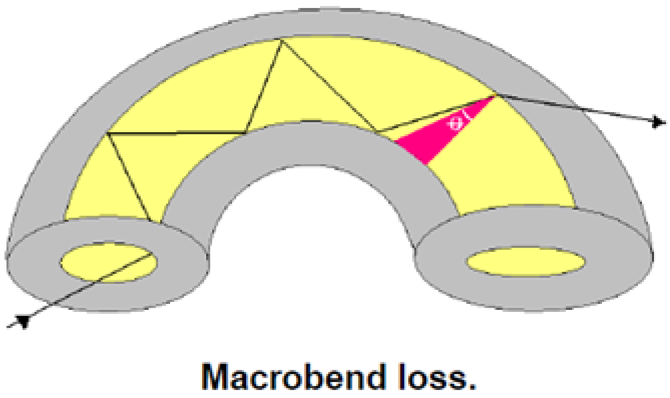

Fig 4.2.6 : Macro bending loss

Corning SMF-28e single mode fibers should not be bent below a radius of 3 inches. 50um graded-index multimode fibers, such as Corning Infinicor 600, should not be bent below a radius of 1.5 inches. 62.5um graded-index multimode fibers, such as Corning Infinicor 300, should be be bend below a radius of 1 inch.

Micro bending Loss

Micro bendings are the small-scale bends in the core-cladding interface. These are localized bends can develop during deployment of the fiber, or can be due to local mechanical stresses placed on the fiber, such as stresses induced by cabling the fiber or wrapping the fiber on a spool or bobbin.

Micro bending can also happen in the fiber manufacturing process. It is sharp but microscopic curvatures that create local axial displacement of a few microns (um) and spatial wavelength displacement of a few millimeters.

Micro bends can cause 1 to 2 dB/km losses in fiber cabling process.

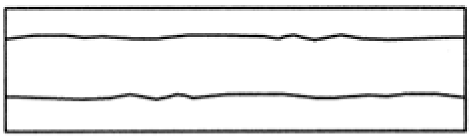

Fig 4.2.7 : single micro bend

The following figure shows the the impact of a single micro bend, at which, analogous to a splice, power can be coupled from the fundamental mode into higher order leaky modes.

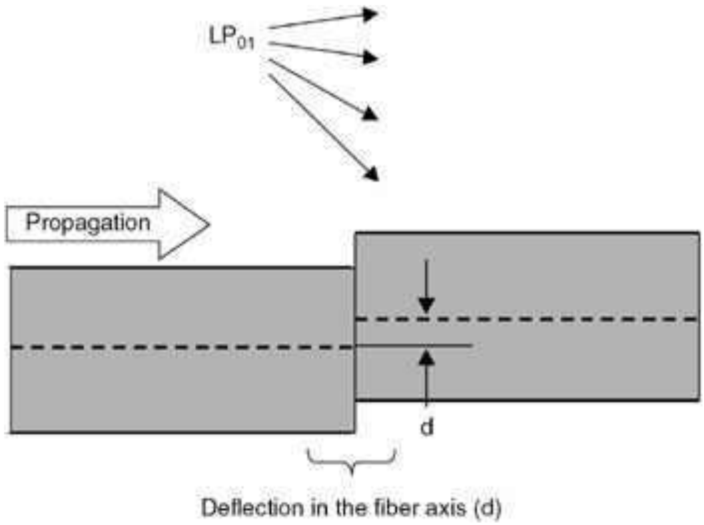

Fig 4.2.8 : Micro bending sensitivity

Because external forces are transmitted to the glass fiber through the polymer coating material, the coating material properties and dimensions, as well as external factors, such as temperature and humidity, affect the micro bending sensitivity of a fiber.

Micro bending sensitivity is also affected by coating irregularities such as variations in coating dimensions, the presence of particles such as those in the pigments of color coatings, and in homogeneities in the properties of the coating materials that vary along the fiber axis.

Interface In homogeneities

Interface in homogeneities can convert high-order modes into lossy modes extending into the cladding where they are removed by the jacket losses.

Impurities trapped at the core-cladding interface or impurities in the fiber buffering can cause these in homogeneities.

Single mode fibers are more susceptible to losses from geometric irregularities or defects in the jacket material.

However, optical fiber manufacturing technology have improved so much that these interface in homogeneities now play a insignificant role in fiber losses.

4.3 Dispersion of transmission lines:

Frequency dispersion refers to the property of microwave transmission lines that have different group velocity versus frequency. This is true for non-TEM transmission lines such as waveguide and micro strip. For wideband signals, you may have to worry about the effects of dispersion distorting your signal, for

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example, when you are trying to put a one nanosecond pulse through a waveguide near the lower cutoff frequency, you could be in a heap of trouble.

In quasi-TEM media such as micro strip, dispersion is a well-known phenomenon. The dispersion of micro strip is just a few percent over a moderate frequency band, and can often be ignored.

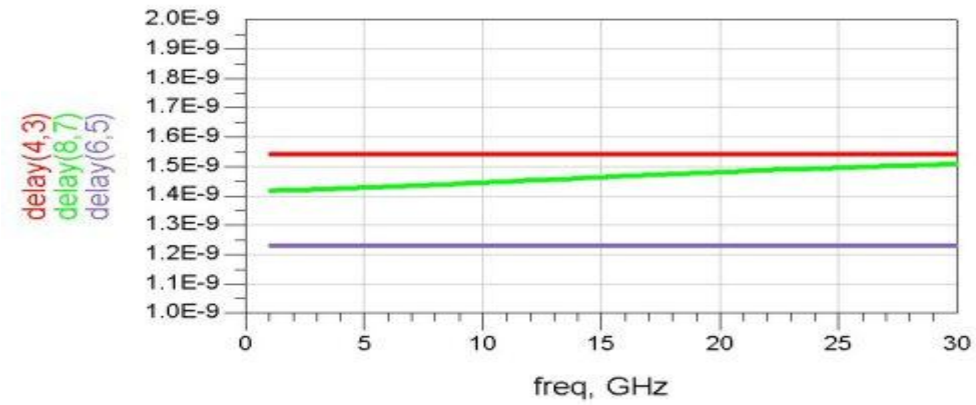

Fig 4.3. : Frequency dispersion

Now let's look at the dispersion of waveguide. Below is a plot of the group delay for a 12 inch piece of WR-90 waveguide. It is much more dispersive than even micro strip, especially near the lower cutoff frequency.

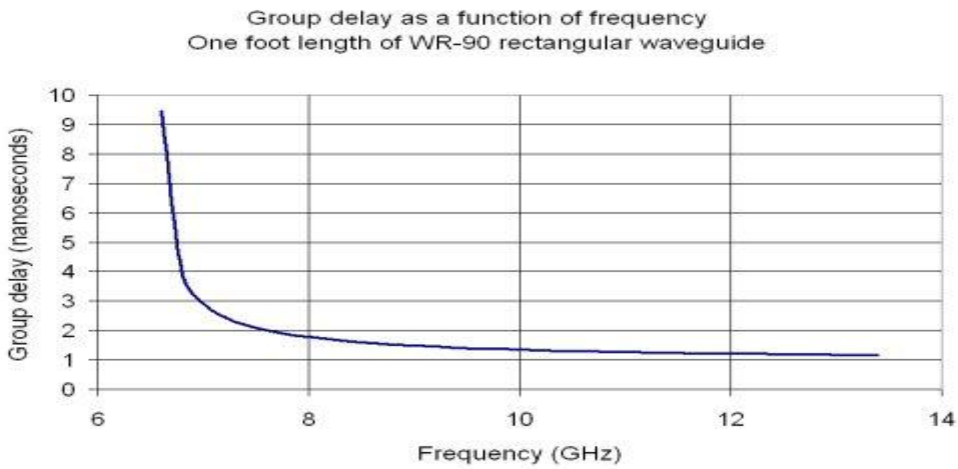

Fig 4.3.1 : waveguide dispersion

Two things to remember about dispersion: for small bandwidths, it is usually not a problem. And the longer your dispersive transmission lines (waveguide or micro strip), the worse the problem gets!

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4.3 Dispersion of Optical fiber:

Dispersion is the phenomenon in which the phase velocity of a wave depends on its frequency, or alternatively when the group velocity depends on the frequency. Media having such a property are termed dispersive media. Dispersion is sometimes called chromatic dispersion to emphasize its wavelength-dependent nature, or group-velocity dispersion (GVD) to emphasize the role of the group velocity.

The most familiar example of dispersion is probably a rainbow, in which dispersion causes the spatial separation of a white light into components of different wavelengths (different colors). However, dispersion also has an effect in many other circumstances: for example, GVD causes pulses to spread in optical fibers, degrading signals over long distances; also, a cancellation between group-velocity dispersion and nonlinear effects leads to soliton waves. Dispersion is most often described for light waves, but it may occur for any kind of wave that interacts with a medium or passes through an inhomogeneous geometry (e.g., a waveguide), such as sound waves.

There are generally two sources of dispersion:

1. Material dispersion
2. Waveguide dispersion.

Material dispersion:

Material dispersion comes from a frequency-dependent response of a material to waves. For example, material dispersion leads to undesired chromatic aberration in alens or the separation of colors in a prism. Waveguide dispersion occurs when the speed of a wave in a waveguide (such as an optical fiber) depends on its frequency for geometric reasons, independent of any frequency dependence of the materials from which it is constructed. More generally, "waveguide" dispersion can occur for waves propagating through any inhomogeneous structure (e.g., aphotonic crystal), whether or not the waves are confined to some region. In general, both types of dispersion may be present, although they are not strictly additive. Their combination leads to signal degradation in optical fibers for telecommunications, because the varying delay in arrival time between different components of a signal "smears out" the signal in time.

Material dispersion in optics

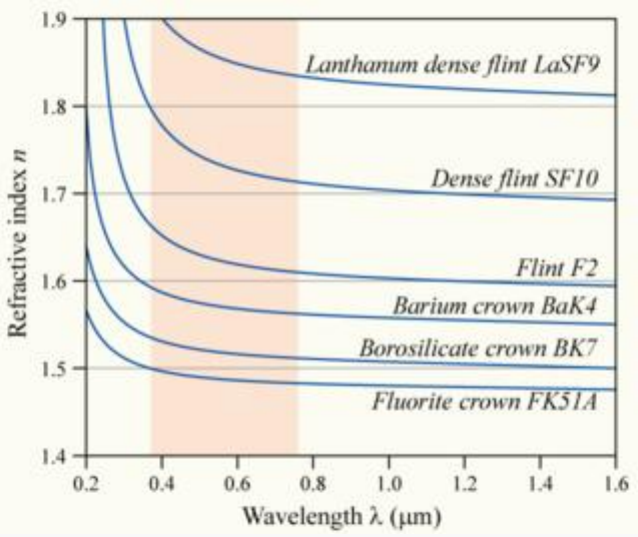

Fig 4.3.2 : dispersion

The variation of refractive index vs. vacuum wavelength for various glasses. The wavelengths of visible light are shaded in red.

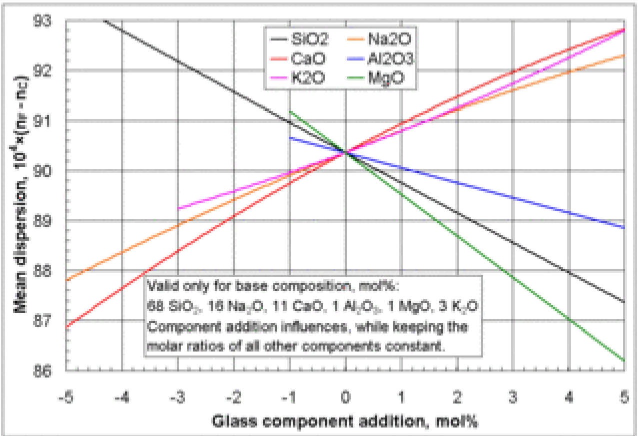

Fig 4.3.3 : Material dispersion

Influences of selected glass component additions on the mean dispersion of a specific base glass (n_F valid for λ = 486 nm (blue), n_C valid for λ = 656 nm (red))

Material dispersion can be a desirable or undesirable effect in optical applications. The dispersion of light by glass prisms is used to onstruct spectrometers and spectroradiometers. Holographic gratings are also used, as they allow more accurate discrimination of wavelengths. However, in lenses, dispersion causes chromatic aberration, an undesired effect that may degrade images in microscopes, telescopes and photographic objectives.

The phase velocity, v, of a wave in a given uniform medium is given by

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

where c is the speed of light in a vacuum and n is the refractive index of the medium. In general, the refractive index is some function of the frequency f of the light, thus n = n(f), or alternatively, with respect to the wave's wavelength n = n(λ). The wavelength dependence of a material's refractive index is usually quantified by its Abbe number or its coefficients in an empirical formula such as the Cauchy or Sellmeier equations.

Because of the Kramers–Kronig relations, the wavelength dependence of the real part of the refractive index is related to the material absorption, described by the imaginary part of the refractive index (also called the extinction coefficient). In particular, for non-magnetic materials ($\mu = \mu_0$), the susceptibility χ that appears in the Kramers–Kronig relations is the electric susceptibility $\chi_e = n^2 - 1$.

The most commonly seen consequence of dispersion in optics is the separation of white light into a color spectrum by aprism. From Snell's law it can be seen that the angle of refraction of light in a prism depends on the refractive index of the prism material. Since that refractive index varies with wavelength, it follows that the angle that the light is refracted by will also vary with wavelength, causing an angular separation of the colors known as angular dispersion.

For visible light, refraction indices n of most transparent materials (e.g., air, glasses) decrease with increasing wavelength λ:

$$1 < n(\lambda_{\text{red}}) < n(\lambda_{\text{yellow}}) < n(\lambda_{\text{blue}}) \ ,$$

or alternatively:

$$\frac{dn}{d\lambda} < 0.$$

In this case, the medium is said to have normal dispersion. Whereas, if the index increases with increasing wavelength (which is typically the case for X-rays), the medium is said to have anomalous dispersion.

At the interface of such a material with air or vacuum (index of ~1), Snell's law predicts that light incident at an angle θ to the normal will be refracted at an angle arcsin(sin(θ)/n). Thus, blue light, with a higher refractive index, will be bent more strongly than red light, resulting in the well-known rainbow pattern.

Dispersion in waveguides:

Optical fibers, which are used in telecommunications, are among the most abundant types of waveguides. Dispersion in these fibers is one of the limiting factors that determine how much data can be transported on a single fiber.

The transverse modes for waves confined laterally within a waveguide generally have different speeds (and field patterns) depending upon their frequency (that is, on the relative size of the wave, the wavelength) compared to the size of the waveguide.

In general, for a waveguide mode with an angular frequency $\omega(\beta)$ at a propagation constant β (so that the electromagnetic fields in the propagation direction (z) oscillate proportional to $e^{i(\beta z - \omega t)}$), the group-velocity dispersion parameter D is defined as:

$$D = -\frac{2\pi c}{\lambda^2}\frac{d^2\beta}{d\omega^2} = \frac{2\pi c}{v_g^2\lambda^2}\frac{dv_g}{d\omega}$$

where $\lambda = 2\pi c / \omega$ is the vacuum wavelength and $v_g = d\omega / d\beta$ is the group velocity. This formula generalizes the one in the previous section for homogeneous media, and includes both waveguide dispersion and material dispersion. The reason for defining the dispersion in this way is that |D| is the (asymptotic) temporal pulse spreading Δt per unit bandwidth $\Delta\lambda$ per unit distance travelled, commonly reported in ps / nm km for optical fibers.

A similar effect due to a somewhat different phenomenon is modal dispersion, caused by a waveguide having multiple modes at a given frequency, each with a different speed. A special case of this is polarization mode dispersion (PMD), which comes from a superposition of two modes that travel at different speeds due to random imperfections that break the symmetry of the waveguide.

Chapter-05

Effect of dispersion

5.1 Non-linear effects:

Nonlinearity effects arose as optical fiber data rates, transmission lengths, number of wavelengths, and optical power levels increased. The only worries that plagued optical fiber in the early day were fiber attenuation and, sometimes, fiber dispersion; however, these issues are easily dealt with using a variety of dispersion avoidance and cancellation techniques. Fiber nonlinearities present a new realm of obstacle that must be overcome. These nonlinearities previously appeared in specialized applications such as undersea installations. However, the new nonlinearities that need special attention when designing state-of-the-art fiber optic systems include stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), four wave mixing (FWM), self-phase modulation (SPM), cross-phase modulation (XPM), and intermodulation. Fiber nonlinearities represent the fundamental limiting mechanisms to the amount of data that can be transmitted on a single optic fiber. System designers must be aware of these limitations and the steps that can be taken to minimize the detrimental effects of fiber nonlinearities.

51.1.Stimulated Brillouin Scattering (SBS):

Stimulated Brillouin scattering (SBS) may be defined as light modulation through thermal molecular vibrations within the fiber. Incident photon produces a phonon of acoustic frequency as well as a scattered photon, and thereby produces an optical frequency shift.

It manifests through the generation of a backward-propagating Stokes wave that carries most of the input energy down-shifted from the frequency of incident light wave by an amount determined by the nonlinear medium. The process of SBS can be described classically as a parametric interaction among the pump wave, the Stokes wave, and an acoustic wave. The phase matching condition for SBS be written as

$$\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_s = 0$$

$$\boldsymbol{k}_s = 0,\ \boldsymbol{k}_1 \cong -\boldsymbol{k}_2$$

where $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$ are wave vectors of two optical fields involved and $\boldsymbol{k}_s$ is the momentum of acoustic phonon which is very small compared to the pump and Stokes waves, thus phase matching can occur only if the Stokes wave propagates in the backward direction. This indicates that frequency shift is a maximum in backward direction reducing to zero in forward direction.

SBS sets an upper limit on the amount of optical power that can be usefully launched into an optical fiber. The SBS effect has a threshold optical power (around 5 to 10mW). The power limitation for SBS effect. SBS threshold about 2 mW is experimentally observed at 1.52 μm in 30 km fiber . When the SBS threshold is exceeded, a significant fraction of the transmitted light is redirected back to the transmitter.

This result in a saturation of optical power that reaches the receiver, as well as problems associated with optical signals being reflected back into the laser. The SBS process also introduces significant noise into the system, resulting in degraded BER performance. As a result, controlling SBS is particularly important in high-speed transmission systems employing external modulators and continuous wave laser sources. It is also of vital importance to the transmission of 1550 nm-based CATV transmission, since these transmitters often have the very characteristics that trigger the SBS effect.

The SBS threshold is strongly dependent on the line width of the optical source with narrow line width sources having considerably lower SBS thresholds. SBS threshold increases proportionally as the optical source line width increases.

5.1.2.Stimulated Raman Scattering (SRS):

Similar to SBS except that a high frequency optical phonon rather than acoustic phonon is generated in the scattering process. In the interaction process, a part of incident light is converted to another optical beam at a frequency downshifted by an amount determined by the vibration modes of the nonlinear medium (called Stokes frequency). The incident light acts as pump for generating the frequency-shifted radiation called the Stokes wave. For intense pump waves, the Stokes wave grows rapidly inside the medium such that most of the pump energy appears in it.

In a quantum mechanical view, a photon of the incident light is annihilated to create an optical phonon at the Stokes frequency and another photon at a new frequency. The phase matching condition can be written as

$$\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_s = 0$$

where $\boldsymbol{k}_s$ is the wave vector of the optical phonon. There are virtually two directions in

fiber, so $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$ have either the same or opposite directions.

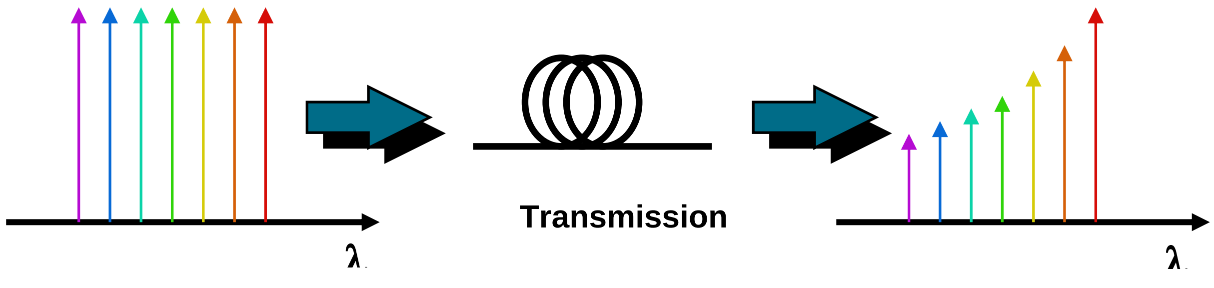

Fig 5..1 : SRS effect in multichannel transmission system

Stimulated Raman scattering (SRS) is much less a problem than SBS, since its threshold (around 1 Watt) is nearly thousand times higher than SBS. If the pump wave is increased beyond the threshold level, the scattering becomes stimulated and the pump wave losses its power to the Stokes wave. The pump wave is thus depleted due to SRS. In multichannel channel system, usually the effect first seen is that the shorter wavelength channels are robbed of power, and that power feeds the longer wavelength channels. That is, the lower frequency channels will be amplified at the expense of the higher frequency channels. The injected power to the lower frequency channels is not any spontaneous noise but from the transmitting power of a higher frequency user. Thus the Raman scattering process impairs the system performance at much lower optical powers for large number of channels.The maximum power limit imposed by SRS in a system with the mentioned parameters.

5.1.3 Self-Phase Modulation (SPM):

Self-phase modulation (SPM) is due to the power dependence of the refractive index of the fiber core. SPM refers the self-induced phase shift experienced by an optical field during its propagation through the optical fiber; change of phase shift of an optical field is given by

$$\phi = (n + n_2|E|^2)k_0 L = \phi_L + \phi_{NL}$$

where $k_0 = 2\pi/\lambda$ and L is fiber length. ϕ_L is the linear part and ϕ_{NL} is the nonlinear part that depends on intensity. ϕ_{NL} is the change of phase of the optical pulse due to the nonlinear refractive index and is responsible for spectral broadening of the pulse. Thus different parts of the pulse undergo different phase shifts, which gives rise to chirping of the pulses. The SPM-induced chirp affects the pulse broadening effects of dispersion.

SPM interacts with the chromatic dispersion in the fiber to change the rate at which the pulse broadens as it travels down the fiber. Whereas increasing the dispersion will reduce the impact of FWM, it will increase the impact of SPM. As an optical pulse travels down the fiber, the leading edge of the pulse causes the refractive index of the fiber to rise causing a blue shift. The falling edge of the pulse decreases the refractive index of the fiber causing a red shift. These red and blue shifts introduce a frequency chirp on each edge, which interacts with the fiber’s dispersion to broaden the pulse.

5.1.4 Cross Phase Modulation (XPM):

Cross phase modulation (XPM) is very similar to SPM except that it involves two pulses of light, whereas SPM needs only one pulse. In Multi-channel WDM systems, all the other interfering channels also modulate the refractive index of the channel under consideration, and therefore its phase. This effect is called Cross Phase Modulation (XPM).

XPM refers the nonlinear phase shift of an optical field induced by co propagating
Channels at different wavelengths; the nonlinear phase shift be given as

$$\phi_{NL} = n_2 k_0 L(\underbrace{|E_1|^2}_{\text{SPM}} + 2\underbrace{|E_2|^2}_{\text{XPM}})$$

where $\boldsymbol{E}_1$ and $\boldsymbol{E}_2$ are the electric fields of two optical waves propagating through the same fiber with two different frequencies.

In XPM, two pulses travel down the fiber, each changing the refractive index as the optical power varies. If these two pulses happen to overlap, they will introduce distortion into the other pulses through XPM. Unlike, SPM, fiber dispersion has little impact on XPM. Increasing the fiber effective area will improve XPM and all other fiber nonlinearities.

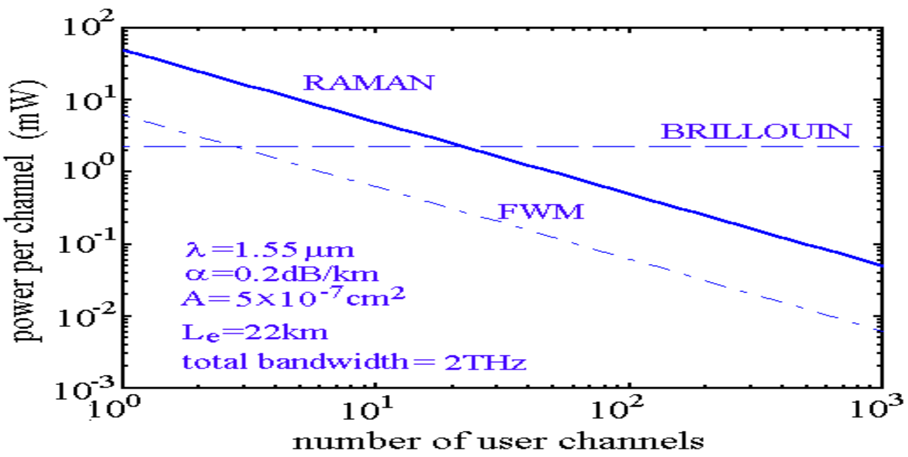

Fig 5.1.3 : Maximum power per channel versus number of channels which ensures system deformation below 1dB for all channels in the case of SRS and SBS.

5.2 Group velocity dispersion:

Another consequence of dispersion manifests itself as a temporal effect. The formula v = c / n calculates the phase velocity of a wave; this is the velocity at which the phase of any one frequency component of the wave will propagate. This is not the same as the group velocity of the wave, that is the rate at which changes in amplitude (known as the envelope of the wave) will propagate. For a homogeneous medium, the group velocity v_g is related to the phase velocity by (here λ is the wavelength in vacuum, not in the medium):

$$v_g = c\left(n - \lambda\frac{dn}{d\lambda}\right)^{-1}.$$

The group velocity v_g is often thought of as the velocity at which energy or information is conveyed along the wave. In most cases this is true, and the group velocity can be thought of as the signal velocity of the waveform. In some unusual circumstances, called cases of anomalous dispersion, the rate of change of the index of refraction with respect to the wavelength changes sign, in which case it is possible for the group velocity to exceed the speed of light ($v_g > c$). Anomalous dispersion occurs, for instance, where the wavelength of the light is close to an absorption resonance of the medium. When the dispersion is anomalous, however, group velocity is no longer an indicator of signal velocity. Instead, a signal travels at the speed of the wave front, which is c irrespective of the index of refraction. Recently, it has become possible to create gases in which the group velocity is not only larger than the speed of light, but even negative. In these cases, a pulse can appear to exit a medium before it enters. Even in these cases, however, a signal travels at, or less than, the speed of light, as demonstrated by Stenner, et al.

The group velocity itself is usually a function of the wave's frequency. This results in group velocity dispersion (GVD), which causes a short pulse of light to spread in time as a result of different frequency components of the pulse travelling at different velocities. GVD is often quantified as the group delay dispersion parameter (again, this formula is for a uniform medium only):

$$D = -\frac{\lambda}{c}\,\frac{d^2 n}{d\lambda^2}.$$

If D is less than zero, the medium is said to have positive dispersion. If D is greater than zero, the medium has negative dispersion. If a light pulse is propagated through a normally dispersive medium, the result is the higher frequency components travel slower than the lower frequency components. The pulse therefore becomes positively chirped, or up-chirped, increasing in frequency with time. Conversely, if a pulse travels through an anomalously dispersive medium, high frequency components travel faster than the lower ones, and the pulse becomes negatively chirped, or down-chirped, decreasing in frequency with time.

The result of GVD, whether negative or positive, is ultimately temporal spreading of the pulse. This makes dispersion management extremely important in optical communications systems based on optical fiber, since if dispersion is too high, a group of pulses representing a bit-stream will spread in time and merge together, rendering the bit-stream unintelligible. This limits the length of fiber that a signal can be sent down without regeneration. One possible answer to this problem is to send signals down the optical fibre at a wavelength where the GVD is zero (e.g., around 1.3–1.5 μm in silica fibres), so pulses at this wavelength suffer minimal spreading from dispersion—in practice, however, this approach causes more problems than it solves because zero GVD unacceptably amplifies other nonlinear effects (such as four wave mixing). Another possible option is to use soliton pulses in the regime of anomalous dispersion, a form of optical pulse which uses a nonlinear optical effect to self-maintain its shape—solitons have the practical problem, however, that they require a certain power level to be maintained in the pulse for the nonlinear effect to be of the correct strength. Instead, the solution that is currently used in practice is to perform dispersion compensation, typically by matching the fiber with another fiber of opposite-sign dispersion so that the dispersion effects cancel; such compensation is ultimately limited by nonlinear effects such as self-phase modulation, which interact with dispersion to make it very difficult to undo.

Dispersion control is also important in lasers that produce short pulses. The overall dispersion of the optical resonator is a major factor in determining the duration of the pulses emitted by the laser. A pair of prisms can be arranged to produce net negative dispersion, which can be used to balance the usually positive dispersion of the laser medium. Diffraction grating scan also be used to produce dispersive effects; these are often used in high-power laser amplifier systems. Recently, an alternative to prisms and gratings has been developed: chirped mirrors. These dielectric mirrors are coated so that different wavelengths have different penetration lengths, and therefore different group delays. The coating layers can be tailored to achieve a net negative dispersion.

5.3.1 Gaussian distribution:

The Gaussian distribution is a continuous distribution that gives a good description of data that cluster around a mean. The graph or plot of the associated probability density has a peak at the mean, and is known as the Gaussian function or bell curve.
The Probability Density Function (PDF) in this case can be defined as:

$$f(x, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

where

e = 2.7182... (Euler's number)
x = data to be plotted
σ = standard deviation
μ = mean, median and mode (all simultaneously)

The formula above can me coded in Matlab easily, like this:

```
function f = gauss_distribution(x, mu, s)
p1 = -.5 * ((x - mu)/s) .^ 2;
p2 = (s * sqrt(2*pi));
f = exp(p1) ./ p2;
```

Now, let's use it in an example

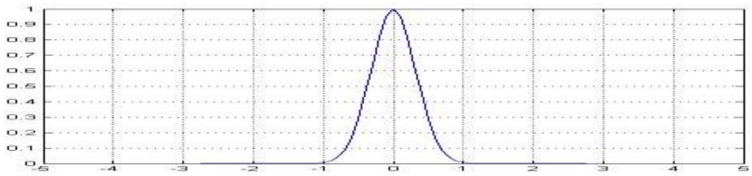

Fig 5.3.1 : Gaussian Distribution

Gaussian Pulses:

Consider the case of a Gaussian pulse for which the incident field is of the form

$$U(O,T) = \exp\left(-\frac{T^2}{2To^2}\right)$$

where To is the haif-wifth introduced

It is customary to use the full width at haif maximum in place of T_o. for a Gaussian pulse, the two are related as

$T_{FWHM}=2(In2)^{1/2}T_o \approx 1.665T_o.$

The amplitude at any point z along the fiber is given by

$$U(z,T)=\frac{To}{(To^{2}-i\beta_{2}z)^{1/2}}\exp\left(-\frac{T^{2}}{2(To^{2}-i\beta_{2}z)}\right)$$

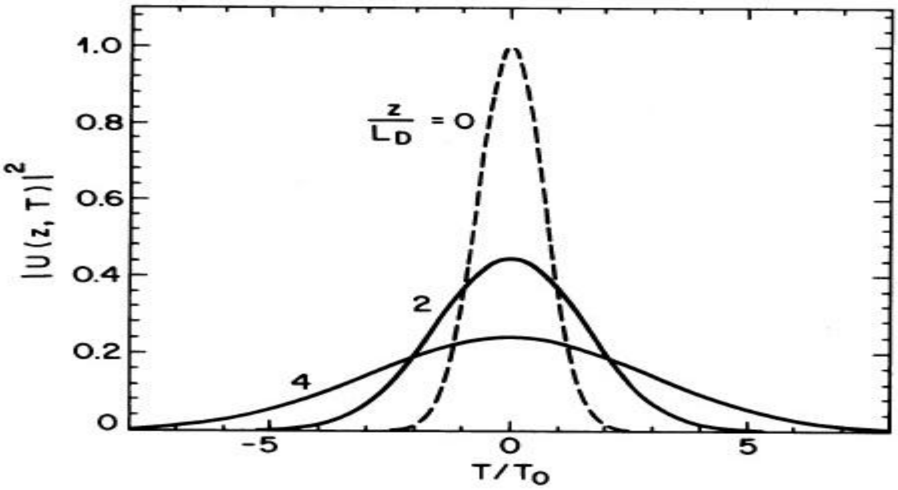

Fig 5.3.1 : Gaussian pulse

5.3.2 Super Gaussian Pulses:

So far we have considered pulse shapes with relatively broad leading and trailing edges. As one may expert, dispersion-induced boarding is sensitive to pulse edge steepness. In general , a pulse with steeper leading and trailing edges broadens more rapidly with propagation simply because such a pulse has a wider spectrum to start with pulses emitted by directly modulated semiconductor lasers fall in this category and cannot generally be a Gaussian pulse. A super-Gaussian shape ca be used to modal the effects of steeps leading and trailing edges on dispersion –induced pulse boarding. For a super Gaussian pulse is generalized to take the form

$$U(O,T)=\exp[-\frac{1+iC}{2}\left(\frac{T}{To}\right)6]$$

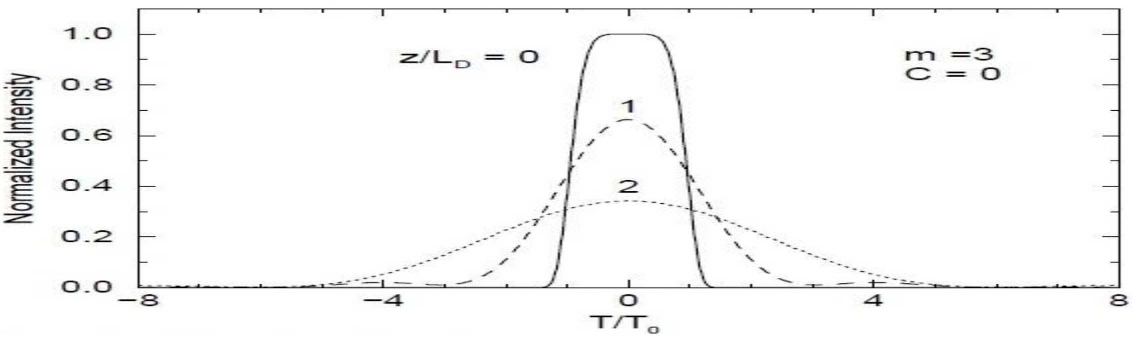

Fig 5.3.2 : Super Gaussian

5.3.3Third-order dispersion:

The dispersion –induced pulse boarding discussed is due to the lowest –order GVD term proportional to β_2 .Although the contribution of this dominates in most cases of practical interest, it is sometimes necessary to include the third order tern proportional to β_3 in this expansion.
Third order dispersion:
Parameter $\Delta\omega/\omega o$ is no longer small enough to justify the truncation of the expansion after the β_2 term. This section considers the dispersive effects by including both β_2 and β_3 terms while still neglecting the nonlinear effects. The appropriate propagation equation for the amplitude A(z,T) is obtained from after setting y=0. Using the equation satisfies the following equation:

$$i\frac{\delta U}{\delta Z}=\frac{\beta 2\ \delta^2 U}{2\delta^{T2}}+\frac{i\beta 3\ \delta^3 U}{6\delta^{T3}}$$

This equation can also be solved by using the Fourier technique. The transmitted field is obtained from

$$U(z,T)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\acute{u}(0,\omega)\exp\left(\frac{i}{2}\beta_2\omega^2 z+\frac{i}{6}\beta_3\omega^3 z-i\omega T\right)d\omega$$

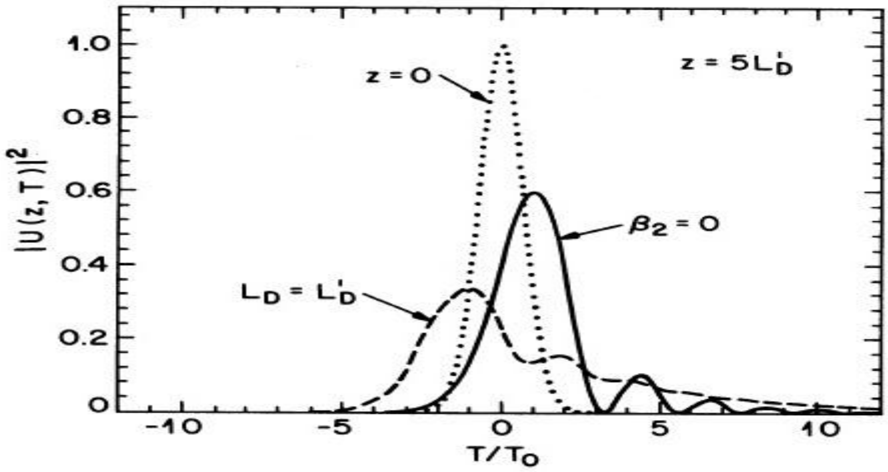

Fig 5.3.3 : Third order dispersion

5.3.4 Chirped Gaussian Pulses:

For an initially unchirped Gaussian pulse shows that dispersion induced broadening of the pulse does not depend on the sign of the GVD parameter β_2. Thus for a given value of the dispersion length L_D , the pulse broadens by the same amount in the normal and anomalous- dispersion regimes of the fiber. this behavior changes if the Gaussian pulsehas an initial frequency chirp. In the case of linearity chirped Gaussian pulses the incident field can be written as

$$U(O,T) = \exp\left[-\frac{(1+iC)}{2}\left(\frac{T}{To}\right)\right]$$

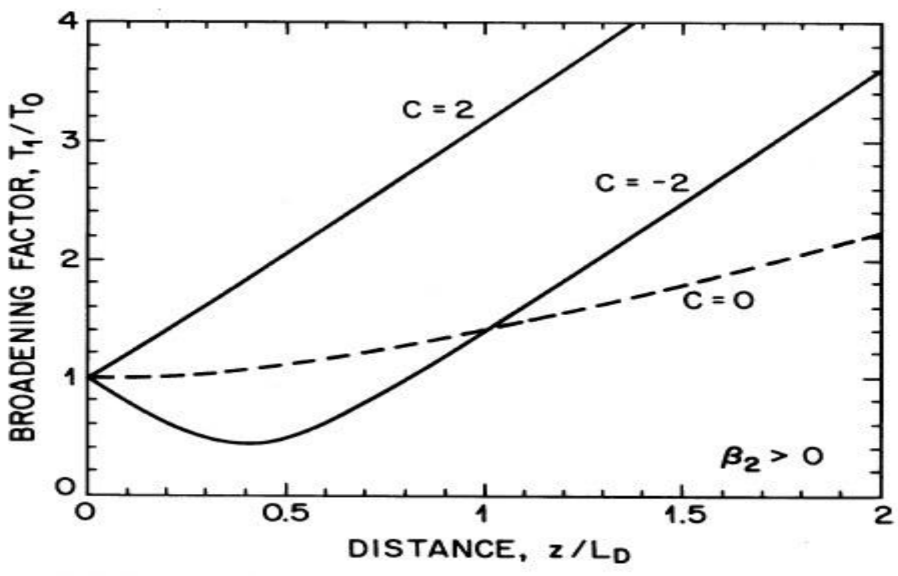

Fig 5.3.4 : Chirped Gaussian pulse

Chapter-06

Simulation:

6.1 Gaussian Pulses

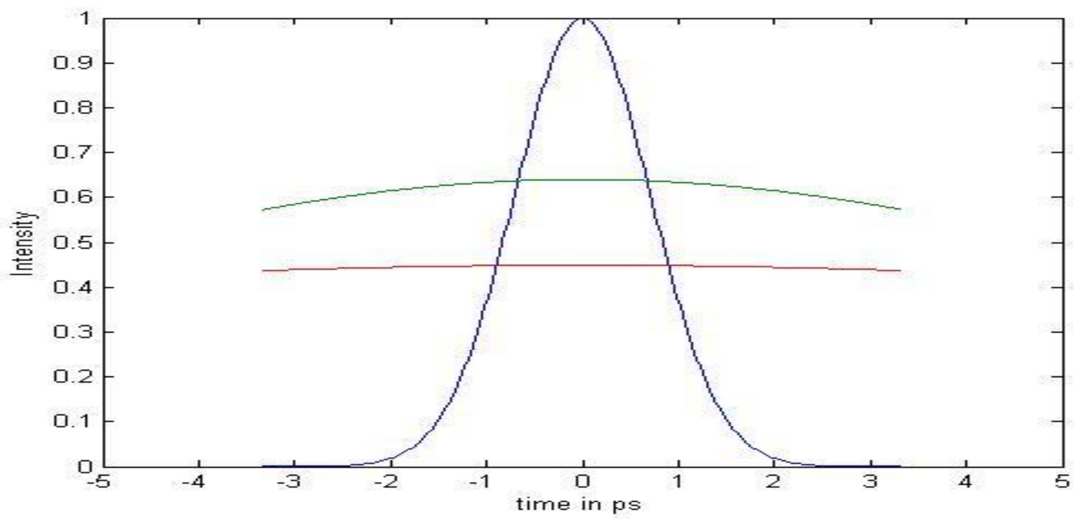

Fig 6.1.1: For 5Gbps pulses

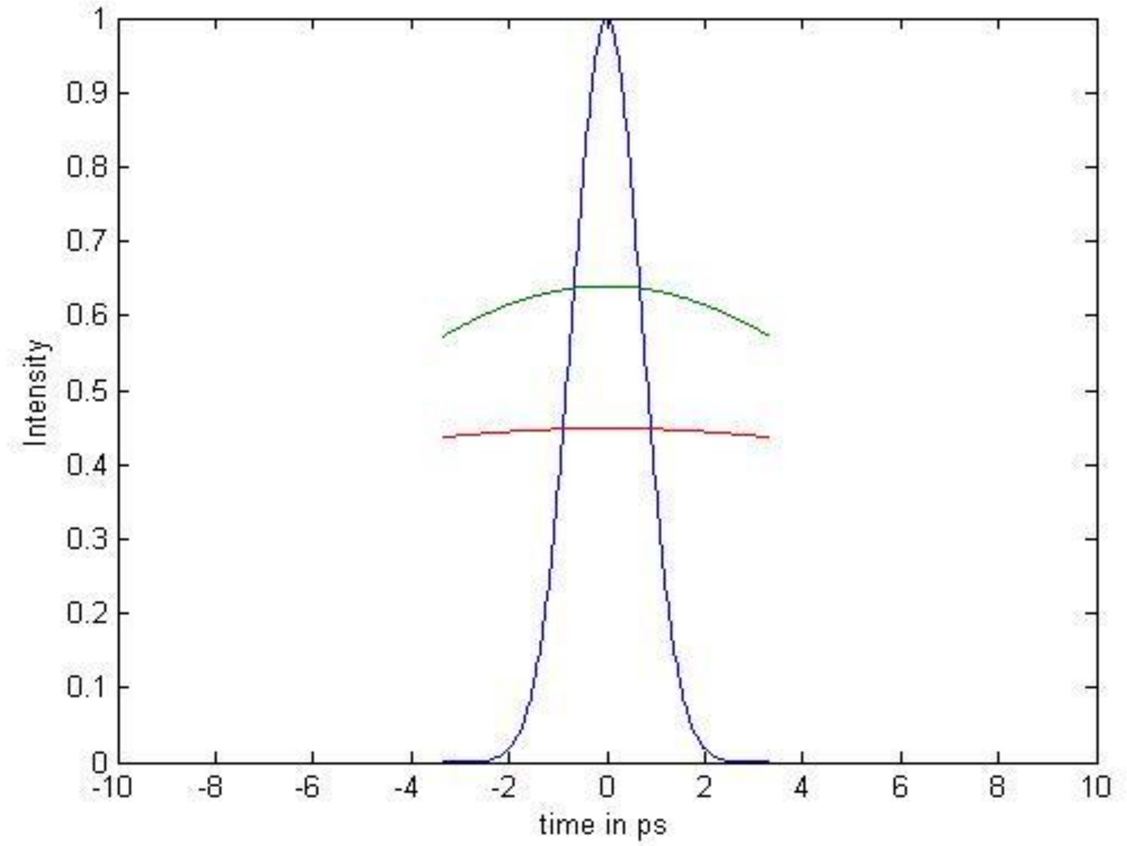

Fig 6.1.2: For 10 Gbps pulses

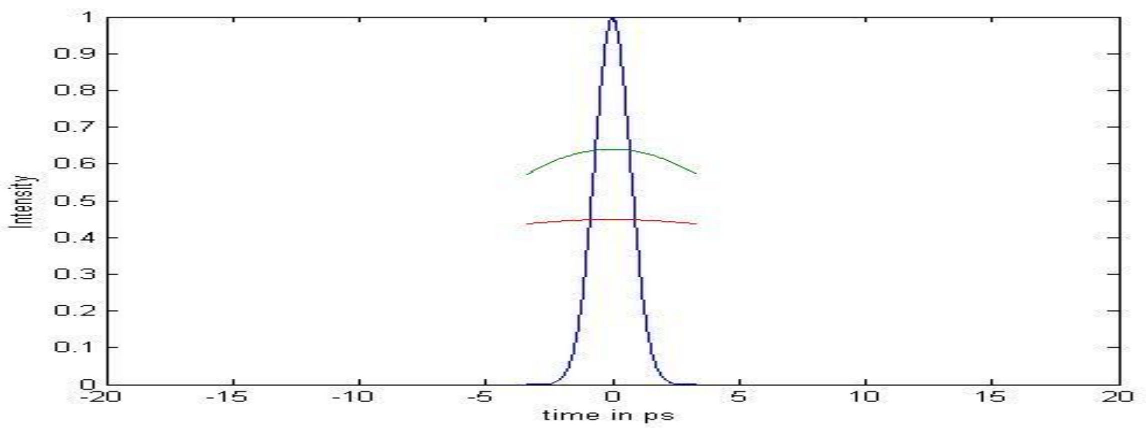

Fig 6.1.3: For 20Gbps pulses

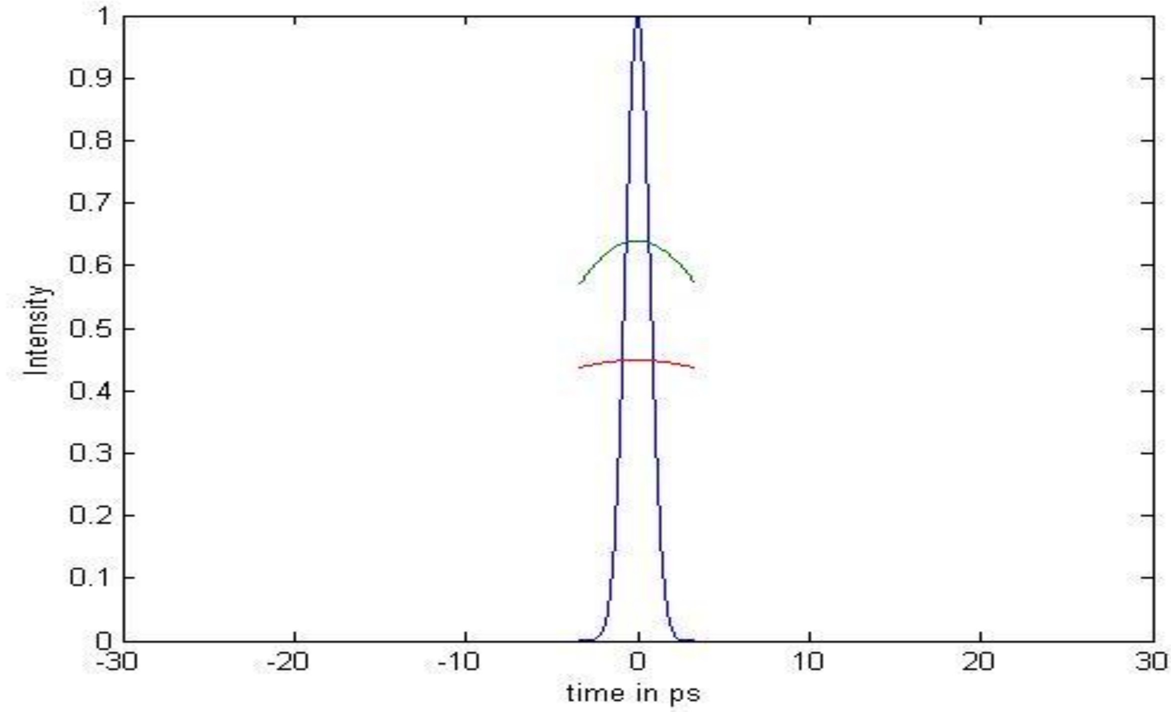

Fig 6.1.4: For 30 Gbps pulses

<u>For 40 Gbps</u>

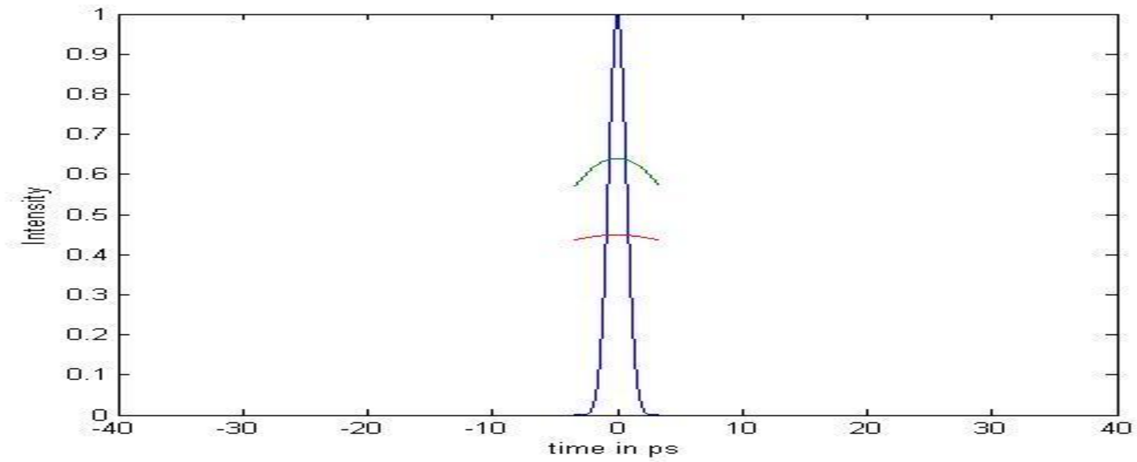

Fig 6.1.5: For 40Gbps pulses

6.2 Super Gaussian Pulses

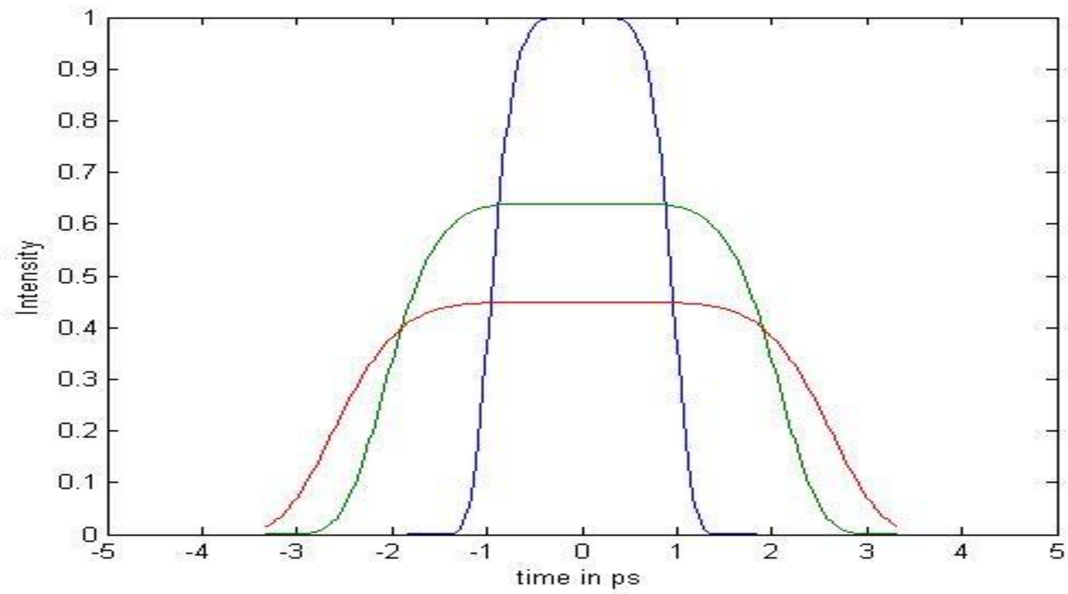

Fig 6.2.1: For 5Gbps pulses

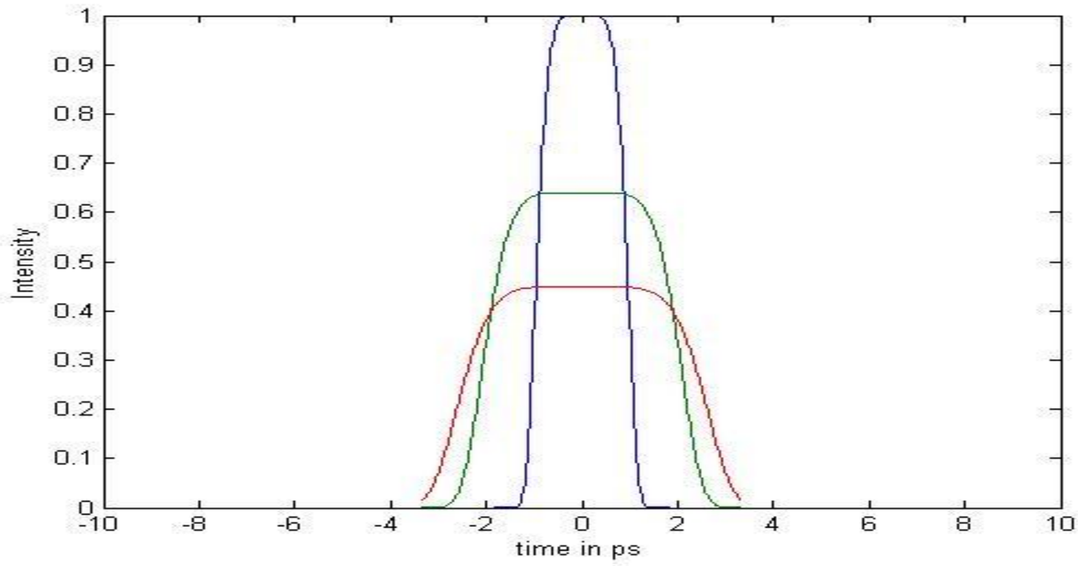

Fig 6.2.2: For 10 Gbps pulses

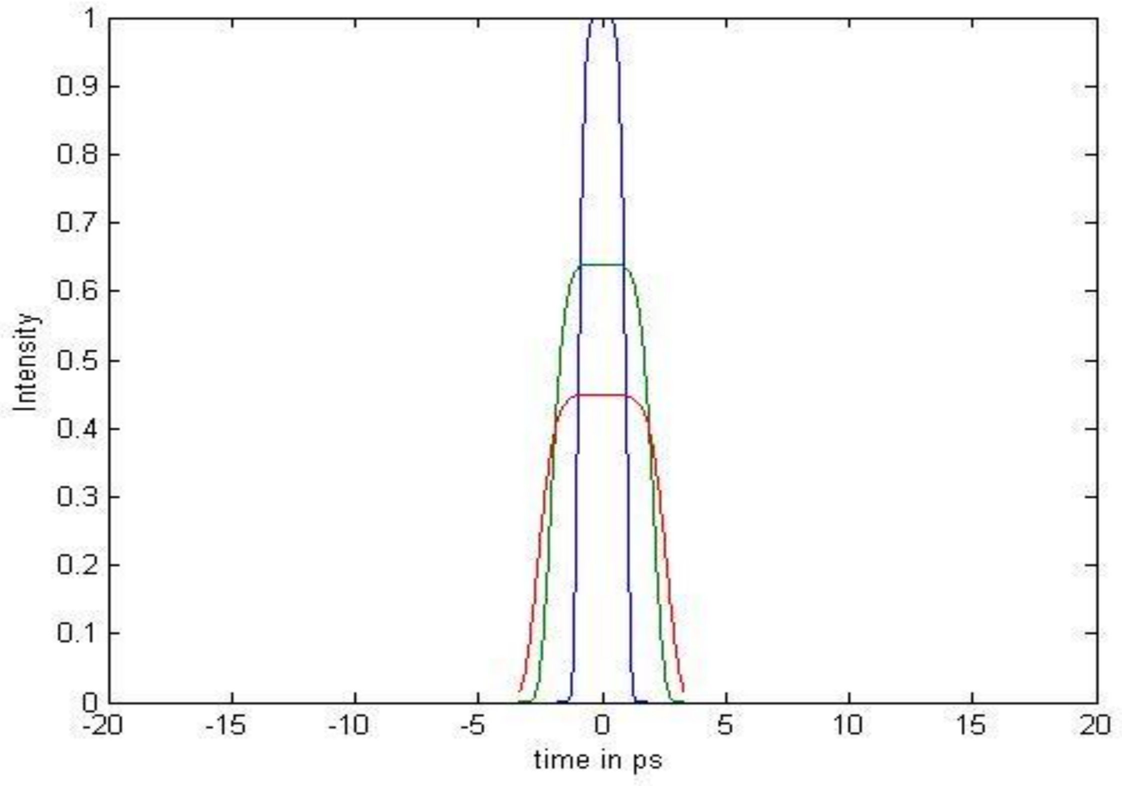

Fig 6.2.3: For 20Gbps pulses

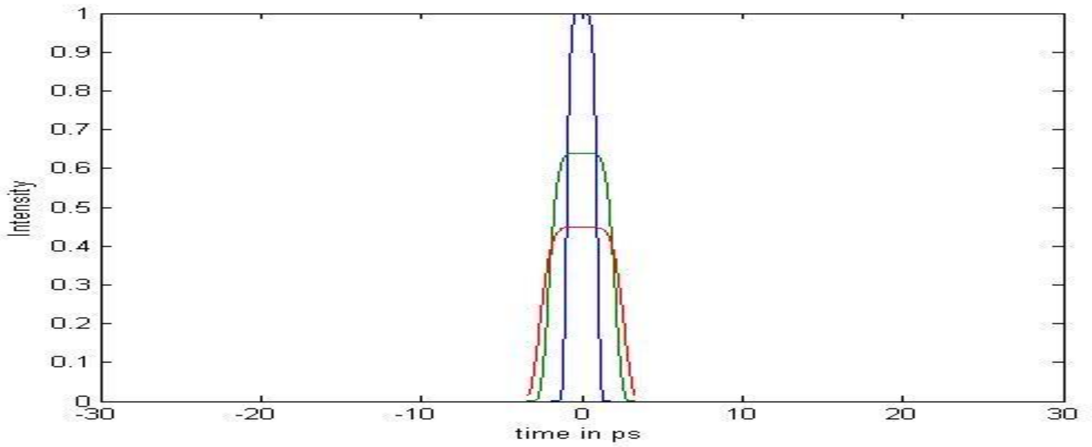

Fig 6.2.4: For 30Gbps pulses

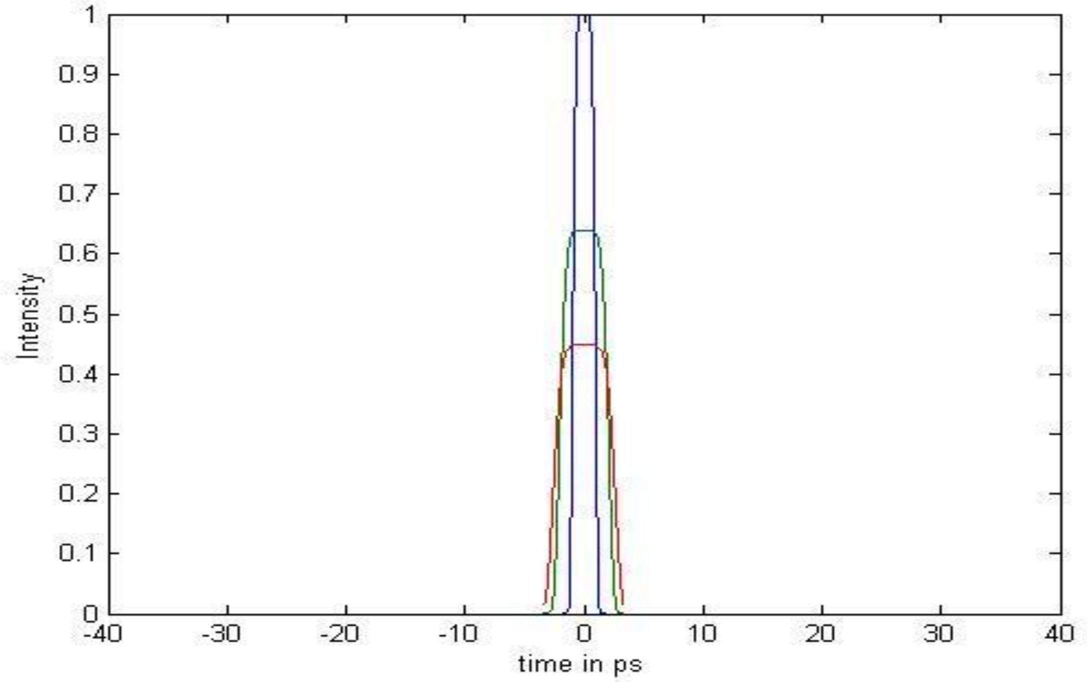

Fig 6.2.5: For 40 Gbps pulses

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6.3 The difference between Gaussian theorem and Super Gaussian Theorem:

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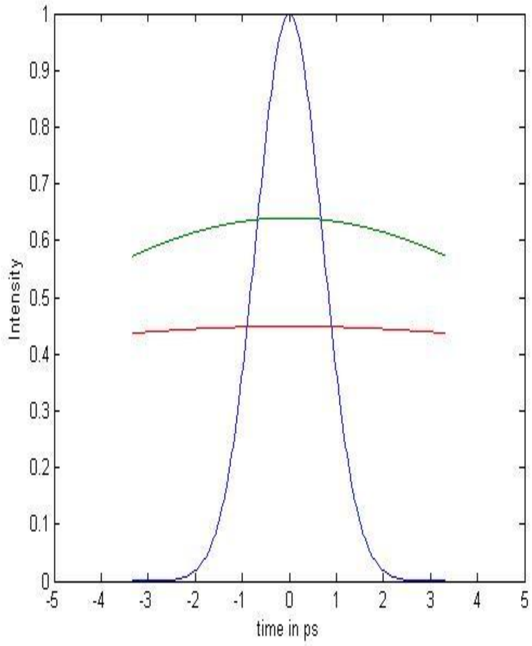
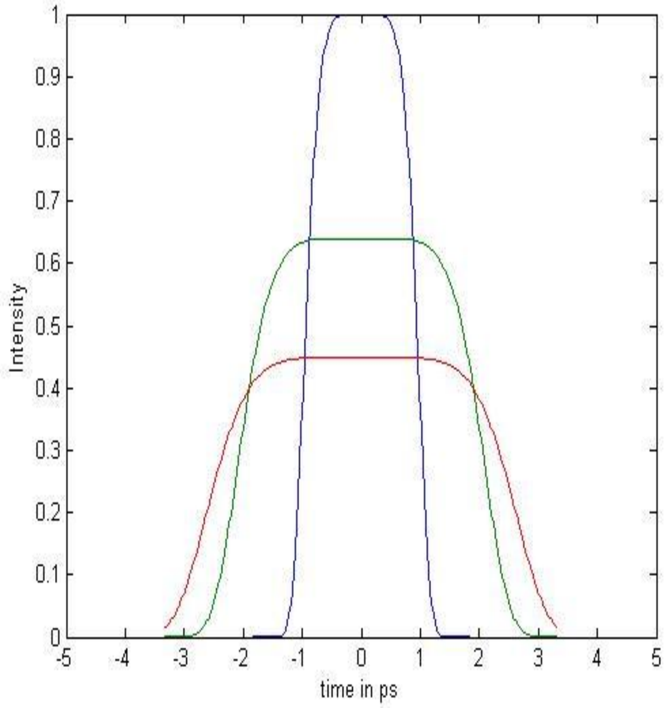
<tr><td>
</td><td>
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<tr><td colspan="2">Fig : When 5 Gbps pulses</td></tr>
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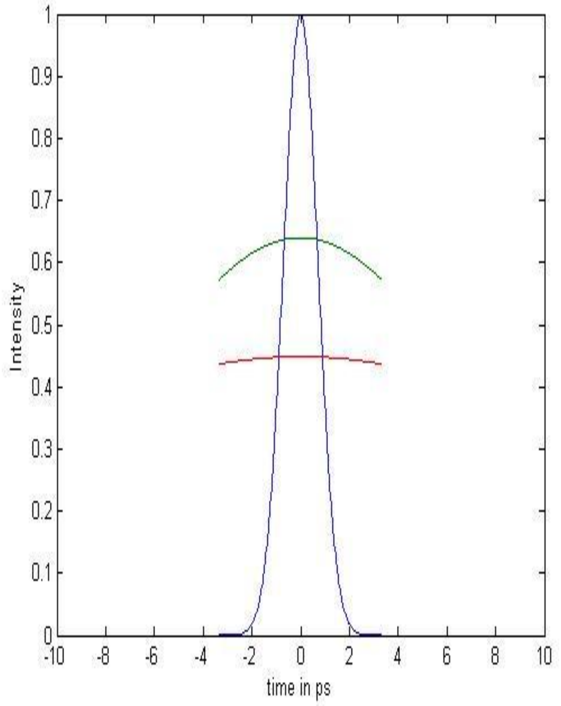


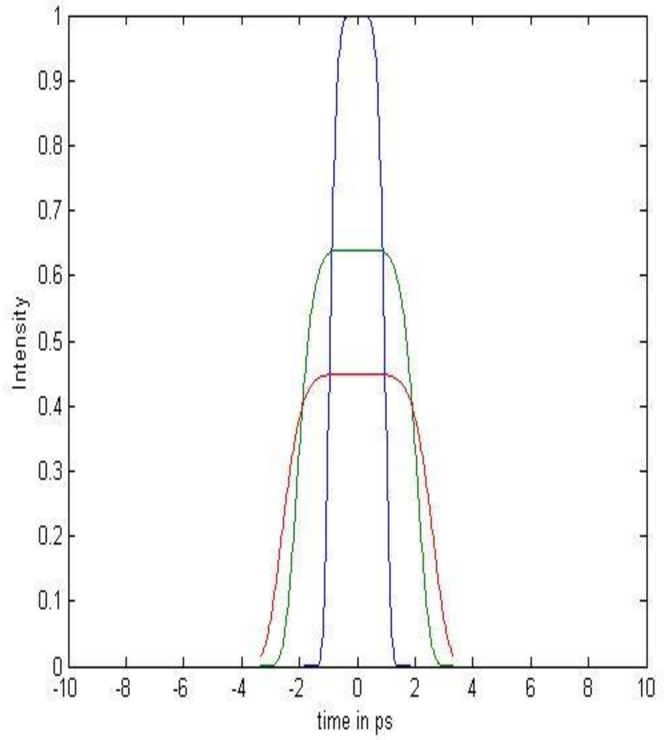
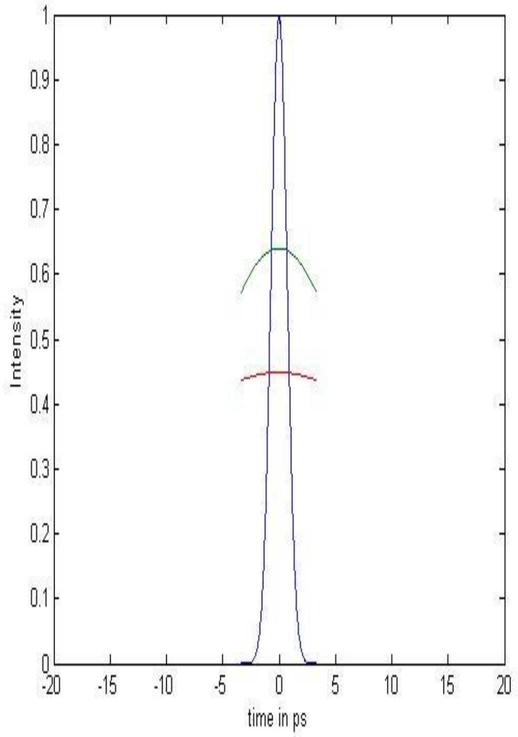


Fig : When 10 Gbps pulses



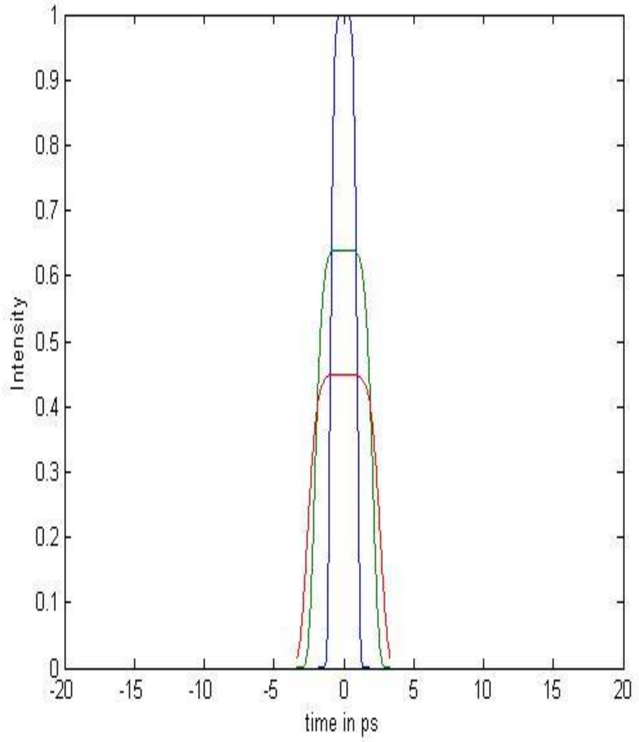
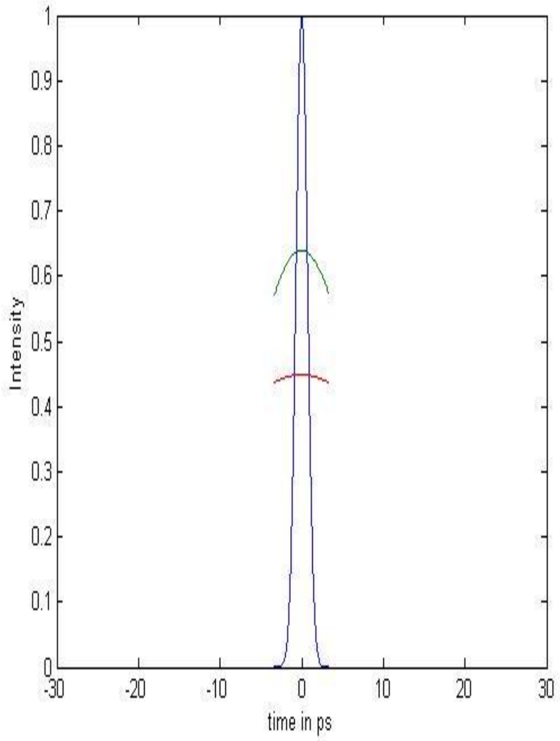


Fig : When 20 Gbps pulses



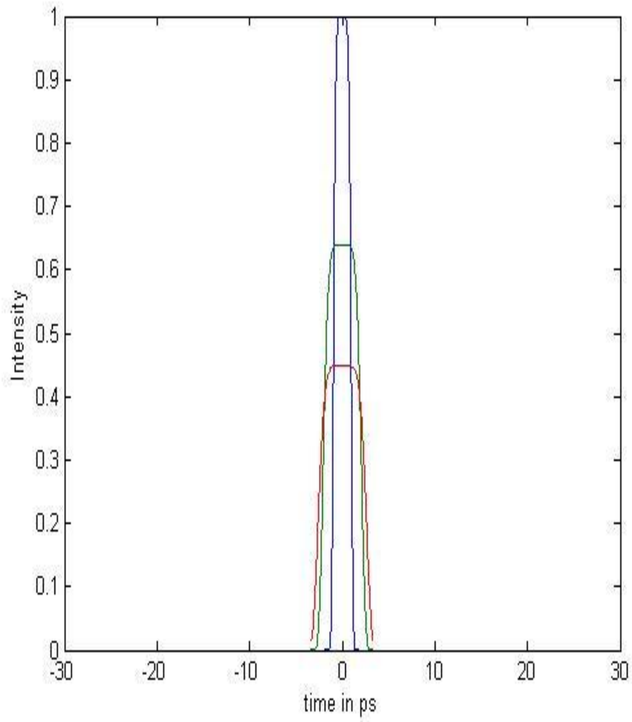
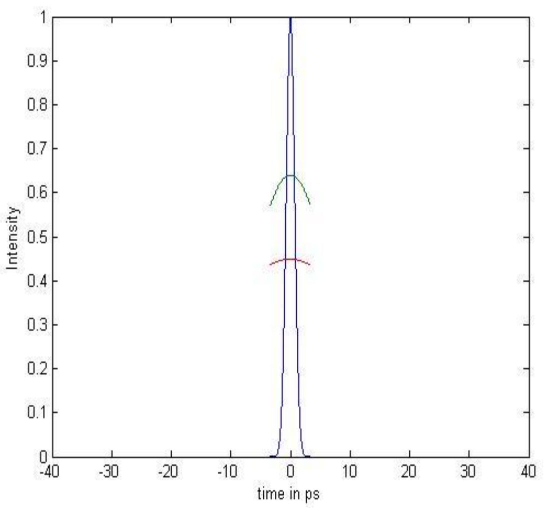


Fig : When 30 Gbps pulses



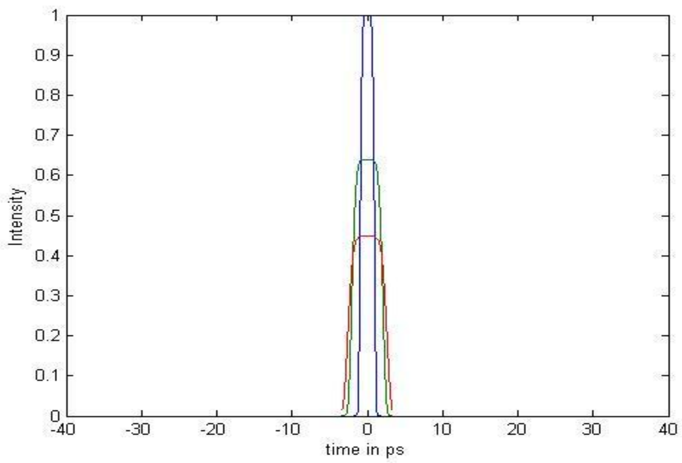


Fig : When 40 Gbps pulses

Fig 6.3: The difference between Gaussian theorem and Super Gaussian Theorem.

Conclusion:

In this report I tried my level best to complete this successfully. I tried to present here how to reduce dispersion from optical fiber. Here I did present basic concept of optical fiber, advantages, types, source and destination of optical fiber, attenuation, dispersion etc. I did collect that information from some well known writer books and some reference links. When I did the report I did try to reduce full dispersion remove. But I see when I am trying to remove full desperation, other losses of optical fiber increasing. We can’t do zero dispersion of optical fiber. By Standard telecom fibers exhibit zero chromatic dispersion in the 1.3-µm wavelength region. This was convenient for early optical fiber communications systems, which often operated around 1310 nm. However, the 1.5-µm region later became more important, because the fiber losses are lower there, and erbium-doped fiber amplifiers (EDFAs) are available for this region (whereas 1.3-µm amplifiers do not reach comparable performance).

This concludes our study of Fiber Optics. We have looked at how they work and how they are made. We have examined the transmitter and receiver of fibers, and how fibers are work. Here briefly explained attenuation and dispersion optical fiber. I have also explained Gaussian Pulse and Super Gaussian Pulses. I got a sound knowledge after that research if we use Super Gaussian Pulses dispersion will be reduced of optical fiber. So that we should use Super Gaussian pulse. Although this presentation does not cover all the aspects of optical fiber work it will have equipped you knowledge and skills essential to the fiber optic industry.

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External links:

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