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A Survey of the Mechanisms Impairing Optical fiber communications performance



Abstract: - The growth of information technology and Internet networks, combined with nearly daily use and many subscribers, has caused the volume of data stored in communication systems to balloon to enormous proportions. Optical fiber cable is the medium for data transfer because it has a bandwidth far more significant than other transmission methods and can span significantly greater distances. The transmission of information from one location to another can be accomplished via a technique known as fiber-optic communication. This involves passing pulses of light over an optical fiber. Optical fiber performance is affected by many effects, including attenuation, dispersion, scattering, and bending. It is feasible to enhance the performance of optical fibers for communications by utilizing carbon nanotubes and multiple coding technologies. This can be accomplished via integrated optical circuits or by making the cable more advanced and developing it further. Photosynthesis is accomplished by utilizing carbon tubes and the optical property inside them.

Keywords: Optical fiber communication, Optical fiber mechanisms losses, Attenuation, Dispersion, and Carbon Nanotubes

I. INTRODUCTION

Data transmission from one location to another is accomplished via fiber-optic communication employing light pulses travelling along an optical fiber. The light can form a modulated electromagnetic carrier wave, carrying information. Fibre optics have largely replaced electrical cables in recent years because of their superior bandwidth, more extended range, and resistance to electromagnetic interference. This form of communication can transmit speech, video, and telemetry over large distances or within a local region, whether through computer networks or local area networks [1] – [2]. The essential purpose of fiber optics required for various applications is efficient transmission of light at the operational wavelength(s) such as in communications of long-distance, lasers of fiber and delivery of optical in medical and surgical fields. Light's dimming intensity as it travels through an optical wire is called attenuation. It is resistant to electromagnetic interference and more affordable. It began with John's early work with light-wave transmission, the development of light-emitting and laser diodes, and wave-division multiplexing on a single transmission line. Optical fiber technologies permeate numerous sectors today. Especially making possible the technology of introducing fiber to the home that makes television transmission in clarity and in very high definition. Data transfer in telecommunications, video control and protection switching, sensors, and power distribution are just some of the many uses for optical fiber communications [3-4]. Videotext, videotelephony, and a switched broadband communication network are all part of the cutting-edge communication infrastructure of today's suburban areas. With the development of technology and the increase in the number of users of communication networks, optical fibers began to be used in most types of communication systems, such as wired and wireless communications, such as digital telephones, cellular mobile phones, the Internet, and television signals via cable. Researchers achieved speeds exceeding 100 petabytes per kilometer per second, and distinguished fibers Optical has extensive bandwidth. CATV, high-definition television, the Internet, and video-on-demand are just a few services that broadcast and cable providers use fiber optic cables to the wire. Fiber optic cables can be used as sensors to measure and monitor various parameters and provide light for illumination and imaging. Internet use has become one of the most fundamental human needs in the modern world. In today's society, having access to the Internet has evolved from being a nicety to a need. Because of the many developments in Internet service, the connection provided by optical fiber is advantageous to the Internet [5 - 6]. An example of optical fiber communication is shown in Figure 1, which refers to moving information from one area to another utilizing light as the channel for carrying the information and optical fibers as the transmission medium. In the past, various optical signals were used for communication, including smoke signals, semaphores, and others. However, these techniques have very little practical application. American physicists developed the ruby laser in the early 1960s. In 1966, Dielectric waveguides or glass optical fibers were independently proposed by Kao, Hockham, and Wert to transport light signals without environmental degradation. Compared to the

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coaxial cables they were meant to replace (which had an attenuation of 5 to 10 dB/km), optical fibers initially had a very high attenuation (1000 dB/km). Losses in 1310 nm optical fibers were decreased to 0.3 dB/km by 1974 from 17 dB/km when first produced in 1970 by the American Corning Company. In 1977, two telephone offices in Chicago, separated by about 7,000 meters, successfully tested the first commercial usage of multimode fibers in a live environment. As a form of communication transmission, optical fibers offer numerous benefits, including enormous communication capacity. As a form of communication transmission, optical fibers offer numerous benefits, including enormous communication capacity. Usually, the carrier frequency determines a communication system's maximum data transfer rate [7]. If the carrier frequency increases, the transmission bandwidth increases, allowing more data to be sent and received. Optical fiber networks offer advantages over metallic cable systems, such as coaxial cables with a bandwidth of around 500 MHz and millimetre wave radio systems. The optical carrier frequencies within the range of 10^{13} to 10^{16} , commonly found in the near-infrared region at 10^{14} Hz to 10^{16} GHz, provide much higher potential transmission bandwidth compared to the current system operating with modulation bandwidths of 700 MHz. Wavelength division multiplexing (WDM) is a highly efficient technique utilised for the optimal utilisation of unutilized fiber-optic bandwidth. That's why we gain several orders of magnitude when using optical fibers. Optical fibers have negligible attenuation or transmission loss compared to the best metallic wire. Optical fibers with loss rates as low as 0.2 dB/km have been manufactured up to this point. Production of lower-attenuation optical fibers will reduce the cost and complexity of communication systems by allowing the installation of lines with significant separation between repeaters (extremely long transmission distances without the usage of intermediary devices). Optical fibers are extraordinarily lightweight and minuscule in diameter, usually scarcely more extensive than human hair. These optical fibers are substantially more compact and lower in weight than their copper equivalents, even after being coated for protection. Fiber-optic cables can function in tight spaces, have a straightforward design, and are simple to install. Because of their ability to act as an electrical insulator, optical fibers composed of glass or plastic polymer are shielded from electromagnetic interference and provide exceptional signal security during transmission (EMI). They can be utilized in electromagnetically dangerous conditions and do not require electromagnetic shielding [7 - 8]. Cross-interference is avoided when numerous, unrelated optical signals travel along a separate fiber of the same fiber-optic cable. The transmission of data using optical fibers often offers a high level of security against external interference or unauthorised access unless there is a deliberate malevolent effort. This is because optical signals within optical fibers do not emit radiation beyond their confines. In contrast to copper, silicon dioxide is a naturally abundant and low-cost raw material utilised in producing fiber optics. Moreover, due to the maturation of the technology used to manufacture optical fibers, the cost of manufacturing optical fibers has decreased significantly. Because of the numerous benefits that optical fibers offer and the development and refinement of production techniques for optical devices and optical fiber systems, optical fiber communication system development, research, and application are thriving. There have been four generations of optical fiber communication development [9]. The initial iteration of optical fiber communication networks employed multimode fibers with a loss rate of 4 dB per kilometer and a diameter measuring 50 micrometers, operating at a relatively short wavelength of 0.85 micrometers. The loss of signal strength increased as the distance between the sender, and receiver increased. LEDs fabricated from III-V semiconductor compound, gallium arsenide (AlGaAs), provided the illumination, and p-i-n (PIN) photodiodes or Si avalanche photodiodes served as the optical detectors (APD). Initially, digital signals down to the third level (E3) of pulse-code modulation (PCM) were transmitted across optical fiber communication networks connecting several central offices (pulse code modulation). As opposed to the 4 dB/km loss of the first generation, the generation of the second in optical fibre communication systems utilized long wavelength 1.31 μ m single-mode fibers. The illumination was provided by III-V semiconductor light-emitting diodes (LEDs) and laser diodes (LDs), and the optical detection was accomplished with InGaAs-PIN/GaAs-FETs. The generation of a second was designed for longer distances (up to 40 kilometers) and higher data rates (up to 400 Mb/s) over longer distances (between central offices or long-haul) without the need for repeaters [10 - 11].

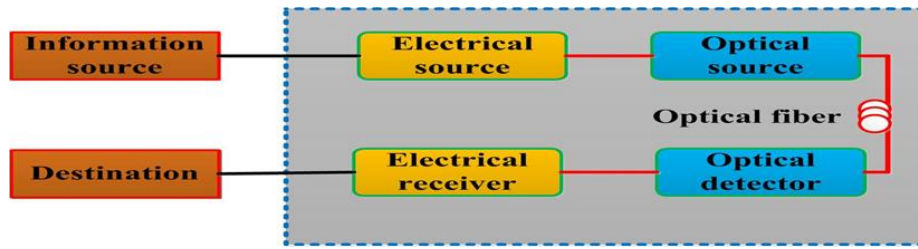


Figure 1 Systems for optical fiber communications

Third-generation optical fibre communication systems use dispersion-shifted single-mode fibers with a loss of 0.2 dB/km or less. The fibers in question function within the wavelength range of 1.55 meters.. Long-haul and undersea long-span communications can benefit from their 2.5 Gb/s data transfer rate and InGaAs LED or distributed feedback (DFB) LD light source. Figure 2 illustrates how fourth-generation optical fibre communication systems enhance their transmission range using optical amplifiers, such as erbium-doped fibre amplifiers (EDFAs) and Raman amplifiers. These setups require 1.55 m wavelength-operating nonzero-dispersion single-mode fibers and wavelength division multiplexing (WDM). The data rate per wavelength is estimated to reach up to 10 Gb/s. Figure 1 depicts the basic layout of a communication system that uses optical fiber. Figure 2 displays a diagrammatic representation of a system that utilizes wavelength division multiplexing. The amount of time spent conducting research into next-generation optical fiber communication technologies is picking up speed. Transmission distance can be increased by increasing the network's ability to transmit data. As a result, researchers are currently working on the development of 40 GB/s systems for various applications, including dynamic dispersion correction, amplification of single-wavelength ultra-wide bandwidth optical fiber signals within the C, L, and S optical frequency ranges, coherent light communication, and optical code division multiple-access. The advancement of Optical fiber communication technology will result in more efficient optical communication networks and systems [12-13].

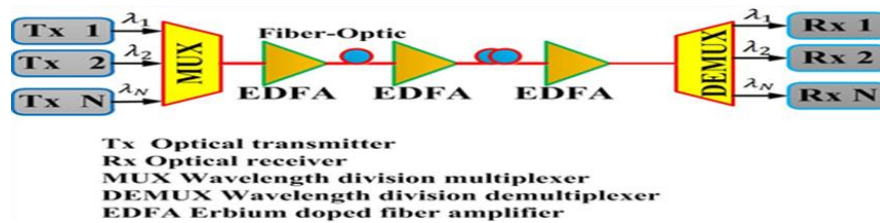


Figure 1.2 Diagrammatic representation of the wavelength division multiplexing system

The present study discusses optical fiber transmission loss mechanisms and the next generation of optical communication systems. To reach a far higher data rate up to Tb/s than current systems using silicon optical devices giving data rate upto Gb/s, as shown in figure 3, carbon nanotubes (CNTs) based devices may be preferable in this next generation of optical communication system. These low-power systems also last far longer than their conventional counterparts. But the emergence of systems based on carbon nanotubes that give optimum performance could satisfy future demands for ultrafast Internet, video, multimedia, and advanced digital services [14].

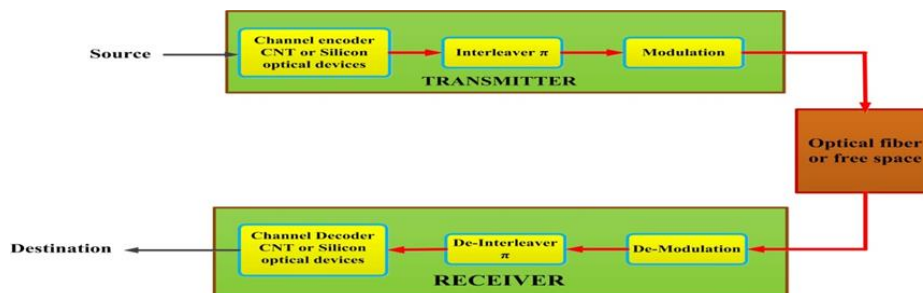


Figure 1.3 Generalized block diagram of an optical communication system with CNT-based encoder/decoder and Silicon optical fiber.

Multiplexing Expands Access to the Optical Code Division System (OCDMA) encoding and decoding user data to enable shared utilization of the optical channel is a major bottleneck in the widespread adoption of OCDMA networking and communication. To address this problem, we require efficient encoding and decoding methods that may be used to generate and identify reliable code sequences. This highlights the significance of OCDMA encoders and decoders in OCDMA networks. In an OCDMA network, each user is assigned a unique waveform, or codeword, derived from a set of OCDMA address codes. For the next generation of broadband access networks, OCDMA holds a lot of potential. In the OCDMA-PON network, the data are encoded into a pseudorandom optical code (OC) by the OCDMA encoder at the transmitter, and multiple users share the same transmission media by assigning different OCs to different users. This is the fundamental structure and operation of an OCDMA PON network. The OCDMA decoder uses matching filtering to identify the OCs at the receiver, with high recognition achieved by auto-correlation for the desirable OC and low levels achieved by cross-correlation for the unwanted OC. Following electrical thresholding, the original data can be reclaimed. OCDMA has the unique characteristics of allowing asynchronous transmission with low latency access, soft capacity on demand, protocol transparency, easier network management, and greater QoS control flexibility due to its all-optical encoding/decoding processing. By encoding the data into pseudo-random OCs before transmission, this technique has the potential to enhance network anonymity further. Each "1" in a user's data is encoded as their preferred address codeword and broadcast in an on-off keying pattern OCDMA network. However, the transmitter will not generate light pulses when sending a "0" bit of data. OCDMA encoders and decoders can be roughly classified as coherent or incoherent depending on how the optical signals are modulated and detected. Time-division multiplexing (TDM) and wavelength division multiplexing are the two most common methods for multiplexing data signals today (WDM). Based on the differences in signal modulation and detection patterns, optical code division multiple access (OCDMA) encoders and decoders can be roughly classified as coherent or incoherent. By encoding and decoding a signal using an optical signature code, optical code division multiple access (OCDMA) allows several users to share a single channel[15]. In the late 1990s, researchers first became interested in using CNTs for photonics. Very soon, the first theoretical investigation into the nonlinear optical features of single-wall CNTs and their extremely high third-order nonlinearity commenced. Since single-wall CNTs are necessary for most photonics applications, we will refer to them as CNTs from here on out. The chiral vector, which represents the arrangement of the honeycomb of carbon atoms concerning the CNT axis, is the sole parameter that controls the optical properties of CNTs, which are intimately tied to their structural and electrical properties [16]. CNTs can function as a direct bandgap semiconductor or a metal depending only on this parameter. The field of fiber optics, particularly in telecommunications, is a realm in which new products and technologies are seemingly introduced daily. The reduction in strength of a signal is referred to as its attenuation in the field of telecommunications. This is possible when transferring signals over extensive distances. In terms of voltage, dB (decibels) can be determined. When transmitting a signal, its purpose is opposed to that of amplification. When signal attenuation is very great, the signal becomes incoherent. For this reason, repeaters are regularly used by most networks to boost signal strength. Any signal, analogue or digital, is susceptible to attenuation or a reduction in strength. Transmission or attenuation losses are commonplace when sending a signal over long distances. In cables like conventional and FOCs are measured in decibels (DBs) per foot, kilometer, or thousand feet, etc. (fiber optic cables). Any cable used to transmit signals over long distances requires one or more repeaters to compensate for the natural attenuation that occurs over time, as repeaters are essential in amplifying the signal power to overcome this challenge. This improves the maximum possible scope of expression. A light pulse experiences temporal dispersion as it travels through the fiber. Dispersion in an optical fiber results from a combination of modal, material, and waveguide dispersion. Modal dispersion is a time-variant distortion caused by the various propagation velocity of the constituent modes in multimode fibers and other waveguides. It's well known that light beams with different angles of incidence entering a fiber will follow different propagation modes. This illustration of a step-index multimode fiber in Figure 4 below shows some of these light rays will travel straight down the middle of the fiber (axial mode). In contrast, others will keep bouncing off the cladding/core barrier and dodging their way down the waveguide. Modal and intermodal dispersion occurs in every collision. The modal dispersion will increase as the length of the trip increases. By way of illustration, the high-order modes (light coming in at sharp angles) cause the most dispersion in the model (light entering at smaller angles). Scattering in optical fibers occurs due to the interaction or collision of light with changes in density and the composition of matter within the fibers. The process of creating optical fibers causes a

shift in density. The molecular density of fiber can vary from one spot to another during production, with both higher and lower densities being formed, as illustrated in light, and is subsequently somewhat scattered in all directions after interacting with the density zones along the fiber's path. Better data transfer rates and smarter switching methods will benefit from creating a brand-new field. An intelligent network quickly adapts to changing traffic conditions and is financially successful. Just like in the past, encouraging optical communications is necessary to keep their unparalleled speed. To maintain their unrivalled speed, optical communications must be promoted just as they were in the past. As optical communications get more refined, they can overcome previously insurmountable obstacles. The quest for ever-increasing speeds, efficiencies, and capacities has driven significant progress in the optical communications field. Due to thermal constraints in the central office, energy efficiency is already a consideration in the design of terrestrial optical transmission networks. It will become even more crucial to ensure the network can keep up with rising demand, reducing its carbon footprint and making eco-friendly network applications possible [17-18].

Though energy has always played a crucial role in the physics of communication, concerns about energy efficiency and carbon footprint have only recently emerged as priorities in technology and system design. Over the past three decades, data networks, in particular, have evolved to the point that they are starting to meet significant physical restrictions related to energy and capacity.

II. DESCRIPTION SYSTEM

Researching the companies making significant headway in this market is a beautiful approach to getting started learning about this sector of the economy. The Internet is an incredible resource for obtaining helpful knowledge concerning this topic. Perform a search on the internet using terms such as "fiber optic communication," "dispersion-shifted fiber," "erbium-doped fiber amplifier," "fiber optic transmitter," "fiber optic modulator," "optical networks," "SONET," and "fiber optic cable" to learn more about fiber optics. This is an additional method for learning more about fiber optics. Optical fibers play a crucial role in optical transmission systems due to their capacity to carry optical signals. The synergistic effect of low signal loss and wide bandwidth facilitates the ability to transmit signals across long distances at high speeds without experiencing degradation. A low-loss optical fiber utilises pure silica as its primary constituent, and the introduction of certain dopants during the production process allows for precise control over the refractive index. The optical fibre comprises two distinct layers for guiding waves: the core, characterised by a refractive index denoted as n_1 , and the cladding, characterised by a refractive index denoted as n_2 . The jacket envelops the core, providing a buffer coating with a refractive index denoted as (n_1) . The cladding has the potential to receive a portion of the power that is concentrated in the core. However, it is essential to note that the core consistently maintains most of the power. Diverse dopants are frequently incorporated into the fiber core to establish a disparity in refractive indices between the core and cladding ($n_1 > n_2$). Optical fibers, referred to as fiber optics, are elongated strands of highly refined glass material with a diameter significantly smaller than a human hair. To enable the transmission of light signals across extensive distances, they are bundled together into what is known as optical cables. The core, the cladding, and the outer coating, also commonly known as the buffer, make up an optical fiber. These three components are arranged concentrically within an optical fiber. These three components comprise an optical fiber. Glass and acrylic, two prevalent types of material, are often utilized in constructing the core. The core of a fiber is the part that transmits light. The covering fully encircles and encompasses the core. The substance that makes up the cladding has an index of refraction that is only somewhat lower than that of the core. Since the core and cladding have different refractive indices, total internal reflection occurs at the interface between the two throughout the fiber. This is because of the dissimilar refractive indices of the core and cladding. As shown in Figure 4, the optical fiber prevents light from leaking out of its sides as it transmits it throughout its length [19-20].

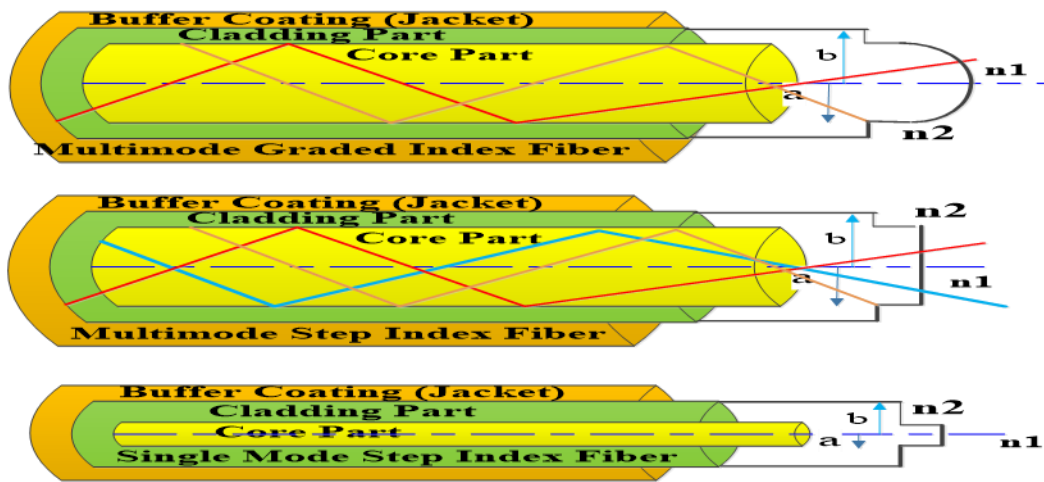


Figure 4 forms of transmission via optical fiber

Components of a single optical fiber include the Core, which is the thin glass section at the fiber's center through which light flows at a refractive index of n_1 . The inner, high-index component is responsible for transmitting light. Cladding is the outside optical material surrounding the core and reflects light into it with a refractive index of n_2 (such that $n_1 > n_2$). The middle layer contains the core's light, which keeps the light from escaping from the center. Compared to the other substance, it possesses a lower index of refraction. A buffer coating is a plastic layer that protects the fibre from potential harm and moisture. An example of this may be seen in figure 4, which is the outermost layer, which acts as a "shock absorber" to prevent damage to the core and the cladding layers that lie behind it in the case of a collision and shields them from the force of the impact. The fundamental objective of the coating, which might comprise many layers of a polymeric substance, is to safeguard the fibre from the detrimental effects of its ambient natural surroundings. The coating is not uncommonly supplemented with metallic sheaths to provide even more excellent protection against the elements. The core of the fibre optic cable experiences total internal reflection when light is injected at an angle more significant than the critical angle between the core and the cladding. Light travels throughout the length of the fiber in a zigzag pattern because the angles of incident and reflection are the same. The center of the object contains all of the light. The cladding absorbs and scatters any incoming light with an angle less than the critical angle. A step-index fiber has a constant refractive index along its length in the core but a sharp change in index at the interface between the core and the cladding. Step-index fibres are offered in a range of core sizes, spanning from 100 millimeters to 1000 millimeters. Because of their high power-to-weight ratio, they are an excellent choice for applications that call for high power densities, such as delivering laser power for use in medical and industrial settings. Because of this, they are an ideal alternative [21-22].

Different Optical Fiber Methods of Transmission

Single mode, multimode graded index, and multimode step-index fiber are the three primary categories of optical cable. The light's wavelength and the fibre's mechanical geometry determine how the light is transmitted along the fiber and, thus, how the fiber is characterized. Figure 4 depicts some instances of their light propagation abilities.

1. The fiber of the Step Index of Multimode

In particular, the entry angle of each mode in a step-index multimode fiber is unique from the other modes' entrance angles. The multimode step-index fibers collect light at a wide variety of entrance angles. As a result, every mode takes a slightly distinct route as it moves through the fiber. The velocities of the various modes of propagation are distinct from one another. When an optical pulse is sent via a multimode fiber, it spreads out as it moves down the fiber. Pulses that enter the system at a significant distance apart from one another will eventually overlap one another. Because of this restriction, the fiber can only transmit data over a certain distance. The example in Figure 4 demonstrates that multimode step-index fibers are not optimal for transmitting data or communications. This is clear by looking at the diagram. As an individual progresses in a radial direction away

from the central region of the core in a multimode fibre featuring a graded index, there is a decrease in the refractive index of the fiber's core. This phenomenon is known as a graded index. This decrease in the index of refraction occurs in proportion to the increasing radial distance from the core. As a direct consequence, the speed of light increases closer to the periphery of the core than it is closer to the center. As a result, the various types of transportation take winding routes that take roughly the same amount of time. This results in a significant reduction in the propagation of optical pulses. The index of refraction of the core of a step-index fiber remains constant up until the point at which it comes into contact with the cladding, at which time it begins to vary in distinct stages. Because the various modes in a step-index fiber journey along varying path lengths as they make their way through the fiber, it is imperative that the distances over which data is transmitted be kept as small as possible to avoid significant issues with modal dispersion. Core diameters ranging from 100 to 1500 m are offered for purchase in step-index fibers. They provide a favourable choice for applications that necessitate high power densities, such as the provision of laser power in the medical and industrial sectors, which are two prominent instances.. They are also a fantastic solution for applications that require high power densities [23-24].

2. The fiber of Multimode Graded Index

When you look at a graded-index fiber, you'll see that the index of refraction gradually decreases from the axis to the cladding as you move away from the center of the fiber. This happens because the index of refraction depends on the fibre's orientation. This is because the cladding is constructed out of a substance with a lower index of refraction than the axis. When light beams reach the cladding, rather than being sharply reflected from the core-cladding border, they gently bend in that direction instead. Light is transmitted over a multimode optical cable in various transverse spatial modes. Different modes of light travel through an optical fiber slightly differently because each mode has its distinct combination of electrical and magnetic components. Multimode optical fibers have varying arrival times to the receiver due to the different path lengths of the modes. Multimode (intermodal dispersion) is responsible for signal distortion and bandwidth restrictions. As shown in Figure 4, the core's refractive index in a fiber with a graded index decreases from its maximum value of n_1 at the axis to a constant value n_2 beyond the core radius and in the cladding. This drop occurs as the fiber moves away from the axis. This decrease occurs from the maximum value of n_1 at the axis. An equation (1) may be written to describe this change in the index:

$$n(r) = \begin{cases} n_1(1 - 2\Delta(\frac{r}{a})^\alpha)^{\frac{1}{2}} & r < a \quad (core) \\ n_1(1 - 2\Delta)^{1/2} = n_2 & r \geq a \quad (cladding) \end{cases} \quad (1)$$

where Δ is the relative difference in refractive index between the two sections, and is the profile parameter that gives the profile that specifies the profile of the refractive index of the fiber core.

Depending on the value, the refractive index of the fiber core can be represented in a variety of different shapes, the most common of which is the step-index profile, which occurs when $\alpha = \infty$; the parabolic profile occurs when $\alpha = 2$; and the triangle profile occurs when $\alpha = 1$; however, the triangle profile occurs most frequently when $\alpha = 1$. According to Figure 5, the graded index profiles that yield the best results for multimode optical propagation have an approximately parabolic refractive index profile and a value of $\alpha = 2$ for the parameter. These graded index profiles also have a value for the parameter equal to two.

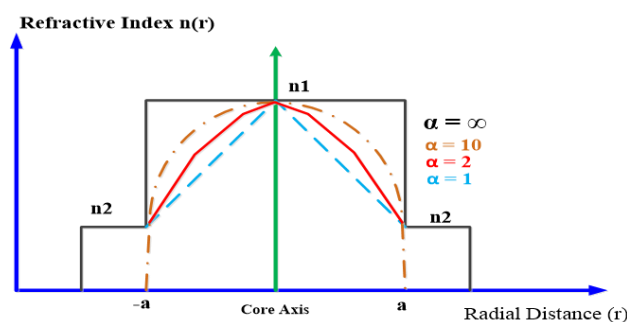


Figure 5 attainable fiber refractive index profiles for α various values

Multimode fibers' core diameters are substantially more significant than single-mode fibers. This results in the propagation of higher-order modes as well. The index of refraction of a graded-index fiber's core gradually drops outward from its center toward its cladding contact. The result is that the speed of light is more incredible at the core's periphery than at its center. The roundabout routes taken by the various types of transportation take about the same amount of time. Because of this, the modal dispersion of the fiber is considerably diminished. Compared to step-index fibers, graded-index fibers have significantly larger bandwidths, but they still can't compare to single-mode fibers. The typical core diameter of a graded-index fibre ranges from 50 to 100 micrometres. Graded-index fibers excel at local area networks and other forms of medium-range communication [23-24].

3. Fiber of Single – Mode Index

Single-mode optical fibers (SMFs) typically have a core diameter of around 8 m and can be manufactured with a refractive index difference between the core and cladding regions of roughly 0.03%. Therefore, the guiding used in today's optical fiber communications systems is feeble. In the late 1970s, the optical fiber communications technology field reached a consensus on this change after much discussion and argument. Only the most fundamental, lowest-order modes can be transmitted using single-mode fibers. The core-cladding sidewalls do not cause reflections along the light's path; therefore, they can pass unimpeded through the fiber. The core diameter of a single-mode fiber, the numerical aperture (NA) of the fiber, and the wavelength it is utilized for all have a role in determining the cutoff wavelength of the fiber. The properties of the fiber can be altered because higher-order modes can propagate below the cutoff wavelength. By utilizing a single-mode fiber, which propagates only the fundamental mode, it is possible to avoid modal dispersion, the primary factor that contributes to pulse overlap. Therefore, single-mode fiber has significantly greater bandwidth than multimode fiber. The result is that pulses can be sent considerably closer to one another in time without interfering. Due to their greater bandwidth, single-mode fibers are used in all cutting-edge long-distance communication systems today. The average diameter of a core is 5-10 um. The core diameter, numerical aperture, and wavelength of the light being sent determine the number of modes fiber can propagate. Based on formula (2), these can be combined to form the V number, also known as the normalized frequency parameter.

$$V = \frac{2\pi a}{\lambda} \sqrt{(n_{core}^2 - n_{cladding}^2)} = \frac{2\pi a}{\lambda} N_A \quad (2)$$

Where a represents the radius of the core, λ represents the wavelength, and n represents the index of both the core and the cladding. The following must be faithful for there to be just one mode of operation:

$$V \leq V_{cutoff} = 2.405 \quad (3)$$

The cutoff wavelength is probably more crucial and helpful than any other factor. Below this wavelength, the fiber will permit the propagation of several modes, and its value can be stated as follows:

$$\geq \lambda_{cutoff} = 2.6a N_A \quad (4)$$

When selecting a fiber, looking for one with a cutoff wavelength just a hair shorter than the ideal operating wavelength, is standard practice. A single-mode fibre's core diameter can range from 3 to 10 micrometres for lasers generally employed as sources (with output wavelengths that fall between 850 and 1550 nanometers) [23 - 24].

III. RESEARCH METHODOLOGY

The Mechanisms Responsible for Optical Fiber Communication Losses

Whenever light is sent over an optical fiber, there is a slight chance that some light will be lost due to one of several possible causes. Insufficient emphasis has been placed on investigating the aspects that impact the performance of optical fibres as a means of transmission, as well as the underlying transmission mechanisms of different types of optical fibre waveguides. This has resulted in inefficient use of optical fibers as a transmission medium. Since this is the case, information is being transmitted less effectively. When determining whether or not optical fibers are suitable for use in communication, the transmission qualities that are being looked at are of the utmost significance. Attenuation (also known as loss) and bandwidth are the two aspects of transmission that

garner the most attention and consideration. When it comes to the efficient construction of fibre-optic networks that span great distances, attenuation is a factor that cannot be overlooked. As a consequence of this, the methods of fabrication have undergone significant advancements over the past 30 years. In the wavelength range of 0.8 to 1.6 meters, the various elements contributing to the attenuation have been measured to be on the order of a few tenths of a dB per kilometer. Total losses for an optical fiber are typically 2–3 dB/km at the 800 nm, 1300 nm, and 1550 nm transmission windows, respectively. It is possible to be dispersion as a consequence of the fact that different wavelengths come into contact with varying propagation constants. Consequently, travel at different velocities results in a longer temporal pulse at the end of the fiber. This phenomenon occurs because of the varying speeds at which different wavelengths propagate. The light pulse retains the same wavelength (frequency) characteristics regardless of the dispersion. Because of its direct impact on the bit rate, dispersion is a very significant aspect to consider when it comes to the field of communications. The losses that have been dealt with up to this point have either been related to the intrinsic qualities of the glass or to the extrinsic properties (such as the amounts of OH and transition metals) that originate from the specific process of production that has been used. In addition to it, there are losses due to bending. These bending losses might be rather significant if the fiber was cabled or put incorrectly in the first place. Micro-bending losses and macro-bending losses are the two categories of bending losses. The difference between micro-bending and macro-bending losses is that nanometer-sized deviations in the fiber cause the former [51,53].

In contrast, the latter is caused by observable bends in the fiber. Attenuation and dispersion are the two most significant factors that significantly impact the operation of transmission systems that use optical fiber. The attenuation of an optical signal would reduce the amount of optical power available along the transmission channel. Furthermore, when the attenuation is very low, dispersion restricts the repeater spacing that is less than what would be possible based on the attenuation factor. At 1300 nm in 1970, the fiber loss was measured at 100 dB/km, which meant that transmission was only possible over a few meters. Since then, this value has been reduced to 0.25 and 0.15 dB/km, which is very close to the theoretically possible transparent limits and transmission over several hundred. The "smart design" of optical fiber architectures has reduced dispersion and pulse broadening, both of which are undesirable properties of optical fibers. Other losses in fiber optical communications can be reduced, including using carbon nanotubes in optical signal amplifiers or using artificial intelligence techniques, as well as the optical code division multiplexing technology [25-26].

3.1 The Optical Fiber Communication Attenuation

For an optical data link to function properly, the modulated light must arrive at the receiver with sufficient strength to be appropriately demodulated. The loss of strength experienced by the light signal during transmission is referred to as attenuation. Passive media components, such as cables, cable splices, and connections, produce attenuation in a transmission medium. Single-mode, as well as multimode transmissions in optical fiber, can experience attenuation. Even though it is substantially less prevalent in optical fiber than it is in other media. Attenuation must be able to be overcome by enough amount of available light for an optical data link to function properly. Attenuation is defined as a drop in signal strength, and this phenomenon can take place in any signal, be it analogue or digital. Because this is a natural result of a signal sent across long distances, it is sometimes called attenuation loss. In other words, the signal weakens. Some cables, like traditional or fiber optic cables (FOCs), will label this information in decibels (DB) per foot, kilometer, tens of thousands of feet, etc. A low attenuation per distance unit means that the cable is very efficient. Any time a wire needs to transmit signals across great distances, a repeater or repeaters must be included in the setup, as repeaters are essential in amplifying the signal power to overcome this challenge. Accordingly, this improves the maximum possible extent of communication. The attenuation that a light signal experiences as it propagates through a fiber largely determines the maximum transmission distance between a transmitter and receiver, or between an optical transmitter and an in-line amplifier, in an optical communication system. Radiative losses, scattered light, and absorption are the three main ways optical energy is weakened inside a fiber. The constituent material and structural flaws in the optical waveguide contribute to the scattering phenomenon, while the absorption phenomenon is directly related to the constituent material. Radiative attenuation originates from micro- and macroscale alterations to the fiber's geometry. Absorption can be generated through three unique mechanisms: extrinsic absorption, which arises from the presence of impurity atoms within the glass material; intrinsic absorption, which stems from the fundamental constituent atoms of the fibre; and absorption resulting from atomic defects in the glass composition. Micro

variations in density cause scattering losses in glass, and these variations arise from compositional fluctuations and structural inhomogeneities or faults that occur during fiber production. The molecular density of the glass will vary in different parts of this structure, with some places having a higher density than others. Glass has several oxides, including SiO₂, GeO₂, and P₂O₅. Therefore variations in its composition are possible. Within the glass, these two phenomena cause refractive index fluctuations across distances much smaller than the wavelength. These disparities in the refraction indices cause light to scatter in a Rayleigh-like fashion. Rayleigh scattering in glass is identical to the scattering of sunlight in the atmosphere, resulting in a blue sky. Scattering can be divided into the linear variety and the nonlinear variety. With linear scattering, the amount of light energy transferred from a wave is proportional to the wave's intensity. The scattered wave retains its original frequency, a defining feature. On the other hand, nonlinear scattering results in a shift in the frequency of scattered light. Increased electric field strengths inside the fiber lead to nonlinear scattering (modest to the high amount of optical power). Large amounts of energy are dispersed in all directions thanks to nonlinear scattering, which can happen in any of three directions: forward, backwards, or laterally. Radiative losses, known as bending losses, are incurred when an optical fiber is bent with a finite radius of curvature. Macroscopic bends are radii much larger than the fiber's diameter, such as when a fiber cable makes a sharp turn. However, minuscule kinks in the fiber's axis are random and can occur whenever the fibers are combined into cables [27-28]. The macro bending phenomenon occurs when the radius of curvature of the fiber is noticeably greater than its diameter (large bends). Power loss due to bending increases dramatically when the radius of the bend is less than a few centimeters. If the radius of a macro bend is sufficiently great, it will not result in a noticeable drop in radiation. Tiny kinks in the core-cladding junction are known as micro bending. Localised bends can form in the fibre during deployment or because of local mechanical pressures, such as those caused by cabling or by wrapping the fiber on a spindle or bobbin. Additionally, micro-bending can occur during the fiber production stage. Tiny yet acute curvatures induce axial displacement at a magnitude of a few micrometres (µm) and spatial wavelength displacement at a magnitude of a few millimetres. It is usual for losses of 1-2 dB/km to occur due to micro-bending during the fibre cabling procedure. Transmission loss, or attenuation, is one of the primary reasons optical fibers have become so widely used in the telecommunications industry. When transmission losses of fibers drop to that of a normal metallic conductor (less than 5 dB/km), channel attenuation is a major factor in determining the maximum transmission distance before signal restoration, which explains why optical fiber communications have become so popular [29].

3.2 The Optical Fiber Communication Absorption

Most of the time, the photon's energy is converted into heat, which slows down the rate at which the photon may move through its environment. The relative decrease in light intensity per unit of path length is denoted by the attenuation coefficient (α). If you take a thin slice out of something much thicker, you'll lose more power than if you took a thicker slice out, according to Beer's law.

$$P_{out} = P_{in} e^{-\alpha L} \quad (5)$$

$$dB \text{ loss} = 10 \log_{10} 10^{(\alpha L)} = 4.34 \alpha L \quad (6)$$

In a slice with a thickness of dz , a certain percentage, dz , of the total light power P is absorbed, where α is the absorption coefficient (cm^{-1}). Commonly, optical fiber loss is measured in decibels per kilometer $\frac{dB}{km}$. When connecting propagation losses to underlying processes, the cm^{-1} unit is employed. Impurities can lower transparency in this range by introducing additional electric and vibrational absorption. Impurities typically take the form of transition metal ions, such as Cu^{+2} , Fe^{+2} and Cr^{+2} or OH^{-} , which triggers an electronic transition in the target material. Because it is so close to the crucially essential wavelength of 1.5µm, which is also the wavelength at which the attenuation in silica fiber is at its lowest, the transition at 1.4µm is highly harmful. Absorption is distinguished because it occurs exclusively in the neighbourhood of specific wavelengths that resonate at or near the material's intrinsic resonant frequencies or harmonics. This is one of the characteristics of absorption. Due to absorption loss, some of the optical power transmitted via the fiber cable is lost. Even though glass fibers are exceedingly clean, trace amounts of contaminants remain as residue even after purification. How much light these contaminants absorb is proportional to the wavelength and amount of contamination present. These three mechanisms are responsible for absorption in optical fiber. Molecular absorption, Two types of

absorption can occur in glass: extrinsic absorption, which occurs when impurity atoms in the glass material take in light, and intrinsic absorption, which occurs when the fundamental constituent atoms of the fiber material take in light. Fibre materials may have atomic defects, such as absent molecules or atom groups clustered in a high density. In comparison to intrinsic and extrinsic losses, absorption losses are minimal. The absorption effect is noticed when fiber is subjected to ionizing radiation, such as in a nuclear reactor, medical therapy, space missions, and other comparable scenarios. This is the most notable instance in which the effect is observed. Fiber damages its interior structure due to radiation [30 -31]. The severity of the damage is directly related to the amount of ionizing particles present.

Consequently, this leads to an increase in attenuation due to atomic flaws that absorb optical radiation. This is the unit that is used to measure the amount of radiation that is absorbed by bulk silicon, and it is used to quantify the overall dosage that a material gets. Extrinsic absorption happens due to electronic transitions between various energy levels and charge changes occurring from one ion to another. These transitions and charge changes both occur as a result of one another. Attenuation in electromagnetic radiation is caused mainly by the process by which impurity ions of metals such as iron, chromium, cobalt, and copper transition. It's possible that these losses could be anything from 1 to 10 dB per kilometer. Glass refining procedures have the potential to lessen the negative impact of metallic impurities. It is possible that refining processes for glass could mitigate the harmful effects of metallic impurities. Absorption resulting from OH (Hydroxyl) ions impurities dissolved in glass is responsible for yet another significant. At wavelengths ranging from 2.7 to 4.2 μm , vibrations can be observed. The three peaks of absorption are located at 1400, 950, and 750 nanometers. The condition necessary for intrinsic absorption in a material is its complete absence of density variation and inhomogeneities. Because of this, the fundamentally lower limit on absorption for any given substance is established by the intrinsic absorption of that material. The bands of atomic vibration in the near-infrared region and the bands of electronic absorption in the ultraviolet range both contribute to the process of intrinsic absorption. Both ranges are found in the visible spectrum. Band gaps in amorphous glass materials are related to the electrical absorption bands present in these materials. The valence band's interaction between a photon and an electron stimulates the electron to a higher energy level. This occurs because the photon causes the electron to reach a higher energy level. This occurs because the photon causes the electron to reach a higher energy level. This is an illustration of the concept of absorption. The decrease in UV absorption that occurs with an increase in wavelength (λ) is exponential. The loss of optical waveguides in the infrared spectrum region beyond 1.2 micrometres is influenced by the existence of OH ions and the inherent infrared absorption properties of the constituent materials [32].

3.3 The Optical Fiber Communication Scattering

Any amount of optical power in one propagating mode can be transferred linearly (proportionally to the mode power) to another mode when linear scattering processes are at work. This can occur when the optical power is converted from one mode to another. Since the transfer may occur in a leaky or radiation mode, neither of which continues propagation within the fiber core, attenuation of the light being sent is typical when this procedure is carried out. This reduces the efficacy of the transmitted light. It is essential to remember that, just like with any linear process, scattering does not result in a change in frequency. Two main types of scattering can be used to categorize linear scattering: Rayleigh scattering and Mie scattering. The less-than-ideal physical qualities of manufactured fibers are the root cause of both issues [33 -34].

3.3.1 Transmission of Information via Rayleigh Scattering in Optical Fibers

Rayleigh scattering is the process that primarily accounts for the intrinsic loss that occurs in the low absorption window that lies between the IR and UV absorption tails. Because random inhomogeneities exist on a scale that is orders of magnitude smaller than the wavelength of the light. When glass is cooled, its lattice structure becomes fixed, resulting in density and compositional differences that cause this refractive index oscillation. Even though improved fabrication can decrease compositional variations, attenuation after Rayleigh scattering is proportional to $1/\lambda^4$ due to changes in the index caused by density fluctuations freezing in. These fluctuations are in almost all directions. Rayleigh scattering is the most common form of a dispersion in glass fibers. In this type of scattering, the wavelength of the dispersed light does not change. When a light wave encounters non-moving, inhomogeneous fluctuations in the refractive index n , a phenomenon known as Rayleigh scattering occurs. These

flaws are maintained at T_f . Because they are caused by random thermal motion in the liquid glass, the scattering process is analogous to how light would scatter from a tiny sphere with a diameter of d and an index of $(n + \Delta n)$, all of which would be buried in a homogeneous medium with an index of (n) . If $(d \ll \lambda)$, an accurate approximation is complex. It has been determined that α_R is

$$\alpha_R = \frac{(\Delta n)^2}{\lambda^4} = \frac{K_B T_f}{\lambda^4} \quad (7)$$

K_B is Boltzmann's constant and $(\Delta n)^2$ The deviation refractive index is the average square of the refractive index. Our eyes are more sensitive to blue light than other colours, so the sky appears blue. The larger the signal's wavelength, the less loss it will experience. For the typical silica SiO₂ glass (which can be made to have a refractive index of 0.8, 0.6, or 0.7), the wavelength is (um).

$$\alpha_R \left(\frac{dB}{km} \right) = \alpha_R = 0.8 \left(\frac{1 \mu m}{\lambda} \right)^4 \quad \text{dB/km} \quad (\text{Silica fiber})$$

- The first opportunity for communication window ($\lambda = 850 \mu m$) $\alpha_R = 1.5 \text{ dB/km}$
- The second opportunity for the telecommunication window ($\lambda = 1.3 \mu m$) $\alpha_R = 0.28 \text{ dB/km}$
- The third opportunity for the telecommunication window ($\lambda = 1.55 \mu m$) $\alpha_R = 0.14 \text{ dB/km}$

For wavelengths longer than 1.55 microns, it is possible to reduce the losses in silica fiber even further. The reason for this phenomenon is that as the wavelength increases, the significance of light absorption through vibrational transitions in the glass material becomes more pronounced compared to Rayleigh scattering. The formation of a V-shaped curve arises due to the interaction between Rayleigh scattering, which occurs at shorter wavelengths, and lattice absorption, which occurs at longer wavelengths. Both of these processes occur at shorter wavelengths. Local minima in attenuation occur at 1.3 and 1.5 microns due to the OH absorption peak at 1.4 microns[35].

3.3.2 The Optical Fiber Communication Mie Scattering

At inhomogeneities around the same size as the guided wavelength, linear scattering is also possible. These result from the waveguide's flawed cylindrical construction and can be caused by defects in the fiber itself, such as variations in diameter, stresses, bubbles, and discrepancies in the core and cladding refractive indices at various locations throughout the fiber's length. Mie scattering refers to the scattering that occurs primarily in the forward direction due to scattering inhomogeneities with a size larger than $\lambda/10$. Depending on the fiber's make-up, It is possible for Mie scattering to generate significant losses in both design and construction. The reduction of inhomogeneity in the product can be achieved to satisfactory levels through enhancements in the processes of glass manufacturing, coating, and extrusion, as well as by augmenting the relative refractive index difference between the coating and the glass.

3.3.3 The Optical Fiber Communication Nonlinear Scattering.

It is crucial to remember that optical waveguides do not always act as perfectly linear channels whose output optical power grows at a constant rate directly proportional to the input optical power. It is imperative to remember that optical waveguides may not consistently function as ideal linear channels. Remembering this knowledge is essential because it is essential to remember optical waveguides. This fact is crucial because optical waveguides don't always act as perfectly linear channels. The consequences of failing to remember this fact are significant. Numerous nonlinear events give rise to notable attenuation due to scattering, most of which are discernible at elevated optical power levels. The observed decrease in intensity is attributed to the phenomenon of scattering, which leads to the dispersion of light. Due to the phenomenon of nonlinear scattering, it is possible for optical power originating from a particular mode to propagate in either the forward or backward direction, affecting the same mode or other modes at varying frequencies. This can happen regardless of whether the modes are in phase or not. This is because the optical power density within the fiber is very sensitive to power levels, becoming significant only when they are far higher than the threshold. Stimulated Brillouin and Raman scattering

are two examples of nonlinear scattering in optical fibers that can only be measured at high optical power densities in extended-mode fibers. This is the case for the majority of nonlinear scattering processes. These scattering mechanisms produce optical gain, although the frequency shift contributes to decreasing light transmission at a given wavelength. On the other hand, it is worth noting that integrated optical techniques can take advantage of such nonlinear events to provide optical amplification [35 -36].

3.3.4 Stimulated Brillouin Scattering in The Optical Fiber Communication

Light can be modulated by heat molecular vibrations within the fiber, and this process is called stimulated Brillouin scattering (SBS). Based on the modulation frequency, the scattering light is divided into two bands, one above and one below the incident light's frequency. The incident photon is split into a scattered photon and a phonon with an acoustic frequency by this scattering mechanism. The optical frequency shifts that occur when a sound wave is scattered depend on the scattering angle, as the frequency of the sound wave changes with the acoustic wavelength. SBS is predominantly a reverse process since the frequency shift is largest while travelling backwards and most diminutive when travelling forward. The importance of Brillouin scattering is discussed, and it is shown that it becomes meaningful only when the power density is beyond a certain threshold. For the sake of argument, let's say that the transmitted light's polarization state is not preserved. Light will be scattered in all directions if the substance's index of refraction, or n , is not perfectly uniform. Rayleigh scattering in glass is nonuniform because of the crystallization of impurities in the liquid. Another nonuniform source of n is an acoustic wave, which causes periodic changes in density and pressure within the material. As a result of the density variation, the material will experience "waves" of different n that travel through it at the speed of sound (V_s). Brillouin scattering is one possible mechanism through which sonic waves disperse light. An alteration in optical frequency is

$$\frac{\Delta V}{V} = \frac{2 \text{ valong ray}}{c/n} = \frac{2n}{c} V_s \sin\theta \quad (8)$$

The incidence angle (θ) and the material's average refractive index (n) are considered. For glass $n = 1.5$ & $V_s = 5 * 10^3$ m/s & $\sin\theta = 1$. $\frac{\Delta V}{V} = 5 * 10^3$ which is for 1500nm. Light corresponds to $\Delta V = 10GHz$ or $\Delta\lambda = 0.075nm$. The intensity of dispersed light resulting from thermal processes is much low for acoustic waves. The acoustic-optic deflector is a viable technique for altering the trajectory of laser beams due to the efficient scattering mechanism exhibited by externally induced sound waves with substantial amplitude. The nonlinearity of Brillouin scattering makes it a significant cause of loss in fibers. This is especially true for narrowband light (where V is less than 10 MHz) [35 -36].

3.3.5 Stimulated Raman Scattering in The Optical Fiber Communication

An analogue of stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS) generates an optical phonon at a high frequency rather than an audible phonon. Stimulated Brillouin scattering, sometimes known as SBS, is the most commonly used term. The optical power threshold of stimulated Raman scattering (SRS) exhibits a potential increase of up to three orders of magnitude compared to the Brillouin threshold. Moreover, SRS is capable of propagating bidirectionally through an optical fiber. The atoms close to one another all move in almost the same direction, making up the collective motion of the acoustic waves. Different kinds of tremors: localized ones, in which atoms in close proximity relocate in opposing directions. This yields simple harmonic motion for motion of modest amplitude, with vibrational frequency f_v provided by equations (9) and (10):

$$f_v = \frac{1}{2\pi} \sqrt{\frac{k}{m_r}} \quad (9)$$

$$m_r = \frac{m_1 m_2}{m_1 + m_2} \quad (10)$$

The conservation of energy applies to Brillouin scattering as well as Raman scattering, therefore the formula for calculating the new (scattered) photon energy, $h\nu^-$ is $h\nu^- = h\nu + hf_v$ Raman shifts. The phenomenon known as Stokes scattering occurs when the frequency of the scattered light drops. The process of anti-Stokes scattering is the polar opposite of Stokes scattering because it reduces the amount of energy that the molecule's vibrations possess to raise the frequency of the light. The fluctuation in temperature induces a concomitant alteration in the

ratio between the probabilities of anti-Stokes scattering and Stokes scattering, resulting in a value below unity. The frequency shift $\nu - \nu$ for Raman scattering is more pronounced compared to Brillouin scattering because of the substantial difference between the localised vibrational frequency ν_v and the average acoustic frequency ν_a . The reason for this phenomenon is attributed to the significantly elevated localised vibrational frequency, denoted as ν_v . The impact of temperature on the ratio between anti-Stokes scattering probabilities and Stokes scattering probabilities is of a magnitude less than unity [35 -36].

3.4 Bending Losses in The Optical Fiber Communication

Whenever there is a bend or curve in the way that optical fibers are going, there is a possibility that radiation loss will occur in the fibers. This is because the energy of the evanescent field at the kink is greater than the speed of light in the cladding. As a direct result, the steering system is hampered, which causes the fiber to emit light energy as a byproduct of the situation. The outer part of the mode needs to move faster than the inner part to maintain the wavefront's perpendicular orientation to the direction of propagation across the bend. In other words, the wavefront must remain perpendicular to its transmitted direction. This means that there must be some component of the mode in the cladding that is capable of travelling at a speed that is greater than the speed of light in that medium. Specifically, this component must be able to move at a speed more considerable than the speed of sound. This is a requirement of the mode. When an optical fiber is bent, the light travelling through it can occasionally divert from the path it was initially intended to take. This results in a loss of power that is being provided by the light that is being guided. The phenomenon that occurs when the light transitions from one direction to another form of guidance is known as mode coupling[37].

3.4.1 The View from Geometrical Optics

If the Ray optics parameter, denoted by R , is too small, the ray will be unguided (c becomes negative). If the amount of ray optics, denoted by $R=a/\Delta$, is insufficient, the coefficient will take on a negative value, and the beam will no longer be directed where it has been presumptively determined that number $\Delta \ll 1$ is the correct response. According to Figure 6, bending loss becomes noticeable for R less than 5 millimeters when the diameter of the core is 100 micrometers and the bending angle is equal to 0.01. Not only is the bend radius a factor in determining the amount of bending loss but also the modes that are now being propagated plays a role. Low-order modes offer more resilience to bending losses and are more stable overall than higher-order modes. The higher-order modes are only slightly stable, and even small deflections quickly destroy them. On the other hand, the lower-order modes are more robust and can withstand more significant amounts of stress [38 -39].

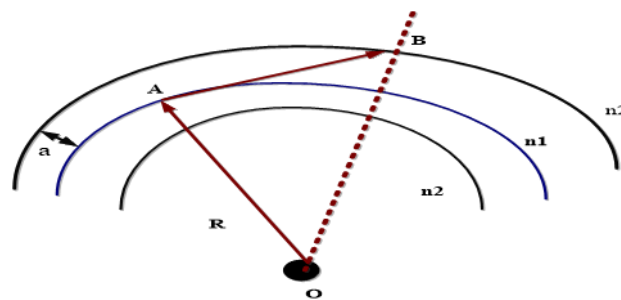


Figure 6 A ray-optics illustration showing light attenuation caused by fiber bending

3.5 The Perspective of Physical Optics

To preserve its shape while traversing the arc, it is imperative for distinct components of the wave to exhibit varying velocities. For the wave to sustain its propagation, this occurrence is crucial. At a specific radial distance, denoted as r_{max} , from the pivot point, it is necessary for the evanescent wave within the cladding to propagate at a velocity greater than the speed of light in the cladding material, symbolised as c/n_2 . Owing to the increased confinement of energy in the evanescent wave, which is a region where energy is dissipated owing to bending, high-order modes exhibit more susceptibility to loss compared to lower-order modes. The reason for the dissipation of energy in the evanescent wave is attributed to its propensity for bending. As a result of the fact that this can no longer be done, the energy that is typically connected with this facet of the mode is being lost in the

form of heat or light. The loss can be modelled the vast majority of the time by making use of a radiation attenuation coefficient, which takes the following form:

$$\alpha_T = c_1 \exp(-c_2 R) \quad (11)$$

R is the radius of curvature of the fiber bend in this equation, while c_1 and c_2 are constants that do not rely on R . In addition, multimode fibers frequently experience significant bending losses when bent at the crucial radius of curvature R_c . The following formula can be used to provide a prediction regarding these bending losses:

$$R_c = \frac{3n_1^2 \lambda}{4\pi(n_1^2 - n_2^2)^{3/2}} \quad (12)$$

It is possible to deduce that the expression shown in equation (12) macro bending losses can be minimized by operating at the shortest possible wavelength and constructing fibers with significant relative refractive index differences. This can be accomplished by designing fibers with significant relative refractive index differences and carrying out operations at the shortest, practically achievable wavelength. The determination of the required radius of curvature for a single-mode fibre can be achieved by employing a formula derived from a theoretical framework based on the concept of a single quasi-guided mode. This can be accomplished by designing fibers with significant relative refractive index differences. The aforementioned criteria pertaining to the mitigation of bend losses are equally applicable to single-mode fibre, as previously delineated. One theoretical framework based on the notion of a solitary quasi-guided mode presents an equation that can be employed to determine the necessary curvature radius for a fibre with a single mode. This radius of curvature can be obtained for single-mode fiber.

$$R_{cs} = \frac{20\lambda}{(n_1 - n_2)^2} (2.748 - 0.996 \frac{\lambda}{\lambda_c})^{-3} \quad (13)$$

Where c is the wavelength light transmission via the single-mode fiber is stopped. Again, this can only be done with a single-mode fiber with a specific cutoff wavelength and relative index difference. As the radius of the bend decreases, so does the critical wavelength of the emitted light [38 -40].

3.5.1 Measurement of Loss due to Bending

The term "macro bending losses" refers to damages incurred due to R-bends that range in size from a few millimeters to a few meters. These losses in a multimode fiber are often relatively small and act mainly on the higher-order modes. Macroscopic bending results in a different kind of spectral attenuation change than microscopic bending. Generally, peaks and valleys are not discernible in macro bending because the cladding does not allow light to travel back into the core. In contrast, microbeads can lead to a different scenario.

3.5.2 Microbending losses micrometer-scale kinks make them trickier to control. Micro bends can arise from various sources that induce crimping or stress on the fibre, such as the storage container. Therefore, every factor that applies such forces possesses the capacity to initiate micro bends. Microbending refers to loss due to highly minor bending or distortion. There is no way to detect such a minute amount of bending. The resulting damage could be attributed to temperature, tension, or crushing changes. Depending on the wavelength of the light being transmitted, the micro-bending of a multimode fiber can cause the spectral attenuation curve to exhibit a sequence of periodic peaks and troughs, increasing attenuation [41].

3.6 The Distortion (Dispersion) in Optical Fiber Communication

Both digital and analogue transmissions suffer from distortion due to the propagation of the transmitted optical signal along optical fibers. Broadening the transmitted light pulses along the channel due to internal dispersion mechanisms is crucial in the widespread adoption of optical fiber transmission using digital modulation. Figure 7 depicts this phenomenon, showing how individual pulses gradually merge into one another and become indistinguishable at the receiver's input as time progresses. With a more pronounced ISI, more errors may occur on the digital optical channel. The error rate is affected by the attenuation of the signal as it travels down the link and the ensuing signal-to-noise ratio (SNR) at the receiver. However, signal dispersion alone with a given optical fiber limits the maximum possible bandwidth to the point where distinguishing between individual symbols

becomes impossible. This is the case when the bandwidth reaches its maximum. The reciprocal of the pulse duration (2τ) after it has been stretched due to dispersion must be less than the digital bit rate, B_T . For there to be no overlapping of light pulses as they travel through an optical fiber link [42 -43].

$$B_T \leq \frac{1}{2\tau} \tag{14}$$

This is based on the assumption that the input pulse duration τ is determined by the pulse broadening generated by dispersion on the channel τ . By solving equation 14, It can make that the maximum bit rate will be no more than $\frac{1}{2\tau}$ For an optical fiber link. If it is assumed that the light pulses at the output have an The utilisation of a Gaussian form, characterised by a root-mean-square width of σ , presents a viable approach to obtaining a more precise estimation of the maximum bit rate achievable across a dispersive optical channel. Suppose the distribution takes on a Gaussian form. This estimate can be found by multiplying the maximum bit rate by the root-mean-square width of the light pulses at the output. This analysis exhibits the ability to withstand a certain degree of signal overlap on the channel without experiencing a decline in the signal-to-noise ratio (SNR), which often happens when the interference between signals gets more pronounced. We can say that to get a rough idea of the top possible bitrate.

$$B_T(\max) \cong \frac{0.2}{\sigma} \text{bits}^{-1} \tag{15}$$

The presence of various dispersive mechanisms within the fibre can result in the manifestation of different pulse forms on the channel. For further information on this topic, see the following; equation 15 provides a reasonably good approximation. Furthermore, it is reasonable to suppose that the impulse response of the channel can be represented by the root-mean-square (rms) value.

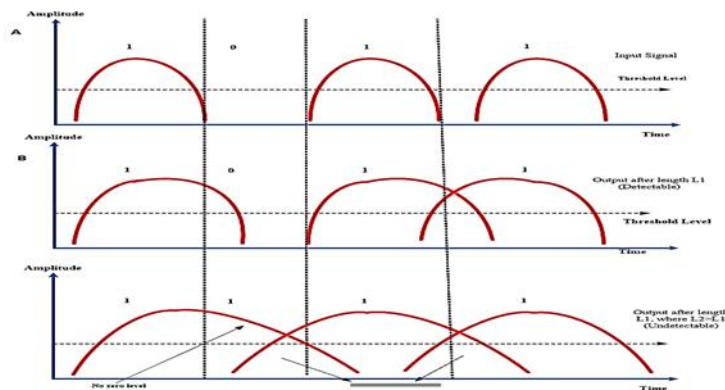


Figure 7 based on the analysis of pulse-dispersion measurements in optical fiber transmission

How the bit rate is converted to hertz also depends on the digital encoding format. As can be seen in Figure 7, Even if it does not reset to zero at the end of the bit period, the binary 1 level stays at its previous value when a nonreturn to zero code is applied. This is because the code does not return to zero. Because each wavelength has two-bit periods, the maximum bandwidth B equals one-half of the maximum data rate. This is because two-bit periods are inside each wavelength (or bits per second per hertz).

$$B_T(\max) = 2B \tag{16}$$

The electrical 3dB point, also known as 1 bit per second per hertz, and $B_T = B$ are the two parameters that determine the typical bandwidth, or B, of metals. The electrical 3dB point can also be written as 1 bit per second per hertz. A representation in the form of a diagram showing the pulse broadening for the three optical fiber topologies most frequently encountered: step index of multimode, graded index of multimode and step index of a single mode. The multimode fiber with the step index transmits a light pulse with tremendous dispersion. Still, the multimode fiber with the graded index has a performance that is much improved.

In conclusion, unlike single-mode fiber, multimode step index fiber is typically only capable of transmitting signals with a bandwidth of a few tens of megahertz at most. On the other hand, the distance between regenerative repeaters for a given optical fiber link limits the bandwidth that can be used. This is because the degree of pulse broadening depends on the distance the pulse travels through the fiber. As optical signals travel through a fiber, they suffer from attenuation mechanisms that cause their strength to weaken and distortion that causes their width to widen. These two elements, throughout some period, will cause an overlap in the pulses of neighbouring neighbours. After a given threshold of overlap, the receiver cannot differentiate between adjacent pulses, which can lead to an incorrect interpretation of the signal that has been received. Various things can contribute to signal weakening, including the Dispersion of higher-order effects, delay of intermodal effects, dispersion of intramodal effects, and dispersion of polarization mode. Observing the guided modes' group velocities provides insight into the origin of these distortions [42 -43].

3.6.1 Intramodal Dispersion or Chromatic Dispersion in Optical Fiber Communication

All optical fibers are susceptible to chromatic or intramodal dispersion due to the limited spectral linewidth of the light source. Examination of the guided modes' group velocities provides insight into the origin of distortions. The signal's propagation time between different spectral components may vary due to the emission characteristics of optical sources. Unlike emitting a single frequency, optical sources emit a range of frequencies. For instance, the injection laser emits a band of frequencies corresponding to a small fraction of the centre frequency. In contrast, the LED emits a band likely to encompass a significant percentage of the centre frequency. This is because optical sources emit a spectrum of frequencies rather than just one. This is because optical sources emit a spectrum of frequencies rather than just one. As a result, each transmitted mode undergoes intramodal broadening. Possible causes for the observed time lags include dispersive properties of the waveguide materials (also known as material dispersion) and guidance effects within the fiber structure (waveguide dispersion). Multimode fibers are the only ones that exhibit simple modal dispersion. The modal delay occurs when the group velocity at a given frequency is not constant across all modes. This effect provides insight into the data-carrying capability of a multimode fiber. Spreading of a pulse across multiple modes in the same signal is called chromatic dispersion. The finite spectral emission width of an optical source causes this broadening. The phenomenon is also known as group velocity dispersion because the group velocity varies as a function of wavelength. This occurs because the function itself induces the dispersion. Because it depends on wavelength, intramodal dispersion's effect on signal distortion develops in proportion to the spectral width of the light source. There are two primary sources of intramodal dispersion. The first is material dispersion; This is due to changes in the core material's refractive index, which depend on the wavelength of the light that is delivered through it. These fluctuations occur when the light is passed through the material. Since a prism has the same effect on a spectrum, dispersing materials is sometimes called "chromatic dispersion." Pulse spreading can occur even at very different wavelengths because the group velocity of any given mode depends on wavelength due to the refractive index. The second reason is that not all optical power travelling through a fiber is contained in the core, which causes the pulses to spread through the waveguide. As the index decreases toward the cladding, the fraction of the light's power that propagates in the cladding moves at a faster rate than the light that remains within the core, causing dispersion. Polarization in its Various Modes In a fiber with a single mode, the light signal energy at a particular wavelength will split between two modes or polarization states that are orthogonal to one another, resulting in dispersion. The phenomenon of material dispersion occurs due to the wavelength-dependent shift in the index of refraction. In order to assess the impact of waveguide dispersion on the spreading of pulses, it is postulated that the refractive index of the material remains constant irrespective of the wavelength. Pulse broadening can also arise from polarisation mode dispersion, which pertains to the impact of fibre birefringence on the polarisation characteristics of an optical signal. This phenomenon can occur when an optical fiber is utilized. This is paramount for long-distance transmission links carrying a large data load. Birefringence phenomena can also be caused by extrinsic factors, such as geometric imperfections of the fiber core or internal tension placed on it [7, 42 -43].

3.6.2 Materials Dispersion in Optical Fiber Communication

Pulse broadening is caused by material dispersion, caused by the varying group velocities of the various spectrum components released from the optical source and launched into the fiber. Material dispersion, in turn, is caused by

the varying group velocities of the various spectrum components. Both of these events take place after the optical source. Dispersion occurs in materials when the refractive index's second differential as a wavelength function is non-zero. A plane wave travelling through a dielectric medium with a phase velocity that is not zero is said to be displaying material dispersion. By taking the optical fiber's group delay τ_g into account, one can calculate the pulse spread caused by material dispersion as given by equation 17. Which of these is the opposite of the group velocity, denoted by v_g .

$$\tau_g = \frac{dB}{dw} = \frac{1}{c} \left(n_1 - \lambda \frac{dn_1}{d\lambda} \right) \quad (17)$$

In this equation, n_1 represents the core material's refractive index. The calculation for the pulse delay τ_m as informed by equation 18, caused by material dispersion in a fiber with a length of L is as follows:

$$\tau_m = \frac{L}{c} \left(n_1 - \lambda \frac{dn_1}{d\lambda} \right) \quad (18)$$

On the other hand, it can be defined in terms of a material dispersion parameter that goes by the name of M , the definition of which can be located in equation 19.

$$M = \frac{1}{c} \frac{d\tau_m}{d\lambda} = \frac{\lambda}{c} \left| \frac{d^2 n_1}{d\lambda^2} \right| \quad (19)$$

3.6.3 Waveguide Dispersion in Optical Fiber Communication

There is also the possibility that the waveguide of the fiber will cause chromatic dispersion. This is a direct consequence of the shift in group velocity as a function of wavelength for a particular mode. This effect is observed for all modes. When looking at it from the perspective of the ray theory, it is the same as the angle between the ray and the axis of the fiber changing with wavelength. This, in turn, causes a change in the time the rays spend in transmission, which results in dispersion. If there is only one mode, the propagation constant can be calculated as follows: is $\frac{d^2 \beta}{d\lambda^2} \neq 0$, The fiber demonstrates waveguide dispersion in its properties. Because the bulk of modes propagates so far away from the cutoff, multimode fibers nearly completely lack the waveguide dispersion that single-mode fibers do. However, even when multimode fibers have waveguide dispersion, it is minimal; it is typically considered to be minimal compared to the dispersion. Because of this, multimode fibers make it possible for the majority of modes to propagate at great distances from the cutoff that is induced by the material (0.1 or 0.2 ns km⁻¹). On the other hand, it is difficult to differentiate between the effects of the various dispersion mechanisms when using single-mode fibres because the fibers only have one mode [44].

3.6.4 Intermodal Dispersion in Optical Fiber Communication

Pulse broadening caused by intermodal dispersion results from changes in the propagation delay experienced by different modes inside a multimode fiber. Intermodal dispersion is commonly denoted as modal or mode dispersion in academic literature. The pulse width at the output of a multimode fibre is contingent upon the transmission times of the slowest and fastest modes, as these modes exhibit differing group velocities while travelling through the channel. The pulse width is proportional to the difference between the slowest and fastest mode transmission times. This particular mechanism for dispersion is responsible for the fundamental difference that can be seen in the total dispersion of the three different fibre types. This is due, in large part, to the fact that the dispersion caused this particular difference. Consequently, multimode fibers with step-index exhibit a significant amount of intermodal dispersion, which brings about the maximum possible broadening of the pulse spectrum. The dispersion of intermodal light in multimode fibers, on the other hand, is something that may be reduced by using a refractive index profile that is optimized. This profile is made possible by most graded index fibers' almost parabolic profile. The nearly parabolic profile offers this profile. In other words, adopting an optimal refractive index profile is the key to reducing intermodal dispersion. As a result, the collective phenomenon of pulse broadening in multimode fibres with a graded index is considerably reduced compared to that observed in multimode fibres with a step-index. This is because the pulse broadening obtained in multimode fibers with a step-index is caused by step-in (in most cases, by a factor of one hundred). Therefore, graded-index multimode fibers offer a significant benefit in terms of bandwidth when utilized with a multimode source. This is compared to step-index multimode fibers, which offer no such benefit. Since there is no intermodal dispersion

when the operation is limited to a single mode, the intramodal dispersion mechanisms can only induce pulse broadening. This is because there is no intermodal dispersion when the operation is limited to a single mode. According to one school of thought, this should occur in single-mode step-index fibers, which limit light transmission to a single mode at a time. Consequently, they exhibit the smallest amount of pulse broadening and have the widest bandwidths that are technically possible. On the other hand, in general, they can only be effectively operated with single-mode sources [41 -43].

3.6.5 Polarization Mode Dispersion in Optical Fiber Communication

Polarisation mode dispersion (PMD) is a recognised phenomenon in optical fibre communications, wherein pulse broadening occurs due to the presence of fibre birefringence. This phenomenon imposes a constraint on the achievable maximum transmission rates in such communication systems. This limit prevents optical fiber communications from achieving higher data transfer rates. The highest data transfer rate that may be accomplished through the use of optical fiber communications is restricted by this limit. Internal and external causes influence the fluctuation in group velocity with polarisation state in produced fibres. Internally, this can be attributed to non-circular fibre core geometry and residual stress in the glass material near the core region. Externally, mechanical loading, bending, or twisting of the fibre also contribute to this effect. Extrinsic variables encompass the application of mechanical loading, bending, and twisting to the fibre. Intrinsic factors encompass the geometric characteristics of the fibre core that deviate from a circular shape.

IV. RELATED WORK

4.1 Carbon Nanotubes (CNTs) in Optical Fiber Communication

Due to their adaptable structure, better performance across a wide range of applications, and faster data transmission rates made possible by exploiting their unique optical properties, carbon nanotubes (CNTs) are quickly becoming an integral part of optical systems. Nonlinear optics has a lot of room to grow thanks to the explosion of nanoscience and nanotechnology. Nonlinear optical (NLO) capabilities have been demonstrated in an increasing variety of nanomaterials, encouraging the development of nano and nano-scale optoelectronic and photonic devices. The chiral vector, which indicates the relative orientation of the tube axis concerning the honeycomb, is the sole parameter that controls the electrical characteristics of single-wall CNTs. Single-wall CNTs can exhibit either semiconductor or metallic behaviour, depending on the value of this parameter. In contrast, the nanotube's diameter determines the size of the electronic band gap in CNTs that act like semiconductors. The electronic band gap of a CNT determines its optical absorption, and its broadband operation results from its widely varying width during manufacture. Materials with high nonlinearity and a fast response time are sought after for roles including optical the physical mechanisms that are responsible for the exceptional optical properties of carbon nanotubes, such as third harmonic generation (THG), the optical Kerr effect, self-focusing, and phase conjugation (CNTs). In this article, we will discuss the manufacturing of CNT-based photonic devices and introduce the key parameters to consider when developing a CNT-based device for various applications. Using CNTs for photonics is an idea that first surfaced in the late '90s. Very soon, the first theoretical investigation into the nonlinear optical features of single-wall CNTs and their highly high third-order nonlinearity began. Since single-wall CNTs are necessary for most photonics applications, we will refer to them as CNTs from here on out. The chiral vector, which specifies the orientation of the carbon atom honeycomb concerning the CNT axis, is the sole parameter that controls the optical properties of CNTs, which are, in turn, tied to their structural and electrical properties. The behaviour of CNTs as either a direct bandgap semiconductor or a metal is determined exclusively by this value [44 -46].

4.2 Optical Code Division Multiplexing in Optical Fiber Communication

Although it was initially developed for radio frequency (RF) communications, optical code division multiplexing (OCDM) has widespread adoption in the optical domain due to its many advantages. OCDM allows channels to access the available bandwidth asynchronously, in contrast to WDM which gives a dedicated wavelength per channel and OTDM, which requires strict synchronization between channels. Therefore, there is room for overlap in each channel's broadcast's time and wavelength domains. In a system like this, multiplexing is accomplished through optical codes. Each transmission channel has its unique optical code imprinted on the

information before it is sent. The optical encoder is subsequently used to apply the channel-specific optical code to the data signal. The channels' data signals are multiplexed into one stream of information before being sent out through the network at different times. Multiple decoders receive identical copies of all incoming data signals at the receiving end. When an aggregate signal is received, a previously recorded version of the encoding vital correlates it with the newly received signal. Those data signals that do not precisely correspond to the decoding code are the ones that are still considered to be incorrectly coded. OCDM is capable of providing a range of functions, including but not limited to asynchronous transmission, soft capacity on demand, secure transmission, and quality of service control. These features are also present in it. OCDM, however, has two primary noise sources that can substantially limit system performance. Misdecoded channels travel through the decoder and are incident on the photodetector, creating multiple access interference (MAI) noise. This MAI can be a bottleneck for system performance as it grows in proportion to the number of channels used. Optical beat noise (OBN) is the outcome of the square law photodetection employed in optical systems and is the second noise source. Given that the photodetector takes in signals from all the channels, the detector's processing of those signals can lead to a frequency-identical beating of the signal of interest [47 -50].

V. CONCLUSION

Voice, video, and telemetry can all be transmitted via this communication method, whether over a short or long distance, over computer networks, or in local area networks. A sizeable portion of the world's telecommunications companies has shifted their focus to optical fiber as the medium for transmitting telephone signals, Internet access, and cable television signals. Optical fiber's ability to reduce a signal's strength is crucial. "fibre loss" also describes "signal loss" in communication. The attenuation of the signal within the fiber places a cap on the maximum distance between a transmitter and a receiver. The number of repeaters needed is also based on the attenuation, and repeater upkeep can be pricey. The ability to resist distortion is yet another crucial aspect of optical fiber. Broadening of the signal pulse as it propagates along the cable. After a specific duration, the wide pulses begin to overlap with one another. This confuses the recipient. Absorption and scattering losses are the primary physical causes of attenuation in optical fibers. Dispersion occurs when light travels along multiple paths, resulting in variable time spent in transit. When travelling along a fiber, light pulses experience a dispersion effect, which causes the pulse to spread in time. The spread of information decreases its throughput. Radiation losses occur when an optical fiber makes a turn or bend in its course. When the speed of light in the cladding is greater than the transient field energy, the guidance mechanism is disabled and light energy is radiated out of the fiber. This results in light energy being radiated. Increases in data rate or transmission bit rate between optical integrate circuit devices and transmission media, improvements in the signal-to-noise ratio of the optical communication system to perform at its capacity, and reductions in bit error rate will all necessitate in the not-too-distant future, the development of a high-capacity system that is based on optical code division multiple access. Carbon nanotubes (CNTs) are more effective at achieving these goals than silicon and thus are better. Numerous commercial photonics solutions utilizing carbon nanotube-based devices have already been implemented. Optical code division multiple access (OCDMA) with carbon nanotubes (CNTs) facilitates ultra-broadband and ultra-high-speed applications thanks to their high third-order nonlinearity susceptibility and fast optical response. Carbon nanotubes (CNTs) in optical communication systems and bioelectronics in medical sets are two areas where OCDMA have made the jump from a material with highly fascinating optical features and promise.

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