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Faculty of Engineering

Department of Electrical and Electronic Engineering

Fiber Optical Communication

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"My Family". They have done a great job to push me through my education period; to my mother and father whose prayers have helped me to keep safe from every dark region of life, and helped me to make my future brighter.

And now, finally I will graduate and I'm very happy to graduate after all of these years. I hope this project proves worthy of your trust and hope that it can be useful for other student to have information they need from it.

Special thanks:

Hayatımdaki en iyi kıza teşekkür etmem gerekir ***"DAL3"***. Bu kız bana yardımcı oldu ve hayatın gerçek anlamını gösterdi. Ve bu kıza onu herkesten çok sevdiğimi söylemek istiyorum. Bu arkadaşıma hayatında mutluluk diliyorum onun için herzaman dua edeceğim. Onunla ömürboyu birlikte olmak istiyordum ama o başka bir kişiyle başka yolu tercih etti.

Kendine iyi bak ve asla unutma, seni ömrüm boyunca bekleyeceğim.

ABSTRACT

In the past years a new technology has become increasingly accepted in the field of communication transmission via cables. In contrast to copper cable technology, here signals are transmitted optically with the aid of optical waveguides also called optical fibers. This development was supported by the availability of suitable semiconductor components such as lasers, light emitting diode, PIN photodiodes and Avalanche Photodiode. Digital transmission systems already in operation were upgraded to meet the demands of optical fiber technology.

This project is intended to make the topic of optical cable technology and plant design understandable to a wider circle of readers. In order to achieve this, physical and chemical contexts are discussed.

CONTENTS

INTRODUACTION

Fiber-optic cable is a networking medium capable of conducting modulated light transmissions. Compared to other networking media, it is more expensive; however, it is not susceptible to electromagnetic interference and is capable of higher data rates than any of the other types of networking media. Fiber-optic cable does not carry electrical impulses, as other forms of networking media that employ copper wire do. Instead, signals that represent bits are converted into beams of light. Even though light is an electromagnetic wave, light in fibers is not considered wireless because the electromagnetic waves are guided in the optical fiber. The term wireless is reserved for radiated, or unguided, electromagnetic waves.

Chapter One: Introductions To Fiber Optical Communication. Discussion the fiber evolution through the past years, optical fiber and other transmission media, the physics of light, fiber optical cable in general, mode of propagation fiber optic cable and the advantages and disadvantages in fiber optical.

Chapter Two: Transducers and Detectors, discussion Fiber optical system, the radiation source in fiber by discussion the LED, LDI, PIN photodiodes and Avalanche Photodiode and the Digital transmission systems.

Chapter Three: Optical fiber cable provides discussion of optical fiber structure, type of cables, cable design choosing cables, connecters, Splicing and couplers.

Chapter Four: Optical Amplifiers & Networks, discussion the Amplifiers system, properties, Applications and Future Developments, Local Area Networks (LANs) and Switches.

1.Introduaction To Fiber Optical Communication:

1.1Introduction:

Fiber optical (optics fibers): are long, thin strands of very pure glass about the diameter of a human hair. They are arranged in bundles called optical cables and used to transmit light signals over long distances [2].

Mankind has always throughout its history had the necessity for communication.Initially communication was done through signals, voice or primitive forms of writing. As time passed by there was a need to communicate through distances, to pass information from one place to another. Many different ways to exchange information over long distances have been used throughout history, some of them exotic such as the use of pigeons and smoke signals. All these methods were the evolutionary steps; which have led to today's modern technologies of long-distance communication. Fiber-optic cable used for networking consists of two fibers encased in separate sheaths. If viewed in cross section, you would see that each optical fiber is surrounded by layers of protective buffer material, usually a plastic such as Kevlar, and an outer jacket. The outer jacket provides protection for the entire cable. Usually made of plastic, it conforms to appropriate fire and building codes [1].

The purpose of the Kevlar is to furnish additional cushioning and protection for the fragile hair-thin glass fibers. Wherever buried fiber-optic cables are required by codes, a stainless steel wire is sometimes included for added strength. The light-guiding parts of an optical fiber are called the core and the cladding [2].

The core is usually very pure glass with a high index of refraction. When the core glass is surrounded by a cladding layer of glass or plastic with a low index of refraction, light can be trapped in the fiber core. This process is called total internal reflection, and it allows the optical fiber to act like a light pipe, guiding light for tremendous distances, even around bends [11].

1.2 The History of Fiber Optics:

Fiber optic technology experienced a phenomenal rate of progress in the second half of the twentieth century. Early success came during the 1950's with the development of the fiberscope. This image-transmitting device, which used the first practical all-glass fiber, was concurrently devised by Brian O'Brien at the American Optical Company and Narinder Kapany (who first coined the term "fiber optics" in 1956) and colleagues at the Imperial College of Science and Technology in London. Early all-glass fibers experienced excessive optical loss, the loss of the light signal as it traveled the fiber, limiting transmission distances [2].

This motivated scientists to develop glass fibers that included a separate glass coating. The innermost region of the fiber, or core, was used to transmit the light, while the glass coating, or cladding, prevented the light from leaking out of the core by reflecting the light within the boundaries of the core. This concept is explained by Snell's Law which states that the angle at which light is reflected is dependent on the refractive indices of the two materials — in this case, the core and the cladding. The lower refractive index of the cladding (with respect to the core) causes the light to be angled back into the core as illustrated in Figure.1.1 [7].

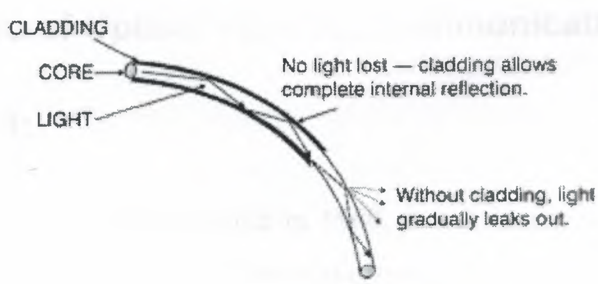

Figure.1.1 optical fiber with cladding.

The basic concept of communication using light has been around for centuries. More recently, applications such as ship-to-ship communications using Morse code was performed using light reflected by mirrors. Alexander Graham Bell even patented an optical telephone system. Methods such as these relied on a direct line of sight and decent weather to ensure visibility. It was not until the invention of the laser in 1960, that light communication, once again, regained interest [2].

In 1966, the first attempts at long distance transmission of light through glass fibers were unsuccessful due to impurities in the glass, which caused high losses of light in the fiber. Many researchers worked on solving the problems of fiber communication, one of which was Charles K. Kao. Kao was convinced that fiber loss could be reduced below 20 decibels per kilometer and a paper detailing his findings was published in 1966. Interested in these findings, the British Post Office spent 12 million pounds for further research, which paid off in 1970 when Corning Glass Works made multimode fibers with a loss below 20 dB/km.

The technology of fiber optics continued to get better over the years, but "it was the development of low-loss fibers with loss coefficients of less than 1 dB/km that has enabled the deployment of high-speed fiber-optic communication systems."

1.3 The Evolution of Optical Fiber for Communication:

1.3.1Background:

When the laser was first demonstrated in 1960, it was immediately recognized as an excellent light source for an optical communications system, assuming that technical development could make it reliable, long-lived, and affordable. Laser light is powerful, nearly monochromatic (i.e., single frequency), coherent (i.e., its light waves travel in phase), and highly directional. Most importantly, light waves are very short (about a millionth of a millimeter). Therefore they correspond to very high frequencies in the electromagnetic spectrum, hence light waves can carry much more information than the electrical pulses used in telephone wires, microwave radio relays, or even the millimeter-waveguide systems then under development in communications laboratories as the next generation in communications systems [11].

Information is carried by modulating the signal waves according to a code, for example, the 0s and 1s (bits) of binary code. Optical waves have a frequency 10^5 (ten thousand) times higher than the high frequency radio waves used in the best coaxial telephone cables, and so their bit rate can be much higher.

Communications companies around the world were constantly on the lookout for higher capacity technologies, because they expected demand to grow strongly for the foreseeable future (not to mention the additional capacity the introduction of AT&T's Picturephone in the 1970s was expected to require). Bell Laboratories, for example, investigated the potential of optical communications in 1945 and again in 1951, and concluded that there was no light source powerful and coherent enough to justify an R&D effort at that time (Fox and Kaminow, 1984:274). Instead, Bell and other telephone enterprises, such as the British Post Office's telecommunications branch, expected to develop millimeter-waveguide systems and put them into service in the 1970s along with satellite communications, supplementing the existing wire, coaxial cable, and microwave radio-relay systems [2].

Like microwave radio, millimeter-waveguide systems were an extension of World War II radar development. Although ultimately proved technically feasible in a field test in 1974, it was clear early on that the stringent degree of circularity and straightness needed in a millimeter waveguide transmission system would make it very difficult and expensive to build and maintain.

However, the work was far from in vain and left a legacy for the future. The knowledge gained in the devices and techniques for high-speed digital systems was invaluable when attention turned to the light-wave medium. The insights gathered on the behavior of multimode guided-wave propagation were important elements in the successful development of low-loss optical fibers.

And, it will be shown, many of the people who worked on millimeter waveguides went on to work on the development of optical fibers in the United States and Great Britain.

As work continued on the laser in the early 1960s, laboratories for communications R&D around the world began to investigate the other key components of a working communications system in addition to the signal source, namely, the signal-carrying medium or channel and the receiver. Receivers in the form of photodiodes already existed and were commercially available. The big barrier was lack of a suitable channel to carry the laser signal .

Beam Waveguides. In 1962-1963, as the problems and limits of the millimeter waveguide became apparent (and because of the lack of a reliable solid-state amplifier at that time), research groups at Bell Telephone Laboratories and ITT's Standard Telecommunications Laboratories Ltd. (STL) in Britain shifted their attention to optical communications. One approach was to use a "light pipe," a hollow tube with a mirrored surface inside to reflect the light beam, but the attenuation or loss of light was too great, especially if the tube was bent, a problem even for point-to-point communications given the curvature of the earth [4].

Researchers at Bell Laboratories investigated the use of a "confocal lens" system to guide the light beam down a tube. A series of glass lenses could keep the beam focused and help bend it around curves. Although the loss of light by each lens due to absorption and scattering might be small, it turned out that the number of lenses needed in real-world conditions (due to the curvature and irregular shape of the earth) added up and the losses required too many amplifiers. In addition, the lenses had to be tied to some sort of sensors and servomechanism system that shifted them to adjust to thermal changes affecting the light beam. Bell's answer was the invention of the gas lens, in which the light rays could be bent with little loss by thermal or density gradients.

Although beam waveguides proved technically feasible in a field experiment, the physical tolerances were extremely close, and the beam was plagued by thermal fluctuations even though the tube was buried in the ground. Like the millimeter waveguide, it was obviously going to be very difficult and costly to build and maintain. At best it was only going to be competitive in uses involving the equivalent of a million voice circuits or more [2].

Optical Fiber. Using glass fibers to transmit light was not a new or untried idea in 1960. British physicist John Tyndall showed that light is guided by a bending water jet in 1854, a demonstration of total internal reflection of light from a boundary with a medium of lower refractive index that is the "underpinning" of optical fibers. In the 1950s, university groups in Britain, The Netherlands, and the United States worked on the development of transparent plastic and glass fibers to use as medical endoscopes.

The idea of cladding the core fiber with a material of slightly lower refractive index to increase the internal reflection of light came out of that work. Soon after (1956), Larry Curtiss, a graduate student at the University of Michigan, created the first clad-glass fiber as part of an endoscope development project. He had been coating optical glass rods from Corning with plastic, with poor results. Curtiss then obtained a glass tube with a lower refractive index than the Corning rods, heated the tube until it collapsed on one of the Corning rods, and drew it into a fiber. It performed well, much better than plastic-clad fibers, and became the basis for the first working fiber-optic endoscope and several patents filed in 1957.

Meanwhile, Will Hicks at American Optical was developing bundles of optical fibers as imagers and as "faceplates" that collect the image from curved tubes on to a flat surface (the military funded the R&D because it wanted to connect image-intensifier tubes in a series to enable soldiers to see better in dim light). Hicks drew finer and finer fibers to increase the detail in the images transmitted by the fiber bundles and began to encounter strange light patterns and colors in individual fibers. Hicks was not trained in electromagnetic theory, and he did not realize he had created single-mode fibers and was perhaps the first person to observe waveguide modes in the visible part of the spectrum. Soon after, Elias Snitzer, a young physicist familiar with electromagnetic theory, was hired by American Optical when, at his employment interview, he recognized the patterns as waveguide modes. He spent several years working out the mode theory for cylindrical dielectric single-mode waveguides. The two articles he published in 1961 were relied on by the later inventors of the first low-loss fiber.

Despite this progress, using optical fibers as the transmission channel for communications did not seem at all promising. The British were the first to investigate it seriously as an alternative to the millimeter waveguide. Although they tried the light pipe and confocal lens systems, such systems would not be very useful in small and built-up Britain, even if their problems could be overcome. Therefore, British researchers were not as put off by the initial finding that attenuation in high-quality optical glass was about 1,000 dB/km, a loss much higher than the 20 dB/km deemed necessary to compete with existing telephone systems in terms of amplifier spacing.

The attenuation problem was substantial, because the amount of light remaining falls logarithmically with distance. A loss of 20 dB/km means that one percent of the light remains; a loss of 1,000 dB/km means that only one part in 10^{100} remains, a vanishingly small amount. The high loss (half the remaining light every meter) was acceptable for endoscopes, faceplates, instrument-panel lighting, and other uses requiring short distances. Most laboratories found the challenge of increasing the clarity of glass so many orders of magnitude too daunting, which is why they tried hollow tubes as transmission channels first.

Antoni E. Karbowiak, who had shifted from heading STL's millimeter-waveguide project to heading the optical systems group in 1962, attributed the problems with confocal lens waveguides to interference and other complications arising from multiple modes. He was familiar with dielectric microwave guides and decided to try to develop a single-mode dielectric optical waveguide, despite the difference in wavelength (several millimeters vs. a thousandth of a millimeter). Karbowiak asked two young engineers, Charles Kao and George Hockham, to find materials clear enough to make low-loss optical waveguides, work they continued after Karbowiak left STL in 1964. Kao and Hockham knew from electromagnetic theory that the best design for an optical fiber would be single-mode waveguide with a very small core and thick cladding that had a refractive index about one percent lower than the core.

The problem was that the material for the core (and also the cladding because a significant amount of the optical power would travel in the latter) had to be much clearer than existing optical glasses. Jeff Hecht emphasizes that Kao approached the problem differently than other researchers. Instead of merely asking what attenuation rates were, he asked what the intrinsic limits of glass were on absorption and scattering of glass were if all impurities, such as transition metal ions (especially iron and copper) and water, were removed. Kao found there was little knowledge in the literature or among the experts he consulted, although an earlier study by Corning's Robert D. Maurer indicated that intrinsic scattering from thermal fluctuations in the density and composition of glass as it cooled could be as low as one dB/km at a wavelength of one micrometer (µm) and even lower at longer wavelengths.

In addition to their theoretical work, Kao and Hockham conducted some empirical investigations of their own on attenuation in different materials, finding losses as low as 0.2 dB/m (200 dB/km) in bulk fused silica between 0.8 and.9 micrometers. They concluded in a paper published in the proceedings of the British Institution of Electrical Engineers in 1966 that if a suitably low-loss material could be developed, a cladded optical fiber could be an important new medium for communications because it would have a larger information capacity and be made of cheaper materials than existing coaxial and radio systems. Most importantly, they saw no fundamental barrier to achieving a low-loss fiber.

The crucial material problem appears to be one which is difficult but not impossible.Certainly, the required loss figure of around 20 dB/km is much higher than the lower limit of the loss figure imposed by fundamental mechanisms.Although most researchers were skeptical, the British Post Office (BPO) along with the British Ministry of Defence began to support work on low-loss fibers at BPO's own laboratory, the University of Southampton, and STL and other companies. BPO also announced its goals-losses less than 20 dB/km , bandwidths of 100 Mbit/sec or more, and low cost-early in 1966, and quoted them to all interested parties, including Corning's UK associate, Electrosil, and William Shaver, a scientist Corning sent around the world looking for opportunities.

Kao continued his attempt to show that low-loss glass was possible. He developed an instrument that could measure losses less than 20 dB/km. He tested samples of bulk fused silica from Corning and Schott and found losses as low as 5 dB/km (Jones and Kao, 1969). That result caused laboratories around the world, including Bell, to begin a serious optical fiber R&D program, if they did not have one already (Hecht, 1997:10-10).

To recap the situation at the end of the 1960s, the laser had been invented and was immediately recognized as the missing light source needed for practical development of optical communications. It was powerful, highly directional, and worked at a single frequency. It was also very amenable to digital coding. Moreover, although the early lasers were far from suitable for practical use in the field, the first semiconductor lasers were developed by 1963 and the outlook for eventually developing continuous wave lasers that worked for long periods at room temperature was good. Indeed, room-temperature semiconductor lasers were demonstrated just a few months after the first low-loss fiber was made.

An optical communications system looked very attractive because it could carry enormous amounts of information. Optical signals are very susceptible to degradation by poor weather and air pollution, and sending laser beams through hollow pipes was going to be difficult and expensive at best. In theory, clad-glass fibers were excellent optical waveguides, but the clearest fibers were still far too opaque to carry detectable light more than a few meters. The British were the first to undertake a serious and sustained investigation of optical fibers for communications, probably because the alternatives, millimeter waveguides and light pipes, were not well suited to their needs.

They conducted a detailed review of what was known theoretically and empirically about material and electromagnetic aspects of optical fibers and did enough experimental work of their own on materials and waveguide models to indicate that optical fibers would probably work and the low-loss materials needed could be developed. After publishing their results with the conclusion that there did not seem to be fundamental obstacles to achieving low-loss optical fibers in 1966, STL researchers continued their basic investigations on materials. They reported in 1968 and 1969 that attenuation in some materials, such as bulk fused silica, was substantially less than believed [16].

1.3.2Breakthrough:

Everyone was aware from Kao's work that pure silica (SiO_2) was the clearest glass system. Everyone else adopted the strategy of purifying compound silicate glasses. The reasons are easy to understand. Pure silica is very difficult to handle because it has to be worked at extremely high melting temperatures (1600 to 1800° C). Compound glasses, made for example by mixing soda and lime with silica, were developed to lower melting temperatures (600-900° C) and make glass easier to work with. The process of drawing fibers was well known from fiberglass manufacturing. Another problem with pure silica was its low refractive index. There was no known material with the lower refractive index required for the cladding [2].

It turned out to be possible to make low-loss fibers with compound glass. The British and Bell Laboratories did it eventually. The British used an innovative double-crucible (actually a crucible within a crucible) apparatus to draw the core and cladding simultaneously. But by then Corning invented a different process for making optical fibers using chemical vapor deposition techniques rather than melting.

The Corning process was more difficult than conventional glassmaking but it became the basis for the standard production of all optical fibers. It proved far superior in reducing loss and optimizing other performance characteristics (e.g., refractive index profile). It also turned out that it could be scaled up to mass-production levels that greatly lowered its cost while preserving its performance.

William Shaver, Corning's traveling scientist, mentioned BPO's interest in optical fiber to Corning's research director, who asked Robert D. Maurer to look into the possibilities. Maurer came to Corning in 1952 after earning a Ph.D. in low-temperature physics from MIT, and became manager of the fundamental physics research group in 1963. He had done the basic work on light scattering in glasses that Kao and Hockham used to conclude that the intrinsic limit on attenuation due to scattering was no more than 1 dB/km at 1 μm. More recently, Maurer had been looking into materials for electronic applications, lasers, and opto-electronic devices [16].

That research would have made him aware that techniques for making extremely pure starting materials for making semiconductors (e.g., $SiCl_4$) were in commercial use that could also be used to make pure or doped silica. Although he did not follow the literature on waveguide behavior (for example, the Corning library did not subscribe to the journal with the Kao and Hockham article), he attended laser conferences where he encountered Eli Snitzer. Snitzer, like Maurer, was trying to make lasers by doping glass with europium (a rare earth), and he introduced Maurer to the waveguide view of optical fibers. Maurer decided to work with pure silica.

Many observers have attributed this in part to his "contrarian" nature, but Maurer's decision suited Corning's position and business strategy. Corning's small size would handicap it in competing head-to-head with the likes of AT&T, ITT, and other big companies in what was likely to be a lengthy brute-force effort to purify compound glasses. Corning's R&D strategy was to look for technological "big hits" or "home runs" that create markets the company could dominate for years, much as light bulbs, fiber glass, Pyrex and Corning Ware, and television bulbs had done before. Besides, Corning already had a great deal of experience with silica. It was the world's leading maker of pure and doped silica mirrors for astronomy telescopes and spy satellites, windows for spacecraft, and ultrasonic equipment for the Navy. Maurer recognized that if Corning could make optical fibers from silica rather than compound glasses, it would have a special advantage in the market.

After some preliminary information gathering and experimentation by Maurer and an MIT graduate student working at Corning for the summer, Maurer decided to assemble a team. He borrowed Peter Schultz, who received his Ph.D. in ceramics from Rutgers in 1967, from Corning's glass chemistry department, and recruited Donald B. Keck, who had just received a Ph.D. in physics from Michigan State [2].

Schultz was the materials expert. He was working on ways to improve Corning's methods of making pure and doped bulk silica. Keck's lead assignment was to develop techniques for coupling light into the fibers and measure their attenuation, dispersion, and other characteristics (Keck interview, 1997). Maurer continued to work on the physics aspects.

Schultz and Keck began with rod-in-tube experiments. In the 1930s, Corning scientist Frank Hyde had invented a chemical vapor deposition process for making virtually pure bulk silica for telescope mirrors. In the early 1940s, Martin Nordberg, another Corning scientist, had improved on the process by adding titanium dioxide as a dopant, which virtually eliminated thermal expansion. Schultz and Keck drilled the tubes from the purest boules of fused silica Corning made at its Canton plant, and the cores from boules of doped silica, to achieve the difference in refractive index needed to make the clad-fiber design work. They was want to heat the silica until hair-thin filaments could be drawn. But the results were poor. They could not avoid creating bubbles and other imperfections at the boundary between the core rod and the cladding tube that scattered a lot of light.

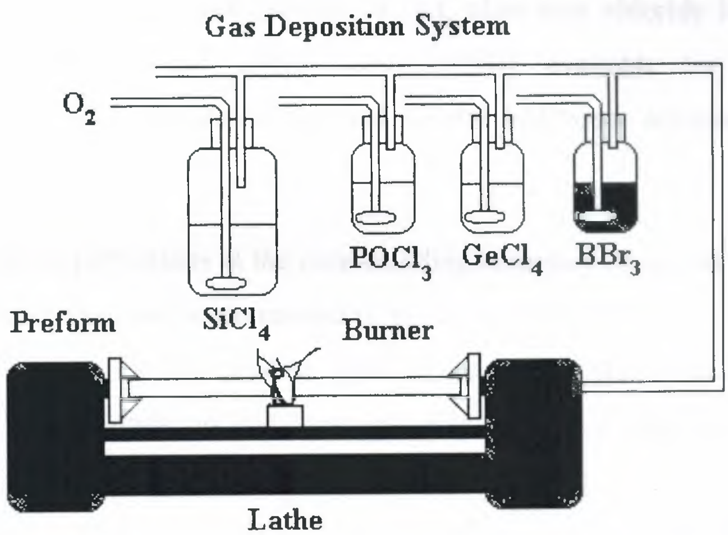

Figure.1.2 MCVD process for making the preform blank.

After a lot of experimentation and brainstorming, Keck thought of sputtering doped silica inside a thick tube. Sputtering is a vapor deposition technique used in making layers of materials in semiconductor chips. Schultz suggested using the "soot" or flame hydrolysis method invented at Corning to make bulk silica to coat the inside of the pure silica tube with titanium-doped silica. Hyde had realized that burning the vapor of the liquid silicon tetrachloride ($SiCl_4$) in the flame of an oxy-hydrogen torch would produce a fine white power or soot of extremely pure silica. If the vapor is fed continuously into the flame, the soot accretes steadily until it forms a large boule. If the boule is heated to near the melting point, it sinters or fuses into a very clear glass. Nordberg showed that the vapors of $SiCl_4$ and $TiCl_4$ could be mixed before burning to create doped silica. Schultz had been trying to improve those processes just before he was tapped for the optical fiber project [12].

Recall that Jones and Kao (1969) determined that bulk fused silica has an attenuation of about 5 dB/km. This is due to several factors that were also key in making low-loss fibers. The process of building up and sintering the soot produces few inhomogeneities that scatter light. The chloride vapors used as the starting materials are pure because they are distilled. The vapor pressure of $SiCl_4$ is much higher than those of unwanted impurities such as iron, copper, and water, and they are left behind. In fact, ultra pure chloride liquids made by multiple distillation steps were already commercially available for semiconductor manufacturing. Chemical vapor deposition had several additional advantages in making optical fibers.

It minimized the imperfections at the core-cladding boundary. It would be easier to use the technique to make the small core needed to make single-mode fiber. To achieve that, he felt, it wasn't enough for the product itself to be unique;Maurer instantly saw that Schultz and Keck's idea would do that. It would give Corning a patented manufacturing process.

Schultz and Keck borrowed a shop vacuum to deposit the soot down the length of the tube the first time. Their equipment soon became more sophisticated, but it was slow going. The initial fibers absorbed a lot of light. The group proceeded empirically, because there was little experimental knowledge and less theory to predict what would happen if they tried this or that. The process did not follow the linear model. Rather, the experimental results drove the research to explain what had happened and why. Hecht describes the process:

They carried out a series of experiments, making preforms, and drawing fibers from them in various ways. They carefully measured the properties of the fibers to see what happened as they changed things. Between experiments, Keck and Schultz analyzed their findings and devised the next round of trials. It was a pattern common to every lab trying to make low-loss fibers: design an experiment, perform it, measure the results, deduce what happened, then design a new experiment.In the spring of 1970, after months of experiments, the group finally figured out how to adjust the materials and the process to achieve a fiber with an attenuation of 16 dB/km.The "915" patent argued that the invention was a completely new and novel approach because of the type of material used: substantially pure fused silica rather than the soft and easily worked compound glasses normally used in the production of optical waveguides. The "262" patent argued that the method of applying a film of material with the optical and physical qualities desired for the core inside a tube of materials with desired qualities for the cladding was a new invention that produced low-loss optical fibers [2].

Maurer et al. wrote a paper for an international conference on trunk telecommunications by guided waves held in London at the end of September 1970 (a revised version was published in Applied Physics Letters). Maurer didn't want to reveal how the low-loss fiber had been made. The papers were ostensibly about radiation losses in some recently made optical fibers and only mentioned in passing that total loss in one fiber was less than 20 dB/km. Moreover, Schultz was not listed as an author, to obscure further that silica had been used. Maurer still got the basic message through. The news shocked the other laboratories, none of which was close to making a low-loss fiber. In addition to the Corning breakthrough, another key event in 1970 was the demonstration of a semiconductor laser that could operate continuously at room temperature by Morton B. Panish and Izuo Hayashi of Bell Laboratories. Although lasers that could meet telephone system standards for ruggedness and reliability were not developed until the late 1970s, these two advances in 1970--low-loss optical fiber and room-temperature semiconductor lasers--may have prevented the implementation of millimeter-waveguide systems. If millimeter waveguides had been built, they might have put off the development of optical fibers for many years.

In 1970, however, Corning's fiber was still a long way from being ready for mass production and field use. As already noted, titanium dioxide made them too brittle. There were many more problems to solve: how to couple light sources into very small cores, how to splice the fibers, how to keep them from breaking, how to make them into cables, and how to connect the cables. In addition to the making optical fibers into practical transmission channels, many advances had to be made in the other components of a communications systems: lasers, modulators, amplifiers, switches, receivers, etc. Progress in the other components affected fiber development in various ways, especially as advances in laser technology made it desirable to design fibersthat work at longer wavelengths (where attenuation and signal dispersion are lowest) [11].

1.4. Light:

1.4.1Theory of light:

The concepts concerning the nature of light have undergone several variations during the history of physic. Until the early seventeenth century it was generally believed that light consisted of a stream of minute particles that were generally emitted by luminous sources. These particles were pictured as traveling in straight lines, and it was assumed that they could penetrate transparent materials but were reflected from opaque ones. This theory adequately described certain large-scale optical effects such as interference and diffraction. The correct explanation of diffraction was given by Fresnel in 1815 [7].

Fresenel showed that the approximately rectilinear propagation character of light could be interpreted on the assumption that light is a wave motion, and that the diffraction fringes could thus be accounted for in detail. Later the work of Maxwell in 1864 theorized that light waves must be electromagnetic in nature [7].

1.4.2 ELECTROMAGNETIC THEORY OF LIGHT:

James Clark Maxwell, a brilliant Scottish scientist Of the middle l9th century, showed, by constructing an oscillating electrical circuit, that electromagnetic waves could move through empty space.

Light eventually was proved to be electromagnetic. Current light theory says that light is made up of very small packets of electromagnetic energy called PHOTONS (the smallest unit of radiant energy). These photons move at a constant speed in the medium through which they travel. Photons move at a faster speed through a vacuum than they do in the atmosphere, and at a slower speed through water than air. The electromagnetic energy of light is a form of electromagnetic radiation. Light and similar forms of radiation are made up of moving electric and magnetic forces and move as waves [5].

Electromagnetic waves move in a manner similar to the waves produced by the pebble dropped in the pool of water. The transverse waves of light from a light source spread out in expanding circles much like the waves in the pool. However, the waves in the pool are very slow and clumsy in comparison with light, which travels approximately 186,000 miles per second. Light radiates from its source in all directions until absorbed or diverted by some substance. The lines drawn from the light source (a light bulb in this instance) to any point on one of these waves indicate the direction in which the waves are moving. These lines, called radii of the spheres, are formed by the waves and are called LIGHT RAYS.

Although single rays of light do not exist, light "rays" as used in illustrations are a convenient method used to show the direction in which light is traveling at any point. A large volume of light is called a beam; a narrow beam is called a pencil; and the smallest portion of a pencil is called a light ray. A ray of light, can be illustrated as a straight line. This straight line drawn from a light source will represent an infinite number of rays radiating in all directions from the source [6].

1.5. THE PHYSICS OF LIGHT:

1.5.1. PHYSICAL OPTICS:

Light is a form of electromagnetic radiation. Like radio waves, microwaves, and other familiar waves used in communications, light is composed of two varying fields-an electric field and a magnetic field (see Figure.1.3). These two fields induce each other and allow light to propagate. The wave model of light is normally simplified to consider a single wave (rather than both the electric and magnetic fields). This simplification leads to the wave equation:

$$Y = A \sin(kx - wt + d) \qquad (1.1)$$

where:

(A):is the Amplitude.

(K):is the wave number.

(d):is the initial phase angle.

(ω): is the angular frequency.

This equation describes a sine wave similar to the wave studied in alternating current (AC) electronics, and it can be used to determine the common properties of waves describe the fundamental properties of the wave although the wave number and angular frequency are generally converted to wavelength and frequency for most wave calculations [4].

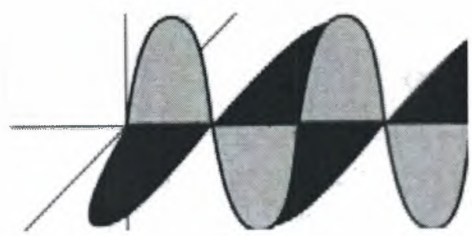

Figure.1.3 Electromagnetic Radiation.

The wave number (k) is related to the wavelength (A) by the equation:

$$k = 2\,p\,/\,l \qquad (1.2)$$

And the frequency (f) is related to the angular frequency (ω) by the equation:

$$w = 2\,p\,f \qquad (1.3)$$

Wave number and angular frequency are useful for writing the equation in its simplest form, but the wavelength and the freq represent actual, physical properties of the wave and are used often in wave calculations [7].

1.5.1.2 Amplitude & Wavelength:

The basic wave properties are summarized in Table 1.1, which also indicates the symbols commonly used to represent them and the base unit used in their measurement. Each wave property is described in detail in the following sections.

The wavelength (λ) is the distance between two like points along the wave, and is usually measured between two peaks. The amplitude (A or E) is the height of the wave and is similar to the peak voltage of an AC signal. Both of these properties are illustrated in Figurte.1.4 [7].

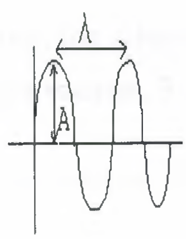

Figure.1.4 Amplitude (A) and Wavelength (A).

1.5.1.2The frequency & velocity:

The frequency and velocity of the wave arise from the motion of the wave. Since the wave is moving, it has a speed or velocity associated with it. The number of wavelengths that pass a fixed point in a second is known as the frequency. The concepts of velocity, frequency, and wavelength can be envisioned by considering a train passing by an intersection. The cars of the train have a certain length (corresponding to wavelength), and the train is traveling at a certain velocity. If you count the number of train cars that pass you in one second, you are measuring the train's frequency.

The train analogy also illustrates the relationship between velocity, wavelength, and frequency. The frequency (number of train cars that pass) is affected by the velocity. If the train moves faster, more cars pass in one second; if the train moves slower, fewer cars pass. In other words frequency and velocity are directly proportional.

Frequency is also affected by wavelength. If each train car is shorter, more cars are able to pass in one second; if each car were longer, fewer cars could pass. The wavelength and the frequency are indirectly proportional [4]. The relationships between wavelength, frequency, and velocity are expressed mathematically as:

$$v = f\lambda \tag{1.4}$$

For most computations, the velocity of light is assumed to be a constant corresponding to the velocity of light in a vacuum, 3×10^8 m/s.

Waves with high frequencies have short wavelengths, whereas waves with low frequencies have long wavelengths. The difference between various types of electromagnetic waves lies in the difference in their wavelength (or frequency). Light waves are high frequency (short wavelength), and radio and TV waves are low frequency (long wavelength). A list of all types of electromagnetic waves in order by frequency or wavelength is known as the electromagnetic spectrum [7].

Table.1.1 Basic Wave Properties.

Wave Property	Symbol	Base Unit
Wavelength	λ	meters
Frequency	v or f	meters
Amplitude	A or E	hertz
Phase	δ	Radians or degrees
Velocity	V	meter /second

1.5.2 OUANTUM OPTICAL:

The principles of quantum optics are based on the theories of quantum mechanics and the structure of the atom. The atom, commonly described as the building block of matter, consists of a central structure called the nucleus which is surrounded by orbiting electrons. The system is somewhat similar to our solar system where the sun is orbited by planets. The nucleus of an atom is composed of two types of particles: the proton, which has a negative charge, and the neutron, which has no charge. The electrons orbiting these particles have a negative charge. The energy level of these electrons is the key to the production of light [7].

Atoms may contain varying amounts of energy depending on their structure. The amount of energy that an atom may contain is quantitized, or limited to specific and discrete amounts. To illustrate this point, consider the makeup of the simplest atom-the hydrogen atom. As shown in(Figure.1.5), the hydrogen atom has a nucleus containing a single proton (no neutrons). Orbiting this nucleus is a single electron. The electron travels around the nucleus; similar to a planet orbiting the sun, but the electron is able to follow one of several possible paths (illustrated by the dotted circles in Figure.1.5). The path (or orbital) the electron chooses depends on the energy state of the atom.

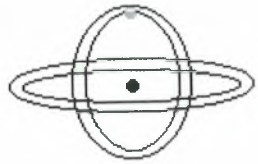

Figure.1.5 The Hydrogen Atom.

The important aspect of the electron orbit is that, although the electron has several possible orbital, it is confined to these orbital and these alone. The electron may use orbital n = 2, 3, 4, etc., but it cannot exist in the areas between. The position of the electron is therefore quantitized.

Since the orbital used by an electron depends on the energy state of the atom, it follows that these energy states must also be quantitized. The atom can, therefore, contain certain specific levels of energy which correspond to certain specific electron orbitals. If energy is supplied to the atom, it will be absorbed in these specific amounts; if energy is released from the atom, it will be released in the same specific amounts.

Exchange of energy by an atom is important to optics since this is how light is produced. Consider an atom which contains its minimum amount of energy (called a ground state atom). Its electron(s) is orbiting close to the nucleus, but if energy were absorbed by this atom, its valence (outermost) electron would be moved to an orbital farther from the atom. After absorbing the energy, the atom is said to be in an excited state.

Atoms do not remain in excited states for very long. After a short time, the atom returns to its ground state by releasing the energy it has absorbed. This released energy is in the form of a particle or packet called a photon, which, depending on the atom and energies involved, could be some form of light. The wavelength of light produced in this manner depends on the amount of energy that the atom absorbed and then released. This relationship is governed by the equation:

$$E = \eta\, l \qquad (1.5)$$

Where:

E: is the Energy.

η: is a constant (known as Planck's constant).

l: is the wavelength.

The relationship between wavelength and energy becomes more significant when it is realized that the energy absorbed and emitted by a particular atom is limited to certain discrete values. Also, the energy values are different for different types of atoms (for example, helium has one set of energies whereas sodium has another). Because of this, we conclude that each type of atom will absorb and emit its own unique group of wavelengths.

Table 1.2 shows some of the wavelengths emitted by common atoms. These emissions can be observed in everyday life by looking at the emissions of known atoms. For example, neon, used in neon signs, emits several bright colors such as red, green, and orange.

Table1.2 Some Emission Wavelengths of Common Atoms.

Range of wavelength (nm)	Name of wavelength	Brightness
404.66	Violet	Faint
447.15	Blue	Bright
501.57	(Blue-green)	Bright
543.00	Green	Faint
546.07	Green	Bright
576.96	Yellow	Bright
632.8-770	Neon (RED)	Bright
More than 770	inferred	Bright

The light that we use it in fiber optical system occupies a wavelength range from (800 to1600)nm. This is falls within the inferred wavelenght.

1.5.3 GEOMETRICAL OPTICS:

The field of geometrical optics, founded on the principle of rectilinear propagation (light travels in a straight line), uses lines (or rays) to illustrate the path that light follows. Two basic concepts are defined in geometrical optics: reflection and refraction. The rules governing the effects of these concepts on the direction that light travels are the fundamental rules of geometrical optics [10].

1.5.3.1 Reflection of Light:

The amount of light reflected depends on the angle α_1 between the incident ray of light and the normal of incidence. Ray of light is used to describe the path is which light energy travels. For the reflected ray and the angle α_2, created by the normal of incidence and the *reflected light ray, the following Figure.1.5 appears that.*

The reflected ray remains in the plane of incidence described by the incident light ray and the normal of incidence, and lines relative to the incident ray on the opposite side of the normal of incidence, and is at same angle to the normal of incidence [7].

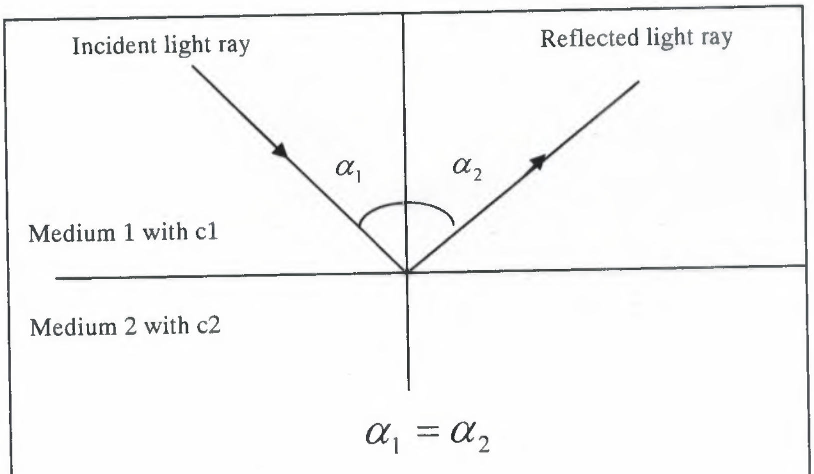

Figure.1.5 Reflection of light.

1.5.3.2 Refraction of Light& Snell's law:

When a ray of light with angle of incidence α enters an optically denser medium (e.g. glass of water) from an optically less dense one (e.g. air), its direction is sent toward an angle of refraction β. In this case of an isotropic medium, i.e. a material or substance that has identical properties in all directions, Snell's law of refraction applies the ratio of the sine of the angle of incidence α to the sine of the angle of refraction β is constant and also identical to the ratio c_1/c_2 of the speeds of light c_1 in the first and c_2 in the second medium as shown in equation (1.6) Fig.1.6 clear the refraction of light.

$$\frac{\sin\alpha}{\sin\beta}=\frac{c_1}{c_2} \qquad (1.6)$$

Where

α: angle of incidence.

β: angle of refraction.

c_1: Speed of light in medium 1.

c_2: Speed of light in medium 2.

With two transparent medium, the one in which the speed of light is slower is described as denser.

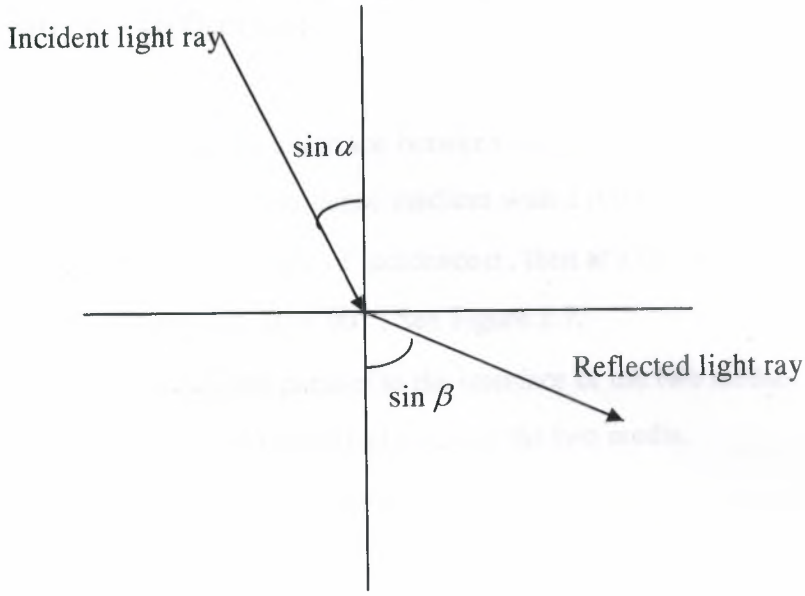

Figure.1.6 Refraction of light.

For the transition from a vacuum (≈air) in which light at the speed of light to a medium with a speed v, the following applies:

$$\frac{\sin\alpha}{\sin\beta} = \frac{c}{v} = n \qquad (1.7)$$

The ratio of the speed of light c in vacuum to the speed of light V in the medium is called the refractive index n (more precisely the phase refractive index) of the respective medium.

The refractive index of vacuum (≈air) n_0 is equal to 1. For two different media with refractive indices n_1, n_2 and their speeds of light c_1 and c_2, the following applies:

$$c_1 = \frac{c}{n_1} \text{ And } c_2 = \frac{c}{n_2} \qquad (1.8)$$

Another form of Snell's law of refraction is derived from that:

$$\frac{\sin\alpha}{\sin\beta} = \frac{n_2}{n_1} \qquad (1.9)$$

The sine of the angle of incidence relative to the sine of the angle of refraction is inversely proportional to their refractive indices.

1.5.3.3 Total Internal Reflection:

When a light ray 1 contacts the interface between an optically dense medium with a refractive index n_1 and an optically less dense medium with a refractive index n_2 at an ever smaller angle, i.e. at an ever higher angle of incidence α, then at a certain angle of incidence α_0 the angle of refraction becomes $\beta_0 = 90^0$. See Figure.1.7.

In this case the light ray 2 propagates parallel to the interface of the two media.

The angle of incidence α_0 is called the critical angle of the two media.

For the critical angle, the following ratio applies:

$$\sin\alpha_0 = \frac{n_2}{n_1} \qquad (1.10)$$

i.e. the critical angle is dependent on the ratio of the refractive indices n_1 and n_2 of the two media.

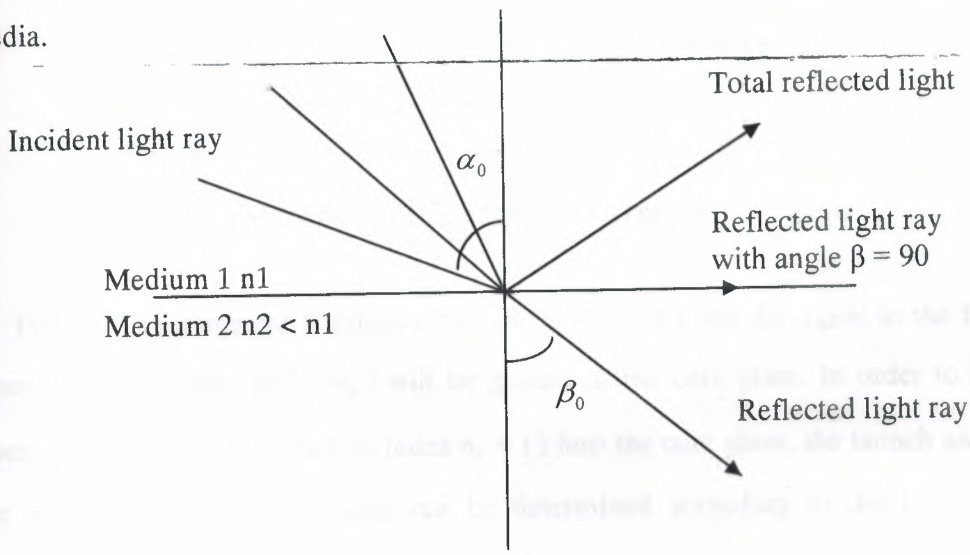

Figure. 1.7 Total internal reflection of light.

For all rays with an angle of incidence α greater than the critical angle α_0 there are no corresponding refracted rays in the optically thinner medium. These light rays are reflected at an interface back into the denser medium. This phenomenon is called total internal reflection. This only occurs at an interface where a light ray propagates from an optically denser niediurn (e.g. glass $n_1 = 1.5$) into an optically less denser medium (e.g. air $n_0 = 1$), never in the reverse case.

1.5.3.4 Numerical Aperture:

The effect if total internal reflection is used in optical waveguides by having "core glass" in the middle of the waveguide with refractive index of n_1 and around it "cladding glass" with a refractive index n_2 with n_1 being slightly higher than n_0. See Figure1.8.

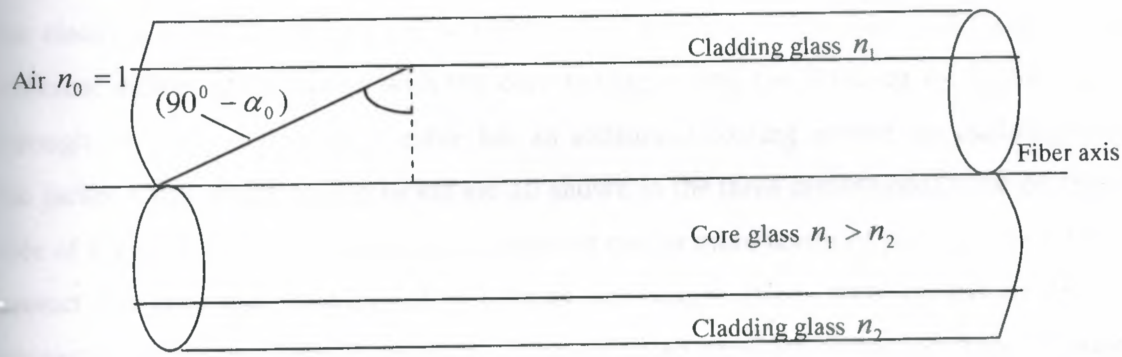

Figure1.8 Light guidance in an optical waveguide.

From the requirement it follows that all rays that are not divergent to the fiber axis by more than the angle $(90^0 - \alpha_0)$ will be guided in the core glass. In order to launch light from outside (air with refractive index $n_0 = 1$) into the core glass, the launch angle between the light ray and the fiber axis can be determined according to the law of refraction equation:

$$\frac{\sin\theta}{\sin(90-\alpha_0)} = \frac{n_1}{n_2} \qquad (1.11)$$

And hence

$$\sin\theta = n_1 \cos\alpha_0 = n_1\sqrt{1-\sin^2\alpha_0} \qquad (1.12)$$

Together with requirements for the critical angle $\sin\alpha_0 = n_2 / n_1$ the result is:

$$\sin\theta = \sqrt{n_1^2 - n_2^2} \qquad (1.13)$$

The greatest possible launch angle θ_{max} is called the acceptance angle of the optical fiber; it in only dependent on the two refractive indices n_1 and n_2. The sine of the acceptance angle is called the numerical aperture NA of the optical fiber (NA= $\sin\theta_{max}$). This quantity has major importance is launching light into the optical fiber.

1.6. Fiber Optic Cable:

Basically, a fiber optic cable is composed of two concentric layers termed the core and the cladding.These are shown on the right side of Figure 1.9. The core and cladding have different indices of refraction with the core having n_1 and the cladding n_2. Light is piped through the core. A fiber optic cable has an additional coating around the cladding called the jacket. Core, cladding and jacket are all shown in the three dimensional view on the left side of Figure 1.9. The jacket usually consists of one or more layers of polymer. Its role is to protect the core and cladding from shocks that might affect their optical or physical properties. It acts as a shock absorber. The jacket also provides protection from abrasions, solvents and other contaminants. The jacket does not have any optical properties that might efect the propagation of light within the fiber cable [13].

The illustration on the left side of Figure 1.9 is somewhat simplistic. In actuality, there may be a strength member added to the fiber optic cable so that it can be pulled during installation.

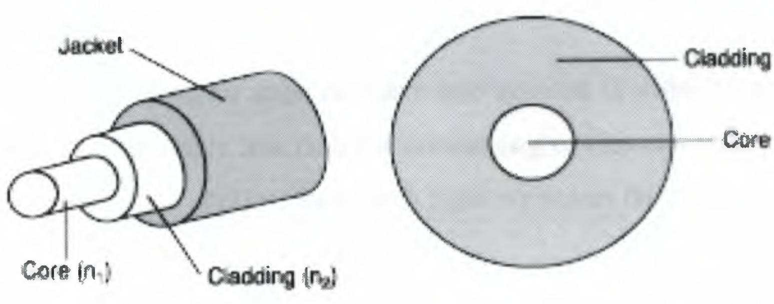

Figure 1.9: Fiber Optic Cable, 3 dimensional view and basic cross section

This would be added just inside the jacket. There may be a buffer between the strength member and the cladding. This protects the core and cladding from damage and allows the fiber optic cable to be bundled with other fiber optic cables. Neither of these is shown.

- How is light guided down the fiber optic cable in the core?

This occurs because the core and cladding have different indices of refraction with the index of the core, n_1, always being greater than the index of the cladding, n_2. Figure 1.9 shows how this is employed to effect the propagation of light down the fiber optic cable and confine it to the core [11].

As illustrated a light ray is injected into the fiber optic cable on the right. If the light ray is injected and strikes the core-to-cladding interface at an angle greater than an entity called the critical angle then it is reflected back into the core. Since the angle of incidence is always equal to the angle of reflection the reflected light will again be reflected. The light ray will then continue this bouncing path down the length of the fiber optic cable. If the light ray strikes the core-to-cladding interface at an angle less than the critical angle then it passes into the cladding where it is attenuated very rapidly with propagation distance.

Light can be guided down the fiber optic cable if it enters at less than the critical angle. This angle is fixed by the indices of refraction of the core and cladding and is given by the formula:

$$Q\chi = \text{arc cos}\,(n_2/n_1). \qquad (1.14)$$

The critical angle is measured from the cylindrical axis of the core. Of course, it must be noted that a light ray enters the core from the air outside, to the left of (Figure 1.10).

The refractive index of the air must be taken into account in order to assure that a light ray in the core will be at an angle less than the critical angle. This can be done fairly simply. The following basic rule then applies. Suppose a light ray enters the core from the air at an angle less than an entity called the external acceptance angle - $Q\varepsilon\xi\tau$ It will be guided down the core. Here

$$Q\varepsilon\xi\tau = \text{arc sin}\,[(n_1/n_0)\sin(Q\chi)] \qquad (1.15)$$

With n0 being the index of refraction of air. This angle is, likewise, measured from the cylindrical axis of the core.

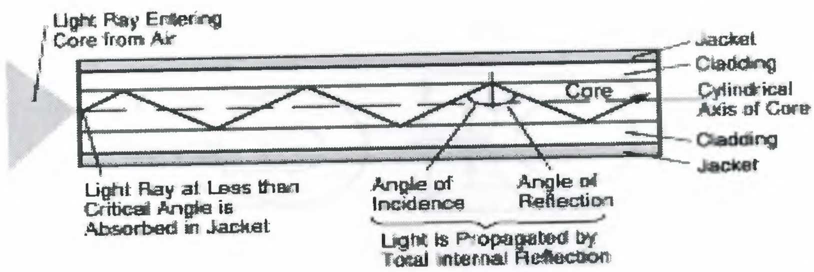

Figure 1.10 Propagation of a light ray down a fiber optic cable

The more light that can be coupled into the core the more light will reach the Receiver and the lower the BER. The lower the attenuation in propagating down the core the more light reaches the Receiver and the lower the BER. The less time dispersion realized in propagating down the core the faster the signaling rate and the higher the end-to-end data rate from source-to-user. Fiber optic cables have exceedingly small diameters. Figure.1.11 illustrates the cross sections of the core and cladding diameters of four commonly used fiber optic cables. The diameter sizes shown are in microns, 10-6 m [11].

To get some feeling for how small these sizes actually are, understand that a human hair has a diameter of 100 microns.

Fiber optic cable sizes are usually expressed by first giving the core size followed by the cladding size. Consequently, 50/125 indicates a core diameter of 50 microns and a cladding diameter of 125 microns; 100/140 indicates a core diameter of 100 microns and a cladding diameter of 140 microns. The larger the core the more light can be coupled into it from external acceptance angle cone. However, larger diameter cores may actually allow too much light in and too much light may cause Receiver saturation problems. The left most cable shown in Fig.1.11, the 125/8 cable, is often found when a fiber optic data link operates with single-mode propagation. The cable that is second from the right in Figure1.11, the 62.5/125 cable, is often found in a fiber optic data link that operates with multi-mode propagation [13].

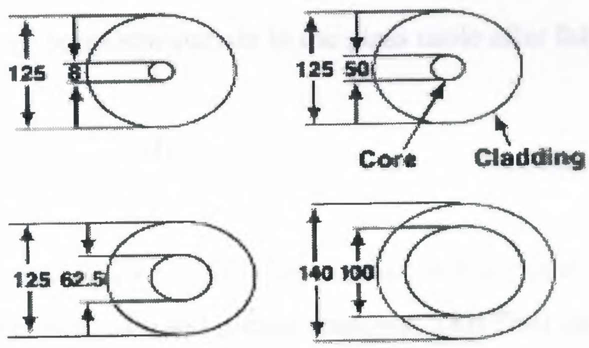

Figure.1.11 Typical core and cladding diameters -Sizes are in microns

Fiber optic cables are of three types:

a. Glass.
b.Plastic.
c.Plastic Clad Silica (PCS).
These three candidate types differ with respect to attenuation and cost.

1.6.1. Glass fiber optic cable:

Glass fiber optic cable has the lowest attenuation and comes at the highest cost. A pure glass fiber optic cable has a glass core and a glass cladding. This candidate has, by far, the most wide spread use. It has been the most popular with link installers and it is the candidate with which installers have the most experience. The glass employed in a fiber optic cable is ultra pure, ultra transparent, silicon dioxide or fused quartz. One reference put this in perspective by noting that "if seawater were as clear as this type of fiber optic cable then you would be able to see to the bottom of the deepest trench in the Pacific Ocean."

During the glass fiber optic cable fabrication process impurities are purposely added to the pure glass so as to obtain the desired indices of refraction needed to guide light. Germanium or phosphorous are added to increase the index of refraction. Boron or fluorine is added to decrease the index of refraction. These residual impurities may increase the attenuation by either scaltering or obsorbing light.

Other impurities may somehow remain in the glass cable after fabrication [11].

1.6.2. Plastic fiber optic cable:

Plastic fiber optic cable has the highest attenuation, but comes at the lowest cost. Plastic fiber optic cable has a plastic core and plastic cladding. This fiber optic cable is quite thick. The core generally consists of PMMA (polymethylmethacrylate) coated with a fluropolymer. Plastic fiber optic cable was pioneered in Japan principally for use in the automotive industry.

It is just beginning to gain attention in the premises data communications market in the United States. The increased interest is due to two reasons. First, the higher attenuation relative to glass may not be a serious obstacle with the short cable runs often required in premise networks. Secondly, the cost advantage sparks interest when network architects are faced with budget decisions. Plastic fiber optic cable does have a problem with flammability. Because of this, it may not be appropriate for certain environments and care has to be given when it is run through a plenum. Otherwise, plastic fiber is considered extremely rugged with a tight bend radius and the ability to withstand abuse [13].

1.6.3. Plastic Clad Silica (PCS):

Plastic Clad Silica (PCS) fiber optic cable has an attenuation that lies between glass and plastic and a cost that lies between their cost as well. Plastic Clad Silica (PCS) fiber optic cable has a glass core which is often vitreous silica while the cladding is plastic - usually a silicone elastomer with a lower refractive index. In 1984 the IEC standardized PCS fiber optic cable to have the following dimensions: core 200 microns, silicone elastomer cladding 380 microns, jacket 600 microns. PCS fabricated with a silicone elastomer cladding suffers from three major defects. It has considerable plasticity. This makes connector application difficult. Adhesive bonding is not possible and it is practically insoluble in organic solvents. All of this makes this type of fiber optic cable not particularly popular with link installers. However, there have been some improvements in it in recent years.

1.7. Mode of propagation fiber optic cable:

There is two types for the mode of propagation fiber optic cable:

- Single-mode.
- Multi-mode.

1.7.1. Single- mode Fiber:

Propagation of more than one mode causes major problems to optical fiber transmission capacity as will be explained later. Hence, it is required to reduce the propagated modes to single one. Reducing the number of modes can be achieved by one or more of the following (from the normalized frequency):

- Reducing the numerical aperture
- Increasing the wavelength
- Reducing the core diameter

Because the amount of light which can be coupled into an optical fiber is very dependent on the numerical aperture, this value should remain as large as possible. On the other hand, it becomes increasingly difficult to build transmitters and receivers for the longer wavelength range; hence the wavelength can not increase. Not to mention that the remaining factor is the core diameter. Actually we reduce this diameter such that we get a single mode optical fiber. The problem here is in the more difficult handling and joining as the diameter is more and more reduced. Therefore, the reduction of the core diameter is limited. On the table 3.2 are set typical dimensions for a single mode fiber [14].

Table 1.3 Typical dimension single mode fiber

Mode field diameter	$2\,w_0$	10μm
Cladding diameter	D	125μm
Core refractive index	n	1.46
Refractive index difference	Δ	0.003 = 0.3%

The term mode field diameter $2\,w_0$ has been introduced to quantify the size (radial field amplitude) of the fundamental mode.

1.7.2. Multi-mode Fiber:

The earlier of fiber types is multimode; it has a constant refractive index of the core. Multimode fiber allows more than one mode to propagate through it. The typical dimensions for a multimode fiber with step-index profile are set in the table 3.1 [14].

Table 1.4 Typical Dimension

Core diameter	2a	100μm
Cladding diameter	D	140μm
Core refractive index	n_1	1.48
Cladding refractive index	n_2	1.46

1.8. Different types of fibers:

We know that the light or the optical signals are guided through the silica glass fibers by total internal reflection. A typical glass fiber consists of a central core glass (50 mm) surrounded by a cladding made of a glass of slightly lower refractive index than the core's refractive index. The overall diameter of the fiber is about 125 to 200 mm. Cladding is necessary to provide proper light guidance i.e. to retain the light energy within the core as well as to provide high mechanical strength and safety to the core from scratches [14]. Based on the refractive index profile we have two types of fibers (a) Step index fiber (b) Graded index fiber.

(a) Step index fiber: In the step index fiber, the refractive index of the core is uniform throughout and undergoes an abrupt or step change at the core cladding boundary. The light rays propagating through the fiber are in the form of meridional rays which will cross the fiber axis during every reflection at the core cladding boundary and are propagating in a zig-zag manner as shown in figure1.12a.

(b) Graded index fiber: In the graded index fiber, the refractive index of the core is made to vary in the parabolic manner such that the maximum value of refractive index is at the centre of the core. The light rays propagating through it are in the form of skew rays or helical rays which will not cross the fiber axis at any time and are propagating around the fiber axis in a helical (or) spiral manner as shown in figure.1.12b.

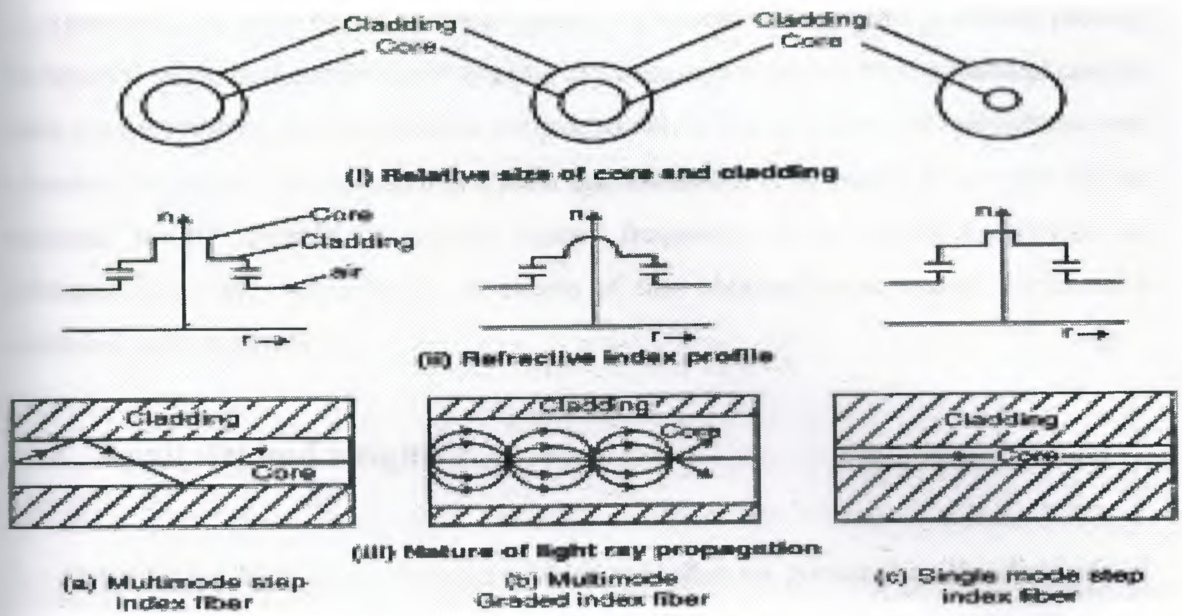

Figure1.12. Different types of fibers.

1.9. Advantages and Disadvantages for Fiber Optical Communication:

1.9.1 Advantages for optical communication system:

1. **Enormous potential bandwidth:**

The optical carrier frequency in the range 10^13 to 10^16 Hz (generally in the near infrared around 10^14 Hz or 10^5 GHz)yields a far greater potential transmission bandwidth than metallic cable systems (i.e. coaxial cable bandwidth up to around 500 MHz)or even millimeter wave radio systems (i.e. systems currently operating with modulation bandwidths of 700 MHz).at present ,the bandwidth available the fiber systems is not fully utilized but modulation at several giga hertz over a few kilometers and hundreds of megahertz over tens of kilometer without intervening electronics (repeaters)is possible.

Therefore , the information carrying capacity of optical fiber systems is already proving far superior to the best copper cable systems .By comparison the losses in wideband coaxial cable systems restrict the transmission distance to only a few kilometers at bandwidths over a hundred megahertz .Moreover, it is certain that the usable fiber system bandwidth will be extended further towards the optical carrier frequency in the future to provide an information-carrying capacity far in excess of that obtained using copper cables or a wideband radio system[10] .

2. Small size and weight:

Optical fiber have small diameters which are often no greater than the diameter of human hair. Hence, even when such fiber is covered with the protective coatings they are far smaller and much lighter than corresponding copper cables. This is a tremendous boon towards the alleviation of duct congestion in cities, as well as allowing for an expansion of signal transmission within mobiles such as aircraft, satellites and even ships.

3. Electrical isolation:

Optical fibers which are fabricated from glass or sometimes a plastic polymer are electrical insulators and therefore, unlike their metallic counterparts, they do not exhibited earth loop and interface problems. Furthermore, this property makes optical fiber transmission ideally suited for communication in electrically hazardous environments as the fiber create no arcing or spark hazard at abrasions or short circuits.

4. Immunity to interference and crosstalk:

Optical fibers from a dielectric waveguide and are therefore free from electromagnetic interference (EMI).

Radiofrequency interference (RFI), or switching transients giving electromagnetic pulses (EMP) .Hence the operation of an optical communication system is unaffected by transition through an electrically noisy environment and the fiber cable requires no shielding from EMI .The fiber cable is also not susceptible to lightning sticks if used overhead rather than underground. Moreover, it is fairly easy to ensure that there is no optical interference between fibers and hence, unlike communication using electrical conductors, crosstalk is negligible, even when many fibers are cabled together.

5. Signal security:

The light from optical fibers does not radiate significantly and therefore they provide a high degree of signal security .Unlike the situation with copper cables, a transmitted optical signal cannot be obtained from a fiber in a non-invasive manner (i.e. without drawing optical power from the fiber).Therefore, in theory, any attempt to acquire message signal transmitted optically may be detected. This feature is obviously attractive for military, banking and general data transmission (i.e. Computer network) applications.

6. Low transition loss:

The development of optical fibers over the last 32 years has resulted in the production of optical fiber cables which exhibit very low attenuation or transmission loss in comparison with the best copper conductors. Fiber fibers have been fabricated with losses as well as 0.2dB km-1 and this feature has become a major advantage of optical fiber communications. It facilitates the implementation of communication links with extremely wide repeater spacing (long transmission distances without intermediate electronics),thus reducing both system cost and complexity .Together with the already proven modulation bandwidth capability of fiber cable this property provides a totally compelling case for the adoption of optical fiber communication in the majority of long-haul telecommunication applications.

7. Ruggedness and flexibility:

Although protective coatings are essential, optical fibers may be manufactured with very high tensile strengths .Perhaps surprisingly for a glassy substance, the fiber may also be bent to quit small radii or twisted without damage. Furthermore, cable structures have been developed which have proved flexible, compact and extremely rugged. The size and weight advantage into account, these optical fiber cables are generally superior in terms of storage, transportation, handling and installation than corresponding copper cables whilst exhibiting at least comparable strength and durability.

8. System Reliability and Ease of Maintenance:

These features primarily stem from low loss property of optical fiber cables which reduces the requirement for intermediate repeaters or line amplifiers to boost the transmitted signal strength.

Hence with fewer repeaters, system reliability is generally enhanced in comparison with conventional electrical conductor systems. Furthermore, the reliability of the optical components is no longer a problem with predicted lifetimes of 20-30 years now quite common .Both these factors also tend to reduce maintenance time and cost.

9. Potential low cost:

The glass which generally provides the optical fiber transmission medium is made from sand –not a scarce resource .So, in comparison with copper conductors, optical fibers offer the potential for low cost line communication .As yet this potential has not been fully realized because of the sophisticated, and therefore expensive, processes required to obtain ultra-pure glass, and the lack of production volume.

At present, optical fiber cable is reasonably competitive with coaxial cable, but not with simple copper wires (e.g. twisted pairs).However it is likely that in the future it will become as cheap to use optical fiber with their superior performance as almost any type of electrical conductor.

Moreover, overall system costs when utilizing optical fiber communication on long-haul links are generally reduced to those of for equivalent electrical line systems because of the low loss and wideband properties of the optical transmission medium .As indicated in (6),the requirement for intermediate repeaters and the associated electronics is reduced ,giving a significant cost advantage .However ,although this cost benefit gives a net gain for long-haul links this is not usually the case in short-haul applications where the additional cost incurred ,due to the electrical –optical conversion (and vice versa),may be a deciding factor .Nevertheless ,there are other possible cost advantage in relation to shipping, handling, installation and maintenance, as well as the features indicated in (3)and(4)which may prove significant in the system choice.

The low cost potential of optical fiber communication not only provides strong competition with electrical line transmission systems .Although these systems are reasonably wideband the relatively short span 'line of sight' transmission necessitates expensive aerial towers at intervals no greater than a few tens of kilometers.

Many advantages are therefore provided by the use of a light wave carrier within a transmission of optical fiber .The fundamental principles giving rise to these enhanced performance characteristics, together with their practical realization, however, a general understanding of the basic nature and properties of the light will be known by backing to the references about physics.

1.9.2 Disadvantages for fiber optical communication system:

A disadvantage of the fiber-optic system is it's incompatibility with the electronic hardware systems that make up today's world. This inability to interconnect easily requires that current communication hardware systems be somewhat retrofitted to the fiber-optic networks. Much of the speed that is gained through optical fiber transmission can be inhibited at the conversion points of a fiber-optic chain. When a portion of the chain experiences heavy use, information becomes jammed in a bottleneck at the points where conversion to, or from, electronic signals is taking place [10]. Bottlenecks like this should become less frequent as microprocessors become more efficient and fiber-optics reach closer to a direct electronic hardware interface.

- Disadvantages for fiber optical communication:

1. Interfacing Cost
2. Strength, weaker than coax.
3. Remote electric power requires metallic cables.
4. Unproven because they are so new.
5. Specialized tools and training are required to splice and repair.

2. TRANSDUCERS AND DETECTORS:

2.1. Fiber-Optical system:

The optical fiber system consists of the transmitter, the receiver and the optical fiber itself shown in figure 2.1.

Fiber optics system consists of three main components: the optical transmitter, the optical receiver, and the optical fiber cable. Just like any other cable connection, in a fiber optics system, the transmitter sends data to the receiver through the cable. The difference between fiber optics systems and conventional cable connections is that fiber optics systems use photons from light to transmit information rather than electrons.

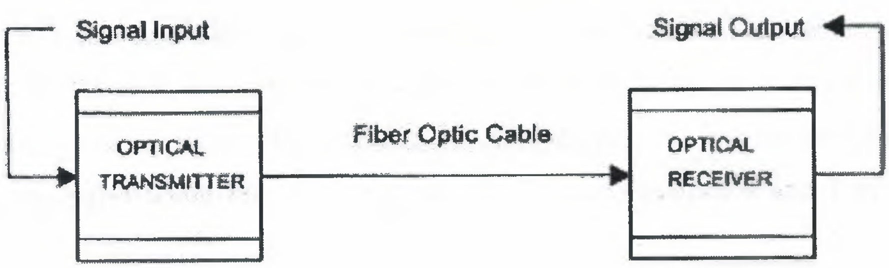

Figure2.1 Optical fiber system

2.1.1. Transmitter:

Optical transmitters can be:

- Laser Diode (LDs).
- Light Emitting Diodes (LEDs)

The optical transmitter of a fiber optics system receives information from another source and converts the information into light, which the transmitter sends. The light used in an optical transmitter can come from either a LED or a laser. LED's are less expensive than lasers and easier to maintain. Unlike lasers, the light a LED produces does not vary drastically with changes in the temperature or electric input. Lasers, however, make better transmitters. Lasers can send data faster and over farther distances than LED's because lasers have a small light emitting area and has the property of light output varying linearly with electrical current input. While LED's have data rates of 200 million bits per second, lasers have data rates of 1 to 2 billion bits per second. Because of the different characteristics of LED's and lasers, LED's are used for slow, short-distance transmissions, and lasers are used for fast and long-distance transmissions.

An optical transmitter can send data in two ways: analog and digital. Using an LED and changing the LED's brightness would be an analog method for a fiber optics system. Digital modulation can be implemented with on/off modulation - 0 if the light is off and 1 if the light is on. Pulse width modulation is another form of digital modulation. One width of pulse can be set as 0, and a different width of pulse can be set as 1. A variation of pulse width modulation is pulse rate modulation. Also digital, pulse rate modulations uses a constant the pulse width but alters the rate of pulse and assigns 0 and 1 to the different rates.

2.1.2. Receiver:

Optical receivers can be:

- PIN photodiodes
- Avalanche photo diodes (APDs).

An optical receiver reverses the process of an optical transmitter. Light is converted into electrical data. An optical receiver consists of a light detector, which converts light into electric signals. An example of a light detector would be a solar cell. Solar cells convert light into electricity, but because the conversion in a solar cell is slow, solar cells are not used in fiber optics. Typical optical receivers use a reverse-biased light detector.

2.1.3. Optical fiber itself:

An optical fiber cable in fiber optics system consists of three concentric layers:

- The core.
- The cladding.
- The buffer coating.

The buffer coating surrounds the cladding, and the cladding surrounds the core. In an optical fiber, light remains inside the core. The light remains inside the core because the index of refraction of the cladding is larger than the index of refraction of the core. Because of the difference in the index of refraction, a wave of light attempting to exit the core refracts back into the core. Protecting the core and cladding from the environment is the only purpose of the buffer coating.

The core and cladding are made out of glass, while the coating is made out of PVC. The core and cladding can be made out of plastic, but light refracts better with glass. Plastic optical fibers are only used for non-data transmitting purposes. There are two basic types of optical fibers: multimode and single-mode. Multimode fibers have a 62.5 microns core and are used with LEDs with wavelengths from 850-1300 nm, and single-mode fibers have a 9 microns core and are used with lasers with wavelengths of 1300-1550 nm. Used with a laser and able to carry higher wavelength, single-mode fibers are faster than multimode.

2.2. Radiation Sources:

2.2.1. Light-Emitting Diode (LED):

Light emitters are a key element in any fiber optic system. This component converts the electrical signal into a corresponding light signal that can be injected into the fiber. The light emitter is an important element because it is often the most costly element in the system, and its characteristics often strongly influence the final performance limits of a given link.

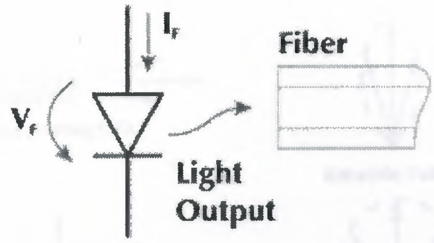

Figure.2.2 LEDs Convert an Electrical Signal to light.

LEDs are complex semiconductors that convert an electrical current into light. The conversion process is fairly efficient in that it generates little heat compared to incandescent lights.

LEDs are of interest for fiber optics because of five inherent characteristics:

1. they are small.
2. They possess high radiance (i.e., they emit lots of light in a small area).
3. the Emitting area is small, comparable to the dimensions of optical fibers.
4. They have a very long life, offering high reliability.
5. They can be modulated (turned off and on) at high speeds.

2.2.1.1. Light Emitter Performance Characteristics:

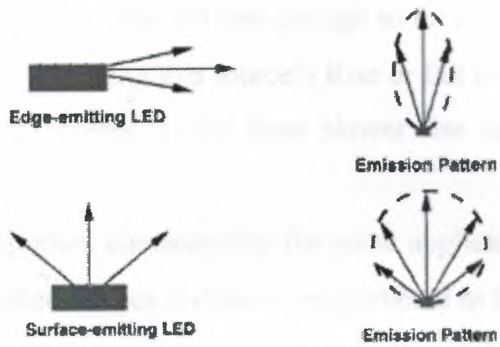

Figure.2.3. LED Structures

Several key characteristics of LEDs determine their usefulness in a given application. These are:

Peak Wavelength: This is the wavelength at which the source emits the most power. It should be matched to the wavelengths that are transmitted with the least attenuation through optical fiber. The most common peak-wavelengths is 780,850 and 1310 nm

Spectral Width: Ideally, all the light emitted from an LED would be at the peak wavelength, but in practice the light is emitted in a range of wavelengths centered at the peak wavelength. This range is called the spectral width of the source.

Emission Pattern: The pattern of emitted light affects the amount of light that can be coupled into the optical fiber. The size of the emitting region should be similar to the diameter of the fiber core.

Power: The best results are usually achieved by coupling as much of a source's power into the fiber as possible. The key requirement is that the output power of the source be strong enough to provide sufficient power to the detector at the receiving end, considering fiber attenuation, coupling losses and other system constraints.

Speed: A source should turn on and off fast enough to meet the bandwidth limits of the system. The speed is given according to a source's Rise or fall time, the time required to go from 10% to 90% of peak power. LEDs have slower rise and fall times than lasers.

Linearity is another important characteristic for some applications. Linearity represents the degree to which the optical output is directly proportional to the electrical current input. Most light sources give little or no attention to linearity, making them usable only for digital applications. Analog applications require close attention to linearity. Nonlinearity in LEDs causes harmonic distortion in the analog signal that is transmitted over an analog fiber optic link.

LEDs are found in a wide variety of consumer electronics products. LEDs are used as visible indicators in most electronics equipment widely used in compact.

The LEDs used in fiber optics differ from the more common indicator LEDs in two ways:

1. the wavelength is generally in the near infrared (because the optical loss of fiber is lowest at these wavelengths).
2. The LED emitting area is generally much smaller in order to allow the highest possible modulation bandwidth and improve the coupling efficiency with small core optical fibers.

2.2.1.2. LED Type:

There are two basic types of LED structures: Edge Emitter and Surface Emitters.

a. Edge Emitter:

Edge emitters are more complex and expensive devices, but offer high output power levels and high speed performance. The output power is high because the emitting spot is very small, typically 30-50 μm, allowing good coupling efficiency to similarly sized optical fibers. Edge emitters also have relatively narrow emission spectra. The full-width, half-maximum (FWHM) is typically about 7% of the central wavelength.

b. Surface Emitter:

Surface emitters have a comparatively simple structure, are relatively inexpensive, offer low-to-moderate output power levels, and are capable of low-to-moderate operating speeds. The total LED chip optical output power is as high as or higher than the edge-emitting LED, but the emitting area is large, causing poor coupling efficiency to the optical fiber. Adding to the coupling efficiency deficit is the fact that surface-emitting LEDs are almost perfect Lambertian emitters. This means that they emit light in all directions. Thus very little of the total light goes in the required direction for injection into an optical fiber.

2.2.1.3. LED Drive Circuits:

LED optical output is approximately proportional to drive current. Other factors, such as temperature, also affect the optical output. Figure.2.4; shows in greater detail the typical behavior of an LED. Two curves are shown. The top curve represents a 0.1% duty cycle with the peak current as shown on the horizontal axis. The bottom curve shows the output with 100% duty cycle. Note the light versus current curve droops below the linear curve.

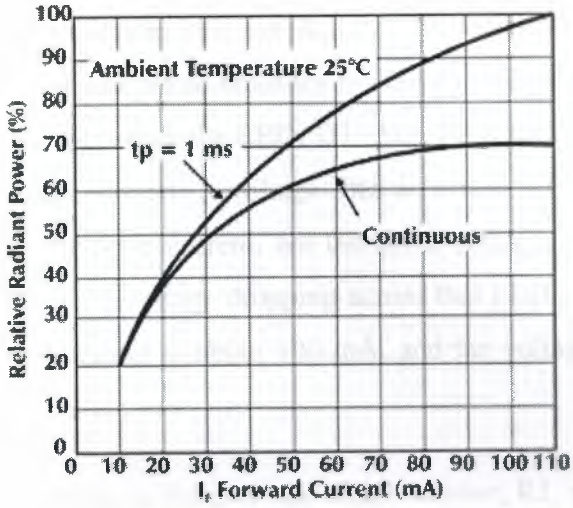

Figure.2.4. Optical Output vs. Current in a LED.

LEDs are usually driven with either a digital signal or an analog signal.

A. Analog LED Driver Circuits :

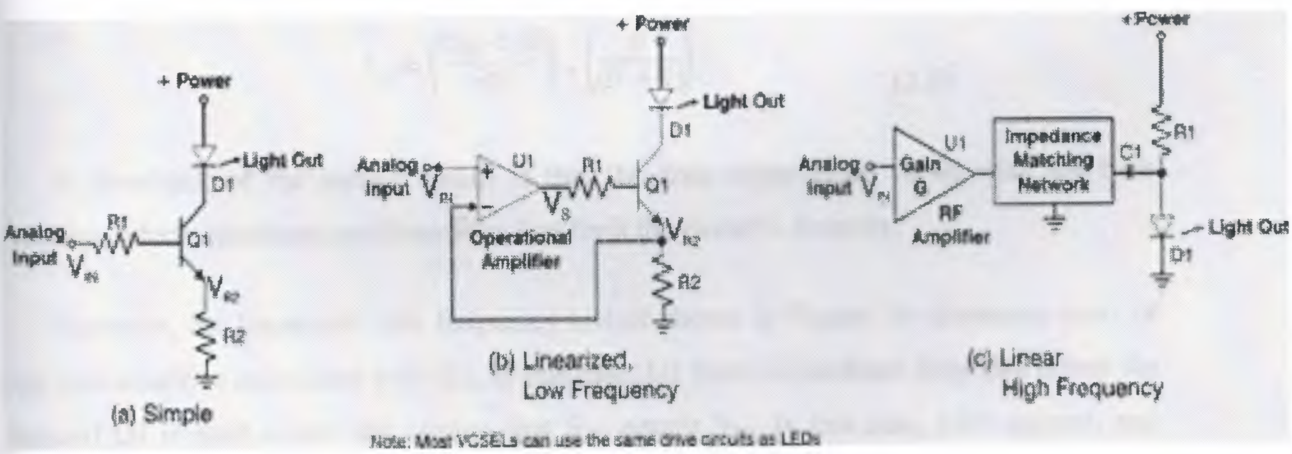

Figure.2.5 shows three configurations for analog LED drive circuits.

Circuit in figure.2.5a illustrates the simplest of the three configurations. It uses a transistor, Q1, and a limited amount of resistors to convert an analog input voltage into a proportional current flowing through the LED, D1. Also referred to as a transconductance amplifier, this configuration converts a voltage into a current. In LEDs, the light output equates proportionally to the drive current, not the drive voltage. While the drive current varies, this circuit illustrates the voltage dropping across that LED and remaining constant. LEDs exhibit a peak drive current at about 100 mA, and the voltage drop is typically 1.5 Volts.

Circuit in figure.2.5a works as follows: the small resistor, R1, prevents oscillations in Q1. The input voltage, V_{IN}, appears on the base of Q1. V_{R2} is the voltage at the emitter of Q1, and it equals the base voltage minus 0.6 Volts. Since these base and emitter voltages only differ by a DC offset voltage, the AC portion of the base equals that of the emitter. The emitter voltage V_{R2} causes a current equal to $V_{R2}/R2$ to flow through R2. Due to the nature of transistors, the Q1 collector current approximately equals the Q1 emitter current. (To be precise, the collector current equals $\beta/(\beta+1)$ times the emitter current. The transistor current gain, β, is usually 10 to 100.) Collectively, we find that the LED current, and thus the output light, relates to the input voltage V_{IN} as follows:

$$I_{D1} = \left(\frac{V_{IN}-0.6}{R2}\right) \cdot \left(\frac{\beta}{\beta+1}\right) \qquad (2.1)$$

A drawback of the simple circuit is that the base capacitance varies with the base voltage, which introduces nonlinearities that limit the circuit's linearity.

However, the linearized, low frequency circuit shown in Figure 5b eliminates most of the nonlinearities associated with Q1. In this case, U1 forms a feedback loop that drives the base of Q1 in such a way that assures that V_{R2} equals V_{IN}. In this case, LED current, and thus the output light, relates to the input voltage V_{IN} as follows:

$$I_{D1} = \left(\frac{V_{IN}}{R2}\right) \cdot \left(\frac{\beta}{(\beta + 1)}\right) \qquad (2.2)$$

The circuit shown in Figure.2.5b still experiences some lesser nonlinearities associated with Q1, but these do not represent the limiting factor. The circuit is limited by the delay associated with the feedback signal in the servo loop formed by U1, allowing the circuit to only achieve a bandwidth of about 10-100 MHz. This limitation makes the circuit in Figure 2.5b work well in application transmitting DC coupled analog signals.

Figure.2.5c shows the highest performance analog LED drive circuit. In this case, resistor, R1 supplies the DC current through D1. Sometimes, a constant current source or a network that includes temperature compensation replaces R11. A wideband RF amplifier, U1, serves two purposes. First it amplifies V_{IN} to allow the use of a small input signal. Second, it isolates the LED from the input circuit, allowing precise impedance matching at the input, V_{IN}, which reduces reflections. The output of U1 is usually 50 Ohms or 75 Ohms. A typical LED may have an input impedance ranging from 5 Ohms to 10 Ohms. An impedance matching network is inserted between the amplifier and D1. Furthermore, capacitor, C1, serves to block any DC level associated with the output of the matching network. This circuit will drive LEDs to their highest possible frequencies. Circuit 5c usually delivers the highest possible linearity. In this case, the LED, D1, usually limits performance.

b. Digital LED Drive Circuits:

When the drive signal is digital, as illustrated in Fig.2.6, there is no concern about LED linearity. The LED is either on or off. There are special problems that need to be addressed when designing an LED driver. The key concern is driving the LED so that the maximum speed is achieved. Figures2.6a,2.6b, and 2.6c show three popular digital LED driver circuits. The first circuit, shown in Figure2.6a, is a simple series driver circuit. The input voltage is applied to the base of transistor Q1 through resistor R1. The transistor will either be off or on.

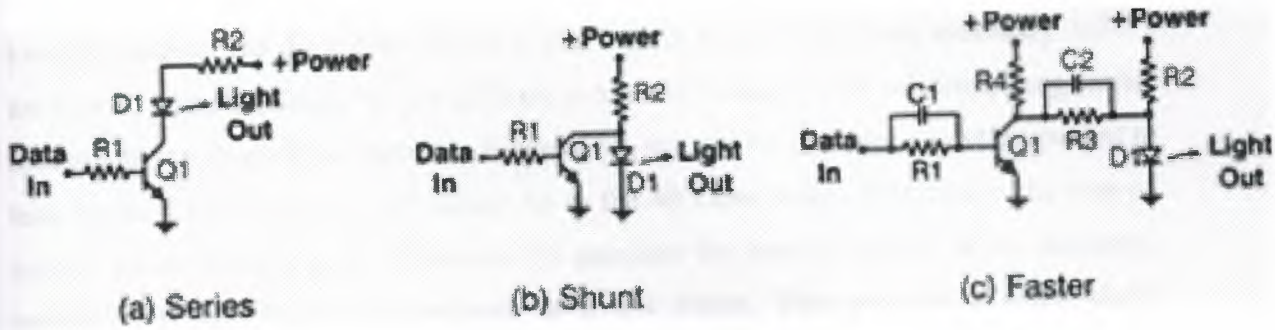

Figure2.6. Digital LED Drive Circuits.

When transistor Q1 is off, no current will flow through the LED, and no light will be emitted. When transistor Q1 is on, the cathode (bottom) of the LED will be pulled low. Transistor Q1 will pull its collector down to about 0.25 Volts. The current is equal to the voltage across resistor R2 divided by the resistance of R2. The voltage across R2 is equal to the power supply voltage less the LED forward voltage drop and the saturation voltage of the drive transistor. The key advantage of the series driver shown in Figure 2.6a is its low average power supply current. If one defines the peak LED drive current as I_{LEDmax} and assumes that the LED duty cycle is 50%, then the average power supply current is only $I_{LEDmax}/2$. Further, the power dissipated is $(I_{LEDmax}/2)\bullet V_{SUPPLY}$ where V_{SUPPLY} is the power supply voltage. The power dissipated by the individual components, the LED, transistor and resistor R1, is equal to the voltage drop across each component multiplied by $(I_{LEDmax}/2)$.

The key disadvantage of the circuit shown in Figure 6a is low speed. This type of driver circuit is rarely used at data rates above 30-50 Mb/s. In general, there are two ways to design an LED drive circuit for low power dissipation. The first is to use a high-efficiency LED and reduce I_{LEDmax} to the lowest possible value. The second is to reduce the duty cycle of the LED to a low value. Usually larger gains can be made with the second method.

The second LED driver circuit, shown in Figure 2.6b, offers much higher speed capability. It uses transistor Q1 to quickly discharge the LED to turn it off. This circuit will drive the LED several times faster than the series drive circuit shown in Figure 2.6a. The key advantage of the shunt drive circuit is that it gives much better drive symmetry. LED's are easy to turn on quickly, but are difficult to turn off because of the relatively long carrier lifetime. In the shunt driver circuit in Figure 2.6b, resistor R2 provides a positive current to turn on the LED. Typically, R2 would be in the 40 Ohm range. This makes the turn-on current about 100 mA peak. Transistor Q1 provides the turnoff current. When saturated, transistor Q1 will have an impedance of a few Ohms. This provides a much larger discharging current allowing the LED to turn off quickly. The key disadvantage of the shunt driver is the power dissipation. It is typically more than double that of the series driver. In fact, the circuit draws more current and power when the LED is off than when the LED is on! The exact power dissipation can be computed by first analyzing the off and on state currents and then combining the two values using information about the operating duty cycle.

The last driver circuit, shown in Figure 2.6c, is a variation on the shunt driver shown in Figure 2.6b.Two additional resistors and two capacitors have been added to the basic circuit. The purpose of these additional components is to further improve the operating speed. Capacitor C1 serves to improve the turn-on and turnoff characteristics of transistor Q1 itself. One has to be careful that C1 is not made too large. If this occurs, the transistor base may be overdriven and damaged. The additional components, resistors R3 and R4 and capacitor C2, provide overdrive when the LED is turned on and underdrive when the transistor is turned off. The overdrive and underdrive accelerates the LED transitions. Typically, the RC time constant of R3 and C2 is made approximately equal to the rise or fall time of the LED itself when driven with a square wave.

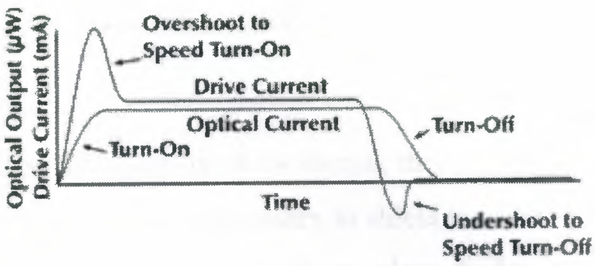

Figure2.7. LED Response to Digital Modulation

Figure 2.7 shows the response of an LED to a digital modulation signal. The electrical signal shown is the type generated by more sophisticated LED driver circuits such as that shown in Figure 6c. Starting at time zero, we first see the digital signal go to a logic level 1. The most remarkable part of this event is the strong overshoot seen on the electrical drive signal. This overshoot may be two times the steady state logic 1 drive current. This overshoot accelerates the turn-on time or rise time of the LED. Even so, we see that the optical output lags behind the electrical signal.

Typical values for very high-performance LED's and driver circuits would be 0.7 ns rise time of the electrical signal and 1.5 ns optical rise time. Later, when the digital signal goes back to logic 0, we see the same process repeated. The electrical signal has a strong undershoot component which acts to accelerate the turn-off of the LED. The undershoot serves to reverse bias the LED, sweeping out the carriers. Even so, the turn-off time of most LED's is always slower than the turn-on time. Typical values for turn-off times are 0.7 ns for the electrical signal and 2.5 ns for the optical signal. Note that while in logic 0 state, the drive current does not quite go to zero. It is common to provide a small amount of pre-bias current, typically a few percent of the peak drive current, to keep the LED forward biased and improve dynamic response.

Another common use of LEDs is to simply use their large forward voltage drop in some part of a circuit. In this case, the fact that the LED emits light is incidental. For instance, if one needed a 2.3 Volt drop in a circuit, then one could use three 1N4148 diodes in series or a single green LED. Obviously, only inexpensive indicator LEDs are candidates for this application. One important consideration for this usage is that all light emitters will also function as detectors.

If the LED is in a sensitive portion of the circuit, then the circuit may become sensitive to ambient light conditions. It may be necessary to shield the LED or coat it with an opaque paint. It is also useful to note that many ordinary glass diodes, such as the 1N4148, also function as light detectors. Keep this in mind when using diodes in circuits that have high gains. One possibility pursued in the past was using ultra-low cost germanium diodes as long wavelength detectors. They in fact work very well, but are somewhat inconsistent from part to part.

2.2.2. Injection-Laser Diode (ILD):

In long distance communication technology, laser diodes are the mainly used type of light transmitting elements.

Light emitters are a key element in any fiber optic system. This component converts the electrical signal into a corresponding light signal that can be injected into the fiber. The light emitter is an important element because it is often the most costly element in the system, and its characteristics often strongly influence the final performance limits of a given link.

The advantages of laser diodes compared to LED are:

- Significantly higher output power, around 1mW
- Extremely narrow spectra width (< 5 ns)
- Good modulation qualities: extremely low delay time

The disadvantages are:

- Higher cost
- Complicated drive circuit for constant output power (ALC)
- Cooling by thermoelectric, cooling unit

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- Shorter service life than LED (MTBF(Mean Time Between Failure) > 15 years)

In principle, a laser diode is a light emitting diode with a wavelength selection element in its simplest form, a fabry-perot resonator, consisting of two semitransparent parallel mirror plates is used. This resonator has the effect that, even for a low total light intensity, the intensity of the light of equal wavelength and equal phase increases, and thus the stimulated emission begins even at a low injection current. Light Amplification by Simulated Emission Radiation (LASER) produces a higher light output power and a greater concentration of emitted light. This enables a significantly higher light power to be coupled into the fiber, and thus correspondingly greater maximum fiber attenuation.

Table 2.1 Typical characteristics of laser diodes at $25^0 C$.

Wavelength	nm	1300 / 1500
Spectra width D	nm	0.1 – 3
Semi-conductor material		GaInAsP/InP
Emission		Coheret
Switching time	ns	< 1
Light power coupled in an optical fiber		
Gradient fiber	mW	1 to 3
Single mode	mW	0.5 to 1.5
Transmission Length	km	Up to approximately 100
Transmission rate	Mbit/sec	> 2400

2.2.2.1. Laser Diode Performance Characteristics:

Several key characteristics lasers determine their usefulness in a given application. These are:

Peak Wavelength: This is the wavelength at which the source emits the most power. It should be matched to the wavelengths that are transmitted with the least attenuation through optical fiber. The most common peak wavelengths are 1310, 1550, and 1625 nm.

Spectral Width: Ideally, all the light emitted from a laser would be at the peak wavelength, but in practice the light is emitted in a range of wavelengths centered at the peak wavelength. This range is called the spectral width of the source.

Emission Pattern: The pattern of emitted light affects the amount of light that can be coupled into the optical fiber. The size of the emitting region should be similar to the diameter of the fiber core. Figure 2 illustrates the emission pattern of a laser.

Figure.2.8. Laser Emission Pattern.

Power: The best results are usually achieved by coupling as much of a source's power into the fiber as possible. The key requirement is that the output power of the source be strong enough to provide sufficient power to the detector at the receiving end, considering fiber attenuation, coupling losses and other system constraints. In general, lasers are more powerful than LEDs.

Speed: A source should turn on and off fast enough to meet the bandwidth limits of the system. The speed is given according to a source's rise or fall time, the time required to go from 10% to 90% of peak power. Lasers have faster rise and fall times than LEDs.

Linearity: is another important characteristic to light sources for some applications. Linearity represents the degree to which the optical output is directly proportional to the electrical current input. Most light sources give little or no attention to linearity, making them usable only for digital applications. Analog applications require close attention to linearity. Nonlinearity in lasers causes harmonic distortion in the analog signal that is transmitted over an analog fiber optic link.

Lasers are temperature sensitive; the lasing threshold will change with the temperature. Figure.2.8 shows the typical behavior of a laser diode. As operating temperature changes, several effects can occur. First, the threshold current changes. The threshold current is always lower at lower temperatures and vice versa. The second change that can be important is the slope efficiency. The slope efficiency is the number of mill watts or microwatts of light output per mill -ampere of increased drive current above threshold. Most lasers show a drop in slope efficiency as temperature increases. Thus, lasers require a method of stabilizing the threshold to achieve maximum performance. Often, a photodiode is used to monitor the light output on the rear facet of the laser. The current from the photodiode changes with variations in light output and provides feedback to adjust the laser drive current.

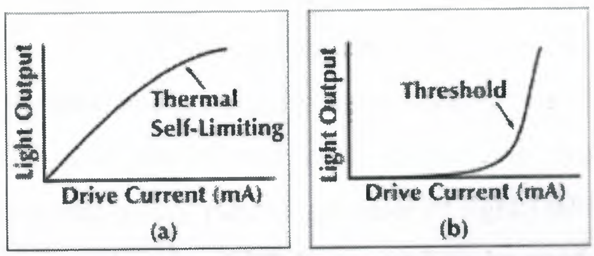


Figure.2.9. Emitters Characteristics.

a) LED b) Laser

Figure.2.9a shows the behavior of an LED, and Figure.2.9b shows the behavior of a laser diode. The plots show the relative amount of light output versus electrical drive current. The LED outputs light that is approximately linear with the drive current. Nearly all LED's exhibit a "droop" in the curve as shown in Figure.2.9b.

This nonlinearity in the LED limits its usefulness in analog applications. The droop can be caused by a number of factors in the LED semiconductor physics but is often largely due to self-heating of the LED chip. All LED's drop in efficiency as their operating temperature increases. Thus, as the LED is driven to higher currents, the LED chip gets hotter causing a drop in conversion efficiency and the droop apparent in Figure 2.9a. LED's are typically operated at currents to about 100 mA peak. Only specialized devices operate at higher current levels.

2.2.2.2. Laser Types:

There are two basic types of laser diode structures:

a. Fabry-Perot (FP).

B. distributed feedback (DFB).

Of the two types of lasers, Fabry-Perot lasers are the most economical, but they are generally noisy, slower devices. DFB lasers are quieter devices (e.g., high signal-to-noise), have narrower spectral widths, and are usually faster devices. DFB lasers offer the highest performance levels and also the highest cost of the two types. They are nearly monochromatic (i.e. they emit a very pure single color of light.) while FP lasers emit light at a number of discrete wavelengths. DFB lasers tend to be used for the highest speed digital applications and for most analog applications because of their faster speed, lower noise, and superior linearity. Fabry-Perot lasers further break down into buried hetero (BH) and multi-quantum well (MQW) types.

BH and related styles ruled for many years, but now MQW types are becoming very widespread. MQW lasers offer significant advantages over all former types of Fabry-Perot lasers. They offer lower threshold current, higher slope efficiency, lower noise, better linearity, and much greater stability over temperature. As a bonus, the performance margins of MQW lasers are so great; laser manufacturers get better yields, so laser cost is reduced.

One disadvantage of MQW lasers is their tendency to be more susceptible to back reflections.

2.2.2.3. Laser Driver Circuits:

a. Analog Laser Drive Circuits:

Figure.2.10 illustrates two common circuit configurations used to drive lasers for analog applications. The simpler of the two, shown in fig.2.10a, offers moderate linearity and good performance in frequencies up to 500 MHz. The analog signal path only involves C1, R1, Q1, R2, and D1, the laser diode. Q1 acts as a transconductant stage in which voltage flows in and current flows out. C1 passes only the AC portion of the analog input signal. R1, usually only a few tens of Ohms, squelches any possible oscillations in Q1. The AC portion of analog input voltage V_{IN} appears at the base of Q1 and also at the emitter of Q1. V_{IN}, the AC voltage at the emitter of Q1, imposes across R2 to create a modulation current $V_{IN}/R2$. U1 supplies DC current to the laser through R3 and R1. U1 creates a servo loop that maintains a constant photodiode current through the rear facet monitor PIN diode.

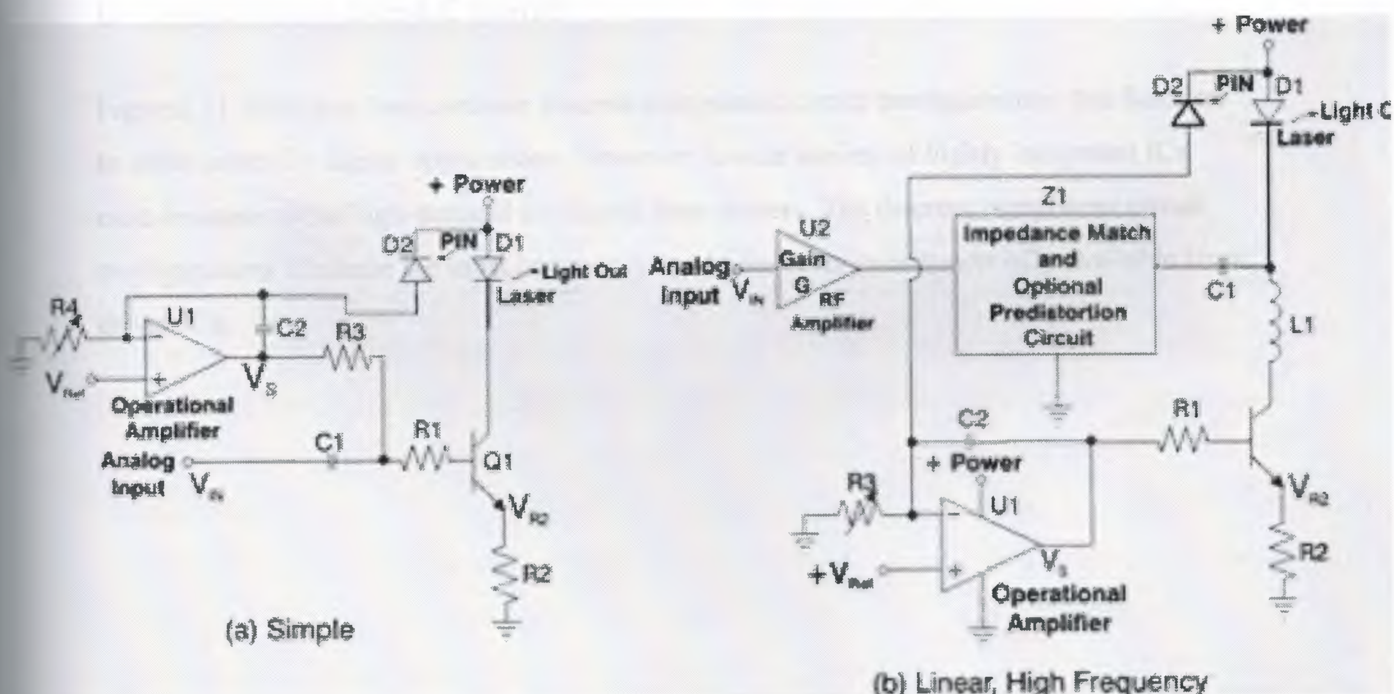


Figure.2.10.Analog Laser Drive Circuits.

The circuit illustrated in Figure.2.10a indirectly maintains constant laser optical output. The rear facet monitor PIN diode receives light from one end of the laser chip while the other end of the chip illuminates the optical fiber. While the light in the fiber correlates to light in the monitor PIN diode, it never matches exactly at all output and environmental conditions, a phenomenon called tracking error.

Figure.2.10b shows a more advanced analog laser circuit, offering good to excellent linearity at very high frequencies (GHz). The signal path of this circuit only involves U2, Z1, C1, and the laser diode, D1. Amplifier U2 provides input matching, gain and isolates the laser from outside conditions. The block labeled Z1 can take on many functions.

At a minimum, it interfaces the output of the amplifier U2, usually 50 or 75Ohms, to the laser that has impedance ranging from 5 Ohms to 25 Ohms. As shown, sometimes the laser package incorporates this impedance matching.

b. Digital Laser Drive Circuits:

Figure2.11 illustrates two common discrete component circuit configurations that function to drive lasers for digital applications. However, a wide variety of highly integrated ICs exist because of the high demand for digital laser drivers. The discrete component circuit configurations illustrate the most commonly used principles in commercially available laser driver ICs.

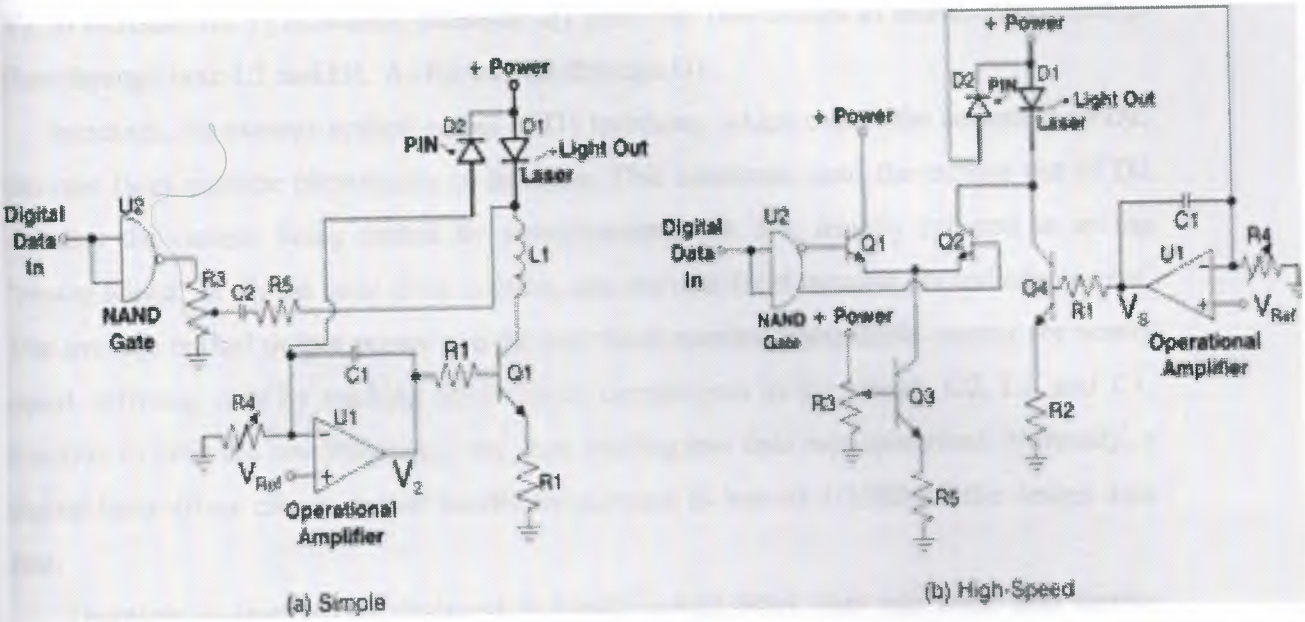


Figure2.11. Digital Laser Circuits.

Figure2.11a illustrates a simple circuit that is utilized at frequencies to several hundred megahertz. "Digital data in" takes a relatively simple path. The NAND gate, U2, buffers the signal and provides fast and consistent edges. Potentiometer, R3, adjusts the amplitude of the laser's oncoming digital signal, usually referred to as a modulation depth adjustment. Capacitor, C2, block any DC component, allowing the AC component of the "digital data in" to pass. Incidentally, nearly all digital laser drive circuits cannot handle a DC component in the "digital data in" signal, meaning that the "digital data in" signal must always have transitions present. Resistor, R5, provides impedance matching into the laser, and feeds directly into the cathode of the laser, D1. Inductor, L1, allows the AC component of the "digital data in" signal to reach the laser, as well as a DC signal. The rear facet monitor photodiode, D2, outputs a current proportional to the laser output. The current out of D2 goes to a servo loop, ensuring that the average optical output of D1 remains constant. U1 forms the heart of the servo loop. Capacitor, C1, configures U1 as an integrator. The +input of U1 remains at a positive voltage, V_{REF}.

The value of V_{REF} usually lies midway between ground and +Power. Potentiometer, R4, adjusts the average optical output power of the laser D1 by sinking a current out of the -input of U1. This negative current causes the output of U1, referred to as V_2, to increase. As V_2 increases, transistor Q1 turns on. This causes an increasing current to flow through both L1 and D1. As the current through D1.

increases, the average optical output of D1 increases, which causes the current from D2, the rear facet monitor photodiode, to increase. This continues until the current out of D2 matches the current being sinked by potentiometer, R4. R4, usually referred to as the "power adjust" in digital laser drive circuits, sets the rear facet monitor photodiode current. The average optical output power and the rear facet monitor photodiode current are nearly equal, differing only by tracking error. Three components in the circuit, C2, L1, and C1, function to limit the low-frequency, and thus limiting low data rate operations. Normally, a digital laser driver circuit should handle frequencies as low as 1/100th of the design data rate.

Therefore, a laser driver designed to handle a 622 Mb/s data rate must also handle frequencies as low as 6.22 MHz. The more complex circuit shown in Figure 8b allows very high, multi-gigabit speeds. With only the omission of L1, the servo loop portion of the circuit matches the circuit in Figure2.11a. L1 is replaced in this circuit by Q4 a very fast , low capacitance transistor. To not interfere with the modulation signal, Q4's collector will appear as a current source. Potentiometer, R4, sets the rear facet monitor photodiode current or average optical output power. The "digital data in" signal first goes through the NAND gate, U2, as in the first circuit. However, this circuit incorporates a NAND gate with the differential outputs of U2 to drive a transistor-based differential amplifier consisting of Q1 and Q2. Transistor Q3 forms a constant current source. The potentiometer, R3, sets the current flowing in the collector of Q3. The current flowing out of Q3 determines the amount of modulation current that is switched to the laser in response to 1's and 0's. The modulation current from the collector of Q3 oscillates between the +power line (by Q1) and the laser, D1, (by Q2), as the outputs of U2 switch back and forth. To avoid a circuit becoming slow, the digital laser circuit must avoid saturation. Q1, Q2 and Q3 all operate in a linear mode in circuit 8b allowing them to operate at very high speeds.

And the table 2.2 below is showing us a Comparison betwen LEDs and Lasers in some characteristic.

Table 2.2 Comparison of LEDs and Lasers.

Characteristic	LEDs	Lasers
Output Power	Linearly proportional to drive current	Proportional to current above the threshold
Current	Drive Current: 50 to 100 mA Peak	Threshold Current: 5 to 40 mA
Coupled Power	Moderate	High
Speed	Slower	Faster
Output Pattern	Higher	Lower
Bandwidth	Moderate	High
Wavelengths Available	0.66 to 1.65 µm	0.78 to 1.65 µm
Spectral Width	Wider (40-190 nm FWHM)	Narrower (0.00001 nm to 10 nm FWHM)
Fiber Type	Multimode Only	SM, MM
Ease of Use	Easier	Harder
Lifetime	Longer	Long
Cost	Low ($5-$300)	High ($100-$10,000)

2.3. Fiber Optical Detectors:

In theory, semiconductors pn-junctions can be utilized not only to excite carriers through light injection but also to detect optically excited charge carriers through separation in the electrical field of the depletion layer, i.e. to receive light. At the end of the transmission path, the light impulses are received be a photo detector which converts them to current impulses proportional to the light power. A low noise amplifier is connected to the photo detector so that the maximum distance of an optical fiber transmission system can increase in proportion to the decrease in the light power that can successfully used by the receiver. A good photo receiver must therefore be able to process generated photo currents of less than 1 µA. Photo detectors differs in their photo-sensitivity, their operating wavelength range, and consequently in their optimum transmission bit rate. There are two types of photo diodes, that is:

- PIN photodiodes: In semiconductors with low absorption coefficients, the insertion of an uncoupled semiconductor layer (i-region, intrinsic) between the p-and n-type semiconductor enlarges the region for absorption of radiation.
- Avalanche photodiodes (APD): When the acceleration of charge carriers in the electrical field reaches such high speeds that further carriers are created. This process is called avalanche breakdown and corresponding photodiode is called an APD.

2.3.1 Important Detector Parameters:

- Responsivity: Ratio of current output to light input. High responsivity equals high receiver sensitivity.
- Quantum Efficiency: Ratio of primary electron-hole pairs created by incident photons to the photons incident on the detector material.
- Capacitance: Dependent upon the active area of the device and the reverse voltage across the device. This relationship is illustrated in Figure 2.12.
- Response Time: Time needed for the photodiode to respond to optical inputs and produce and external current.

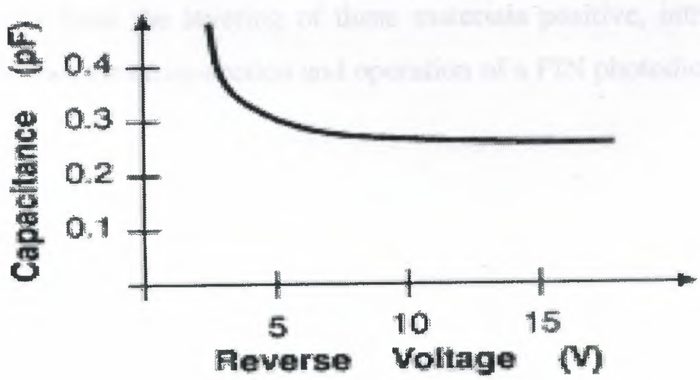


Figure2.12 C-V Curve.

Response time can be affected by dark current, noise, linearity, back-reflection, and edge effect (see figure2.13). Edge effect results from the fact that detectors only provide fast response in their center region. The outer region of the detector has a higher responsivity than the center region, which can cause problems when aligning the fiber to the detector. The higher responsivity may fool one into thinking they have aligned the fiber to the center region. Because response is much slower at the edge, this misalignment will reduce the response time of the detector.

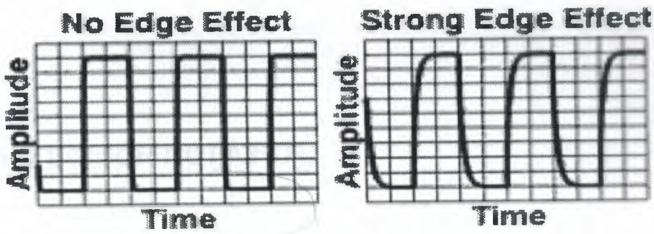


Figure2.13 Edge Effect.

2.3.2. Type of Fiber optical Detectors:

2.3.2.1. PIN Photodiode:

A p-n diode's deficiencies are related to the fact that the depletion area (active detection area) is small; many electron-hole pairs recombine before they can create a current in the external circuit. In the PIN photodiode, the depleted region is made as large as possible. A lightly doped intrinsic layer separates the more heavily doped p-types and n-types. The diode's name comes from the layering of these materials positive, intrinsic, negative — PIN. Figure 2.14 shows the cross-section and operation of a PIN photodiode.

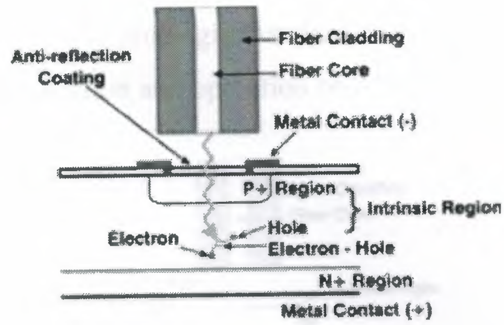


Figure 2.14 PIN Photodiode.

2.3.2.2Avalanche Photodiode (APD):

The avalanche photodiode (APD) operates as the primary carriers, the free electrons and holes created by absorbed photons, accelerate, gaining several electron Volts of kinetic energy. A collision of these fast carriers with neutral atoms causes the accelerated carriers to use some of their own energy to help the bound electrons break out of the valence shell. Free electron-hole pairs, called secondary carriers, appear. Collision ionization is the name for the process that creates these secondary carriers. As primary carriers create secondary carriers, the secondary carriers themselves accelerate and create new carriers. Collectively, this process is known as photo-multiplication. Typical multiplication ranges in the tens and hundreds. For example, a multiplication factor of eighty means that, on average, eighty external electrons flow for every photon of light absorbed.

APDs require high-voltage power supplies for their operation. The voltage can range from 30 or 70 Volts for InGaAs APDs to over 300 Volts for Si APDs. This adds circuit complexity. Also, APDs are very temperature sensitive, further complicating circuit requirements. In general, APDs are only useful for digital systems because they possess very poor linearity. Because of the added circuit complexity and the high voltages that the parts are subjected to, APDs are always less reliable than PIN detectors. This, added to the fact that at lower data rates, PIN detector-based receivers can almost match the performance of APD-based receivers, makes PIN detectors the first choice for most deployed low-speed systems. At multi-gigabit data rates, however, APDs rule supreme. Figure 2.15 shows the cross-section and operation of APD.

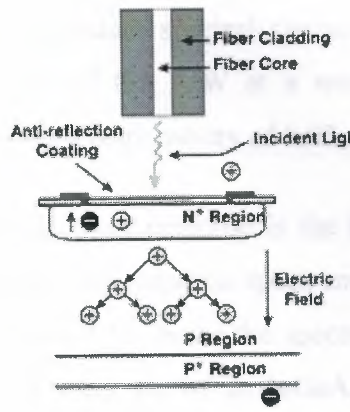


Figure2.15 APD.

And the table below showing us an a Comparison of PIN Photodiodes and APDs

Table 2.3 Comparison of PIN Photodiodes and APDs.

Parameter	PIN Photodiodes	APDs
Construction Materials	Si, Ge, InGaAs	Si, Ge, InGaAs
Bandwidth	DC to 40+ GHz	DC to 40+ GHz
Wavelength	0.6 to 1.8 μm	0.6 to 1.8 μm
Conversion Efficiency	0.5 to 1.0 Amps/Watt	0.5 to 100 Amps/Watt
Support Circuitry Required	None	High Voltage, Temperature Stabilization
Cost (Fiber Ready)	$1 to $500	$100 to $2,000

2.3.3. Light Emitters as Detectors:

Light emitter such as LEDs and lasers, will also function as light detectors, allowing a unique technology to evolve, using light emitters as half-duplex fiber optic communication devices. This scheme involves using the LED or laser alternately as a light emitter, then as a light detector, which allows the transmission of information in either direction over the fiber. While all LEDs and lasers have the ability to act as detectors, a few perform this task much better than most. The key parameter to look for is very efficient coupling between the light emitter and the fiber. This allows good performance in both modes. It is also important that the LEDs have consistent spectral characteristics. While a good InGaAs detector may have a responsivity of 0.8 A/W at a wavelength of 1310 nm, an LED operating as a detector may provide a responsivity of 0.08 A/W at 1310 nm.

The main reason for the much lower response is the fact that the LED operating as a detector has a relatively narrow spectral response spectrum that does not fully overlap with the LED emission spectrum. Figure 2.16 shows the spectral response of a typical InGaAs detector as well as the emission spectrum of an InGaAsP LED and the LEDs spectral response as a detector. It can be seen that a normal InGaAs detector has a very broad spectral response from 800 nm to beyond 1600 nm. Because the response is so wide, the detector responds to all photons emitted by the LED.

The spectral emission of the LED is a relatively narrow spectrum, perhaps 60 nm wide, centered around 1310 nm. Notice that the spectral response of the same LED operating as a detector is shifted to the left. The center of the spectral response is centered at perhaps 1270 nm. The overall response as a detector is a bit wider than the emissions as an LED. However, note that the overlap between the LED emissions and the LED spectral response is rather low. This accounts for poor responsivity attributed to most LEDs operating as detectors. The problem becomes even worse when the emitting LED and the detecting LED are at different operating temperatures. This causes the individual spectral responses to drift with respect to each other. This will either increase or decrease the amount of overlap. The overwhelming concern when applying full-duplex LEDs is considering the different temperatures that the two ends will see. Laser diodes exhibit similar characteristics to the LED shown in figure 2.16.

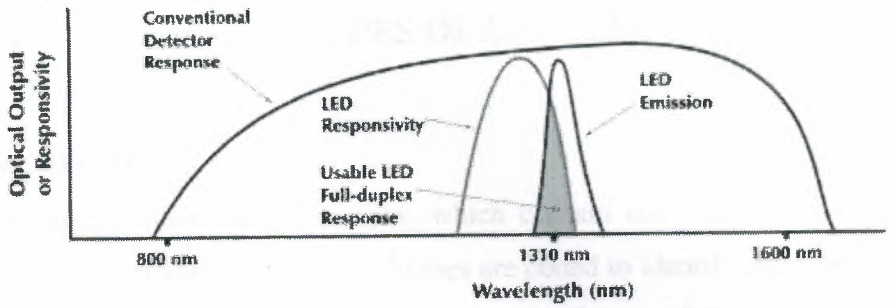


Figure 2.16 Ping-Pong (Full-Duplex) LED.

3. TYPES OF CABLES

3.1 Cable Structure

The OF cable contain many of tubes, which contain many of fibers. To ensure the security & correct installing, the fiber and tubes are coded to identify the connector location on the module. The diameter of the cable is constant 22mm and the maximum of tubes in the cable is 8 tubes, and every tube has 6 fibers. The table 3.1 below show tubes color, and the table 3.2 shows fiber color code (Siemens).

Table 3.1 Tubes color & code of OF.

Color	Code	Color	Code
Blue	1	Gray	5
Orange	2	White	6
Green	3	Red	7
Brown	4	Black	8

Table 3.2 Tubes color & code according to Siemens

Color	Code	Color	Code
Blue	1	Brown	4
Orange	2	Gray	5
Green	3	White	6

Let us take a look on the cable structure of the optical fiber which is illustrated in figure 3.1.

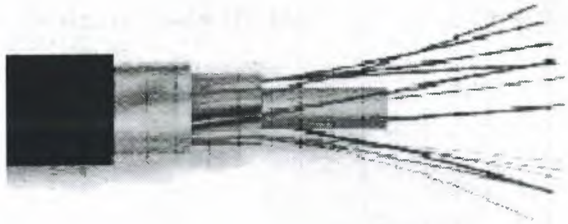


Figure 3.1 Cable structure.

This figure shows the main parts of the O.F. cable and the other layers of the cable like outers heath, steel, and inner sheath are for mechanical and protection purposes.

3.2 Cable Types:

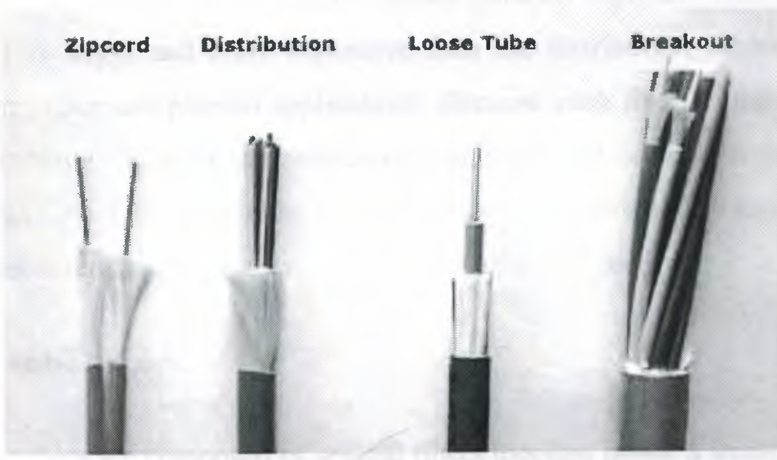


Figure 3.2 Cable Types: Zipcord, Distibution, Losse Tube & Breakout.

1. Simplex and zip cord:

Simplex cables are one fiber, tight-buffered (coated with a 900 micron buffer over the primary buffer coating) with Kevlar (aramid fiber) strength members and jacketed for indoor use. The jacket is usually 3mm (1/8 in.) diameter. Zip cord is simply two of these joined with a thin web. It's used mostly for patch cord and backplane applications, but zip cord can also be used for desktop connections.

2. Distribution cables:

They contain several tight-buffered fibers bundled under the same jacket with Kevlar strength members and sometimes fiberglass rod reinforcement to stiffen the cable and prevent kinking. These cables are small in size, and used for short, dry conduit runs, riser and plenum applications. The fibers are double buffered and can be directly terminated, but because their fibers are not individually reinforced, these cables need to be broken out with a "breakout box" or terminated inside a patch panel or junction box.

3. Breakout cables:

They are made of several simplex cables bundled together. This is a strong, rugged design, but is larger and more expensive than the distribution cables. It is suitable for conduit runs, riser and plenum applications. Because each fiber is individually reinforced, this design allows for quick termination to connectors and does not require patch panels or boxes. Breakout cable can be more economic where fiber count isn't too large and distances too long, because is requires so much less labor to terminate.

4. Loose tube cables:

These cables are composed of several fibers together inside a small plastic tube, which are in turn wound around a central strength member and jacketed, providing a small, high fiber count cable. This type of cable is ideal for outside plant trunking applications, as it can be made with the loose tubes filled with gel or water absorbent powder to prevent harm to the fibers from water. It can be used in conduits, strung overhead or buried directly into the ground. Since the fibers have only a thin buffer coating, they must be carefully handled and protected to prevent damage.

5. Ribbon Cable:

This cable offers the highest packing density, since all the fibers are laid out in rows, typically of 12 fibers, and laid on top of each other. This way 144 fibers only has a cross section of about 1/4 inch or 6 mm! Some cable designs use a "slotted core" with up to 6 of these 144 fiber ribbon assemblies for 864 fibers in one cable! Since it's outside plant cable, it's gel-filled for water blocking.

6. Armored Cable:

Cable installed by direct burial in areas where rodents are a problem usually have metal armoring between two jackets to prevent rodent penetration. This means the cable is conductive, so it must be grounded properly.

7. Aerial cable:

Aerial cables are for outside installation on poles. They can be lashed to a messenger or another cable (common in CATV) or have metal or aramid strength members to make them self supporting.

Even More Types Are Available: Every manufacturer has it's own favorites, so it's a good idea to get literature from as many cable makers as possible. And check out the little guys; often they can save you a bundle by making special cable just for you, even in relative small quantities.

3.3 Cable Design Criteria:

1. Pulling Strength:

Some cable is simply laid into cable trays or ditches, so pull strength is not too important. But other cable may be pulled thorough 2 km or more of conduit. Even with lots of cable lubricant, pulling tension can be high. Most cables get their strength from an aramid fiber (Kevlar is the Dupont trade name), a unique polymer fiber that is very strong but does not stretch - so pulling on it will not stress the other components in the cable. The simplest simplex cable has a pull strength of 100-200 pounds, while outside plant cable may have a specification of over 800 pounds.

2. Water Protection:

Outdoors, every cable must be protected from water or moisture. It starts with a moisture resistant jacket, usually PE (polyethylene), and a filling of water-blocking material. The usual way is to flood the cable with a water-blocking gel. It's effective but messy - requiring a gel remover (use the commercial stuff - it's best- -but bottled lemon juice works in a pinch!). A newer alternative is dry water blocking using a miracle powder - the stuff developed to absorb moisture in disposable diapers. Check with your cable supplier to see if they offer it.

3. Fire Code Ratings:

Every cable installed indoors must meet fire codes. That means the jacket must be rated for fire resistance, with ratings for general use, riser (a vertical cable feeds flames more than horizontal) and plenum (for installation in air-handling areas. Most indoor cables us PVC (polyvinyl chloride) jacketing for fire retardance. In the United States, all premises cables must carry identification and flammability ratings per the NEC National Electrical

Table 3.3 Fire Code Rating

NEC Rating	Description
OFN	Optical fiber non-conductive
OFC	Optical fiber conductive
OFNG or OFCG	General purpose
OFNR or OFCR	Riser rated cable for vertical runs
OFNP or OFCP	Plenum rated cables for use in air-handling plenums
OFN-LS	Low smoke density

Cables without markings should never be installed as they will not pass inspections! Outdoor cables are not fire-rated and can only be used up to 50 feet indoors. If you need to bring an outdoor cable indoors, consider a double-jacketed cable with PE jacket over a PVC UL-rated indoor jacket. Simply remove the outdoor jacket when you come indoors and you will not have to terminate at the entry point.

3.4. Choosing a Cable:

With so much choice in cables, it is hard to find the right one. The Table 3.4 below summarizes the choices, applications and advantages of each.

Table 3.4 summarizes the choices, applications and advantages of each.

Cable Type	**Application**	**Advantages**
Tight Buffer	Premises	Makes rugged patch cords
Distribution	Premises	Small size for lots of fibers, inexpensive
Breakout	Premises	Rugged, easy to terminate, no hardware needed
Loose Tube	Outside Plant	Rugged, gel or dry water-blocking
Armored	Outside Plant	Prevents rodent damage
Ribbon	Outside Plant	Highest fiber count for small size

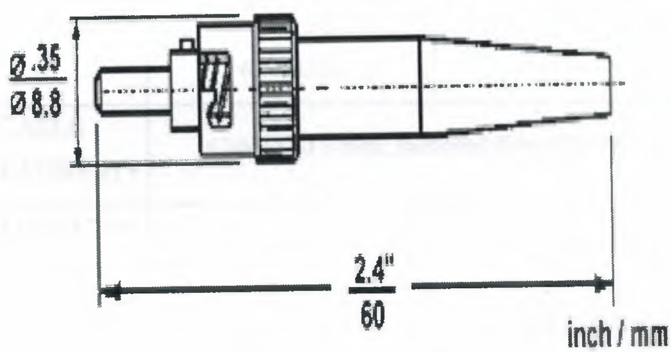
3.5. Optical Fiber Connectors:

The basic two types of optical fiber connectors that are used commonly are the ST connector and the SC connector.

3.5.1 ST Connector:

ST with bayonet coupling is specially designed for distribution applications and is fully compatible with existing ST hardware. Zirconia ceramic ferrules with pre-radiused end finish improve optical performance. Connectors are made from nickel plated cooper alloy by mechanical turning rather than casting increasing precision and durability. Epoxy or Anaerobic termination and double crimping (of the jacket and aramid strength member) ensure the quality of the construction. Multimomode and singlemode versions are available.And the Figure 3.3 below showing the ST optical fiber connector .

(a)



(b)

Figure 3.3 ST optical fiber connector

Table 3.5 ST information

STYLE	ST-Compatible Series	
SINGLEMODE/ MULTIMODE	MM	SM
PART NUMBER	0200-2410	0200-2415
PRICE	$2.39	$5.85
COUPLING TYPE	Bayonet lock, keyed	
MATERIAL	Ferrule: ceramic Body: metal Boot: plastic	
ABUTTMENT	Pre-radiused, physical contact, spring loaded ferrule	
FIBER COMPATIBILITY	MM 125 um cladding (example: 50/125, 62.5/125)	SM 125 um cladding (example: 9.5/125)
CABLE COMPATIBILITY	Cable OD 3 mm; Buffered fiber OD 900 um	
TERMINATION METHOD	Anaerobic or Epoxy-Crimp-Polish	
RECOMMENDED POLISH	Hand or machine	PC: Hand or machine Super PC, Ultra PC: machine
OPTICAL PERFORMANCE	Insertion loss: < .2 dB typ < .3 dB max	Insertion loss: < .2 dB typ < .3 dB max Return loss: PC < - 30 dB Super PC < - 40 dB Ultra PC < - 50 dB
MATING LIFE	500 cycles min	500 cycles min
VIBRATION	10 to 55 Hz	10 to 55 Hz
IMPACT	Height 5 ft (1.5 m)	Height 5 ft (1.5 m)
OPERATING	-40…+167° F	-40…+167° F

TEMPERATURE	-40...+75° C	-40...+75° C
STORAGE TEMPERATURE	-40...+185° F -40...+85° C	-40...+185° F -40...+85° C

3.5.2 SC Connector

SC cables are specially designed for CATV and network applications and are fully compatible with existing SC hardware. Push-pull coupling mechanism is convenient for frequent switching. Zirconia ceramic ferrules with pre-radiused end finish improve optical performance. Angle PC for the better return loss is available. Epoxy termination and double crimping (of the jacket and aramid strength member) ensures the quality of the construction. Different body colors indicate the type of the connector; the coupling clip easy configures two SC connectors to Duplex format.

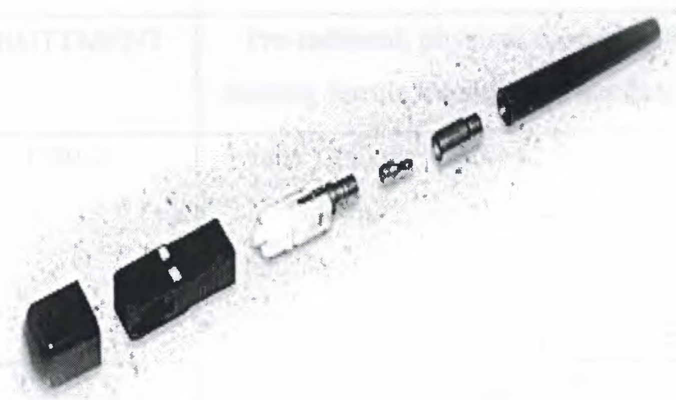


Figure 3.4 SC optical fiber connector

Table 3.6 SC information

STYLE	SC Series	
SINGLEMODE/ MULTIMODE	MM	SM
PART NUMBER	0200-2420	0200-2425
PRICE	\$3.79	\$5.95
COUPLING TYPE	Push-pull	
MATERIAL	Ferrule: ceramic (APC:8°) Body: plastic Color: Black (MM), Blue (SM), Green (APC) Boot: plastic	
ABUTTMENT	Pre-radiused, physical contact, full floating ferrule, non-disconnect design	
FIBER COMPATIBILITY	MM 125 um cladding (example: 50/125, 62.5/125)	SM 125 um cladding (example: 9.5/125)
CABLE COMPATIBILITY	Cable OD 3 mm; Buffered fiber OD 900 um	
TERMINATION METHOD	Anaerobic or Epoxy-Crimp-Polish	
RECOMMENDED POLISH	Hand or machine	PC: Hand or machine SPC, UPC, APC: machine

OPTICAL PERFORMANCE	Insertion loss: < .2 dB typ < .3 dB max	Insertion loss: < .2 dB typ < .3 dB max Return loss: PC < - 30 dB Super PC < - 40 dB Ultra PC < - 50 dB Angle PC < - 65 dB
MATING LIFE	200 cycles min	200 cycles min
VIBRATION	10 to 55 Hz	10 to 55 Hz
IMPACT	Height 5 ft (1.5 m)	Height 5 ft (1.5 m)
OPERATING TEMPERATURE	-40…+167° F -40…+75° C	-40…+167° F -40…+75° C

3.5.3 ST - ST Coupling Adapter:

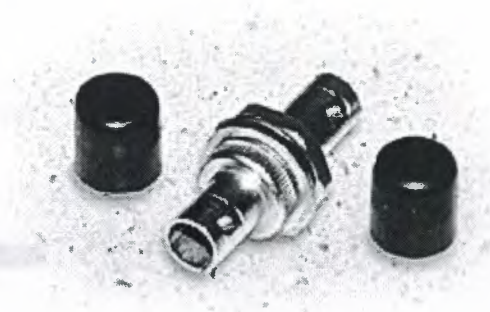


Figure 3.5 ST-ST coupling adapter

3.5.4 SC - SC Coupling Adapter

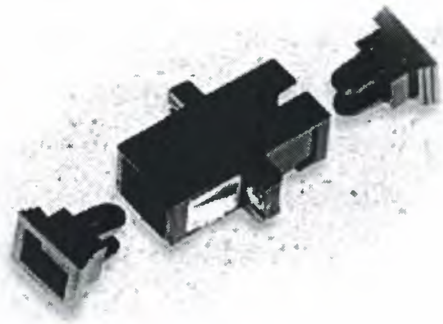


Figure 3.6 SC-SC coupling adapter

And here are other types of optical cable connectors shown in the figure 3.7 below.

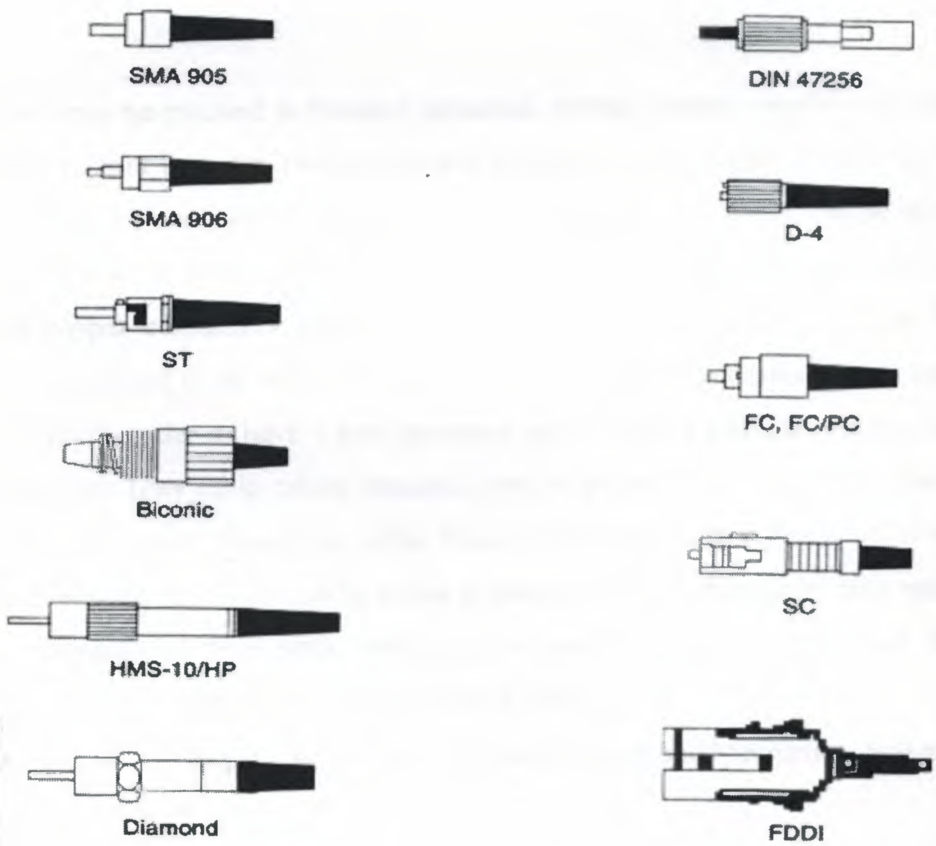


Figure 3.7 Common types of connectors.

3.6 Optical Fiber Splicing:

A splice is a device to connect one fiber optic cable to another permanently. It is the attribute of permanence that distinguishes a splice from connectors. Nonetheless, some vendors offer splices that can be disconnected that are not permanent so that they can be disconnected for repairs or rearrangements. The terminology can get confusing.Fiber optic cables may have to be spliced together for any of a number of reasons.

One reason is to realize a link of a particular length. The network installer may have in his inventory several fiber optic cables but, none long enough to satisfy the required link length. This may easily arise since cable manufacturers offer cables in limited lengths - usually 1 to 6 km. If a link of 10 km has to be installed this can be done by splicing several together.

The installer may then satisfy the distance requirement and not have to buy a new FOC.

Splices may be required at building entrances, wiring closets, couplers and literally any intermediary point between Transmitter and Receiver. At first glance you may think that splicing two fiber optic cables together is like connecting two wires. To the contrary, the requirements for a fiber-optic connection and a wire connection are very different.

Two copper connectors can be joined by solder or by connectors that have been crimped or soldered to the wires. The purpose is to create an intimate contact between the mated halves in order to have a low resistance path across a junction. On the other hand, connecting two fiber optic cables requires precise alignment of the mated fiber cores or spots in a single-mode fiber optic cable. This is demanded so that nearly all of the light is coupled from one fiber optic cable across a junction to the other fiber optic cable. Actual contact between the fiber optic cables is not even mandatory. The need for precise alignment creates a challenge to a designer of a splice.

There are two principal types of splices:Fusion Splices and Mechanical Splices.

3.6.1 principal types of splices:

3.6.1.1 Fusion Splicing:

The fiber cables are melted together. It is the most common method of splicing fiber is long distance networks.

Requirements of splices and connectors are:

- Ease of installation
- Low attenuation
- Good repeatability
- Economical (fusion splice costs less but tools are expensive. Mechanical splice is expensive, but tools are cheap)

On account of these factors, fusion splicing is used in long distance networks, where quality of splice and attenuation are important. Mechanical splicing is mainly used for indoor applications, such as LANs. Fusion splice is better than a mechanical splice because of their low cost and high quality.

Fusion splicing of optical fiber is done by heating clean, accurately cut fibers ends to their melting point, while simultaneously pressing them against each other longitudinally, the fibers will fuse and form a splice with very low loss, normally less than 0.08 dB.

Steps in fusion splicing of optical fiber are:

1. Alignment, control of cutting angle and cleanness.
2. Perfusion: Arc between the electrodes burns off small particles of dirt, and rounds the cut edges.
3. Final adjustment and fiber check.
4. Fusion for approximately 5 seconds with a fusion current of 10-20 mA.
5. Fibers are pushed towards each other to compensate for the consumption of a certain amount of glass.

3.6.1.2 Mechanical Splicing:

This is primarily used in networks for local installation. Mechanical fibers join two fibers ends either by clamping within a structure or by gluing them together. Bach reflections can occur in mechanical splices, but they can be reduced by inserting into the splice a fluid or gel with a refractive index close that of glass. The index matching gel suppresses the reflections that can occur at a glass-air interface.

The most important types of mechanical splices are:

3.6.1.2.1 Capillary Splice

One of the simplest types of splices relies on inserting two fiber ends into a thin capillary tube, with index matching gel inserted to reduce reflections.and the Figure 3.8 blow showing the Capillary splice form.

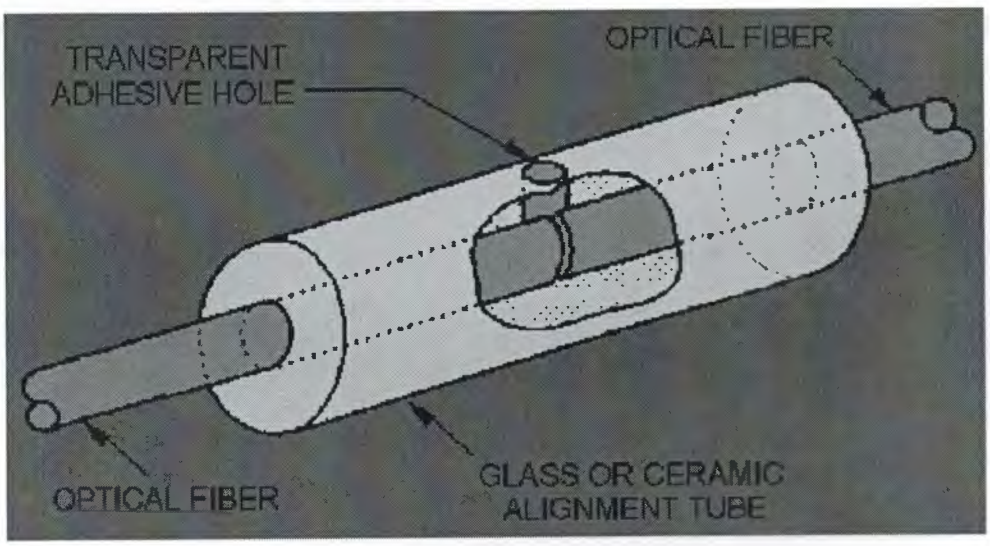


Figure 3.8 Capillary splice.

3.6.1.2.2 Rotary or Polished-Ferrule Splice:

Each fiber end is inserted into separate ferrule and its end is cleaved and polished to a smooth surface. The two polished ferrules are mated within a jacket. It offers more precise way of matting fibers, and hence suitable for splicing polarization-sensitive fibers.

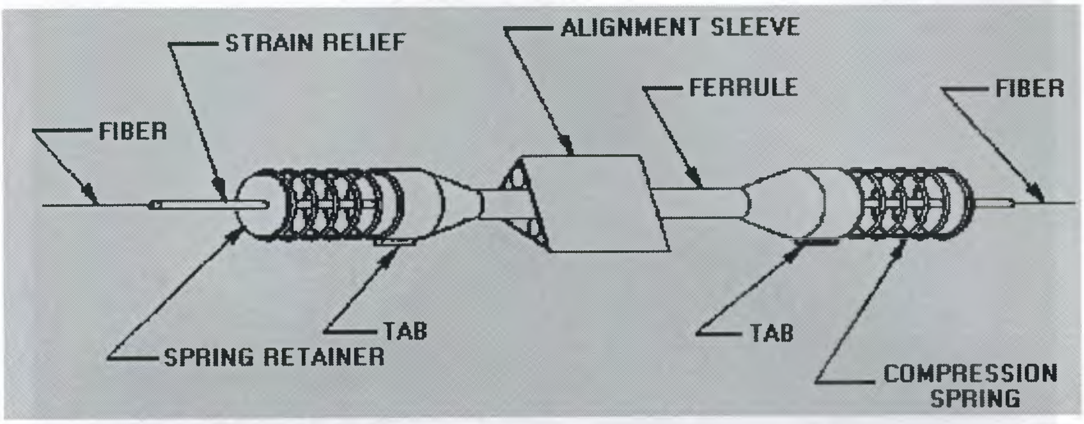


Figure 3.9 Rotary or polished-ferrule splice

3.6.1.2.3 V-Groove Splicing:

Here fibers are held in V shaped grooves in a plate. The ends are polished before they are mated and aligned with another plate.

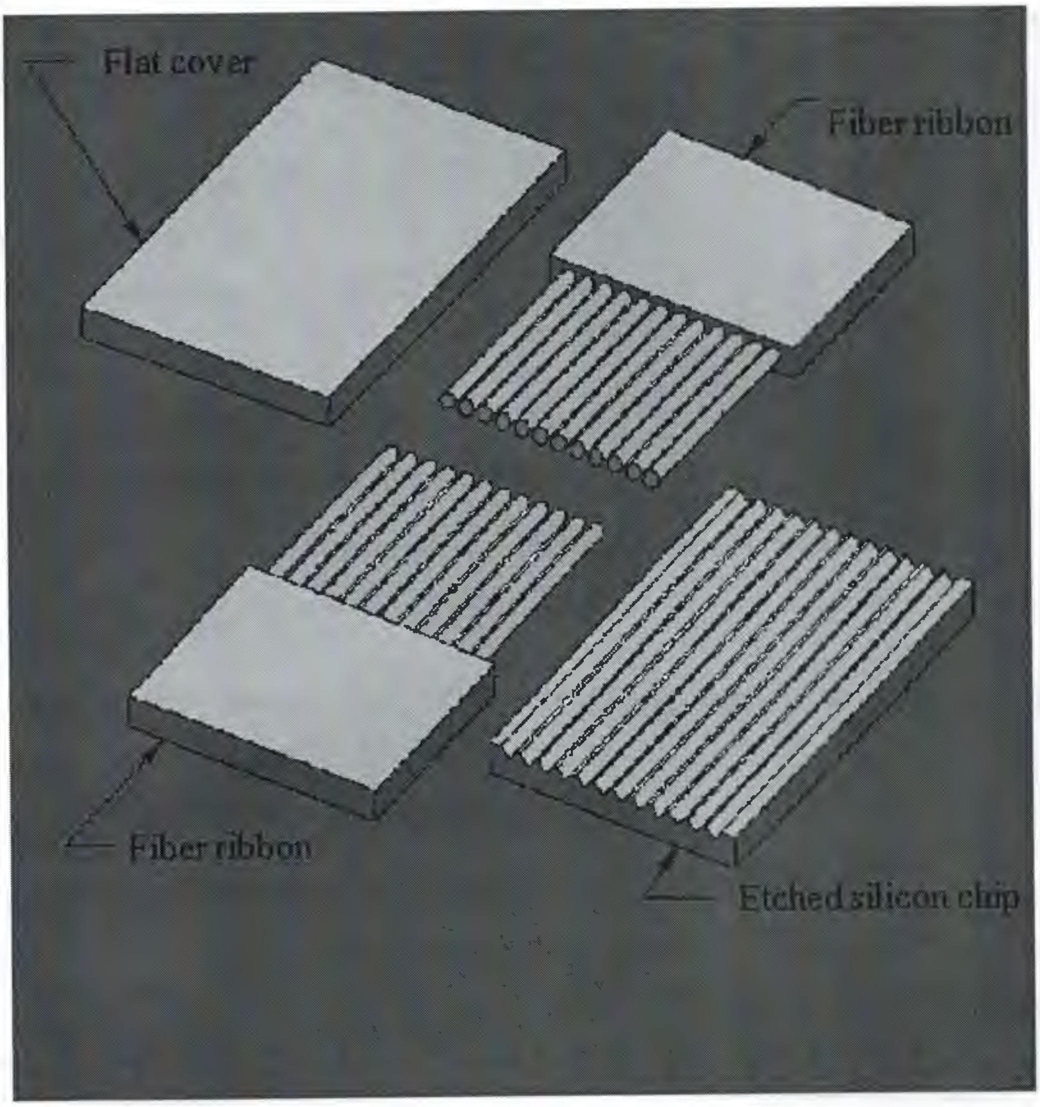


Figure 3.10 V-Groove splicing.

3.6.2 Semi-Permanent Splice:

This splice is used in networks where subscribers move equipment around. E.g. in local area networks.

3.7 Connector Loss Test Measurements:

The ideal interconnection of one fiber to another would have two fibers that are optically and physically identical held by a connector or splice that squarely aligns them on their center axes. However, in the real world, system loss due to fiber interconnection is a factor. Insertion loss is the primary consideration for connector performance.

There are three types of insertion loss:

1. fiber-related loss
2. connector-related loss,
3. System factors.

3.7.1 Measurement System Components:

There are several components required to test interconnection losses.

3.7.1.1 Light Source:

Light sources include lasers, LEDs, broadband sources, or monochromators.

A) Lasers and light-emitting diodes (LEDs):

Are widely used as sources. Important characteristics include output power, speed, output pattern or numerical aperture (NA), spectral width, fiber-type compatibility, ease of use, lifetime, and cost. Figure 3.11 illustrates various methods for interfacing a light source to an optical fiber.

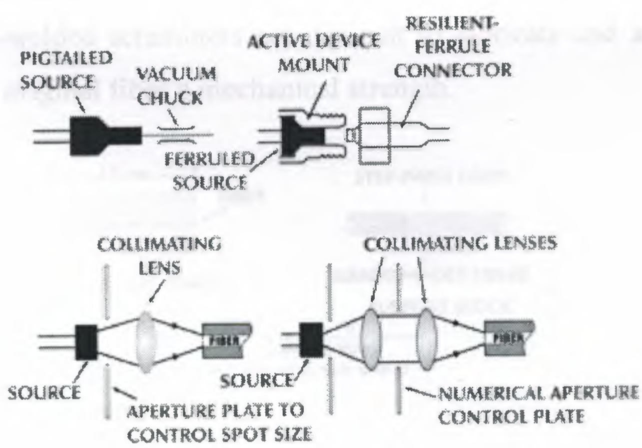


Figure 3.11 Methods of Interfacing a Source to a Fiber.

B) Broadband Source:

Once popular but now seldom used, typical incandescent sources include quartz, halogen, or xenon arc lamps with interference filters. If possible, the filter should have a band pass that approximates the output of the source to be used in the proposed system to better account for wavelength-dependent fiber characteristics such as NA, attenuation, and dispersion.

C) Monochromator:

This device isolates narrow portions of light by dispersing light into its component wavelengths. Most commercial monochromators exhibit very low energy on the output side, and they select a very narrow bandwidth.

3.7.1.2. Mode Scramblers:

Mode scramblers mix light to excite every possible mode of transmission within the fiber. The easiest to make is a 15-cm tube at least 7 cm in diameter filled with 1-mm lead shot through which the bare fiber passes. Another type uses a row of one-eighth inch diameter brass pins through which the fiber zigzags. The resulting bends in either type cause mode coupling that fills the fiber. A more complex scrambler is a butt-welded (fusion-spliced) length of alternating graded-index, step-index, graded-index fibers. The step-index fiber generally has a length of one meter. The discontinuities that result mix the light; however, butt-welded scramblers are difficult to fabricate and are weak, exhibiting less than 20% of the original fiber's mechanical strength.

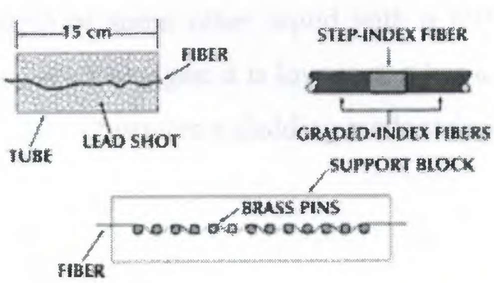


Figure 3.12 Mode Scramblers.

3.7.1.3. Core Mode Filter:

Mandrel wrap core mode filters allow high-order mode signals from the core to be removed. High-order modes traveling through several hundred meters of fiber leak into the cladding and are lost. This results in an exit numerical aperture less than the material NA of the fiber. A fiber that has reached modal equilibrium, along with the reduced NA, is said to exhibit long-launch conditions.

Rather than testing connector loss over several hundred meters of fiber, core mode filters simulate this distance. The standard recommended core mode filter for smaller fibers is 12.5-mm diameter mandrel around which the fiber is wrapped five times under zero tensions. The mandrel wrap reduces the exit NA to about 50% of the fiber's material NA. The mandrel wrap also reduces the light-emitting area of the core of a graded-index fiber by about 50%. This reduction in the emitting area affects the performance of a connector or a splice during loss measurements.

3.7.1.4. Cladding Mode Stripper:

The use of the mandrel wrap described above scrambles the modes or strips the high-order modes. This stripped light has nowhere to go except the cladding. In short fiber runs or in setups where the mandrel wrap occurs at the end of the fiber, this light deflected to the cladding can be substantial.

It is necessary to use to remove these modes, a cladding mode stripper, which incorporates a fiber, stripped of its cladding buffer, and covered in Corona Dope (available from TV repair suppliers) or some other liquid with a refractive index higher than the cladding. Corona Dope has advantages: it is low-cost, it has a high refractive index, and the coating is black. Figure 3.13 illustrates a cladding mode stripper.

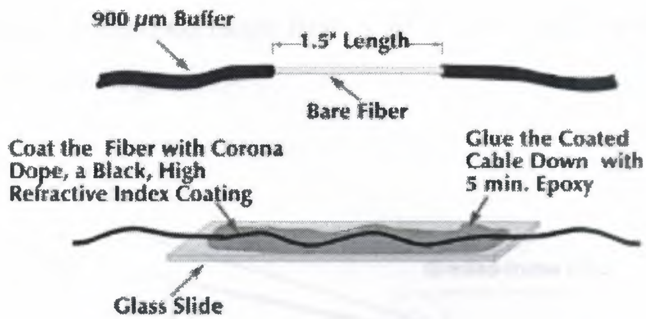


Figure 3.13 Cladding Mode Strippers.

3.7.1.5. Detector System:

Optical millimeters, also called optical power meters, read optical power levels. The meter is completely electronic with sensors that plug into the unit. Different sensors are available for use at different power levels and operating wavelengths. Adapters permit bare fibers or a variety of popular connectors to be connected to a sensor. A drawback of the millimeter is that in many applications both ends of the fiber must be available. An optical time-domain reflects meter allows testing when only one end of the fiber is available. This device relies on the backscattering of light that occurs in an optical fiber for detection.

3.7.2. System Related Losses:

System-related factors in connector loss involve the launch and receive conditions. These conditions result from the mode distribution in the fibers. The performance of the connector depends on modal conditions and the connector's position in the system. These launch conditions must be controlled in order to provide repeatable measurements. Long-launch conditions are generally preferred. Long-launch or receive conditions mean that equilibrium mode distribution (EMD), illustrated in Figure 3.14, exists in the fiber. The Electronic Industry Association (EIA) recommends a 70/70 launch: 70% of the fiber core diameter and 70% of the fiber NA should be filled. This recommendation corresponds to the EMD in a graded-index fiber. EMD can be reached three ways: by the optical approach, filtering, or long fiber length. In general, connector losses under long-launch conditions range from 0.4-0.5 dB. Under short-launch conditions, losses are in the 1.3-1.4 dB range.

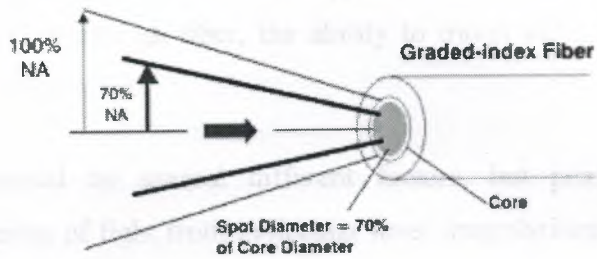


Figure 3.14 Equilibrium Mode Distributions.

3.8. How to Choose Optical Fiber:

The key optical performance parameters for single-mode fibers are attenuation, dispersion, and mode-field diameter.

Optical fiber performance parameters can vary significantly among fibers from different manufacturers in ways that can affect your system's performance. It is important to understand how to specify the fiber that best meets system requirements.

3.8.1. Attenuation:

Attenuation is the reduction of signal strength or light power over the length of the light-carrying medium. Fiber attenuation is measured in decibels per kilometer (dB/km).

Optical fiber offers superior performance over other transmission media because it combines high bandwidth with low attenuation. This allows signals to be transmitted over longer distances while using fewer regenerators or amplifiers, thus reducing cost and improving signal reliability.

Attenuation of an optical signal varies as a function of wavelength *(see* Figure 3.15*)*. Attenuation is very low, as compared to other transmission media (i.e., copper, coaxial cable, etc.), with a typical value of 0.35 dB/km at 1300 nm for standard single-mode fiber. Attenuation at 1550 nm is even lower, with a typical value of 0.25 dB/km. This gives an optical signal, transmitted through fiber, the ability to travel more than 100 km without regeneration or amplification.

Attenuation is caused by several different factors, but primarily scattering and absorption. The scattering of light from molecular level irregularities in the glass structure leads to the general shape of the attenuation curve *(see* Figure 3.15*)*. Further attenuation is caused by light absorbed by residual materials, such as metals or water ions, within the fiber core and inner cladding. It is these water ions that cause the "water peak" region on the attenuation curve, typically around 1383 nm. The removal of water ions is of particular interest to fiber manufacturers as this "water peak" region has a broadening effect and contributes to attenuation loss for nearby wavelengths. Some manufacturers now offer low water peak single-mode fibers, which offer additional bandwidth and flexibility compared with standard single-mode fibers. Light leakage due to bending, splices, connectors, or other outside forces are other factors resulting in attenuation.

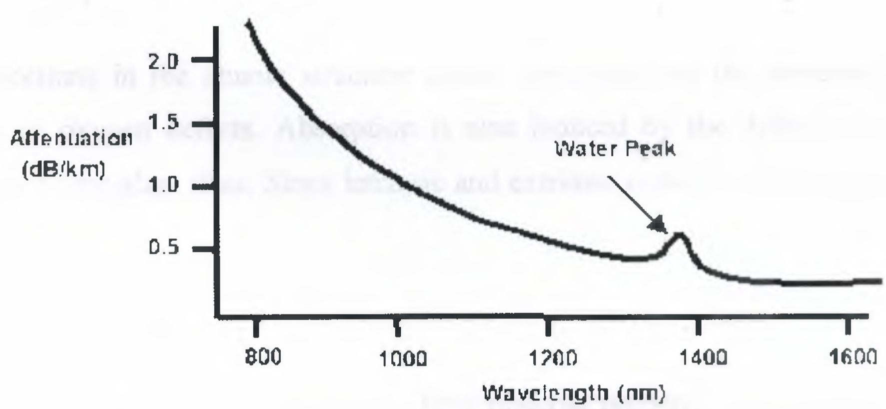


Figure 3.15. Typical Attenuation vs. Wavelength.

The following equation (3.1) defines signal attenuation as a unit of length:

$$\text{attenuation} = \left(\frac{10}{L}\right)\log_{10}\left(\frac{P_i}{P_o}\right) \qquad (3.1)$$

Signal attenuation is a log relationship. Length (L) is expressed in kilometers. Therefore, the unit of attenuation is decibels/kilometer (dB/km). As previously stated, attenuation is caused by absorption, scattering, and bending losses. Each mechanism of loss is influenced by fiber-material properties and fiber structure. However, loss is also present at fiber connections.

3.8.1.1. Attenuation properties:

3.8.1.1.1. ABSORPTION:

Absorption is a major cause of signal loss in an optical fiber. Absorption is defined as the portion of attenuation resulting from the conversion of optical power into another energy form, such as heat. Absorption in optical fibers is explained by three factors:

- Imperfections in the atomic structure of the fiber material
- The intrinsic or basic fiber-material properties
- The extrinsic (presence of impurities) fiber-material properties

Imperfections in the atomic structure induce absorption by the presence of missing molecules or oxygen defects. Absorption is also induced by the diffusion of hydrogen molecules into the glass fiber. Since intrinsic and extrinsic material properties are the main cause of absorption.

1. Intrinsic Absorption:

Intrinsic absorption is caused by basic fiber-material properties. If an optical fiber were absolutely pure, with no imperfections or impurities, then all absorption would be intrinsic. Intrinsic absorption sets the minimal level of absorption.

In fiber optics, silica (pure glass) fibers are used predominately. Silica fibers are used because of their low intrinsic material absorption at the wavelengths of operation.

In silica glass, the wavelengths of operation range from 700 nanometers (nm) to 1600 nm. Figure 2-21 shows the level of attenuation at the wavelengths of operation. This wavelength of operation is between two intrinsic absorption regions. The first region is the ultraviolet region (below 400-nm wavelength). The second region is the infrared region (above 2000-nm wavelength).

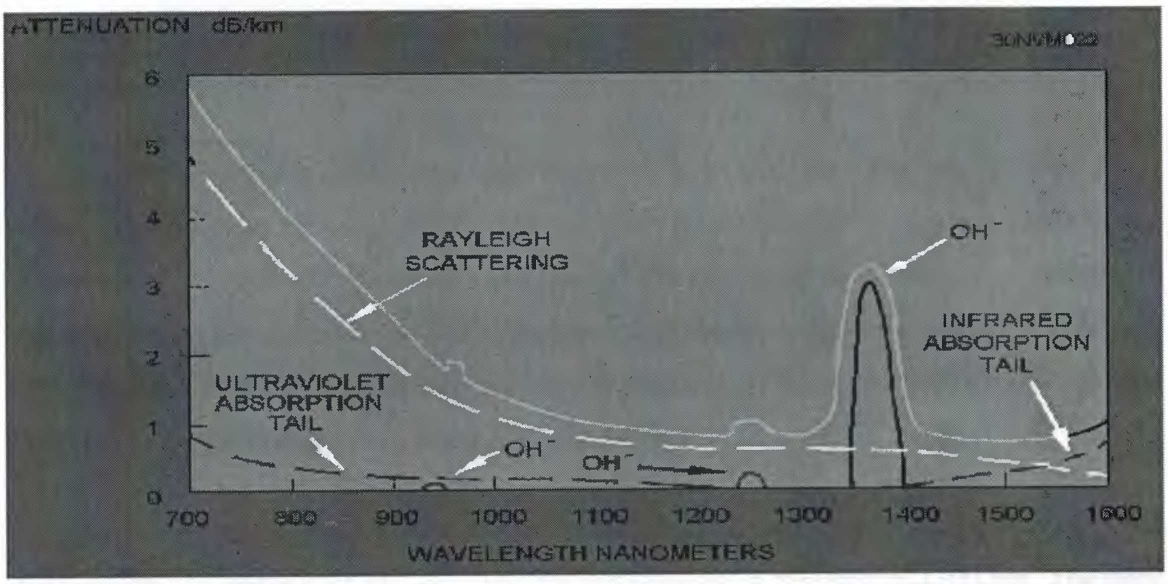


Figure 3.16 Fiber losses.

Intrinsic absorption in the ultraviolet region is caused by electronic absorption bands. Basically, absorption occurs when a light particle (photon) interacts with an electron and excites it to a higher energy level. The tail of the ultraviolet absorption band is shown in figure 3.16.

The main cause of intrinsic absorption in the infrared region is the characteristic vibration frequency of atomic bonds. In silica glass, absorption is caused by the vibration of silicon-oxygen (Si-O) bonds. The interaction between the vibrating bond and the electromagnetic field of the optical signal causes intrinsic absorption. Light energy is transferred from the electromagnetic field to the bond. The tail of the infrared absorption band is shown in figure 3.16.

2. Extrinsic Absorption:

Extrinsic absorption is caused by impurities introduced into the fiber material. Trace metal impurities, such as iron, nickel, and chromium, are introduced into the fiber during fabrication. Extrinsic absorption is caused by the electronic transition of these metal ions from one energy level to another.

Extrinsic absorption also occurs when hydroxyl ions (OH^-) are introduced into the fiber. Water in silica glass forms a silicon-hydroxyl (Si-OH) bond. This bond has a fundamental absorption at 2700 nm. However, the harmonics or overtones of the fundamental absorption occur in the region of operation. These harmonics increase extrinsic absorption at 1383 nm, 1250 nm, and 950 nm. Figure 3.16 shows the presence of the three OH^- harmonics. The level of the OH^- harmonic absorption is also indicated.

These absorption peaks define three regions or windows of preferred operation. The first window is centered at 850 nm. The second window is centered at 1300 nm. The third window is centered at 1550 nm. Fiber optic systems operate at wavelengths defined by one of these windows.

The amount of water (OH^-) impurities present in a fiber should be less than a few parts per billion. Fiber attenuation caused by extrinsic absorption is affected by the level of impurities (OH^-) present in the fiber. If the amount of impurities in a fiber is reduced, then fiber attenuation is reduced.

3.8.1.1.2. SCATTERING:

Basically, scattering losses are caused by the interaction of light with density fluctuations within a fiber. Density changes are produced when optical fibers are manufactured.

During manufacturing, regions of higher and lower molecular density areas, relative to the average density of the fiber, are created. Light traveling through the fiber interacts with the density areas as shown in figure 3.17. Light is then partially scattered in all directions.

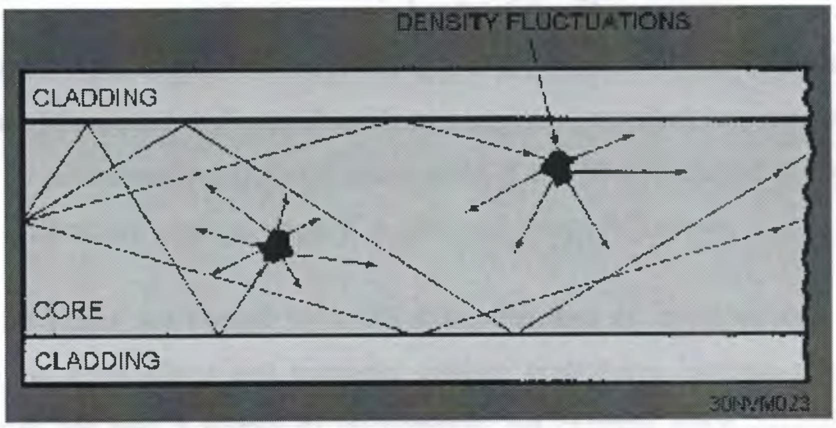


Figure 3.17. Light scattering.

In commercial fibers operating between 700-nm and 1600-nm wavelength, the main source of loss is called Rayleigh scattering. Rayleigh scattering is the main loss mechanism between the ultraviolet and infrared regions as shown in figure 3.16. Rayleigh scattering occurs when the size of the density fluctuation (fiber defect) is less than one-tenth of the operating wavelength of light. Loss caused by Rayleigh scattering is proportional to the fourth power of the wavelength ($1/\lambda^4$). As the wavelength increases, the loss caused by Rayleigh scattering decreases.

If the size of the defect is greater than one-tenth of the wavelength of light, the scattering mechanism is called Mie scattering. Mie scattering, caused by these large defects in the fiber core, scatters light out of the fiber core. However, in commercial fibers, the effects of Mie scattering are insignificant. Optical fibers are manufactured with very few large defects.

3.8.1.1.3. BENDING LOSS:

Bending the fiber also causes attenuation. Bending loss is classified according to the bend radius of curvature: microbend loss or macrobend loss.

1. Microbends loss:

Microbend losses are small microscopic bends of the fiber axis that occur mainly when a fiber is cabled. Macrobends are bends having a large radius of curvature relative to the fiber diameter. Microbend and macrobend losses are very important loss mechanisms. Fiber loss caused by microbending can still occur even if the fiber is cabled correctly. During installation, if fibers are bent too sharply, macrobend losses will occur.

Microbend losses are caused by small discontinuities or imperfections in the fiber. Uneven coating applications and improper cabling procedures increase microbend loss. External forces are also a source of microbends. An external force deforms the cabled jacket surrounding the fiber but causes only a small bend in the fiber. Microbends change the path that propagating modes take, as shown in figure 3.18. Microbend loss increases attenuation because low-order modes become coupled with high-order modes that are naturally lossy.

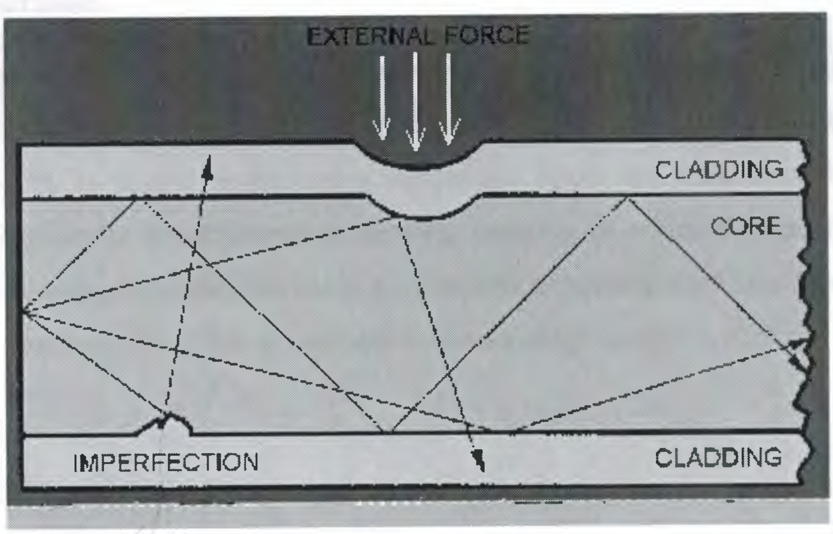


Figure 3.18. Microbend loss.

2. Macrobend losses:

Macrobend losses are observed when a fiber bend's radius of curvature is large compared to the fiber diameter.

These bends become a great source of loss when the radius of curvature is less than several centimeters. Light propagating at the inner side of the bend travels a shorter distance than that on the outer side. To maintain the phase of the light wave, the mode phase velocity must increase. When the fiber bend is less than some critical radius, the mode phase velocity must increase to a speed greater than the speed of light. However, it is impossible to exceed the speed of light. This condition causes some of the light within the fiber to be converted to high-order modes. These high-order modes are then lost or radiated out of the fiber.

Fiber sensitivity to bending losses can be reduced. If the refractive index of the core is increased, then fiber sensitivity decreases. Sensitivity also decreases as the diameter of the overall fiber increases. However, increases in the fiber core diameter increase fiber sensitivity. Fibers with larger core size propagate more modes. These additional modes tend to be more lossy.

3.8.2. Dispersion:

Dispersion is the time distortion of an optical signal that results from the time of flight differences of different components of that signal, typically resulting in pulse broadening (see Figure3.19). In digital transmission, dispersion limits the maximum data rate, the maximum distance, or the information-carrying capacity of a single-mode fiber link. In analog transmission, dispersion can cause a waveform to become significantly distorted and can result in unacceptable levels of composite second-order distortion (CSO).

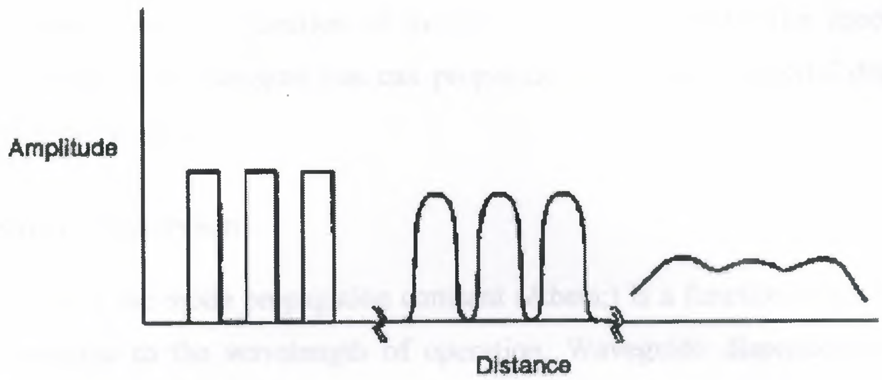


Figure 3.19. Impact of Dispersion

There are two different types of dispersion in optical fibers.

The types are:

1. Intramodal or chromatic dispersion.

2. Intermodal or modal dispersion.

3.8.2.1.intramodal or chromatic dispersion:

Intramodal, or chromatic, dispersion depends primarily on fiber materials. There are two types of intramodal dispersion. Intramodal dispersion occurs because different colors of light travel through different materials and different waveguide structures at different speeds.

1. Material dispersion:

Occurs because the spreading of a light pulse is dependent on the wavelengths' interaction with the refractive index of the fiber core. Different wavelengths travel at different speeds in the fiber material. Different wavelengths of a light pulse that enter a fiber at one time exit the fiber at different times.

Material dispersion is a function of the source spectral width. The spectral width specifies the range of wavelengths that can propagate in the fiber. Material dispersion is less at longer wavelengths.

2. Waveguide dispersion:

Occurs because the mode propagation constant (β) is a function of the size of the fiber's core relative to the wavelength of operation. Waveguide dispersion also occurs because light propagates differently in the core than in the cladding.

In multimode fibers, waveguide dispersion and material dispersion are basically separate properties. Multimode waveguide dispersion is generally small compared to material dispersion. Waveguide dispersion is usually neglected.

However, in single mode fibers, material and waveguide dispersion are interrelated.

The total dispersion present in single mode fibers may be minimized by trading material and waveguide properties depending on the wavelength of operation.

3.8.2.2. Intermodal or modal dispersion:

Intermodal or modal dispersion causes the input light pulse to spread. The input light pulse is made up of a group of modes. As the modes propagate along the fiber, light energy distributed among the modes is delayed by different amounts. The pulse spreads because each mode propagates along the fiber at different speeds. Since modes travel in different directions, some modes travel longer distances. Modal dispersion occurs because each mode travels a different distance over the same time span, as shown in figure 3.20. The modes of a light pulse that enter the fiber at one time exit the fiber a different times. This condition causes the light pulse to spread. As the length of the fiber increases, modal dispersion increases.

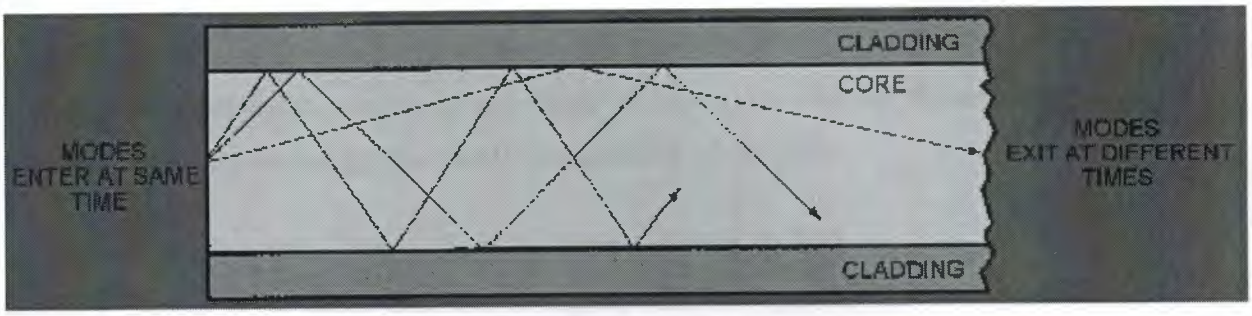


Figure 3.20 Distance traveled by each mode over the same time span.

Modal dispersion is the dominant source of dispersion in multimode fibers. Modal dispersion does not exist in single mode fibers. Single mode fibers propagate only the fundamental mode. Therefore, single mode fibers exhibit the lowest amount of total dispersion. Single mode fibers also exhibit the highest possible bandwidth.

3.8.3. Dispersion vs. Wavelength:

Single-mode fiber dispersion varies with wavelength and is controlled by fiber design (see Figure 3.21). The wavelength at which dispersion equals zero is called the zero-dispersion wavelength (λ). This is the wavelength at which fiber has its maximum information-carrying capacity. For standard single-mode fibers, this is in the region of 1310 nm. The units for dispersion are also shown in Figure3.20..

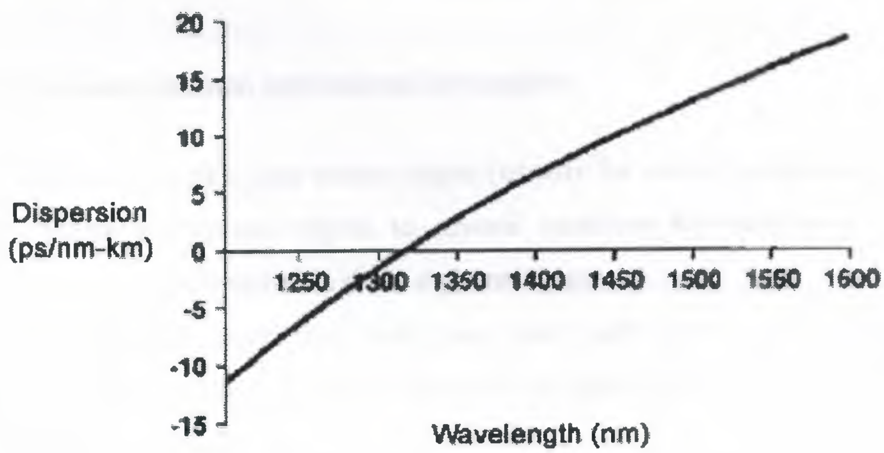


Figure 3.20. Typical Dispersion vs. Wavelength Curve.

Chromatic dispersion consists of two kinds of dispersion. Material dispersion refers to the pulse spreading caused by the specific composition of the glass.

Waveguide dispersion results from the light traveling in both the core and the inner cladding glasses at the same time but at slightly different speeds. The two types can be balanced to produce a wavelength of zero dispersion anywhere within the 1310 nm to 1650 nm operating window.

3.9. Couplers:

Fiber optic couplers either split optical signals into multiple paths or combine multiple signals on one path. Optical signals are more complex than electrical signals, making optical couplers trickier to design than their electrical counterparts. Like electrical currents, a flow of signal carriers, in this case photons, comprise the optical signal. However, an optical signal does not flow through the receiver to the ground. Rather, at the receiver, a detector absorbs the signal flow.

Multiple receivers, connected in a series, would receive no signal past the first receiver which would absorb the entire signal. Thus, multiple parallel optical output ports must divide the signal between the ports, reducing its magnitude. The number of input and output ports, expressed as an N x M configuration, characterizes a coupler. The letter N represents the number of input fibers, and M represents the number of output fibers. Fused couplers can be made in any configuration, but they commonly use multiples of two (2 x 2, 4 x 4, 8 x 8, etc.).

Some of the most common applications for couplers:

- Local monitoring of a light source output (usually for control purposes).
- Distributing a common signal to several locations simultaneously. An 8-port coupler allows a single transmitter to drive eight receivers.
- Making a linear, tapped fiber optic bus. Here, each splitter would be a 95%-5% device that allows a small portion of the energy to be tapped while the bulk of the energy continues down the main trunk.

4. Optical Amplifiers & Networks:

4.1Optical Amplifiers:

In fiber optics, an optical amplifier is a device that amplifies an optical signal directly, without the need to convert it to an electrical signal, amplify it electrically, then reconvert it to an optical signal.

With the demand for longer transmission lengths, optical amplifiers have become an essential component in long-haul fiber optic systems. Semiconductor optical amplifiers (SOAs), erbium doped fiber amplifiers (EDFAs), and Raman optical amplifiers lessen the effects of dispersion and attenuation allowing improved performance of long-haul optical systems.

4.1.1 Semiconductor Optical Amplifiers:

Semiconductor optical amplifiers (SOAs) are essentially laser diodes, without end mirrors, which have fiber attached to both ends. They amplify any optical signal that comes from either fiber and transmit an amplified version of the signal out of the second fiber. SOAs are typically constructed in a small package, and they work for 1310 nm and 1550 nm systems. In addition, they transmit bidirectionally, making the reduced size of the device an advantage over regenerators of EDFAs. However, the drawbacks to SOAs include high-coupling loss, polarization dependence, and a higher noise figure. Figure 4.1 illustrates the basics of a Semiconductor optical amplifier

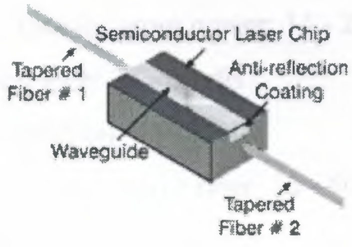


Figure 4.1 Semiconductors Optical Amplifier.

Modern optical networks utilize SOAs in the follow ways: Power Boosters: Many tunable laser designs output low optical power levels and must be immediately followed by an optical amplifier. (A power booster can use either an SOA or EDFA.) In-Line Amplifier: Allows signals to be amplified within the signal path. Wavelength Conversion: Involves changing the wavelength of an optical signal. Receiver Preamplifier: SOAs can be placed in front of detectors to enhance sensitivity.

4.1.2. Erbium Doped Fiber Amplifiers (EDFAs):

The explosion of dense wavelength-division multiplexing (DWDM) applications makes these optical amplifiers an essential fiber optic system building block. EDFAs allow information to be transmitted over longer distances without the need for conventional repeaters. The fiber is doped with erbium, a rare earth element that has the appropriate energy levels in their atomic structures for amplifying light. EDFAs are designed to amplify light at 1550 nm. The device utilizes a 980 nm or 1480nm pump laser to inject energy into the doped fiber. When a weak signal at 1310 nm or 1550 nm enters the fiber, the light stimulates the rare earth atoms to release their stored energy as additional 1550 nm or 1310 nm light. This process continues as the signal passes down the fiber, growing stronger and stronger as it goes.

Typical values for commercial EDFAs :-

- Frequency of operation: C and L band (approx. 1530 to 1605 nm).
  - For S-band (below 1480 nm) other dopants are necessary.
- low noise with noise figure 3-6dB
- high gain(20-40dB) and less sensitivity to polarization of the light signal.
- Max. optical output power: 14 - 25 dBm
- Internal gain: 25 - 50 dB
- Gain variation: +/- 0.5 dB
- Length of the active fiber: 10 - 60 m for C-band EDFAs and 50 - 300 m for L-band EDFAs
- Quantity of pump lasers: 1 - 6

- Pump wavelength: 980 nm or 1480 nm

Figure4.2 shows a fully featured, dual pump EDFA that includes all of the common components of a modern EDFA.

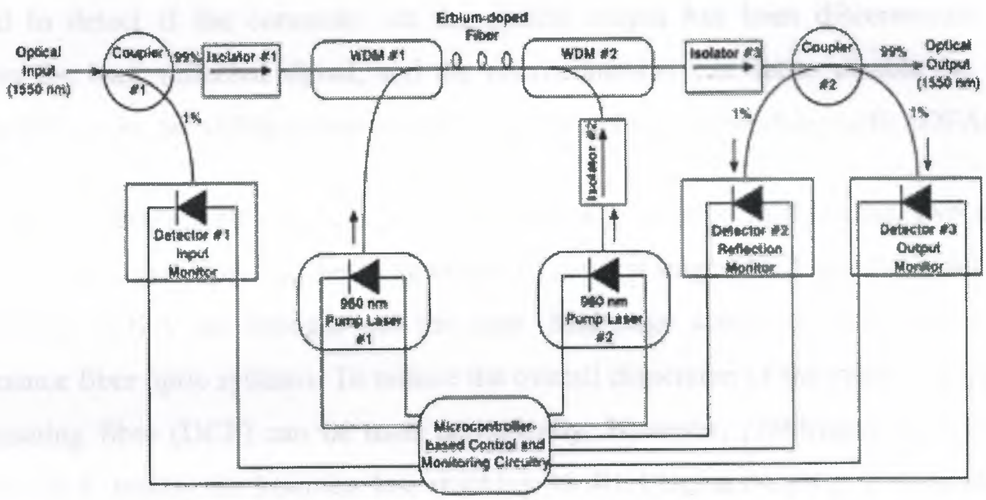


Figure 4.2 Block Diagram of an EDFA.

The input coupler, Coupler #1, allows the microcontroller to monitor the input light via detector #1. The input isolator, isolator #1 is almost always present. WDM #1 is always present, and provides a means of injecting the 980 nm pump wavelength into the length of erbium-doped fiber. WDM #1 also allows the optical input signal to be coupled into the erbium-doped fiber with minimal optical loss. The erbium-doped optical fiber is usually tens of meters long. The 980 nm energy pumps the erbium atom into a slowly decaying, excited state.

When energy in the 1550 nm band travels through the fiber it causes stimulated emission of radiation, much like in a laser, allowing the 1550 nm signal to gain strength. The erbium fiber has relatively high optical loss, so its length is optimized to provide maximum power output in the desired 1550 nm band. WDM #2 is present only in dual pumped EDFAs. It couples additional 980 nm energy from Pump Laser #2 into the other end of the erbium-doped fiber, increasing gain and output power. Isolator #3 is almost always present. Coupler #2 is optional and may have only one of the two ports shown or may be omitted altogether.

The tap that goes to Detector #3 is used to monitor the optical output power. The tap that goes to Detector #2 is used to monitor reflections back into the EDFA. This feature can be used to detect if the connector on the optical output has been disconnected. This increases the back reflected signal, and the microcontroller can set to disable the pump lasers in this event, providing a measure of safety for technicians working with EDFAs.

Figure 4.3 shows a two-stage EDFA with mid-stage access. In this case, two single-stage EDFAs are packaged together. The output of the first stage EDFA and the input of the second stage EDFA are brought out the user. Mid-stage access is important in high performance fiber optic systems. To reduce the overall dispersion of the system, dispersion compensating fiber (DCF) can be used periodically. However, problems can arise from using the DCF, mostly the insertion loss reaching 10 dB. Placing the DCF at the mid-stage access point of the two-stage EDFA reduces detrimental effects on the system, and allows the users noticeable gain.

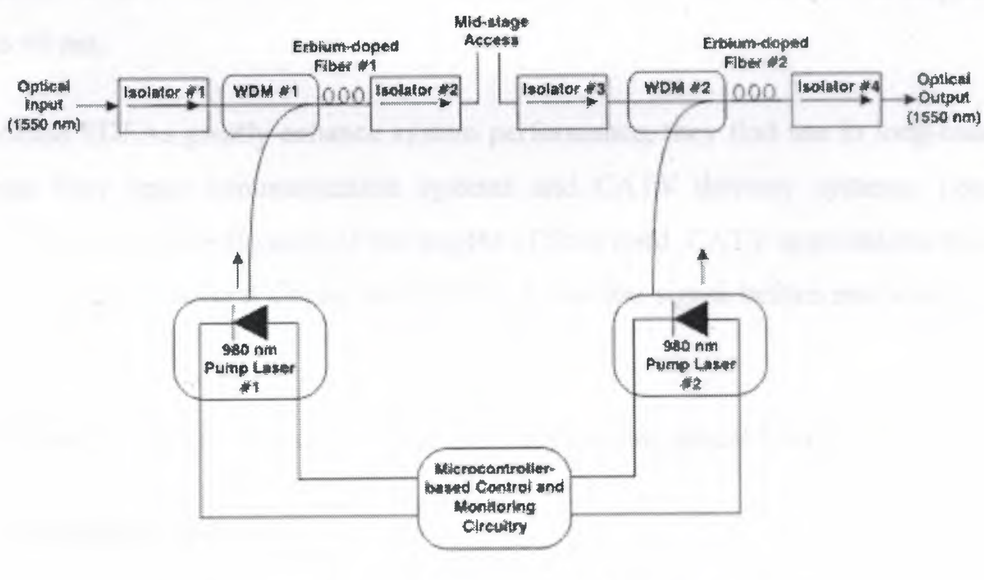


Figure 4.3 Two-stage EDFA with Mid-stage Access

The optical input first passes through optical Isolator #1. Next the light passes through WDM #1, which provides a means of injecting the 980 nm pump wavelength into the first length of erbium-doped fiber. WDM #1 also allows the optical input signal to be coupled into the erbium-doped fiber with minimal optical loss. The erbium-doped optical fiber is usually tens of meters long. Like the fully feature, dual pumped EDFA, the 980 nm energy pumps the erbium atoms into an excited state that decays slowly. When light in the 1550 nm band travels through the erbium-doped fiber it causes stimulated emission of radiation. As the optical signal gains strength, output of the erbium-doped fiber then goes into the optical isolator #2, the output of which is available to the user.

Typically, a dispersion compensating device will be connected at the mid-stage access point. The light then travels through isolator #3 and WDM #2, which couples additional 980 nm energy from a second pump laser into the other end of a second length of erbium-doped fiber, increasing gain and output power. Finally, the light travels through isolator #4.

Photons amplify the signal avoiding almost all active components, a benefit of EDFAs. Since the output power of an EDFA can be large, any given system design can require fewer amplifiers. Yet another benefit of EDFAs is the data rate independence means that system upgrades only require changing the launch/receive terminals. The most basic EDFA design amplifies light over a narrow, 12 nm, band. Adding gain equalization filters can increase the band to more than 25 nm. Other exotic doped fibers increase the amplification band to 40 nm.

Because EDFAs greatly enhance system performance, they find use in long-haul, high data rate fiber optic communication systems and CATV delivery systems. Long-haul systems need amplifiers because of the lengths of fiber used. CATV applications often need to split a signal to several fibers, and EDFAs boost the signal before and after the fiber splits.

There are four major applications that generally require optical fiber amplifiers:

1. Power amplifier/booster.

2. In-line amplifier.

3. Preamplifier or Loss compensation for optical networks.

Below are detailed descriptions of each application.

4.1.2.1. Optical Fiber Amplifiers Applications

There are many applications on the optical fiber amplifiers such as :

1. Power Amplifier/Booster:

Figure 4 illustrates the first three applications for optical amplifiers. Power amplifiers (also referred to as booster amplifiers) are placed directly after the optical transmitter. This application requires the EDFA to take a large signal input and provide the maximum output level. Small signal response is not as important because the direct transmitter output is usually -10 dBm or higher. The noise added by the amplifier at this point is also not as critical because the incoming signal has a large signal-to-noise ratio (SNR).

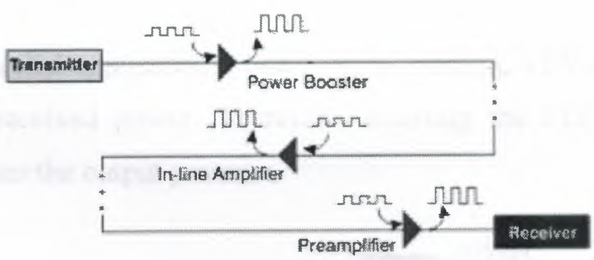


Figure 4.4 Three Applications for an EDFA.

2. in-Line Amplifiers:

In-line amplifiers or in-line repeaters modify a small input signal and boost it for retransmission down the fiber. Controlling the small signal performance and noise added by the EDFA reduces the risk of limiting a system's length due to the noise produced by the amplifying components.

3. Preamplifiers or Loss in Optical Networks:

Past receiver sensitivity of -30 dBm at 622 Mb/s was acceptable; however, presently, the demands require sensitivity of -40 dBm or -45 dBm. This performance can be achieved by placing an optical amplifier prior to the receiver. Boosting the signal at this point presents a much larger signal into the receiver, thus easing the demands of the receiver design.

This application requires careful attention to the noise added by the EDFA; the noise added by the amplifier must be minimal to maximize the received SNR.

Inserting an EDFA before an 8 x 1 optical splitter increases the power to almost +19 dBm allowing each of the eight output legs to provide +9 dBm, making the output almost equal to the original transmitter power. The optical splitter alone has a nominal optical insertion loss of 10 dB. The transmitter has an optical output of +10 dBm, meaning that the optical splitter outputs without an EDFA would be 0 dBm. This output power would be acceptable for most digital applications; however, in analog CATV applications this is the minimal acceptable received power. Therefore, inserting the EDFA before the optical splitter greatly increases the output power.

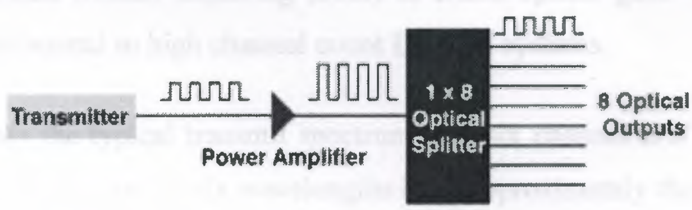


Figure 4.5 Loss Compensation in Optical Networks.

4.1.2.2. Wideband EDFAs:

Optical communication systems carrying 100 or more optical wavelengths require and increase in the bandwidth of the optical amplifier to nearly 80 nm. Normally employing a hybrid optical amplifier, consisting of two separate optical amplifiers, allows for separate amplification, one for the lower 40 nm band and the second for the upper 40 nm band.

Figure4.6 exemplifies the optical gain spectrum of a hybrid optical amplifier. The solid lines illustrate the response of two individual amplifier sections. The dotted line, which has been increased by 1 dB for clarity, shows the response of the combined hybrid amplifier.

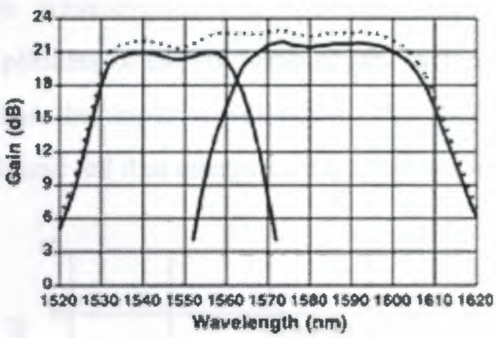


Figure4.6 Optical Gain Spectrum of a Hybrid Optical Amplifier.

4.1.3. Raman Optical Amplifiers:

Raman optical amplifiers differ in principle from EDFAs or conventional lasers in that they utilize stimulated Raman scattering (SRS) to create optical gain. Initially, SRS was considered too detrimental to high channel count DWDM systems.

Figure4.7 shows the typical transmit spectrum of a six channel DWDM system in the 1550 nm window. Notice that all six wavelengths have approximately the same amplitude.

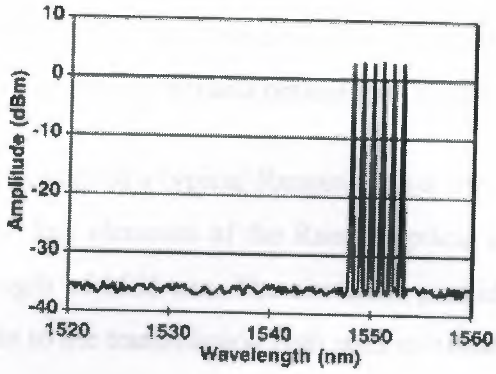


Figure 4.7DWDM Transmit Spectrum with Six Wavelengths

By applying SRS the wavelengths, it is obvious that the noise background has increased, making the amplitudes of the six wavelengths different. The lower wavelengths have smaller amplitude than the upper wavelengths. The SRS effectively robbed energy from the lower wavelength and fed that energy to the upper wavelength.

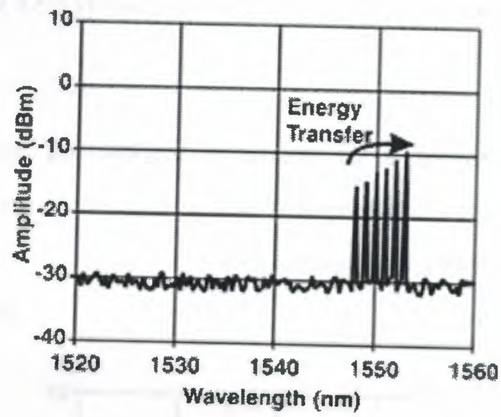


Figure 4.8 Received Spectrum after SRS is on a Long Fiber.

A Raman optical amplifier is little more that a high-power pump laser, and a WDM or directional coupler. The optical amplification occurs in the transmission fiber itself, distributed along the transmission path. Optical signals are amplified up to 10 dB in the network optical fiber. The Raman optical amplifiers have a wide gain bandwidth (up to 10 nm). They can use any installed transmission optical fiber. Consequently, they reduce the effective span loss to improve noise performance by boosting the optical signal in transit. They can be combined with EDFAs to expand optical gain flattened bandwidth.

Figure4.9 shows the topology of a typical Raman optical amplifier. The pump laser and circulator comprise the two key elements of the Raman optical amplifier. The pump laser, in this case, has a wavelength of 1535 nm. The circulator provides a convenient means of injecting light backwards in to the transmission path with minimal optical loss.

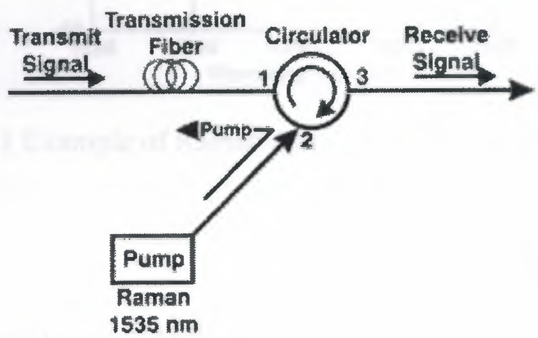


Figure 4.9 Typical Raman Amplifier Configuration.

Figure 4.10 illustrates the optical spectrum of a forward-pumped Raman optical amplifier. The pump laser is injected at the transmit end rather than the receive end as shown in figure4.9. The pump laser has a wavelength of 1535 nm; the amplitude is much larger than the data signals.

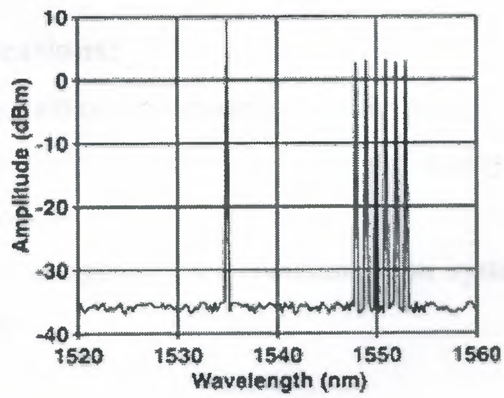


Figure 4.10 Example of Raman Amplifier -- Transmitted Spectrum.

As before, applying SRS makes the amplitude of the six data signals much stronger. The energy from the 1535 nm pump laser is redistributed to the six data signals.

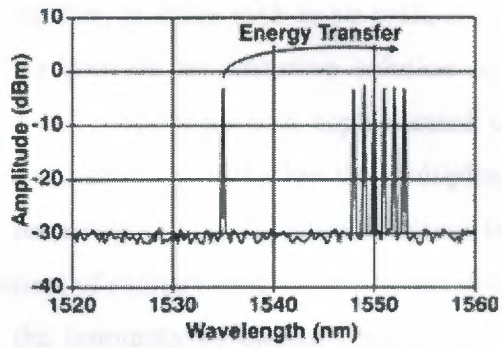


Figure 4.11 Example of Raman Amplifier -- Received Spectrum

4.2. Applications and Future Developments:

4.2.1. Public Network Applications:

- Trunk network
- Junction network
- Local access network
- Synchronous network

4.2.2. Military Applications:

In these applications, although economics are important, there are usually other. Possibly overriding, considerations such as size, weight, deploy ability, survivability and other advantage and security.

The special attributes of optical fiber communication systems, therefore often lend themselves to military use.

4.2.3. Mobiles:

One of the most promising areas of military applications for optical fiber communications is within military mobiles such as air craft, ships and tanks. The small size and weight of optical fiber provide an attractive solution to space problems in these mobiles, which are increasingly equipped with sophisticated electronics. Also the wide band nature of optical fiber transmission will allow the multiplexing of a number of signals on to a common bus. The immunity of optical communications to electromagnetic interface in the often noisy environment of military mobiles is a tremendous advantage.

This also applies to the immunity of optical fiber to lightning and electromagnetic pulses especially within avionics.

The electrical solution, and therefore safety, aspect of optical fiber communications, allowing routing through both fuel tanks and magazines.

4.2.4. Computer Applications:

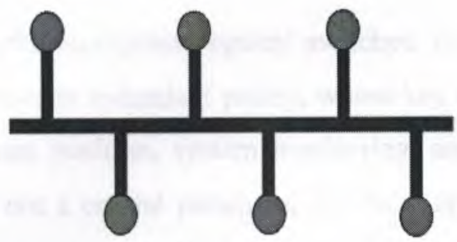
Modern computer systems consist of large number of interconnections. These range from lengths of few micrometers to perhaps thousands of kilometers for terrestrial links in computer networks.

The transmission rate over these interconnections also covers a wide range from around 100 $bits^{-1}$ for some type terminals to several hundred $M bits^{-1}$ for the on chip connections. Optical fibers are starting to find application in this connection hierarchy where source, interference free transmission is required.

4.3. Local Area Networks (LANs):

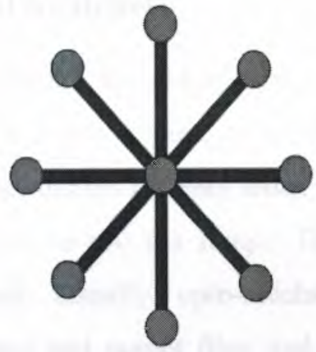
A local area network (LAN), unlike the local telecommunication network, is an interconnection topology which is usually confined to either a single building or group of buildings contained entirely within a confined site or establishment (e.g. industrial, educational, military, etc).

The LAN is therefore operated and controlled by the owning body rather than by a common carrier. Optical fiber communication topology is finding application within LANs to meet the on-site communication requirements of large commercial organizations and to enable access to distributed or centralized computing resources.



(A)

(B)



(C)

Figure 4.12 Common LAN topologies: (A) Linear Bus; (B) Ring; (C) Star.

4.4. Switches:

Many optical networks incorporate optical switches. Networks that require protection switching (switching between redundant paths), where key attributes must operate reliably after a long period in one position, system monitoring, and diagnosis commonly feature these devises. Speed is not a crucial parameter for these applications, as speed as high as tens of milliseconds are acceptable. However in the future, dynamic optical routing will require much faster switching speeds. Figure4.13 below illustrates common switch configurations.

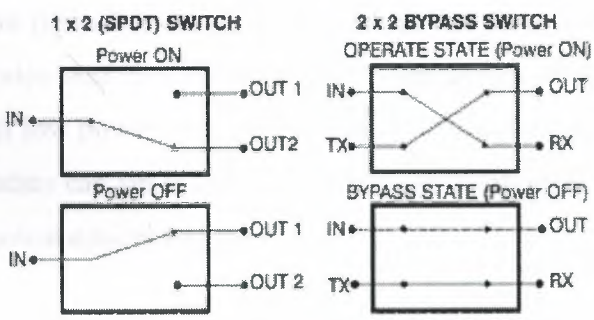


Figure 4.13 Typical Switch Configurations.

4.4.1. Opto-Mechanical Switches:

Opto-mechanical switches are the oldest type of optical switch and the most widely deployed at the time. These devices achieve switching by moving fiber or other bulk optic elements by means of stepper motors or relay arms. This causes them to be relatively slow with switching times in the 10-100 ms range. They can achieve excellent reliability, insertion loss, and crosstalk. Usually, opto-mechanical optical switches collimate the optical beam from each input and output fiber and move these collimated beams around inside the device. This allows for low optical loss, and allows distance between the input and output fiber without deleterious effects. These devices have more bulk compared to other alternatives, although new micro-mechanical devices overcome this.

4.4.2. Thermo-optic Switches:

Thermo-optic switches are normally based on waveguides made in polymers or silica. For operation, they rely on the change of refractive index with temperature created by a resistive heater placed above the waveguide. Their slowness does not limit them in current applications.

4.4.3. Electro-optic Switches:

These are typically semiconductor-based, and their operation depends on the change of refractive index with electric field. This characteristic makes them intrinsically high-speed devices with low power consumption. However, neither the electro-optic nor thermo-optic optical switches can yet match the insertion loss, backreflection, and long-term stability of opto-mechanical optical switches.

The latest technology incorporates all-optical switches that can cross-connect fibers without translating the signal into the electrical domain. This greatly increases switching speed, allowing today's Telcos and Networks to increase data rates. However, this technology is only now in development, and deployed systems cost much more than systems that use traditional Opto-Mechanical Switches.

CONCLUSION

Over the past few years, fiber optic cable has become more affordable. It's now used for dozens of applications that require complete immunity to electrical interference. Fiber is ideal for high data-rate systems such as FDDI, multimedia, ATM, or any other network that requires the transfer of large, time-consuming data files. Other advantages of fiber optic cable cover cooper include:

- **Greater distance**: you can run fiber as far as several kilometers.
- **Low attenuation**: the light signals meet little resistance, so data can travel farther.
- **Security**: Taps in fiber optic cable are easy to detect. If tapped, the cable leaks light, causing the system to fail.
- **Greater bandwidth**: Fiber can carry more data than copper.
- **Immunity**: Fiber optics is immune to interference.
- **Flexibility**: High degree of flexibility.
- **No cross talk**: there is no interference in the signals transmitted through the cable.
- **Low weight.**
- **Small size.**
- **No ground loop problems.**

Although fiber optic cable is still more expensive than other types of cable, it's favored for today's high-speed data communications because it eliminates the problems of twisted-pair cable, such as near-end crosstalk (NEXT), electromagnetic interference (EMI), and security breaches.

It can be used in many fields as Public Network Applications, Military Applications, Mobiles, and Computer Applications (LANs and WANs). But there are some disadvantages of the optical fiber especially in the complex system of the Laser diode and the price is little expensive for some applications.

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