UNIVERSITY OF ÇUKUROVA
INSTITUTE OF NATURAL AND
APPLIED SCIENCES

MSc THESIS

MİNE TÜLİN TOKGÖZ

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T.C. YÜKSEKÖĞRETİM KURULU
DOKÜMANTASYON MERKEZİ

Ultra-Short Pulse Propagation in Single-Mode Optical Fibers

DEPARTMENT OF ELECTRICAL AND
ELECTRONICS ENGINEERING

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ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

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YÜKSEK LİSANS TEZİ

ELEKTRİK-ELEKTRONİK ANA BİLİM DALI

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ABSTRACT

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Prof. Dr. Süleyman GÜNGÖR

The propagation of short pulses in single mode optical fibers is affected by a number of linear and nonlinear effects. The influence of different effects on pulse propagation depends on the pulse power and width and the fiber properties. Picosecond pulse propagation at wavelengths far from the dispersion minimum is described by the effects of the group velocity dispersion and the refractive-index nonlinearity. Stable pulse-propagation without changes of pulse spectral and temporal shapes can exist as a result of the cancellation of the effect of pulse broadening through dispersion by the refractive index nonlinearity. Solitary waves pass through one another without deformations due to the collisions. The optical soliton in fibers is the solitary wave of an envelope of a light wave. The optical soliton belongs to an envelope soliton. The pulse shape represents an envelope of a light wave. An envelope of a wave which propagates in a strongly dispersive nonlinear medium,in which the wave property depends on the amplitude as well as on the wavelength of the wave , has a solitary wave solution had been known for waves in plasmas. In our simulation we will investigate pulse propagation in single-mode optical fibers. We will analyze the influence of different effects on pulse propagation.In this analysis, we will use nonlinear schrodinger equation which describes soliton wave and split-step fourier method to solve this equation. These effects depend on the pulse power and width and also linear and nonlinear fiber properties.

Keywords : Ultra-short pulse propagation, single mode optical fiber, refractive index, soliton, nonlinear schrodinger equation, split-step fourier method.

T.C. YÜKSEKÖĞRETİM KURULU
DOKÜMANTASYON MERKEZİ

ÖZ

YÜKSEK LİSANS TEZİ

TEK MODLU OPTİK FİBERLERDE ÇOK KISA PALSLARIN YAYILIMI

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Tek modlu optik fiberlerdeki kısa palsların yayılımı, bazı lineer ve lineer olmayan faktörleden etkilenir. Değişik faktörlerin pals yayılımına etkisi pals gücüne, pals genişliğine ve fiber özelliklerine (yayılma, lineer olmayan özellikler ve kayıplar) bağlıdır.Minimum yayılmadan uzak dalga boylarındaki pikosaniye pals yayılımı, kırılma-indis nonlineeritesi ve grup hızı yayılımı faktörleri ile tanımlanır. Pals spektral ve geçici şekil değişiklikleri olmaksızın kararlı pals yayılımı, kırılma indis nonlineeritesi ile yayılım boyunca pals genişlemesi etkisinin ihmal edilmesi sonucunda oluşur. Tek dalgalar, iç çarpışmalara bağlı bozulmalara uğramadan birbiri içinden geçer. Optik soliton, bir ışık dalga zarfının tek dalgasıdır. Buna göre fiberdeki optik soliton, bir zarf solitonuna aittir. Pals şekli ışık dalgasının zarfını gösterir.Güçlü lineer olmayan yayılım ortamında,öyle ki bu ortam dalganın dalgaboyuna ve büyüklüğüne bağlı dalga özelliği gösterir, yayılan bir dalga zarfı, plazmadaki dalgalar için de bilinen tek dalga çözümüne sahiptir.Bizim çalışmamızda, tek modlu fiberlerdeki dalga yayılımını inceleyeceğiz. Pals yayılımına değişik faktörlerin etkisini analiz edeceğiz. Bu analizde, soliton dalgasını tanımlayan lineer olmayan schrodinger denklemini ve denklemi çözmek için split-step fourier metodunu kullanacağız. Bu faktörler pals gücüne ve genişliğine ve ayrıca lineer ve lineer olmayan fiber özelliklerine bağlıdır.

Anahtar Kelimeler: Çok kısa pals yayılımı, tek modlu optik fiber, soliton, lineer olmayan schrodinger denklemi, kırılma indisi.

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NOTATIONS

n_1	refractive index along the axis of the fiber
Δ	normalized refractive index difference
r	distance from the axis of the fiber in μm
a	core radius in μm
g	profile exponent
n_2	refractive index of the cladding
λ	wavelength of the light
NA	numerical aperture of the core glass
k	wave number of the light
α_{dB}	signal attenuation per unit lengths in decibels
L	fiber length
γ_R	Rayleigh scattering coefficient
β_c	isothermal compressibility
K	Boltzman constant
T_F	fictive temperature
n	refractive index of the medium
p	average photoelastic coefficient

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1. HISTORICAL DEVELOPMENT

Optical communication systems were being used two centuries ago, in the "optical telegraph". It was invented by Claude Chappe in the 1790s. His system was mounted on towers, and thanks to it the messages were relayed from one tower to the next. But in the mid-19th century the optical telegraph was replaced by the electric telegraph.

In the forthcoming years, optical transmission was adapted for communications. Optical transmission for communications was a phenomenon that has depended on the total internal reflection, which can confine light in a material surrounded by other materials with lower refractive index, such as glass in air. In the 1840s, Daniel Collodon and Jacques Babinet have showed that light could be guided along jets of water for fountain displays. In 1854, John Tyndall has demonstrated guiding light in a jet of water flowing from a tank. A few years later, it was invented that bent quartz rods could carry light and then the inventors have patented them as dental illuminators.

In 1880, Alexander Graham Bell patented an optical telephone system, named as Photophone. Before the invention of the optical telephone system, light was used to send signals between ships.

In 1920, John Logie Baird and Clarence W. Hansell have used arrays of hollow pipes to transmit images for television or facsimile systems. Then they have patented this idea. In 1951, Holger Moeller Hansen applied for a Danish patent on fiber-optic imaging. Until 1954, there has been no reports on fiber bundles. At this time, Abraham van Heel, Harold. H. Hopkins and Narinder Kapany separately announced imaging bundles.

Neither van Heel nor Hopkins and Kapany made bundles that could carry light far, but their reports the fiber optics revolution. van Heel covered a bare fiber or glass or plastic with a transparent cladding of lower refractive index. This protected the total-reflection surface from contamination, and greatly reduced crosstalk between fibers.

The next key step was development of glass-clad fibers, by Lawrence Curtiss to develop an endoscope to examine the inside of the stomach with Basil Hirschowitz and C. Wilbur Peters. By 1960, glass-clad fibers had attenuation of about one decibel per meter, fine for medical imaging, but much too high for communications.

Meanwhile, telecommunications engineers were seeking more transmission bandwidth. Radio and microwave frequencies were in heavy use, so they looked to higher frequencies to carry loads they expected to continue increasing with the growth of television and telephone traffic. In 1958, Alec Reeves realized to work at higher optical frequencies, and he invented digital pulse-code modulation. And at the same year, Hicks, Paul Kiritsy and Chat Thompson left American Optical to form first fiber optic company(Mosaic fabrications) .

Laser was invented in 1960 by Theodore Maiman. He thought that usable communications channels in the electromagnetic spectrum may be extended by development of an experimental optical-frequency amplifier. Then Ali Javan made first helium-neon laser at Bell Labs.

In 1961, Elias Snitzer at American Optical, working with Hicks at Mosaic Fabrications, demonstrated the similarity by drawing fibers with cores so small they carried light in only one waveguide mode. However virtually everyone considered fibers too lossy for communications; attenuation of a decibel per meter was fine for looking inside the body, but communications operated over much longer distances, and required loss no more than 10 or 20 decibels per kilometer.

Robert N. Hall’s group at General Electric made the first semiconductor diode laser, in 1962.

In 1963, Karbowiak proposed flexible thin-film waveguide.

But, serious work on optical communications were done after inventing of the continuouswave helium-neon laser. While air is far more transparent at optical wavelengths than to millimeter waves, electronics engineers realized that rain, haze, clouds, and atmospheric turbulence limited the reliability of long-distance atmospheric laser links. In 1965, researchers thought the biggest problem was the lack of adequate repeaters; millimeter waveguides had low loss, although only if they were kept precisely straight. Stewart Miller's group at Bell Telephone Laboratories was working on a system of gas lenses to focus laser beams along hollow waveguides for long-distance telecommunications. Most people for example working at industries thought that milimetric waveguides would be used in many applications in the future. But optical fibers attracted some attention because they were analogous in theory to plastic dielectric waveguides which were used in microwave applications.

Kao researched at fiber attenuation. He collected samples from fiber makers, and carefully investigated the properties of bulk glasses. As a result of these studies, he believed that the high losses of fibers were due to impurities, not to silica glass itself. In the midst of this research, in the beginning of 1965, Kao worked out a proposal for long-distance communications over single-mode fibers. Kao believed that fiber loss should be reducible below 20 decibels per kilometer. In1966 he wrote an article about this subject,as a matter of fact about laser focus.

In the Standard Telecommunications Laboratories, C. K. Kao observed that the experimental optical waveguide has an information-carrying capacity of one gigacycle, which is equivalent to about 200 tv channels or in another words more than 200,000 telephone channels. He determined STL's device which consists of a glass core about three or four microns in diameter, clad with a coaxial layer of another glass which has a refractive index about one percent smaller than that of the core. The result of these studies, he found that total diameter of the waveguide is between 300 and 400 microns and surface optical waves had propagated along the interface between the two types of glass. According to his investigations, Kao saw that the fiber was strong and could be supported. But at that time low-loss material had a loss of about 1000 dB/km, Standard Telecommunications Laboratories (STL) believed that they would be able to reduce materials having losses of only tens of decibels per kilometer. Kao and Hockham analyzed fiber loss could be reduced below 20 dB/km in the July 1966.

In the end of the 1967, Maurer and Peter Schultz(he was working at Corning Glass's chemistry department) worked together to make pure glasses.

Donald Keck began to work with Maurer at the Corning Glass as the first full-time fiber developer. Then Frank Zimar joined them. Frank Zimar had drawn fiber in a high-temperature furnace he built, in January 1968.

At the same time, Kao and M. W. Jones measured intrinsic loss of bulk fused silica at 4 decibels per kilometer. This was the the first evidence of ultratransparent glass toconsider fiber optics by Bell Labs seriously.

In August 1968, Dick Dyott of British Post Office worked about pulling clad optical fibers from molten glass .

Martin Chown working at Standard Telecommunications Labs showed fiber-optic repeater at Physical Society exhibition, in 1969.

In 1967, Shojiro Kawakami proposed graded index optical fibers. Then Maurer made a research to reduce high loss in fibers using titania-doped cores and pure-silica cladding. Robert Maurer, Donald Keck and Peter Schultz started with fused silica, a material that can be made extremely pure, but has a high melting point and a low refractive index. They made cylindrical performs by depositing purified materials from the vapor phase, adding carefully controlled levels of dopants to make the refractive index of the core slightly higher than that of the cladding, without raising attenuation dramatically. In September 1970, they announced they had made single-mode fibers with attenuation at the 633-nanometer helium-neon line below 20 dB/km. The fibers were fragile but have low loss.

In the same year, Bell Labs inventors made the first semiconductor diode lasers able to emit continuouswave at room temperature. During the next several years, fiber losses were dropped by improved fabrication methods and by the shift to longer wavelengths where fibers have lower attenuation.

In 1970, the investigations showed that single-mode fibers had cores several micrometers in diameter.

In April 1970, Standard Telecommunications Labs demonstrated fiber optic transmission at Physics Exhibition in London.

First continuous-wave room-temperature semiconductor lasers was made in May by Zhores Alferov's group at the Ioffe Physical Institute in Leningrad (now St. Petersburg) and on June 1 by Mort Panish and Izuo Hayashi at Bell Labs in 1970.

The following development was introduced by AT&T as Picturephone in Pittsburgh. By using this, millimeter waveguides to provide the needed extra capacity could be installed.

At the same year, Maurer, Donald Keck, Peter Schultz, and Frank Zimar at Corning Glass worked together and improved a single-mode fiber with loss of 17 dB/km at 633 nanometers by doping titanium into fiber core.

As a result of this study, Maurer reported results at London conference devoted mainly to progress in millimeter waveguides.

In November 1970, some measurements were done at British Post Office and Standard Telecommunications Labs. Then they were verified as right by comparing Corning results.

Dick Dyott working at Post Office and Felix Kapron working at Corning Glass separately found and then introduced pulse spreading which was lowest at 1.2 to 1.3 micrometers wavelengths in the years between 1970 and 1971.

Murray Ramsay working at Standard Telecommunication Labs showed digital video over fiber to Queen Elizabeth at the Centenary of the Institution of Electrical Engineers in May 1971.

In the years between 1971 and 1972, researches shifted to graded-index fibers. Because the single-mode fibers offered few advantages and many problems at 850 nanometers, they couldn't give sufficient values at this wavelength.

In the middle of the 1972, Maurer, Keck and Schultz worked at multimode germania-doped fiber with 4 decibel per kilometer loss and much greater strength than titania-doped fiber.

At the same year, Standard telecommunications Labs modulated diode laser at 1 Gbit/s. Then, after this invention, Bell Labs left its last work on hollow light pipes.

In December 1972, John Fulenwider introduced a fiber-optic communication network to carry video and other signals to homes at International Wire and Cable Symposium.

Then Maurer, Keck and Schultz made multimedia germania-doped fiber with 4 decibel Per kilometer loss and much greater than titania-doped fiber in 1972. In the same year, STL modulated diode laser at 1 Gbit/s.

In the beginning of 1973, at the Bell Labs, John MacChesney developed modified chemical vapor deposition process for fiber manufacture. Alittle bit time later, Investigations showed that the diode laser lifetime reached 1000 hours.

Bell Labs inventors improved that graded index fibers with 50-100 micrometer cores in 1974.

One year later, in 1975, Laser Diode Labs offered first commercial continuous-wave semiconductor laser that operates at room temperatures.

In the same year in September, Dorset (in UK) police after lightning knocks out their communication system installed first non-experimental fiber-optic link. In October, British Post Office began tests of millimeter waveguide (as Bell Labs made before), the tests were successful, but they couldn't have applied at that time..

Dave Payne and Alex Gambling at University of Southampton calculated pulse spreading should be zero at 1.27 micrometers in 1975.

In February 1975 Bell completed installation of 14 kilometers of millimeter waveguide in New Jersey.

Bell Labs began graded-index fiber-optic system's tests transmitting 45 million bits per second at its Norcross, Georgia plant in 1976. But in this system laser lifetime was main problem.

In the same year, Valtec launched Communications Fiberoptics division. And at that time, Masaharu Horiguchi (NTT Ibaraki Lab) and Hiroshi Osanai (Fujikura Cable) made first fibers with low loss ,0.47 decibel per kilometer, at long wavelengths, 1.2 micrometers.

In March 1976, Japan's Ministry for International Trade and Industry announces had planed for Hi-OVIS fiber-optic "wired city" experiment including 150 homes.

Bell Labs reached lifetime of best laboratory lasers which is 100,000 hours (10 years) at room temperature in 1976.

Another development was invented by Horiguchi and Osanai. They found third window in 1976.

The last invention of 1976 was InGaAsP lasers emitting continuously at 1.25 micrometers which was made by J. Jim Hsieh.

In April 1977, AT&T sent first test signals through field test system in Chicago's Loop district.

And then in April 22 1977, General Telephone and Electronics sent first live telephone traffic through fiber optics, 6 Mbit/s, in Long Beach, California.

A little bit time later, Bell System began to send live telephone traffic through fibers at 45 Mbit/s fiber link in downtown Chicago in May 1977.

After these developments, British Post Office started to launch live telephone traffic through fibers in underground ducts near Martlesham Heath in June 1977.

In 1977, Bell Labs engineers improved one-million hours (100-year) lifetime with diode lasers.

In the end of the 1977, AT&T Labs and other telephone companies settle on 850 nanometer gallium arsenide light sources and graded-index fibers for commercial systems operating at 45 million bits per second.

Those first-generation systems could transmit light several kilometers without repeaters, but were limited by loss of about 2 dB/km in the fiber.

A second generation was made using new InGaAsP lasers which emitted at 1.3 micrometer, where fiber attenuation was as low as 0.5 dB/km, and pulse dispersion was lower than at 850 nm.

In 1977-1978, There were new researches in single-mode fibers with low loss at long wavelengths.

First fiber optic trade show was made in Boston in May 22-23, 1978, Fiber Optic Conference.

By Japan's Hi OVIS project, optical fibers had been started to use at homes in July 1978.

There was another development that NTT transmitted 32 million bits per second through 53 kilometers of graded-index fiber at 1.3 micrometers wavelength in August 1978.

In September 1978, Richard Epworth explained modal noise problems in graded-index fibers.

In the same time, France Telecom made plans for connecting 1500 homes by using optical fibers.

AT&T, British Post Office and Standar Telecommunications Lab. worked together and developed a single mode transatlantic fiber cable by using the 1.3-micrometer window. After that development, Bell Labs abandoned improving of new coaxial cables for submarine systems in 1978.

A variety of studies such as development of hardware for the first transatlantic fiber cable showed that single-mode systems were feasible. In the beginning of 1980s, the carriers built national backbone systems of single-mode fiber with 1300-nm sources because deregulation opened the long-distance phone market. That technology has spread into other telecommunication applications, and remained the standard for most fiber systems.

In January 1980, AT&T designed Northeast Corridor system from Boston to Washington to carry three different wavelengths through graded-index fiber at 45 Mbit/s.

In the same year, graded-index fiber system were used to carry video signals for 1980 Winter Olympics in Lake Placid, New York, at 850 nanometers.

STL and British Post Office committed to make 9.5 km submarine cable which had included single-mode and graded-index fibers in Loch Fyne, Scotland in February 1980.

In the middle of 1980, Bell Labs used the single-mode technology with 1.3-micrometer wavelength for the first transatlantic fiber-optic cable, TAT-8.

In July 27, 1981, ITT licensed Corning communication fiber patents.

We can give another example of developments of fiber optics. In 1981, commercial second-generation systems were determined operating at 1.3 micrometer wavelebgth among graded-index fibers.

In the same year, British Telecom sent 140 million bits per second through 49 kilometers of single-mode fiber at 1.3 micrometers. After that, investigations on optical fibers began to shift to single-mode.

Canada started using of fiber optics at homes in Elie, Manitoba.

One year later, British Telecom modified field trial of single-mode fiber, and they rearrenged their plans abandoning graded-index fibers by using single mode.

In December 1982, a system was installed by using single-mode fiber from New York to Washington in America. That system was operated at 400 million bits per second at 1.3 micrometers. After that, American companies began to shift to single-mode fiber.

AT&T splitted off its seven regional operating companies, but anyway it kept long-distance transmission and also equipment manufacture in January 1, 1984.

British Telecom installed first submarine fiber to carry regular traffic, to the Isle of Wight in 1984.

In 1985, the developments were going on towards. Single-mode fiber spreads across America to carry long-distance telephone signals at 400 million bits per second and up.

One year later, in 1986, first fiber-optic cable across the English Channel was started to service.

And at the same time, AT&T sent 1.7 billion bits per second through single-mode fibers originally installed to carry 400 million bits per second.

Many researches followed these studies. In 1987, Dave Payne, at University of Southampton, developed erbium-doped fiber amplifier which had operated at 1.55 micrometers wavelength.

In 1988, Linn Mollenauer who was working at Bell Labs explained soliton transmission through 4000 kilometers by using single-mode fiber.

We can introduce the last invention of 1988. TAT-8 started to service which was the first transatlantic fiber-optic cable by using 1.3-micrometer lasers and single-mode fiber.

The other generation of single-mode systems was used in submarine cables and systems serving large numbers of subscribers. They operated at 1.55 micrometers, where fiber loss was 0.2 to 0.3 dB/km. This allowed longer repeater spacings. There is an important topic that erbium-doped optical fibers could be used as optical amplifiers at 1.55 μm wavelength, without using electro-optic regenerators. The optical amplifiers in submarine cables could operate at speeds to 5 gigabits per second. Also these amplifiers could be upgraded from lower speeds simply to changing terminal electronics. Optical fiber amplifiers could compensate losses in seperating the signals through many terminals. In other words, these amplifiers are useful for optical fiber systems because of delivering the same signals to many terminals (http://www.sff.net).

In February 1991, Masataka Nakazawa who was working at NTT intoduced sending soliton signals through a million kilometers of fiber.

Two years later, in 1993, Nakazawa sent soliton signals along 180 million kilometers.

Linn Mollenauer working at Bell Labs launched 10 billion bits through 20,000 kilometers of fibers. He used a simple soliton system in 1993.

After that developments, in February 1996, Fujitsu, NTT Labs, and Bell Labs sent one trillion bits per second through single optical fibers in separate experiments using different techniques.

Today telephone and cable television companies can cost-justify installing fiber links to remote sites serving tens to a few hundreds of customers. However, terminal equipment remains too expensive to justify installing fibers all the way to homes, at least for present services. Instead, cable and phone companies run twisted wire pairs or coaxial cables from optical network units to individual homes.

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2. INTRODUCTION

Communications systems that carry information through a guided fiber cable are called fiber optic systems. The fiber optic systems use light as the carrier of information. It is necessary to understand the meaning of the word "light". Light is something that makes vision possible. But many fiber optic systems employ "light" that is completely invisible to the human eye. Therefore, for the purpose of fiber optic systems, the word "light" includes electromagnetic radiation in the infrared, visible, and ultraviolet range.

During the past decade there has been a phenomenal increase in audio, data, and video communications. This revolution has led to more economical and larger capacity communication systems. Terrestrial microwave systems and satellite systems can provide only a temporary relief to the ever increasing demand. The size, weight, and bandwidth capabilities of fiber optic systems make them the most economical choice to meet all future demands.

Before the explaining fiber optic structure, I want to tell about frequency spectrum.

The frequency spectrum extends from a few hertz (subsonic) to 10^{22} Hz (cosmic rays). The frequency spectrum of visible light used for fiber optics extends from approximately 10^{14} to 10^{15} Hz. When dealing with such high frequencies, it is more convenient to express them in terms of wavelength (λ).

The relation between frequency and wavelength is given by:

$$f = C/\lambda \tag{1}$$

where f is frequency in hertz (Hz); C is velocity of light (3×10^8 m/s in free space); λ is wavelength in meters (m).

The frequency spectrum from 10^{14} to 10^{15} Hz refers to wavelengths range from 1700 nm to 800 nm. The visible portion of the optical spectrum extends from 390 nm to 770 nm. The longest visible wavelength produces the sensation of red. As the wavelengths decrease, the color sensations change gradually through orange, yellow, green, blue and violet. The wavelength of 390 nm produces sensation of very dark violet color.

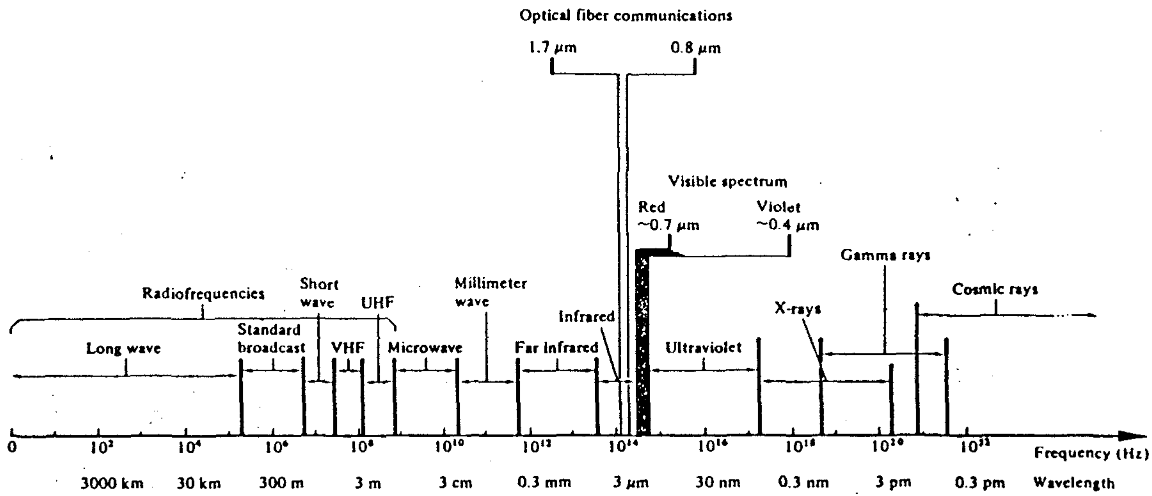
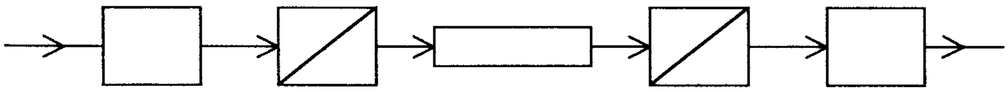


Fig.2.1 The electromagnetic frequency spectrum showing the region used for optical fiber communications.

The information carrying capacity of a communication system is directly proportional to its bandwidth. The bandwidth of a system itself depends upon its carrier frequency. Thus higher the carrier frequency, wider is the bandwidth and hence higher is the information carrying capacity. Bandwidth is always expressed as percentage of carrier frequency. For instance, in very high frequency (VHF) range a carrier at 100 megahertz (MHz) with 10% bandwidth has a bandwidth of 10 MHz. Such a bandwidth can carry only one TV channel. In microwave range, a carrier at 6 gigahertz (GHz) with 10% bandwidth has a bandwidth of 600 MHz. Thus a 6 GHz carrier can carry 60 times more information than a 100 MHz carrier. A light carrier at 10^{15} Hz (10^6 GHz) with 10% bandwidth has a bandwidth of 10^5 GHz (100,000 GHz). A carrier at 10^{15} GHz theoretically carries 166,666 times the information carried by a carrier at 6 GHz. Therefore, because of such a high information carrying capacity, the fiber optic systems are the ideal for growing communication needs.

2.1.Basic Fiber Optic System



e/o : Transducer electro/optic (Transmitter)

o/e : Transducer opto/electric (Receiver)

Fig.2.2 Schematic of an optical fiber transmission system

The basic principle of fiber optic light transmission is very simple. A light-emitting diode or a laser diode generates a light beam. This light carrier is modulated by the digital information to be carried. A portion of modulated light is injected into a fiber optic cable. The light rays bounce back and forth between the walls of the fiber cable until they reach the receiving end of the fiber. At the receiving end a photo-detector is used to translate the modulated light beam back into an electrical signal.

However, the fiber optic transmission is not as simple as it appears. The practical application of this simple principle has proved to be far more complex. Over three decades of research and development in optical materials, light sources, detectors, and manufacturing processes were required to make the doors open for this technology. A high-quality, high-capacity and efficient fiber optic communications system is required to make this technology a success.

The building blocks of fiber optic communications link are shown in fig.2.2 . The transmitter side consists of a driver, a modulator, a light source and a source-to-fiber coupling. The input signal to the driver is a digital data. If the information is in the analogue form, it must be converted into the digital data. The light source can either be a light emitting diode (LED) or an injection laser diode (ILD). The light radiation is modulated by the digital data. The light is then coupled into the optical fiber cable.

The optical fiber consists of an ultra pure glass or a plastic core, a cladding and a protective jacket. To join two pieces of fiber, a fiber-to-fiber coupling (or connector) is required.

The receiver side consists of a fiber-to-light detector coupling, a light detector, a demodulator and an amplifier. The modulated light guided through the optical fiber is coupled to a light detector. The demodulator recovers the digital information which is available at the output through the driver. The light detector is either a PIN photodiode or an avalanche photodiode.

The effectiveness of an optical link is expressed as the ratio of the output signal to the input signal. To improve the effectiveness of an optical link, all possible sources of attenuation must be avoided. The areas of potential attenuation or distortion include:

(1) input coupling loss,

(2) attenuation within the fiber,

(3) dispersion within the fiber,

(4) fiber-to-fiber connector insertion loss,

(5) output coupling loss,

(6) efficiency of light source and

(7) efficiency of the light detector.

The size, weight, attenuation and bandwidth capabilities of fiber optic cables make them most economical choice in various communication systems. The advantages and disadvantages of fiber systems over conventional systems are:

The advantages of fiber systems over conventional systems are:

(a) Information carrying capacity: Fiber optic systems use light frequencies as carriers and thus they have much larger available bandwidths.

(b) Immunity to interference: Fiber optic systems are immune to cross-talk between cables caused by magnetic induction. Fiber optic systems are also immune to static interference caused by electrical noise sources like electric motors and florescent lights.

(c) Information tapping: It is virtually impossible to tap information from a fiber cable without letting the user know about it.

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(d) Resistivity to temperature and environmental changes: Fiber cables can operate over large temperature variations and are less affected by corrosive liquids and gases.

(e) Inductance and capacitance: Metallic cables exhibit capacitance between and inductance along their lengths which act like low pass filters and limit the bandwidth of the systems. Fiber cables are free from this limitation.

(f) Easy installation: Fiber cables are safer and easier to install without worrying about volatile liquids and gases. These cable require less space.

(g) Light weight: Fiber cables are smaller and weigh lesser than metallic cables. (http://www.computersandinternet.com)

The most significant are the reduced power consumption exhibited by optical fiber systems in comparison with their metallic cable counterparts and their ability to provide for an expansion in the system capability often without fundamental and costly changes to the system configuration. For instance, a system may be upgraded by simply changing from an LED to an injection laser source, by replacing a p-i-n photodiode with an APD detector, or alternatively by operating at a longer wavelength without replacing the fiber cable.

There are some disadvantages for optical communication using fibers. They are:

a) the fragility of the bare fibers;
b) the small size of the fibers and cables which creates some difficulties with splicing and forming connectors;
c) some problems involved with forming low loss T-couplers;
d) some doubt in relation to the long-term reliability of optical fibers in the presence of moisture (effects of stress corrosion);
e) an independent electrical power feed is required for any repeaters;
f) new equipment and field practices are required;

testing procedures tend to be more complex.

2.1.1.The Structure of Optical Fiber

An optical fiber consists of a central core and an outer cladding . The core is made up of a material with higher index of refraction than the cladding material.

Glass (fused silica) and plastic are the two materials used to produce optical fibers. Glass has superior optical qualities but is more expensive and fragile than plastic. There are three varieties of optical fibers available today. These are:

1. Plastic core and cladding
2. Glass core with plastic cladding (plastic clad silica)
3. Glass core with glass cladding (silica clad silica)

Plastic fibers are more flexible and rugged than glass. They are less expensive but they do not propagate light as efficiently as glass. As plastic fibers offer higher attenuation, they are used only for short distances. Glass fibers are used for high speed applications or where long transmission paths are involved. Silica clad silica fibers have best propagation characteristics but are expensive and least rugged. An intermediate option is plastic clad silica fibers.

2.1.2. Propagation of Light:

Light can propagate through an optical fiber by two different methods. These are:

1. Total internal reflection; and
2. Continuous refraction

The name step index signifies a sharp step change at core/cladding interface. The cable is essentially a very small diameter fiber rod (clear glass or plastic). A small amount of selected contaminants has been added to make the cladding have a different index of refraction than the central core. The cladding always has lower index of refraction than the central core. Optical fibers that propagate light by total internal reflection are most widely used. The core of these fibers have a constant and uniform refractive index. A different method of light propagation is called continuous refraction.

2.1.3. Modes of Propagation

The word “mode” simply means path. Therefore modes can be defined as the various paths that light can take in travelling down the fiber. If there is only one path for light to take down the cable, it is called single mode. If there are more than one path, it is called multimode.

For a single mode propagation, the central core of the fiber is so small that there is only one path that light can take as it propagates down the cable.

For multimode propagation the central core is much larger . Different paths for several light rays entering a fiber at the same time but at various angles. Rays travel at different speeds. This speed difference between various modes results in model dispersion. Assuming that the input is a sharp narrow pulse, the output will be of a longer duration and a lower amplitude due to the division of energy between the various modes. This spreading of pulse during propagation is known as model dispersion.

By reducing the fiber core diameter to the point where it will propagate only one mode efficiently, model dispersion can be completely eliminated. For single mode propagation, the maximum core diameter is about 15 microns.

2.2.Optical Sources

To transmit light signals in an optical fiber, suitable transmitter and receiver elements are needed to convert electrical signals into optical signals, and vice versa.

At the transmitter side, an electrical signal modulates the intensity of a light source. The optical signal is coupled into the optical fiber and arrives at the receiver; a photoreceiver reconverts the optical signal into an electrical signal.

In semiconductor technology, electrooptic transducers are used. This means that there are electrooptic interactions in a semiconductor. These have been three processes which are named as absorption, spontaneous emission and stimulated emission. The photodiode makes use of absorption, the light emitting diode uses stimulated emission and the laser diode utilizes stimulated emission.

2.2.1 Transmitters

2.2.1.1 LED

A semiconductor diode that radiates light by spontaneous emission is called a light emitting diode (LED).

The qualify of the conversion of electrical current into light is described by the external *quantum efficiency*. It describes the number of photons emitted per unit of time. Because the quantum efficiency decreases as the temperature increases, a heating of recombination zone have to be avoided.

For the operation of LED, the wavelength of the light is also important.

$$\lambda = \frac{1.24}{E_g} \tag{2}$$

λ : wavelength in µm

E_g : energy gap in eV

$h\nu$: 1.24

For gallium arsenide (GaAs) diodes, Eg =1.43 eV and λ = 0.89 µm

For indium phosphide (InP) diodes, Eg =1.35 eV and λ = 0.92 µm (at room temperature).

The spectral width $\Delta\lambda$ of a LED is proportional to the square of the wavelength λ. So the spectral width increases toward longer wavelengths.

The response time which is related to the rise time of diode is an important characteristic to determine the diode process. The average lifetime of the excess charge carriers is the determining factor in light emission after the current is turned off. Below this limit, the diode cannot follow changes in the injection current. Typical minimum lifetime is a few nanoseconds that corresponds to 100 MHz modulation bandwidth.

Three examples of transmitter diodes are:,

Planar GaAs diode for $\lambda \approx 900$ nm

High radiance AlGaAs/GaAs diodes for $\lambda \approx 830$ nm

High radiance InGaAsP/InP diodes for $\lambda \approx 1300$ nm

Characteristics of LED are shown in table 2.1 (Mahlke/Gössing, 1987).

Table 2.1. Characteristics of LED

a: Infrared emitting diode

b: Product of bit rate and length is constant.

Type	λ (nm)	$\Delta\lambda$ (nm)	S/c material	Structure	Emission	Rise Time (ns)	Light power With core diam. 50 μm (μW)	Trans. Dist.[b]	
								km	Mbit/s
IRED[a]	880 to 950	50	GaAs	Planar	Spontane.	20 to 100	2	0.01 to 0.1	5 to 10

2.2.1.2 Laser Diode

A laser (light amplification by stimulated emission of radiation) diode is a source of radiation. It has high current density and a strong stimulated emission.

In contrast to LED's with their broad spectral distribution, the emission in laser operation narrows to one or only a few spectral lines.

The width of a transmitter spectrum is usually given as the full width at half maximum (FWHM) $\Delta\lambda$ or as the full root mean square width (FRMS) $\Delta\lambda_{FRMS}$, the relation:

$$\Delta\lambda = (\ln 4)^{1/2}\, \Delta\lambda_{FRMS} \approx 1.18\, \Delta\lambda_{FRMS} \tag{3}$$

or

$$\Delta\lambda_{FRMS} \approx 0.85\, \Delta\lambda \tag{4}$$

In contrast to the emission of LED, the radiation of a laser diode is spatially coherent due to the stimulated emission. The radiation beam is narrower than the LED.

Two types (related to their structures) of laser diodes are:

Gain Guided Laser Diodes (GLD),

Index Guided Laser Diodes (ILD).

Characteristics of laser diodes are shown in table 2.2 (Mahlke/Gössing, 1987).

Table.2.2 : Characteristics of laser diodes

a: Product of bit rate and length is constant

Type	λ (nm)	Δλ (nm)	S/c material	Structure	Emission	Rise Time (ns)	Light power		Trans. Dist.[a]	
							Core diam.	M.f. diam.	App. km	Mbit/s
LD	880 to 885	3 to 5	GaAlAs/ GaAs	Double hetero	Coherent	<1	1 to 5	—	5 to 20	≤565
LD-MCRW	1300/ 1550	3 to 5	GaInAsP / InP	Double hetero	Coherent	<1	1 to 3	0.5 to 1.5	To 35	≤1200
High radian. IRED	880 to 885	45	AlGaAs/ GaAs	Double hetero-struc.	Spontane.	5 to 20	30 to 100	—	1 to 5	30 to 100
High radian. IRED	1300/ 1550	100	InGaAsP / InP	Double hetero-struc.	Spontane.	5 to 20	50 to 100	—	1 to 5	50 to 200

2.2.2.Detectors (Receivers)

A photodiode takes advantage of the effect of absorption of light rays in semiconductors. For production of receivers, silicon and germanium are most frequently used.

2.2.2.1.PIN Photodiode

In semiconductors having low absorption coefficients, if an undoped semiconductor layer is inserted between the p- and n-type semiconductor it enlarges the region for absorption of the radiation. Silicon photodiodes for wavelengths up to 1100 nm is an example for this condition. Infrared light enters the diode through the p-region, the surface having an Si_3N_4 coating to prevent reflection losses.

Field effect transistors (FET) is used to increase the sensitivity of PIN photodiodes.

2.2.2.2 Avalanche Photodiodes

In this process a strong photocurrent is created by impact ionization. There are two types of APDs such as:

Silicon Avalanche Photodiode (APD) for wavelengths up to 1100nm

and

InGaAs/InP Avalanche Photodiodes for 1300 nm.

In the first type, the voltage required for avalanche breakdown is very high. In the second type, these diodes are the combination of an InGaAs/InP photodiode with an GaAs-FET.

Characteristics of receiver diodes are shown in table 2.3 (Mahlke/Gössing, 1987).

Table 2.3. Characteristics of receiver diodes

a: With coating

Type	Wavelength(nm)	S/C material	Structure	Amplification	Spectral sensitivity (A/W)
PIN-PD	400 to 1000	Si	Planar/PIN	None	0.7 to 0.9[a]
APD	400 to 1000	Si	Planar	×10 to ×100	
PIN-PD	1300	Ge	Mesa/planar	None	
APD	1300	Ge	Mesa/planar	×10	
PIN-PD	900 to 1600	InGaAs/InP	Mesa/planar	None	
APD	900 to 1600	InGaAs/InP	Mesa/planar	×10 to ×50	

2.3. Applications of Optical Fibers

The size, weight, attenuation and bandwidth capabilities of fiber optic cables make them most economical choice in various communication systems.

The combination of the numerous attributes and surmountable problems makes optical fiber transmission a very attractive proposition for use within national and international telecommunication networks. The technology has progressed from what may be termed first generation systems using multimode step index and operating in the shorter wavelength region (0.8-0.9 μm), to second generation systems utilizing multimode graded index fiber operating in both the shorter and longer wavelength regions (0.8-1.6 μm). Furthermore, fully engineered third generation systems incorporating single mode fiber predominantly for operation in the longer wavelength region (1.1-1.6 μm) have been accepted for commercial operation in the public telecommunications network. In addition many alternative fiber systems applications have become apparent in other areas of communications where often first and second generation systems provide an ideal solution. Also the growing utilization of optical fiber systems has stimulated tremendous research efforts towards enhanced fiber design.

2.3.1 Public Network Applications

The public telecommunications network provides a variety of applications for optical fiber communication systems. It was in this general area that the suitability of optical fibers for line transmission first made an impact. The current plans of the major PTT administrations around the world feature the installation of increasing numbers of optical links as an alternative to coaxial and high frequency pair cable systems.

The trunk or toll network is used for carrying telephone traffic between major conurbations. Hence there is a generally a requirement for the use of transmission systems which have a high capacity in order to minimize costs per circuit. Therefore transmission systems which exhibit low attenuation and hence give a maximum distance of unrepeatered operation are the most economically viable. Optical fiber systems with their increased bandwidth and repeater spacings offer a distinct advantage. Optical fiber systems show a significant cost advantage over coaxial cable systems and compete favorably with milimetric waveguide systems at all but the highest capacities. Integrated digital public network which means that the majority of trunk routes will employ digital transmission systems.

It may be noted that the single mode fiber system has a lower total system margin than the multimode fiber system operating at 0.85 μm. This is caused by the difficulty of launching light into the smaller single mode fiber as well as the reduced sensitivity of the PIN – FET hybrid receiver operating at 1.3 μm in comparison with the silicon APD receiver operating at 0.85 μm. The high speed systems are more appropriate to very long haul trunk routes.

The junction of interoffice network usually consists of routes within major conurbations over distances. However, the distribution of distances between switching centers (telephone exchanges) or offices in the junction network of large urban areas varies considerably for various countries.

The mean power launched from the laser is reduced below the level obtained with similar dimensioned multimode graded index fiber in the optical power budget.

Optical fibers are also used in the local and rural networks. The local and rural network or subscriber loop connects telephone subscribers to the local switching center or office. Possible network configurations include a ring, tree and star topology from the local switching center. In a ring network any information fed into the network by a subscriber passes through all the network nodes and hence a number of transmission channels must be provided between all nodes. This may be supplied by a time division multiplex system utilizing a broadband transmission medium. In this case only information addressed to a particular subscriber is taken from the network at that subscriber node. The tree network, which consists of several branches must also provide a number of transmission channels on its common links. In comparison with the ring network it has the advantage of greater flexibility in relation to topological enlargement. Nevertheless in common with the ring network, the number of subscribers is limited by the transmission capacity of the links used.

In contrast, the star network provides a separate link for every subscriber to the local switching center. Hence the amount of cable required is considerably increased over the ring or tree network, but is offset by enhanced reliability and availability for the subscribers. In addition, simple subscriber equipment is adequate and network expansion is straightforward. Thus virtually all local and rural telephone networks utilize a star configuration based on copper conductors (twisted pair) for full duplex (bothway) speech transmission. There is substantial interest in the possibility of replacing the existing narrowband local and rural network twisted pairs with optical fibers. These cac also be utilized in the star configuration to provide wideband services (videoband, television, stereo hi-fi, facsimile, data, etc.) to the subscriber together with the narrowband speech channel. Alternatively the enhanced bandwidth offered by optical fibers will allow the use of ring ot tree configurations in local and rural networks. The cost of optical fiber cable may be reduced towards the cost of copper twisted pairs with the large production volume required for the local and rural networks.

Another optical fiber application is submerged systems. Undersea cable systems are an integral part of the international telecommunications network. They found application on shorter routes especially in Europe. On longer routes, such as across the Atlantic, they provide route diversity in conjuction with satellite links. The number of submerged cable routes and their capacities are steadily increasing and hence there is a desire to minimize the costs per channel. Digital optical fiber communication systems offer substantial advantages over current analog FDM and digital PCM coaxial cable systems. High capacity coaxial cable systems require high quality, large diameter cable to overcome attenuation. By comparison, single mode optical fiber systems operating at 1.3μm or 1.55μm provide longer repeater spacings than the coaxial cables.

Research and development of single mode fiber submerged cable systems is progressings in a number of countries including the UK, France, the USA and Japan.

2.3.2.Military Applications

Although economics are important, there are considerations such as size, weight, deployability, survavibility (in both conventional and nuclear attack) and security. The special attributes of optical fiber communication systems therefore often lend themselves to military use.

One of the most promising areas of military for optical fiber communications is within military mobiles such as aircraft, ships and tanks. The small size and weigth of optical fibers provide an attractive solution to space problems in these mobiles which are increasingly equipped with sophisticated electronics. Also the wideband nature of optical fiber transmission allow the multiplexing of a number of signals onto a common bus. Furthermore, the immunity of optical transmission of electromagnetic interference (EMI) in the often noisy environment of military mobiles is a tremendous advantage. This also applies to the immunity of optical fibers to lightning and electromagnetic pulses (EMP) especially within avionics. The electrical isolation, and therefore safety, aspect of optical fiber communications also proves invaluable in these applications, allowing routing through both fuel tanks and magazines.

In the former case, the time division multiplex system allows ring or star configurations to be realized, or mixtures of both to create bus networks. The multiple access data highway allows an optical signal injected any access point to appear at all other access points.

However, significant problems were encountered with optical connection, fiber fragility and low light levels from the LED source. Nevertheless it was concluded that these drawbacks could be reduced by the use of spliced connections, star couplers rather than T-couplers and smaller diameter fibers, which would make it possible to produce cables with smaller radii of curvature, and in which the fiber would be free.

The other major area for the application of optical fiber communications in the military sphere includes both short and long distance communication links. Short distance optical fiber systems may be utilized to connect closely spaced items of electronic equipment in such areas as operations rooms and computer installations. A large number of these systems have already been installed in military installations in the UK. There is also a requirement for long distance communication between military installations which could benefit from the use of optical fibers. In both these cases advantages may be gained in terms of bandwidth, security and immunity to electrical interference and earth loop problems over conventional copper systems.

Other long distance applications include torpedo and missile guidance, information links between military vessels and maritime, towed sensor arrays. In these areas the available bandwith and long unrepeatered transmission distances of optical fiber systems provide a solution which is not generally available with conventional technology.

Investigations have also been carried out with regard to the use of optical fibers in tactical communications systems. In order to control sophisticated weapons systems in conjuction with dispersed military units there is a requirement for tactical command and control communications. These communication systems must be rapidly deployable, highly mobile, reliable and have the ability to survive in military environments. Existing multichannel communication cable links employing coaxial cable or wire pairs do not always meet these requirements. They tend to be bulky, difficult to install (requiring long installation times), and are susceptible to damage. In contrast optical fiber cables offer special features which may overcome these operational deficiencies. These include small size, light weight, increased flexibility, enhanced bandwidth, low attenuation removing the need for intermediate repeaters, and immunity to both EMI and EMP. Furthermore, optical fiber cables generally demonstrate greater ruggedness than conventional deployable cables, making them appear ideally suited for this application.

2.3.3.Civil and Consumer Applications

In these applications, optical fiber communication techniques may be utilized on the railways and along pipe and electrical power lines. Although high capacity transmission is not usually required, optical fibers may provide a relatively low cost solution; also giving enhanced protection in harsh environments, especially in relation to EMI and EMP.

Optical fibers are eminently suitable for video transmission. Thus optical fiber systems are starting to find use in commercial television transmission. These applications include short distance links between studio and outside broadcast vans, links between studios and broadcast or receiving aerials, and close circuit television (CCTV) links for security and traffic surveillance. The implementation of larger networks for cable and common antenna television (CATV) has demonstrated the successful use of optical fiber communications in this area where it provides significant advantages, in terms of bandwidth and unrepeatered transmission distance, over conventional video links.

Various techniques have been utilized for video transmission including baseband intensity modulation, subcarrier intensity modulation, pulse analog techniques, and digital pulse code modulation. Generally digital transmission is preferred on larger CATV networks as it allows time division multiplexing as well as greater unrepeatered transmission distance. It also avoids problems associated with the nonlinearities of optical sources.

Digital transmission of video signals is not always economic, owing to the cost and complexity of the terminal equipment. Hence, optical fiber systems using direct intensity modulation often provide an adequate performance for a relatively small system cost.

In common with the military applications, other potential civil uses for optical fiber systems include short distance communications within buildings (e.g. broadcast and recording studios) and within mobiles such as aircraft and ships.

A major consumer application for optical fiber systems is within automotive electronics. Work is progressing within the automobile industry towards this end together with the use of microcomputers for engine and transmission control as well as control of convenience features such as power windows and seat controls. Optical fiber communication links in this area provide advantages of reduced size and weight together with the elimination of EMI. Furthermore, it is likely they will reduce costs by allowing for an increased number of control signals in the confined space

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presented by the steering column and internal transmission paths within the vehicle through multiplexing of signals onto a common optical highway.

Single plastic fibers are utilized in automobile multiplex systems within the passenger compartment, whereas glass fibers is required to stand the high temperatures (120 °C) encountered in the engine compartment.

2.3.4.Industrial Applications

Optical fiber systems offer reliable telemetry and control communications for industrial environments where EMI and EMP cause problems for metallic cable links. Furthermore, optical fiber systems provide a far safer solution than conventional electrical monitoring in situations where explosive or corrosive gases are abundant (e.g. chemical processing and petroleum refining plants).

3. OPTICAL WAVEGUIDE PROFILES

There are many different types of optical fibers. We will tell about its configurations, structures and properties. But before explaining these fibers, we must determine the refractive index profiles. Because refractive index profile specifies the configurations (or types) of optical fibers.

Let n be the refractive index of the fiber (of the core or the cladding). If the refractive index n of an optical waveguide is considered as a function of the radius r, then the term *refractive index profile* is used. It describes the radial change of the refractive index from the axis of the fiber in the core glass outwards toward the cladding glass:

$$n = n(\mathrm{r}) \tag{5}$$

The propagation of the modes in an optical waveguide depends on the shape of this refractive index profile (Fig.3.1)

The refractive index profiles is described as:

$$n^2(r) = n_1^2[1-2\Delta(r/a)^g] \qquad \text{for } r < a \text{ in the core and} \tag{6}$$

$$n^2(r) = n_2^2 = \text{constant} \qquad \text{for } r > a \text{ in the cladding} \tag{7}$$

where

n_1 refractive index along the axis of the fiber

Δ normalized refractive index difference

r distance from the axis of the fiber in µm

a core radius in µm

g profile exponent

n_2 refractive index of the cladding.

The normalized refractive index difference is related to the numerical aperture NA or the refractive indices n_1 and n_2 as follows:

$$\Delta = \frac{NA^2}{2n_1^2} = \frac{n_1^2 - n_2^2}{2n_1^2} \tag{8}$$

Some special cases are:

g = 1	triangular profile
g = 2	parabolic profile
g $\rightarrow \propto$	step profile (limit of g being infinite)

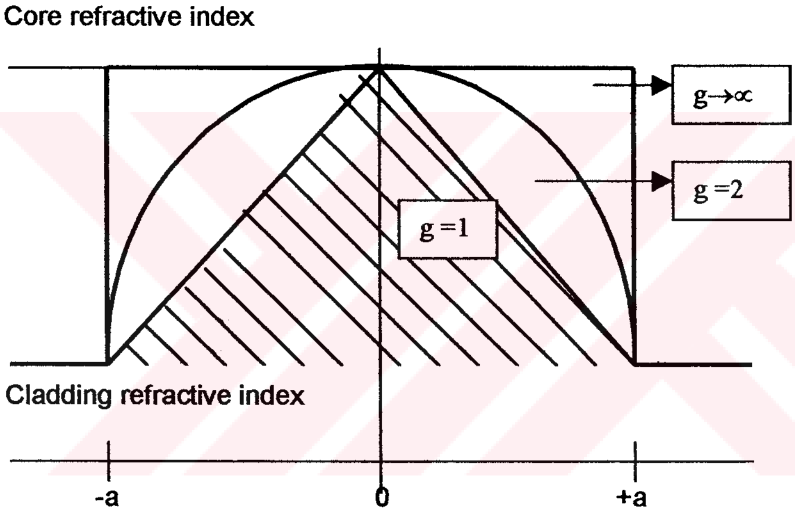

Fig.3.1. Refractive index profile of an optical waveguide

These profiles are called graded index profiles. For parabolic profile, optical fibers have very good lightguiding qualities.

V, normalized frequency , is one of the important quantity for the description of an optical fiber. It is dimensionless parameter:

$$V = 2\pi(a/\lambda)NA = k\,a\,NA \tag{9}$$

where

a core radius

λ wavelength of the light

NA numerical aperture of the core glass

k wave number of the light.

N is the number of modes guided in the core glass . It is approximately

$$N \approx (V^2/2)(g/g+2) \tag{10}$$

The number of modes in a step index profile ($g \to \infty$) is approximately

$$N \approx V^2/2 \tag{10a}$$

For the graded index profile (g=2) the number of modes is

$$N \approx V^2/4 \tag{10b}$$

An optical waveguide with several modes is called a multimode fiber.

If the V number in an optical fiber with a step index profile ($g \to \infty$) becomes smaller than the constant $V_{c\infty} = 2.405$, only a single mode, *fundamental mode* LP_{01} , can propagate in the core. This optical fiber is called a single mode fiber.

λ_c is the cut-off wavelength and corresponds to the cut-off value V_c .

$$\lambda_c = \pi 2aNA/V_c \tag{11}$$

For all wavelengths $\geq \lambda_c$ only one mode can propagate in single mode fiber.

3.1 Optical Fiber Configurations

The optical fibers can be divided into three configurations depending upon the method of propagation of light. The three types are:

1. single-mode step index
2. multimode step index, and
3. multimode graded index.

3.1.1 Single-mode step-index fiber

A single mode step index fiber has a central core that is sufficiently small so that there is only one mode of propagation. This type of fiber is shown in fig.3.2 (Senior, 1985). The refractive index of the cladding n_2 is slightly less than that of the central core n_1. The index profile is also shown in the fig.3.2. It can be seen that there is an abrupt change in the refractive index at the core/cladding interface. The name step-index signifies a sharp step change at the core/cladding interface.

The fiber core diameter should be sufficiently small so that is will propagate only one mode efficiently. This limits the core diameter to a maximum size of about 2.5 micron. It is extremely difficult to work with such a small fiber core. By making the difference between refractive indices of core and cladding to its lowest practical value, the core diameter of up to about 15 microns can be used and still allow only one mode to propagate within the fiber. Single mode step-index fiber has a high critical angle of about 77°. This results in a small acceptance angle and a narrow source-to-fiber aperture. (http://www.computersandinternet.com)

The major operational disadvantages are the difficulties of aligning and driving these fibers. In order to inject sufficient amount of light into the fiber, injection laser diode is the only device that can be suitable. The core must be precisely aligned with the emitting area of an injection laser diode.

For a single-mode fiber, the interconnecting ends should be parallel, highly polished, perfectly aligned and flushed with one another. Connectors for these fibers must be precision devices. All these factors contribute to the high cost of using single-mode step-index fiber, but it is the most efficient of all optical fibers.

3.1.2 Multimode step index fiber

A multimode step index fiber is similar to the single mode step index fiber except that the center core (50-200 μm) is much larger as shown in fig.3.3 (Senior, 1985). This type of fiber has a larger light-to-fiber aperture and has good light gathering ability. It is easier to use and is least expensive to manufacture. Multimode step index fibers are available in all the three varieties: (a) silica clad silica (all glass), (b) plastic clad silica and (c) plastic cladding and core. (http://www.computersandinternet.com)

The index profile of multimode step index fiber is also shown in fig.3.3. There is an abrupt change in the refractive index at the core cladding interface. Thus in multimode step index fiber, the light can take many paths or modes.

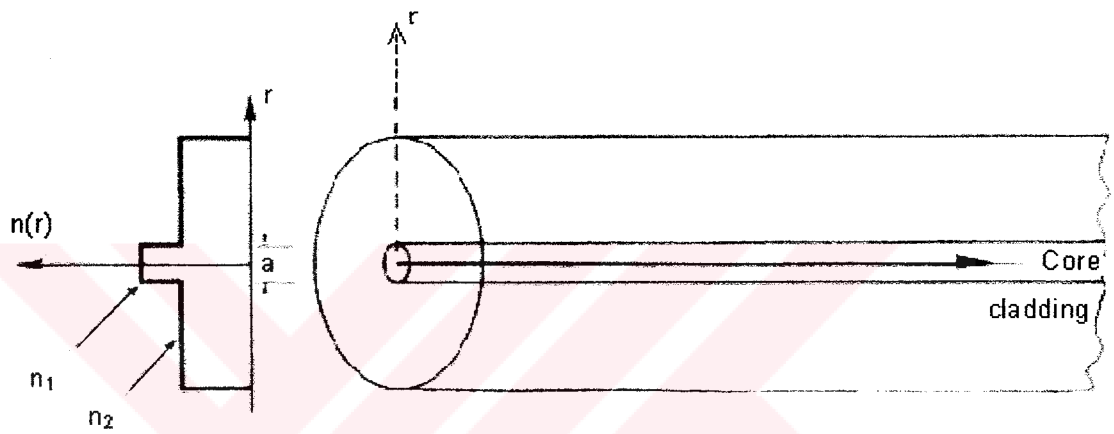

Fig.3.2. The refractive index profile and ray transmission in single mode step index profile.

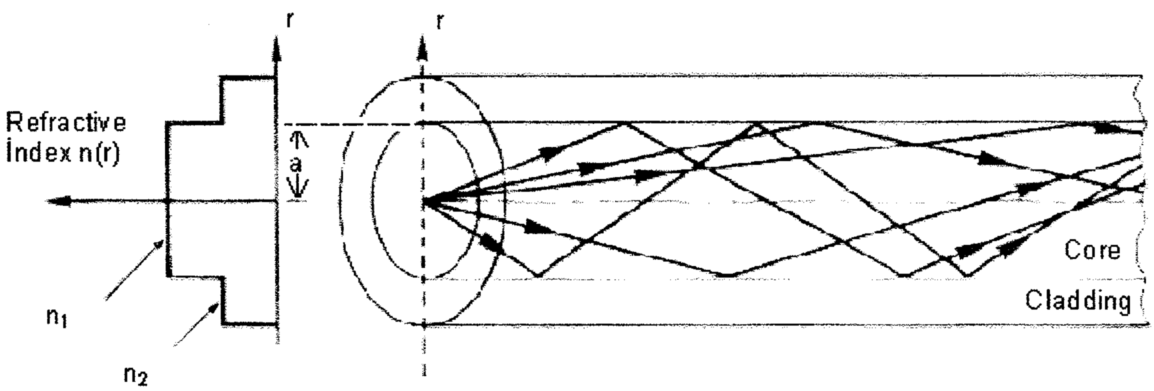

Fig.3.3.The refractive index profile and ray transmission in multimode step index fiber.

3.1.3 Multimode graded index fiber

Multimode graded-index fiber shown in fig.3.4 (Senior, 1985) is a variable index fiber. The index profile has its highest value in the center and slopes away gradually. Light propagates through this fiber by a method called continuous refraction. A graded index fiber can be considered as a fiber having an infinite number of layers whose index profile resembles that shown. The light rays travelling in the fiber are constantly being refracted which results in continuous bending of the light rays.

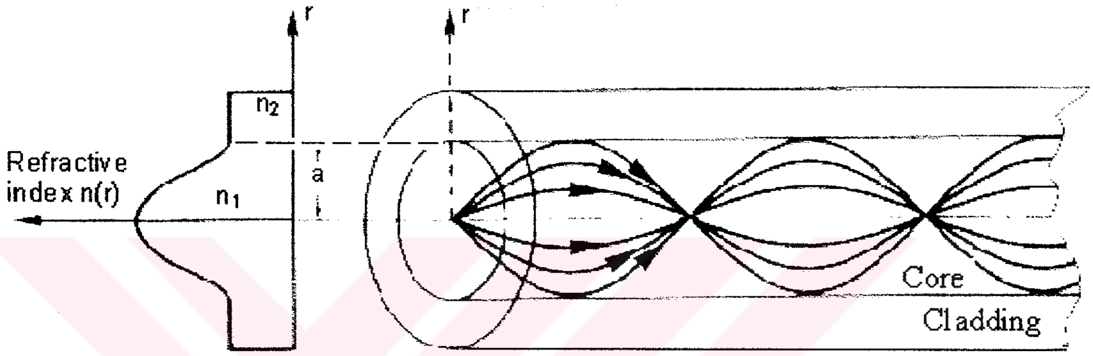

Fig.3.4. Fiber with graded index profile

Light enters the fiber at many different angles. The light rays that travel in the outer most area of the fiber, travel a greater distance than the rays travelling near the center. But the light rays travelling in outer areas travel faster than the rays travelling near the center of the fiber. It is because the velocity is inversely proportional to the refractive index.

The mode having optical path is called the high order mode. The high mode also has the highest average speed. Modes of decreasing order have corresponding slower average speeds. Thus even though each mode has a different path length, its average speed of propagation is almost the same. This results in very low model dispersion.

Multimode graded index fiber provides a compromise between the inefficient (but inexpensive) multimode step-index fiber and the efficient (but highly expensive) single mode step-index fiber. Core diameters for graded index fibers range from 50 to 100 microns which makes it much easier to work with than the 3 to 15 micron single mode fibers (http://www.computersandinternet.com).

3.2 TRANSMISSION CHARACTERISTICS of OPTICAL FIBERS

3.2.1 Losses in Optical Fiber

Other than the losses exhibited when coupling LEDs or LDs into a fiber, there are losses that occur as the light travels through the actual fiber. The core of an optical fiber is made of ultra-pure low-loss glass. Considering that light has to pass through thousands of feet or more of fiber core, the purity of the glass must be extremely high. To appreciate the purity of this glass, consider the glass in common windowpanes. We think of windowpanes as "clear," allowing light to pass freely through, but this is because they are only 1/16 to ¼ inch thick. In contrast to this clear appearance, the edges of a broken windowpane look green and almost opaque. In this case, the light is passing edgewise into the glass, through several inches. Just imagine how little light would be able to pass through a thousand feet of window glass!

Most general purpose optical fiber exhibits losses of 4 to 6 dB per km (a 60% to 75% loss per km) at a wavelength of 850nm. When the wavelength is changed to 1300nm, the loss drops to about 3 to 4 dB (50% to 60%) per km. At 1550nm, it is even lower. Premium fibers are available with loss figures of 3 dB (50%) per km at 850nm and 1 dB (20%) per km at 1300nm. Losses of 0.2 dB (10%) per km at 1550 nm are not uncommon. These losses are primarily the result of random scattering of light and absorption by actual impurities within the glass. Another source of loss within the fiber is due to excessive bending, which causes some of the light to leave the core area of the fiber. The smaller the bend radius, the greater the loss. Because of this, bends along a fiber optic cable should have a turning radius of at least an inch. (www.vgav.com.au)

3.2.2 Optical Fiber Bandwidth

All of the above attenuation factors result in simple attenuation that is independent of bandwidth. In other words, a 3 dB loss means that 50% of the light will be lost whether it is being modulated at 10 Hz or 100 MHz. There is an actual bandwidth limitation of optical fiber however, and this is measured in MHz per km.

Different rays (or modes) of light reach the end of the fiber at different times, even though the original source is the same LED or LD. This produces a "smearing" effect or uncertainty as to where the start and end of a pulse occurs at the output end of the fiber which in turn limits the maximum frequency that can be transmitted. In short, the less modes, the higher the bandwidth of the fiber. The way that the number of modes is reduced is by making the core of the fiber as small as possible. Single-mode fiber, with a core measuring only 8 to 10 microns in diameter, has a much higher bandwidth because it allows only a few modes of light to propagate along its core. Fibers with a wider core diameter, such as 50 and 62.5 microns, allow many more modes to propagate and are therefore referred to as "multimode" fibers.

Typical bandwidths for common fibers range from a few MHz per km for very large core fibers, to hundreds of MHz per km for standard multimode fiber, to thousands of MHz per km for single-mode fibers. And as the length of fiber increases, its bandwidth will decrease proportionally. For example, a fiber cable that can support 500 MHz bandwidth at a distance of one kilometer will only be able to support 250 MHz at 2 kilometers and 100 MHz at 5 kilometers.

Because single-mode fiber has such a high inherent bandwidth, the "bandwidth reduction as a function of length" factor is not a real issue of concern when using this type of fiber. However, it is a consideration when using multimode fiber, as its maximum bandwidth often falls within the range of the signals most often used in point-to-point transmission systems. (www.vgav.com.au)

3.2.3 Attenuation

The attenuation or transmission loss of optical fibers is one of the most important factors in telecommunications. Signal attenuation within optical fibers is expressed by:

$$\textit{Signal attenuation (dB)} = 10\log_{10}\frac{P_i}{P_o} \tag{12}$$

In optical fiber communications the attenuation is usually expressed in decibels per unit length (dB km^{-1}) following:

$$\alpha_{dB}L = 10\log_{10}\frac{p_i}{p_o} \tag{13}$$

α_{dB} : signal attenuation per unit lengths in decibels

L : fiber length

Attenuation characteristics is shown in Fig.3.5 (Senior, 1985) due to the single mode and multimode fibers.

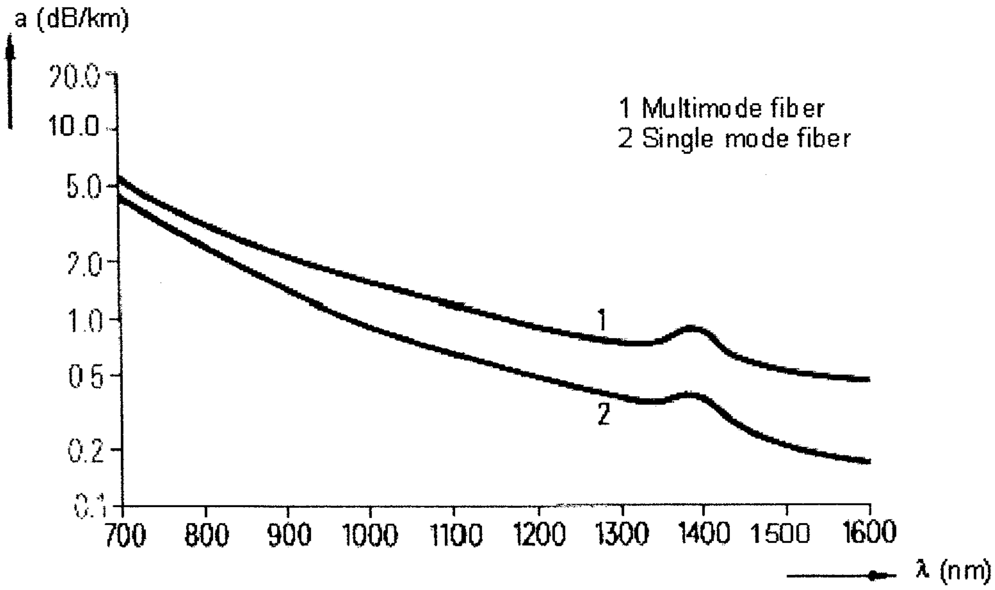

Fig.3.5. Spectral curve of the attenuation coefficient of a single mode and multimode fiber.

There are several mechanisms causing signal attenuation within optical fibers. These mechanisms are effected by the material composition, the preparation and purification technique, and the waveguide structure. They include material absorption, material scattering (linear and nonlinear scattering), curve and microbending losses, mode coupling radiation losses and losses due to leaky modes. There are also losses at connectors and splices.

3.2.4 Material Absorption Losses

Material absorption is a loss mechanism which is related to the material composition and the fabrication process for the fiber. It results in the dissipation of some of the transmitted optical power as heat in the waveguide.

3.2.4 Intrinsic Absorption

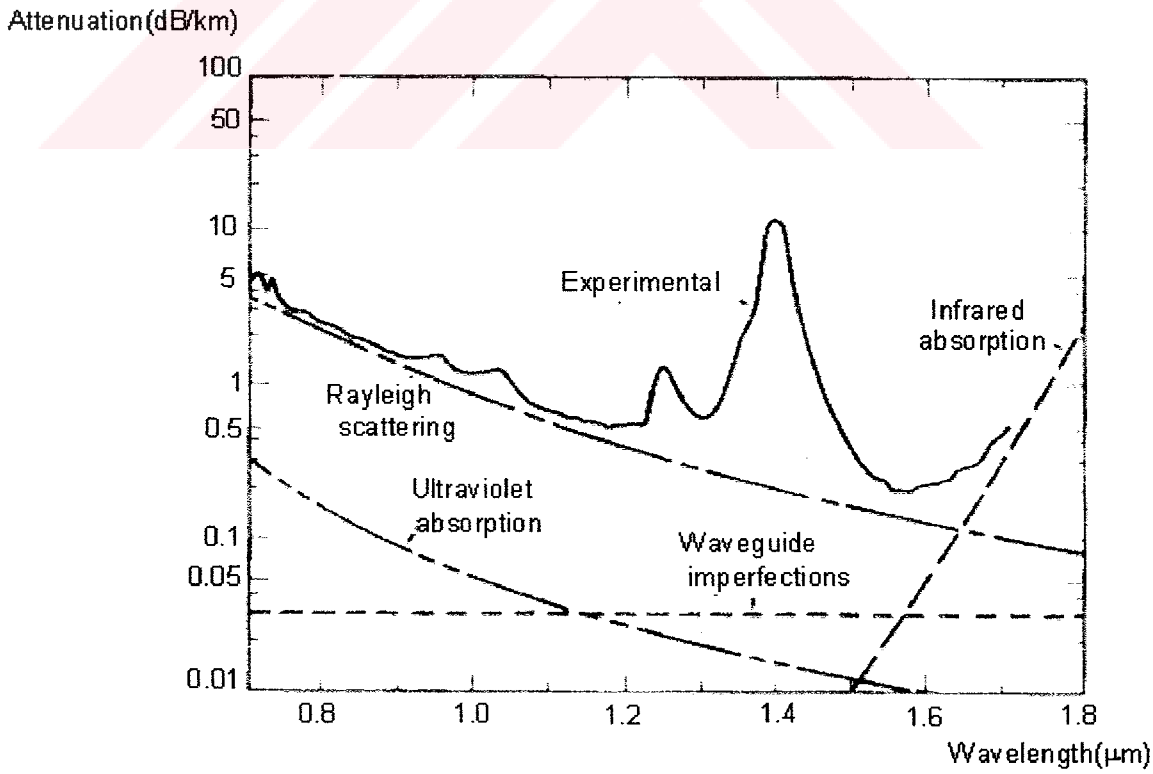

Fig.3.6.The attenuation spectra for the intrinsic loss mechanisms in pure GEO_2 – SiO_2 glass

The interaction with one or more of the major components of the glass causes intrinsic absorption. An absolutely pure glass has little intrinsic absorption due to its basic material structure in the near infrared region (0.8-1.7 μm wavelength range). In ultraviolet region the peaks are centered and there is a fundamental absorption edge because of the stimulation of electron transitions within the glass by higher energy excitations. This causes absorption region to extend at the shorter wavelengths. In infrared and far infrared (at wavelengths above 7 μm) , fundamentals of absorption bands from the interaction of photons with moleculer vibrations within the glass occur. This causes to extend absorption region again. The strong absorption bands occur due to oscillations of structural units such as Si-O (9.2 μm), P-O (8.1 μm), B-O (7.2 μm) and Ge-O (11.0 μm) within the glass.

3.2.4.2 Extrinsic Absorption

A major source of signal attenuation is extrinsic absorption from transition metal element impurities. Metallic impurities such as chromium and copper can cause 1 dB km^{-1} attenuation in the near infrared region.

One of the major extrinsic loss mechanism is caused by absorption due to water (OH ion) dissolved in the glass. These OH ions are bonded into the glass structure and have fundamental stretching vibrations that occur at wavelengths between 2.7 and 4.2 μm. These ranges depend on group position in the glass network. Vibrations cause losses. These losses are shown in Fig.3.7.

3.2.5 Linear Scattering Losses

Linear scattering mechanisms cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly into a different mode.

Linear scattering is divided two major types: Rayleigh and Mie scattering. Nonideal physical properties of the manufactured fiber cause these losses.

3.2.5.1 Rayleigh Scattering

Rayleigh scattering is the dominant intrinsic loss mechanism between the ultraviolet and infrared absorption regions that have low absorption. Some inhomogeneties that behaves like refractive index fluctuations occur with the wavelength of the light. These fluctuations arise from density and compositional variations that are frozen into the glass lattice on cooling. Compositional variations may be reduced by improved fabrication but index fluctuations caused by the freezing-in of density inhomogeneties cannot be avoided. So attenuation that is proportional to $1/\lambda^4$ occurs.

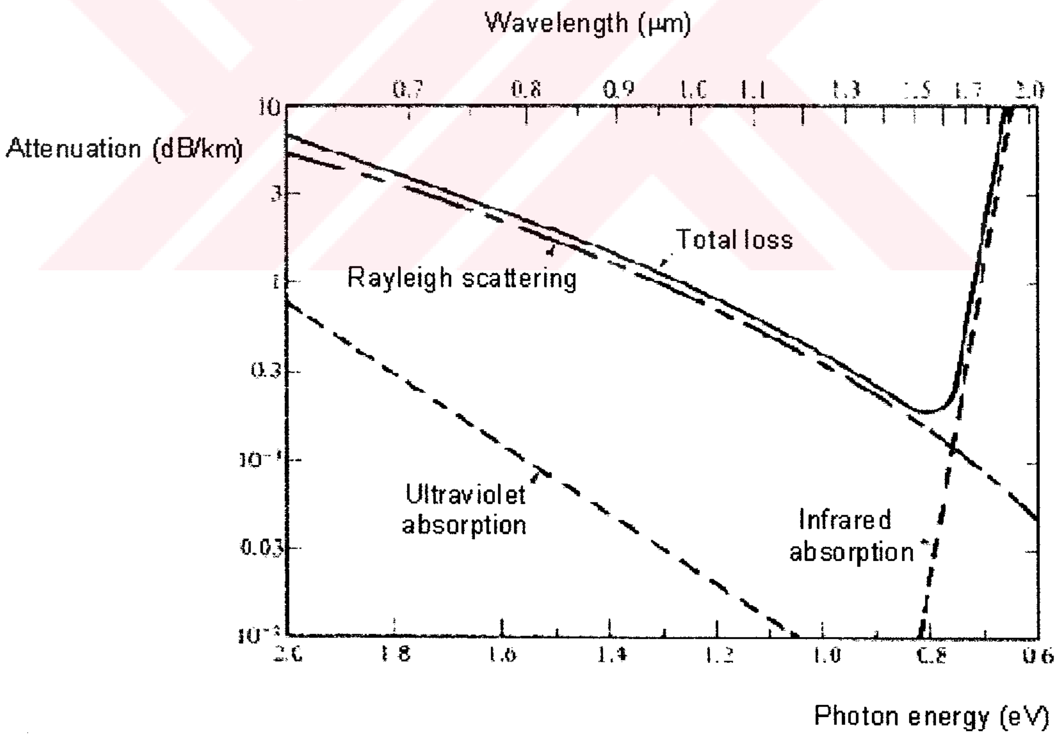

Fig.3.7. The measured attenuation spectrum for an ultra low loss single mode fiber (solid line) with the calculated attenuation spectra for some of the loss mechanisms contributing to the overall fiber attenuation (dashed and dotted lines).

Rayleigh scattering is defined as :

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F \tag{14}$$

γ_R : Rayleigh scattering coefficient

λ : optical wavelength

β_c : isothermal compressibility

K : Boltzman constant

T_F : fictive temperature

n : refractive index of the medium

p : average photoelastic coefficient

If we use longer wavelength ranges , Rayleigh scattering loss may be reduced in negligible values.

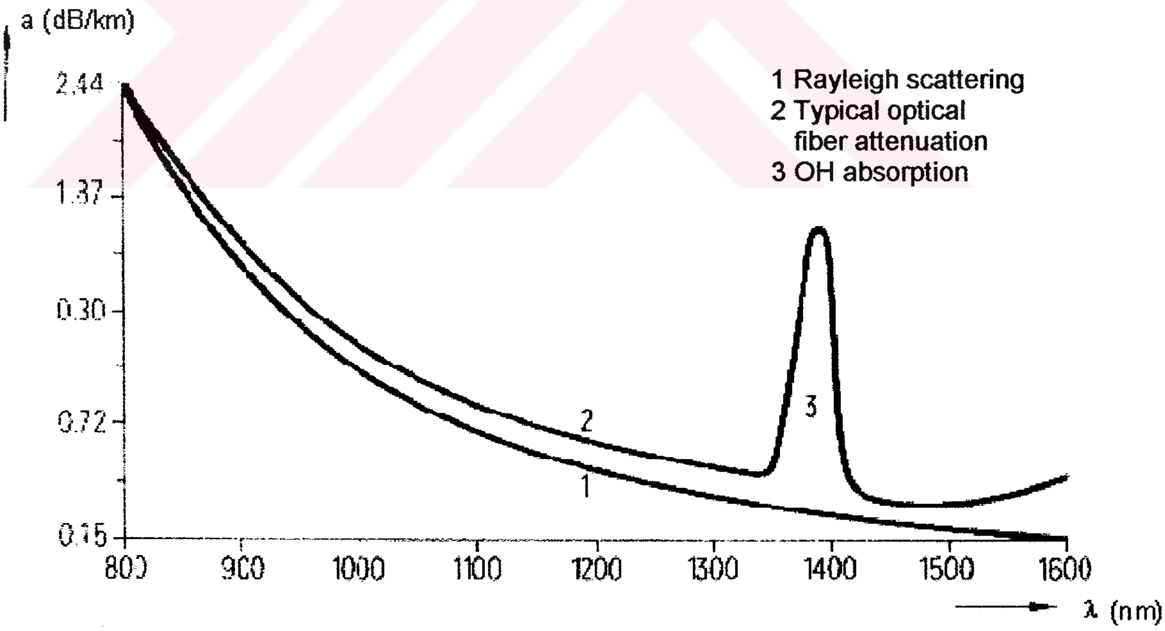

Fig.3.8. Rayleigh scattering

Rayleigh scattering coefficient is related to the transmission loss factor (transmissivity) of the fiber ℓ is determined by :

$$\mathcal{L} = \exp(-\gamma_R L) \qquad (15)$$

L : fiber length

The lowest reported value for Rayleigh scattering in silica at 0.6328 μm wavelength is 3.9 dB/km.

3.2.5.2 Mie Scattering

There are some imperfections such as irregularities in the core-cladding interface, diameter fluctuations, core-cladding refractive index differences along the fiber length, strains and bubbles. Because of these inhomogeneties, a scattering occurs and it is called Mie scattering. This scattering depends on the fiber material, design and manufacture factors. So Mie scattering causes significant losses. But these inhomogeneties may be reduced by :

- removing imperfections due to the glass manufacturing process;
- carefully controlled extrusion and coating fiber;
- increasing the fiber guidance by increasing the relative index difference.

These processes reduce Mie scattering to insignificant levels.

3.2.6 Nonlinear Scattering Losses

Linear channels has a proportion between the output optical power and the input optical power. Output optical power increases linearly due to the input optical power. But optical waveguides are different from linear channels. At high optical power levels, some nonlinear effects such as scattering occur. In this condition, the optical power is transferred from one mode either the forward or backward direction to the same or other modes at a different frequency. So nonlinear scattering depends on the optical power density within the fiber and it is important above threshold power levels.

Nonlinear scattering types are stimulated Brillouin and Raman scattering. They are observed at high optical power densities in long single mode fibers. These scattering mechanisms give optical gain but with a shift in frequency. Thus nonlinear scattering contributes to attenuation for light transmission at a specific wavelength.

3.2.6.1 Stimulated Brillouin Scattering

Brillouin scattering is as the modulation of light through thermal molecular vibrations within the fiber. The scattered light becomes as upper and lower sidebands that are separated from the incident light. It has modulation frequency. The end of the this process, a phonon of acoustic frequency is produced as well as a photon. Then an optical frequency shift that changes with the scattering angle occurs because of the varying the frequency of sound wave with acoustic wavelength. Thus the frequency shift is a maximum in the backward direction which reduces to zero in the forward direction making Brillouin scattering a mainly backward process.

The threshold power P_B that must be launched into a single mode optical fiber before Brillouin scattering occurs is given by :

$$P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} \nu \quad \text{watts} \tag{16}$$

d : fiber core diameter (μm)

λ : operating wavelength (μm)

α_{dB} : fiber attenuation (dB/km)

ν : source bandwidth (i.e. injection laser, GHz,)

This threshold value is as low as 10mW in single mode fibers. But this value is still a high power level for optical communications may be avoided.

3.2.6.2 Stimulated Raman Scattering

Raman scattering is similar to the Brillouin scattering. But in this process, a high frequency optical phonon rather than an acoustic phonon is produced. And

Raman scattering occurs in the forward direction. It has an optical power threshold of up to three orders of magnitude higher than the Brillouin threshold .

The threshold optical power for stimulated Raman scattering P_R in a long single mode fiber is given by:

$$P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_{dB} \quad \text{watts} \tag{17}$$

d, λ and α_{dB} are defined as written below.

Brillouin and Raman scattering are not observed in multimode fibers because their large core diameter make the threshold optical power levels extremely high.

3.2.7 Fiber Bend Loss

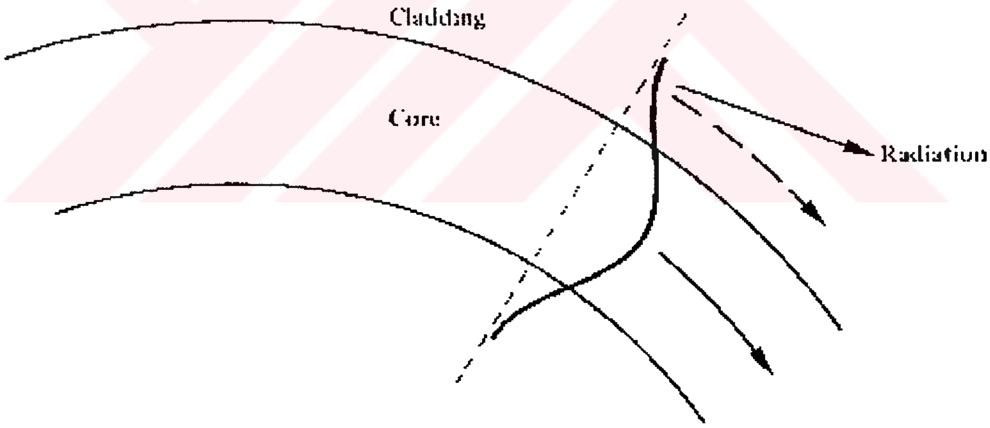

Fig. 3.9. Radiation loss at a fiber bend

Radiation losses occur on optical fibers paths. This is due to the energy in the evanescent field at the bend exceeding the velocity of light in the cladding . So guidance mechanism that causes light energy to be radiated from the fiber is inhibited. Part of the mode in the cladding needs to travel faster than the velocity of light in this medium and energy is lost through radiation. The loss may be represented by a radiation attenuation coefficient that has the form :

$$\alpha_r = c_1 \exp(-c_2 R) \tag{18}$$

R : radius of the curvature of the fiber bend

c_1 , c_2 : constants (independent of R)

Large bending losses occur at a critical radius of curvature R_c which is determined by :

$$R_c \cong \frac{3n_1^{\,2}\lambda}{4\pi\left(n_1^{\,2} - n_2^{\,2}\right)^{3/2}} \tag{19}$$

According to this equation, we see that we may reduce bending losses by :

- designing fibers with large relative refractive index differences;
- operating at the shortest wavelength possible.

The critical radius of curvature is sufficiently small (for instance 9 μm) to avoid attenuation of the guided mode(s) at fiber bends. Modes propagating close to cutoff may radiate at larger radii of curvature. So it is important to avoid sharp bends when fiber cabling. Because in this case it approximates to the fiber radius.

3.2.8 Dispersion

Dispersion is a property of fiber that causes light pulses to spread. This effect limits the bit-rate and distances that can be bridged over the fiber.

3.2.8.1 Intramodal Dispersion

Intramodal or chromatic dispersion may occur in all types of optical fiber and results from the finite spectral linewidth of the optical source. When the optical sources do not emit a single frequency but a band of frequencies, it becomes propagation delay differences between the different spectral components of the transmitted signal. The end of this process, broadening of each transmitted mode occurs and it is called as intramodal dispersion. It is shown in figure 3.10.

3.2.8.2 Material Dispersion

Pulse broadening due to the material dispersion results from the different group velocities of the various spectral components launched into the fiber from the optical source. Since the phase velocity of a plane wave propagating in the dielectric medium changes nonlinearly with wavelength or when the second differential of the refractive index with respect to wavelength is not zero ($d^2n/d\lambda^2 \neq 0$), then material dispersion occurs. The pulse spread is due to the material dispersion may be obtained by considering the group delay τ_g in the fiber. Group delay is given by :

$$\tau_g = \frac{d\beta}{d\omega} = \frac{1}{c}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right) \qquad (20)$$

The pulse delay τ_m due to the material dispersion in a fiber length L is :

$$\tau_m = \frac{L}{c}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right) \qquad (21)$$

n_1 : core refractive index

The rms pulse broadening σ_m ,which depends on the rms spectral width σ_λ and a mean wavelength λ, is defined as:

$$\sigma_m \cong \sigma_\lambda \frac{d\tau_m}{d\lambda} \qquad (22)$$

The material dispersion for optical fibers is given by $\left|\lambda^2\left(d^2n_1/d\lambda^2\right)\right|$ or simply $\left|d^2n_1/d\lambda^2\right|$.

Material dispersion parameter is determined by:

$$M = \frac{1}{L}\frac{d\tau_m}{d\lambda} = \frac{\lambda}{c}\left|\frac{d^2 n_1}{d\lambda^2}\right| \tag{23}$$

that is defined in units of ps nm^{-1} km^{-1} .

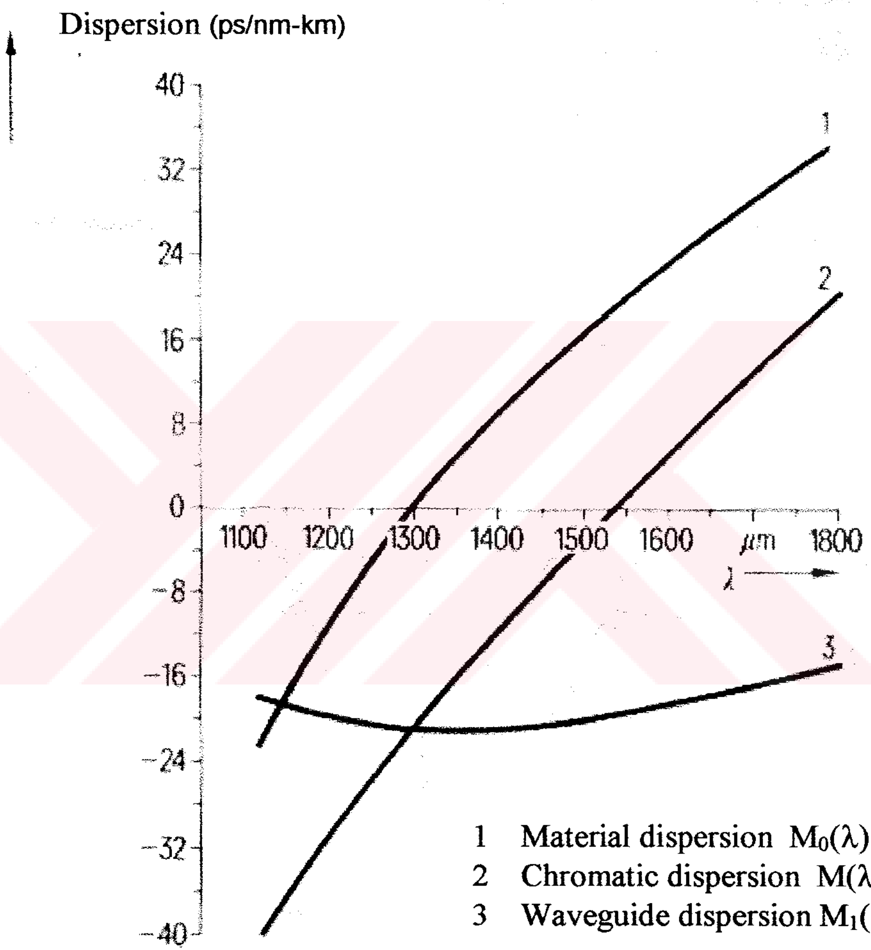

Fig.3.10. Dispersion curves of a single-mode fibers

Material dispersion may be zero or minimum in the longer wavelength region around 1.3 μm (for pure silica).

When we use an injection laser with a narrow spectral width instead of a LED as the optical source, it leads a reduction in the pulse broadening due to material dispersion, even in the shorter wavelength region.

3.2.8.3. Waveguide Dispersion

Intramodal dispersion may also occur because of waveguiding of the fiber. When the angle between the ray and the fiber axes changing with wavelength leads to a variation in the transmission times for the rays, waveguide dispersion occurs. For a single mode whose propagation constant is β, the fiber exhibits waveguide dispersion when $(d^2\beta)/(d\lambda^2) \neq 0$.

In single mode fibers, waveguide dispersion becomes significant. Because the effect of different dispersion mechanisms are hard to separate. But in multimode fibers, majority of modes propagate far from cutoff. So they are free of waveguide dispersion and usually material dispersion is negligible ($\cong 0.1 - 0.2$ ns km^{-1}).

3.2.9 Intermodal Dispersion

Intermodal dispersion is also known as modal or mode dispersion. Pulse broadening due to modal dispersion results from the propagation delay differences between modes within a multimode fiber. Different modes travel at different velocities. The pulse width at the output depends on transmission times of the slowest and fastest modes. Multimode step index fibers have a large amount of modal dispersion that gives the greatest pulse broadening. Anyway, modal dispersion in multimode fibers may be reduced by adoption of an optimum refractive index profile that is provided by the near parabolic profile of most graded index fibers. The overall pulse broadening in multimode graded index fibers is less than that obtained in the multimode step index fibers (approximately by a factor of 100). So graded index fibers with a multimode source has more advantage about bandwidth against multimode step index fibers.

But single mode fibers have no intermodal dispersion. Pulse broadening in single mode fibers only depends on the intramodal dispersion. Thus single mode step index fibers have the least pulse broadening and the greatest bandwidths because of propagating only a single mode.

4.NONLINEAR SCHRODINGER EQUATION in OPTICAL FIBERS

The propagation of an optical pulse in single mode fibers is described by the equation(24). This equation is named as nonlinear schrödinger equation. We will use this equation to determine ultra-short optical pulses with 100 fs pulse widths (AGRAWAL, 1989). The spectrum of ultra-short pulses is wide enough ≥5 THz. The equation(24) includes the effects of fiber loss through α, of chromatic dispersion(or group velocity dispersion) through β_2, and of fiber nonlinearity through γ, of higher order dispersion, of self-steepening and of self-frequency shift.

We can write nonlinear schrodinger equation as:

$$\frac{\partial q}{\partial z}+\frac{\alpha}{2}q+\frac{i}{2}\beta_2\frac{\partial^2 q}{\partial T^2}-\frac{1}{6}\beta_3\frac{\partial^3 q}{\partial T^3}=i\gamma\left[|q|^2 q+\frac{2i}{\omega_0}\frac{\partial}{\partial T}\left(|q|^2 q-T_R q\frac{\partial |q|^2}{\partial T}\right)\right] \quad (24)$$

In this equation:

$\frac{i}{2}\beta_2\frac{\partial^2 q}{\partial T^2}$: chromatic dispersion (group velocity dispersion) (24a)

$\frac{1}{6}\beta_3\frac{\partial^3 q}{\partial T^3}$: higher-order dispersion (24b)

$\frac{\alpha}{2}q$: attenuation (α is the attenuation constant) (24c)

$\gamma|q|^2 q$: fiber nonlinearity (γ is the nonlinear coefficient) (24d)

$\frac{2i}{\omega_0 q}\frac{\partial}{\partial T}\left(|q|^2 q\right)$: self-steepening (nonlinear polarization) (24e)

$T_R \dfrac{\partial |q|^2}{\partial T}$: self frequency shift (T_R is the response time,2-4 fs) (24f)

According to the nonlinear-schrodinger equation, In single-mode fibers, γ can vary between 1-30 W^{-1} km^{-1} at wavelength 1.55μm. We got the values β_2 =1 and γ =1 and λ=1.55μm. And we supposed that higher order-dispersion, attenuation, self-steepening and self-frequency shift is equal to zero. The study of most nonlinear effects in optical fibers involves the use of short pulses with widths between ranges 10 ns-10 fs. When these pulses propagate inside the fiber, dispersive and nonlinear effects influence their shape and spectrum. In our study we will use ultra-short pulses with widths 100 fs. After that these conditions, we will use soliton pulses and arrange the equation(24) due to the soliton pulses. We must determine the soliton to understand why we use soliton pulses. Because these waves pass through one another without deformations due to the collisions and without changes of pulse spectral and temporal shapes. Solitary waves are formed as a train .These solitary waves are called solitons that behave like particles. Soliton *pulse width*($\Delta\tau_p$) is proportional by *group velocity dispersion/soliton energy* and the *peak power* is defined as *soliton energy/group velocity dispersion*. These are the soliton parameters which describe the soliton stability. Optical amplification and losses affect soliton stability. As a result of a small optical amplification, soliton energy inreases, nonlinearity becomes stronger and the soliton pulse is compressed, which reestablishes the balance. Solitons are broadened under small losses. When dispersion decreases , soliton is compressed.

The optical soliton in fibers is the solitary wave of an envelope of a light wave (HASEGAWA, 1989). The optical pulses which are used in communications are created by the pulse modulation of a light wave. The pulse shape represents an envelope of a light wave. An envelope of a wave which propagates in a strongly dispersive nonlinear medium has a solitary wave solution. Nonlinear Schrodinger equation describes the envelope soliton propagation.

Soliton equation :

$$i\frac{\partial q}{\partial z}+\frac{1}{2}\frac{\partial^2 q}{\partial T^2}+|q|^2 q=0 \tag{25}$$

In this equation, q is the complex amplitude which is varying envelope of the square root of the intensity of the optical field. z represents the distance along the direction of propagation, T represents the time. The second term originates from the dispersion of the group velocity,that is dependent of the wavelength. The third term indicates nonlinear effects.

There are some numerical methods to solve the soliton equation. Two major methods are: a) the finite-difference methods and b) the pseudospectral methods(AGRAWAL, 1989). We will use finite-difference methods ,which include split-step Fourier method , to solve the pulse propagation problem in nonlinear dispersive media.

According to the split-step Fourier method, we will write nonlinear and differential expressions seperately. To solve this problem we will write equation(25) in this form:

$$\frac{\partial q}{\partial z}=\left(\hat{D}+\hat{N}\right)q \tag{26}$$

In this form,

$\hat{D}$: is the differential operator that accounts for dispersion and absorption in a linear medium

$\hat{N}$: is the nonlinear operator that governs the effect of fiber nonlinearities on pulse propagation.

We will seperate equation(25) in differential and nonlinear parts:

Firstly equation(25) must be written as the form of equation(26),

$$\frac{\partial q}{\partial z}=-i\frac{1}{2}\frac{\partial^2 q}{\partial T^2}+i|q|^2 q \tag{27}$$

$$\frac{\partial q}{\partial z}=\left(-i\frac{1}{2}\frac{\partial^2}{\partial T^2}+i|q|^2\right)q \tag{27a}$$

In this eqution,

$$\hat{D}=-i\frac{1}{2}\frac{\partial^2}{\partial T^2} \tag{28}$$

and

$$\hat{N}=i|q|^2 \tag{29}$$

The split-step Fourier method obtains an approximate solution by assuming that n propagating the optical field over a small distance h. The dispersive and nonlinear effects can be pretended to act independently :

In first step : $\hat{N}=0$;

In second step : $\hat{D}=0$; z $\rightarrow$ z+h

$$q(z+h,T)\approx \exp\left(h\hat{D}\right)\exp\left(h\hat{N}\right)q(z,T) \tag{30}$$

In Fourier domain :

$$\exp(h\hat{D})b(z,T)=\left\{F^{-1}\exp\left[h\hat{D}(i\omega)\right]F\right\}b(z,T) \tag{31}$$

$\hat{D}(i\omega)$ is obtained from equation(28) by replacing the differential operator $\partial/\partial T$ by $i\omega$. ω is the ferquency in the fourier domain.

To estimate the accuracy of the split-step Fourier method :

$$q(z+h,T)=\exp\left[h\left(\hat{D}+\hat{N}\right)\right]q(z,T) \tag{32}$$

$\hat{N}$ is independent of z .

Baker-Hausdorff formula :

$$\exp(\hat{a})\exp(\hat{b}) = \exp\left(\hat{a}+\hat{b}+\frac{1}{2}\left[\hat{a},\hat{b}\right]+\frac{1}{12}\left[\hat{a}-\hat{b},\left[\hat{a},\hat{b}\right]\right]+.........\right) \tag{33}$$

$$\left[\hat{a},\hat{b}\right] = \hat{a}.\hat{b}-\hat{b}.\hat{a} \tag{34}$$

$\hat{a} = h\hat{D}$, $\hat{b} = h\hat{N}$, error term : $\frac{1}{2}h^2\left[\hat{D},\hat{N}\right]$

The split-step fourier method for the second-order :

The optical pulse over one segment (from z to z+h) :

$$q(z+h,T) = \exp\left(\frac{h}{2}\hat{D}\right).\exp\left[\int_z^{z+h} N(z').dz'\right].\exp\left(\frac{h}{2}\hat{D}\right).q(z,T) \tag{35}$$

in this equation N is dependent of z.

$$\int_z^{z+h}\hat{N}(z').dz' \cong \frac{h}{2}\left[\hat{N}(z)+\hat{N}(z+h)\right] \tag{36}$$

N(z+h) is unknown at the midsegment located at $z+\frac{h}{2}$.

$\hat{N}(z+h) \approx \hat{N}(z)$ (first value of N(z+h))

Then we will rewrite equation(36) by placing the first value of N(z+h), so

$$\int_z^{z+h}\hat{N}(z').dz' = \frac{h}{2}.\left[\hat{N}(z)+\hat{N}(z+h)\right]$$

$$= \frac{h}{2}\left[\hat{N}(z)+\hat{N}(z)\right]$$

$$= h\left[\hat{N}(z)\right] \qquad \text{(for the first value of N(z+h))} \qquad (37)$$

we will write the value of equation(37) in equation(35) ,

$$q(z+h,T) = \exp\left[\frac{h}{2}\hat{D}\right].\exp\left[h\hat{N}(z)\right]\exp\left[\frac{h}{2}\hat{D}\right].q(z,T) \qquad (38)$$

The expression of $\hat{N}(z+h)$ can be rewritten according to the equation(29) ,

$$\hat{N}(z+h) = i.\left[\left|q(z+h,T)\right|^2\right] \qquad (39)$$

The value of equation(39) will be written in equation(36) ,

$$\int_z^{z+h} \hat{N}(z').dz' \cong \frac{h}{2}.\left[\hat{N}(z) + \hat{N}(z+h)\right]$$

$$\int_z^{z+h} \hat{N}(z').dz' \cong \frac{h}{2}.i.\left[\left|q\right|^2 + \left|q(z+h,T)\right|^2\right] \qquad (40)$$

And now equation(40) will be written in equation(38) ,

$$q(z+h,T) = \exp\left[\frac{h}{2}\hat{D}\right].\exp\frac{h}{2}\left[\hat{N}(z) + \hat{N}(z+h)\right]\exp\left[\frac{h}{2}\hat{D}\right].q(z,T) \qquad (41)$$

Equation(28),(29) and (39) can be written in equation(41) ;

$$q(z+h,T) = \exp\left[-i\frac{h}{2}\frac{\partial^2}{\partial T^2}\right].\exp i.\frac{h}{2}\left[\left|q\right|^2 + \left|q(z+h,T)\right|^2\right]\exp\left[-i\frac{h}{2}\frac{\partial^2}{\partial T^2}\right].q(z,T) \qquad (42)$$

Equation(42) is our solution but we investigate nonlinear and differential effects seperately, so

For only dispersion effect, $\hat{N}=0$:
Equation (41) can be rewritten as,

$$q(z+h,T)=\exp\left[\frac{h}{2}\hat{D}\right].\exp\left[\frac{h}{2}\hat{D}\right].q(z,T) \tag{43}$$

$$q(z+h,T)=\exp\left[h\hat{D}\right]q(z,T) \tag{43a}$$

Equation(28) is written instead of $\hat{D}$ operator and then the equation shown above will be ,

$$q(z+h,T)=\exp\left[h.\left(-\frac{i}{2}.\frac{\partial^2}{\partial T^2}\right)\right].q(z,T) \tag{44}$$

$$q(z+h,T)=\exp h\left[-\frac{i}{2}.\frac{\partial^2 q(z,T)}{\partial T^2}\right] \tag{44a}$$

The equation(44a) is the solution which has only dispersion effect.

And now we investigate the solution for only nonlinear effect , $\hat{D}=0$:
Equation(41) can be rewritten for only nonlinearity,

$$q(z+h,T)=\exp\left[\frac{h}{2}.\left[\hat{N}(z)+\hat{N}(z+h)\right]\right].q(z,T) \tag{45}$$

By using equation(28) and equation(39) , we will get;

$$\hat{N}(z)+\hat{N}(z+h)=i.\left[\left|q(z,T)\right|^2+\left|q(z+h,T)\right|^2\right] \tag{46}$$

If we rewrite equation(38) without dispersion ;

$$q(z+h,T)=\exp\left(h.\hat{N}(z)\right)q(z,T) \tag{47}$$

Equation(47) is written in equation(46) and we obtain ;

$$\hat{N}(z)+\hat{N}(z+h)=i.\left[\left|q(z,T)\right|^2+\left|\exp\left(h\hat{N}(z)\right)\right|^2.\left|q(z,T)\right|^2\right] \tag{48}$$

$$\hat{N}(z)+\hat{N}(z+h)=i.\left|q(z,T)\right|^2.\left[1+\left|\exp\left(h.\hat{N}(z)\right)\right|^2\right] \tag{48a}$$

Then we will put equation(48a) in equation(46) :

$$q(z+h,T)=\exp\left[\frac{h}{2}.i.\left|q(z,T)\right|^2.\left[1+\left|\exp\left(h.\hat{N}(z)\right)\right|^2\right]\right].q(z,T) \tag{49}$$

Now , equation(29) will be written in equation(49) ,

$$q(z+h,T)=\exp\left[\frac{h}{2}.i.\left|q(z,T)\right|^2.\left[1+\left|\exp\left(i.h.q(z,T)\right)\right|^2\right]\right].q(z,T) \tag{50}$$

Thus we obtained the solution for only nonlinear effects.

5. NUMERICAL RESULTS

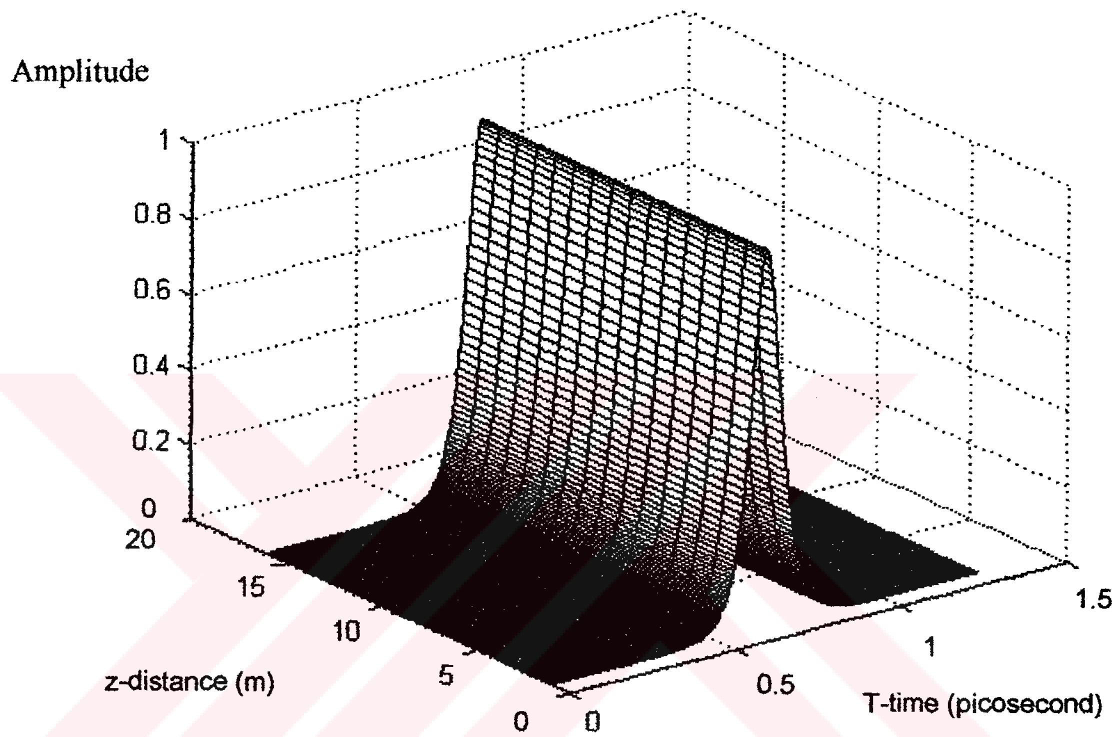

Fig. 5.1. Pulse propagation along the fiber for the first order and fiber loss is 0 dB/km.

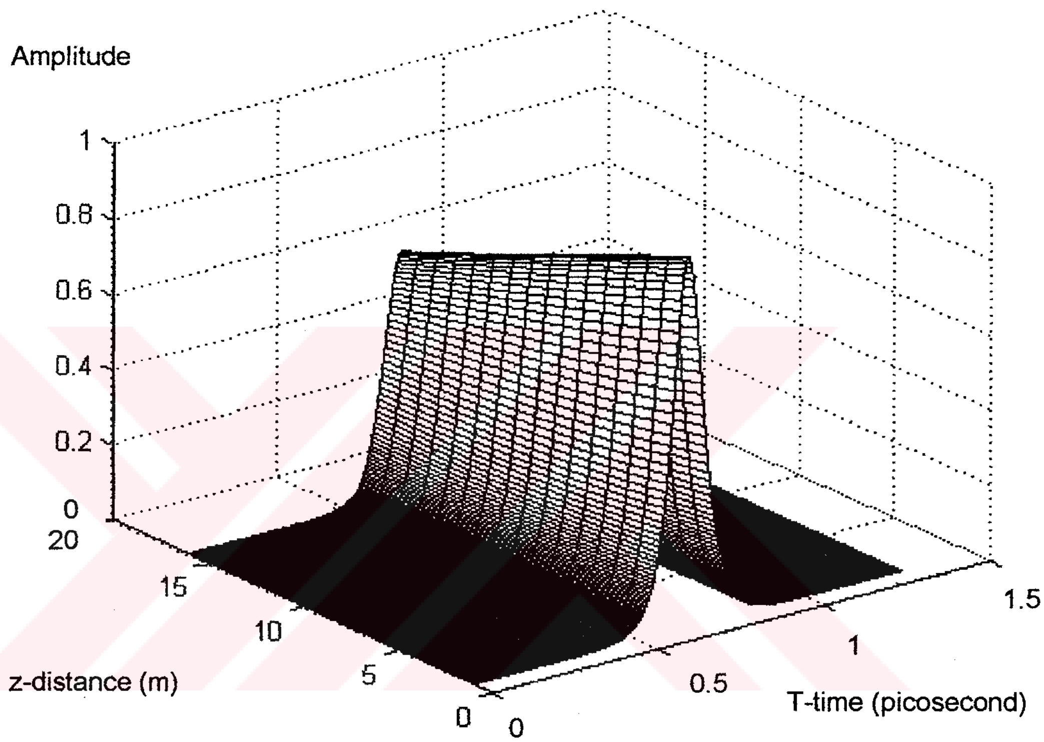

Fig.5.2. Pulse propagation along the fiber for the first order and fiber loss is 0.2 dB/km.

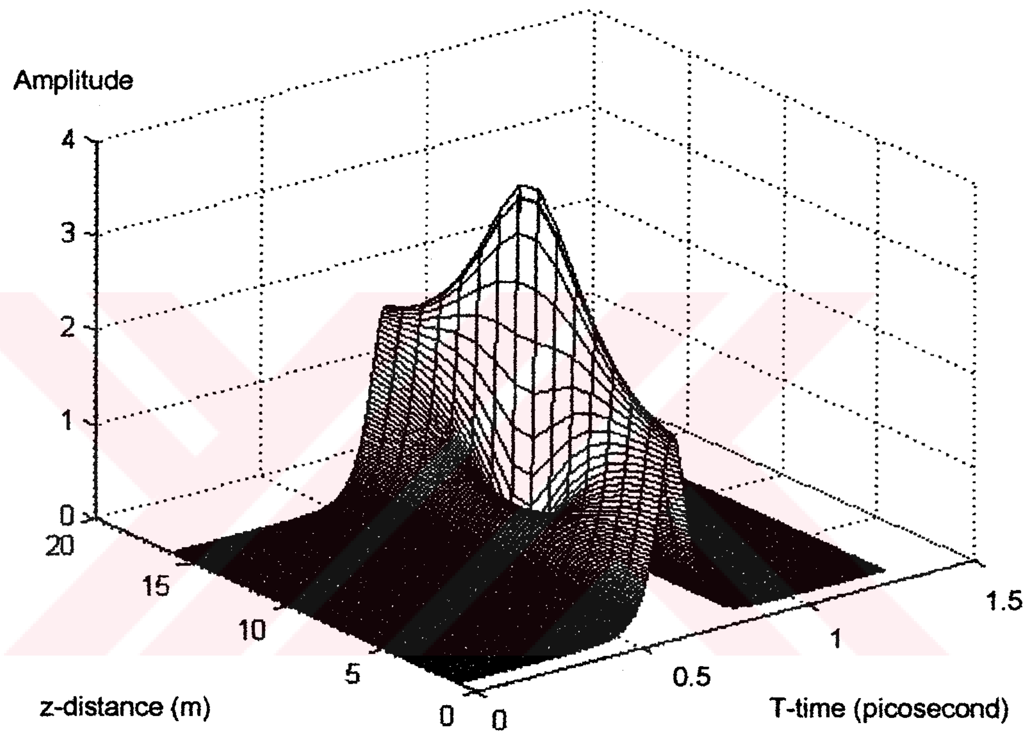

Fig.5.3. Pulse propagation along the fiber for the second order and fiber loss is 0 dB/km.

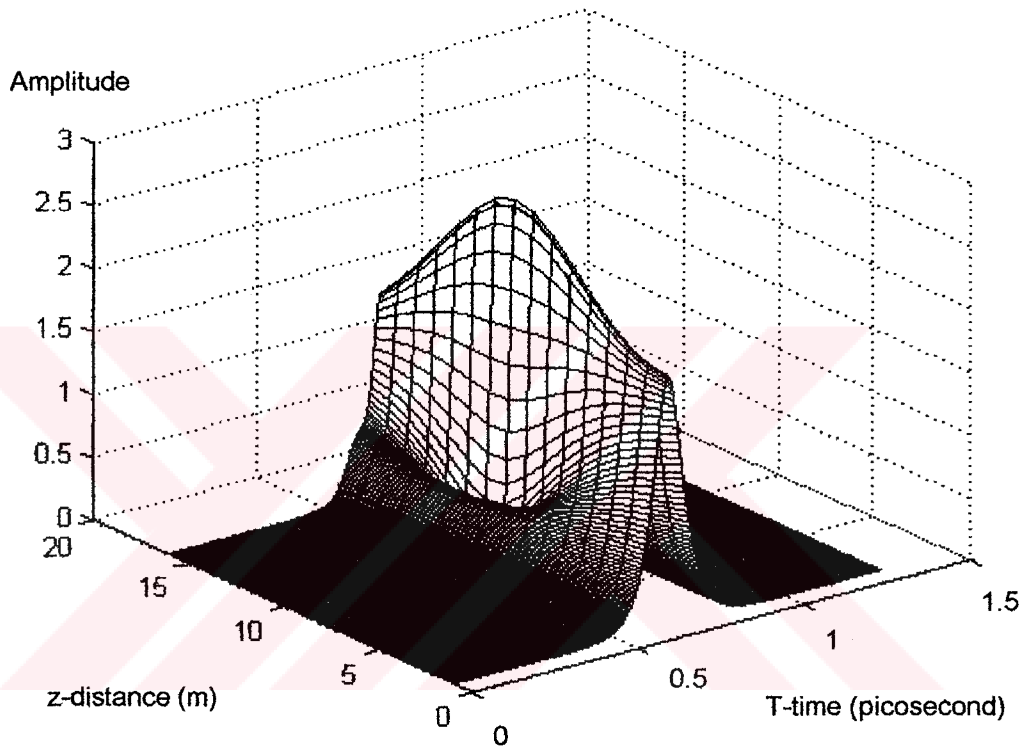

Fig.5.4. Pulse propagation along the fiber for the second order and fiber loss is 0.2 dB/km.

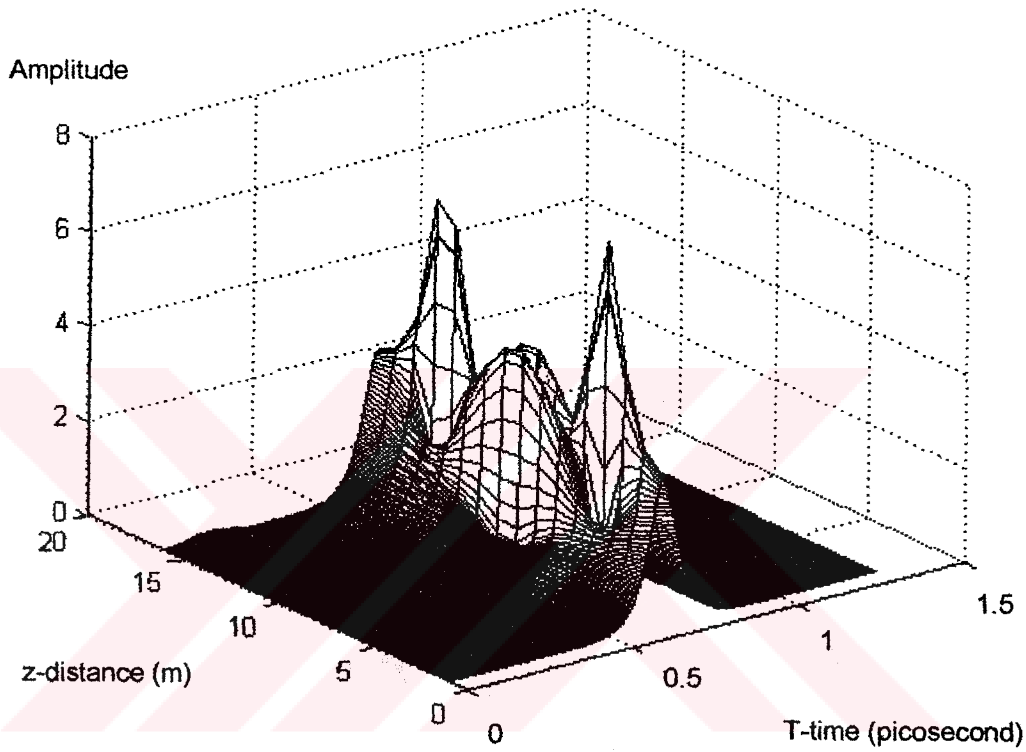

Fig.5.5 Pulse propagation along the fiber for third order and fiber loss is 0 dB/km.

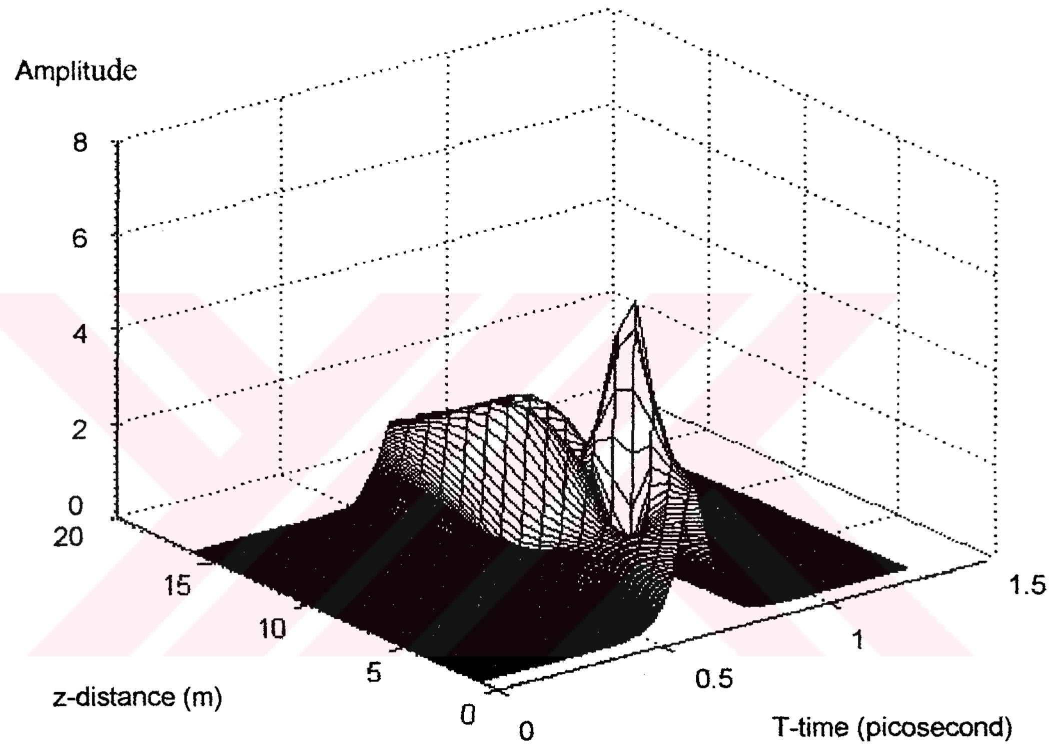

Fig.5.6 Pulse propagation along the fiber for third order and fiber loss is 0.2 dB/km.

6. CONCLUSION

We obtained six results to explain propagation of ultra-short pulses in optical fibers.

Many factors affect pulse propagation. These effects are chromatic dispersion (or group velocity dispersion), self-phase modulation, self-steepening (or nonlinear polarization), fiber attenuation (or loss), higher order dispersion and self-frequency shift.

In our analysis, we used only chromatic dispersion, self-phase modulation and fiber attenuation affects. We got pulse width as 100 fs (or 0.1 ps) and fiber length is 15 m.

To analyze these factors effects, we used nonlinear schrodinger equation which describes electromagnetic wave equation.

In other words, nonlinear schrodinger equation characterizes pulse propagation in the optical fibers and determines the soliton waves which we used. We want that the waves keep their shapes when propagating along the fiber. Because we want to deal low loss, high gain and high efficiency. And so, the soliton waves are suitable for our study because they keep their spectral and temporal shapes when passing each other and as a result propagating along the fiber length.

According to the fig.5.1, we got the values at the first order and fiber loss 0 dB/km. Soliton's shape didn't change along the fiber length. It seems like a solitary waves train. It is very stable. And we must note that we used $q(0,T) = n.\mathrm{sech}(T)$,n describes order, function as ideal soliton pulse at the input of the fiber in all analysis results.

In fig.5.2, we got the values as first order again and now loss 0.2 dB/km. And we saw that soliton pulse shape changed at a little bit rate and because of the loss its amplitude decreased at a rate of 20%.

In fig.5.3, our values are second order and fiber loss 0 dB/km. As we see in this figure, pulse shape changes related to its order.

In fig.5.4, our values are at the second order and loss 0.2 dB/km. We saw that the pulse was compressed by increasing of soliton order and pulse broadening occured .

In fig.5.5, we got the values at the third order and loss 0 dB/km. It can be seen clearly that pulse is compressed strongly.

In fig.5.6, our values are at the third order and loss 0.2 dB/km. Soliton pulse was compressed again but pulse amplitude decreased on its peaks values. At the end of the fiber we saw that pulse broadening occured much more.

For all figures, in loss conditions pulse amplitude value decreased approximately 20% of its value without loss.

According to these results, in the single mode optical fibers, the first order gives the best results which are very useful to receive data in communications. And the pulses we used to propagate waves don't change their shapes so much. First order gives the best results; but anyway the other results , for second order and third order, can also be used for receiving data. These results can be advanced . Soliton pulses can be applied much longer fiber lengths to investigate pulse propagating with low losses and low deformations in their shapes. And also single mode fibers are very attractive with their high efficiency and they can be used widely in much more applications. If we use erbium doped fiber optic amplifiers, we can decrease the attenuation and obtain much more efficiency due to the high bit rate soliton pulse transmission.

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BIOGRAPHY

I was born in Adana, July 27, 1975. I graduated from high school in 1992. And two years later, in 1994, I entered to Electrical and Electronics Engineering of Dumlupınar University in Kütahya. I received my B. S. Degree in 1998. Then, in 1999, I entered to Electrical and Electronics Engineering of Çukurova University as an MS student and began to work as a research assistant there. I have still been working there at same position.

APPENDIX

A.1. Multimode Step Index Fibers

A.1.1 Structure:

Core diameter : 50-400 μm

Cladding diameter : 125-500 μm

Buffer jacket diameter : 250-1000 μm

Numerical aperture : 0.16-0.5.

A.1.2. Performance characteristics:

Attenuation : 4-50 dB km^{-1} limited by absorption or scattering.

Bandwidth : 6-25 MHz km.

Applications : These fibers are available for short-distance, limited bandwidth and low cost applications.

A.2. Multimode Graded Index Fibers

A.2.1. Structure:

Core diameter : 30-100 μm (50 μm is used for telecommunications applications.)

Cladding diameter : 100-150 μm (125 μm is used for telecommunications applications.)

Buffer jacket diameter : 250-1000 μm

Numerical aperture : 0.2-0.3.

A.2.2. Performance characteristics:

Attenuation : 2-10 $dBkm^{-1}$ limited by scattering.

Bandwidth : 150 MHz km to 2 GHz km .

Applications : These fibers are used for medium haul, medium to high bandwidth applications using LEDs and injection lasers (incoherent and coherent multimode sources respectively.)

A.3. Single Mode Fibers

A.3.1. Structure:

Core diameter	: 3-10 μm
Cladding diameter	: 50-125 μm
Buffer jacket diameter	: 250-1000 μm
Numerical aperture	: 0.08-0.15 usually around 0.10.

A.3.2. Performance characteristics:

Attenuation : 2-5 km^{-1} with a scattering limit of around 1 dB km^{-1} at a wavelength of 0.85 μm. Significantly lower losses are possible in the longer wavelength region.

Bandwidth : > 500 MHz km. In theory the bandwidth is limited by waveguide and material dispersion to approximately 40 GHz km at a wavelength of 0.85 μm.

Applications : These fibers are suited for high bandwidth very long haul applications using single mode injection laser sources . (Senior, 1985)

A.4. Plastic-clad Fibers

A.4.1. Structure:

Core diameter	: Step index	100-500 μm
	Graded index	50-100 μm
Cladding diameter	: Step index	300-800 μm

	Graded index	125-150 μm
Buffer jacket diameter:	Step index	500-1000 μm
	Graded index	250-1000 μm
Numerical aperture :	Step index	0.2-0.5
	Graded index	0.2-0.3

A.4.2 Performance characteristics:

Attenuation :	Step index	5-50 μm
	Graded index	4-15 μm
Bandwidth :	Step index	5-25 MHz km
	Graded index	200-400 MHz km

Applications : These fibers are used on lower bandwidth, shorter haul links where fiber costs need to be limited.

A.5. All-plastic Fibers

A.5.1. Structure:

Core diameter : 200-600 μm

Cladding diameter : 450-1000 μm

Numerical aperture : 0.5-0.6 .

A.5.2. Performance characteristics:

Bandwidth : This is not usually specified as transmission is generally limited to tens of meters.

Applications : These fibers are suited for very short-haul (for example 'in-house') low cost links.

T.C. YÜKSEKÖĞRETİM KURULU DOKÜMANTASYON MERKEZİ