ANALYSIS OF COUPLING COEFFICIENT AND CROSSTALK IN A HOMOGENOUS MULTICORE OPTICAL FIBER

A thesis submitted in partial fulfillment of the requirement for the degree of

Bachelor of Science

In

Electrical, Electronic and Communication Engineering

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DECLARATION

This is to certify that the work presented in this paper is the yield of study, analysis and research work carried out by the undersigned group of students of the Department of Electrical, Electronic and Communication Engineering(EECE), Military Institute of Science and Technology (MIST), Mirpur Cantonment, under the supervision of Group Captain Md Afzal Hossain ,Senior Instructor , Department of Computer Science and Engineering (CSE), Military Institute of Science and Technology(MIST), Mirpur Cantonment, Dhaka 1216

It is also declared that this thesis paper is not submitted elsewhere for the award of any degree or any other publication.

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CERTIFICATION

This thesis paper titled **"ANALYSIS OF COUPLING COEFFICIENT AND CROSSTALK IN A HOMOGENOUS MULTICORE OPTICAL FIBER"** is submitted by the group as mentioned below has been accepted as satisfactory and met the required standard in partial fulfillment of the requirement for the degree of Bachelor of Science in Electrical Electronic and Communication Engineering (EECE) for LEVEL-4 on December, 2017

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ABSTRACT

Analysis is presented for an optical communication channel using seven core homogeneous Multicore Optical Fiber (MCF) considering the effect of coupling among the cores. The crosstalk due to inter-core coupling affects the performance of the channel in terms of Bit Error Rate (BER). Analysis is further extended to find the output of the MCF with given signal power taking into consideration the crosstalk with varying core to core distance (pitch), core radius and relative refractive index contrast at a given data rate in terms of Signal to Cross Talk plus Noise Ratio (SCNR). We have analyzed the coupling coefficient which measures the crosstalk caused by inter-core coupling in the homogeneous MCF. The crosstalk power and performance deterioration in terms of Bit Error Rate (BER) in an optical communication link of homogenous seven core MCF have also been evaluated and presented in this paper. The outcome of this research work will find its use in designing fiber optic system with homogeneous MCF.

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CHAPTER 1

INTRODUCTION

1.1 Introduction to Optical Fiber Communication:

We have come a long way since the very first instances of verbal and written communication. From the early stages of speech, along with the primitive use of symbols and pictures to convey messages to one another, we have evolved into a communication power house. Data has never been transferred faster and communication has thus never been more sophisticated than it is right now. From the last century communication technology has become one of the most emerging sectors and research and contribution .Along systems are replaced by digital switching networks are getting to be upgraded to optical networks. Kbps are replaced with Tbps .

a. **Optical Fiber Communication**: Communication engineers have alaways dreamt of higher information band width for wire and coaxial lines ,the frequency available for information transmission ex-tends from 10^8 to 10^9 hz.with modulted light,the transmission frequencies are in the 10^{10} hz range and thus,here an encrease in several orders of magnitude in potential band width is possible.As a matter of light fact ,the portion of the electromagnetic spectrum,has been used for communication purposes for hundreds,if not thousands ,of years. Examples include Hilltop beacons,smoke signal that means reflected light and even Alexander Graham Bell's photophone,a device that modulated the recived sunlight and reflected it severel hundred meters for detection and demodulation back into speech.the main drawback with these communication systems using light transmission was it involved the principle of line of sight communications systems.here the light signal is unguided and it is also transmitted through atmosphere where it is subjected to attenuation and distortion even when weather is fair.the subjected to being scattered or blocked entirely by physical obstacles, and unfortunately for those message are confidential,anyone can intercept the signal and understand it provided they know the code.therefore ,a better light wave communication system would certainly need a light guide to help preserve the signal and so increase the reliability and distance of transmissionThe development of LASER in 1960 was a landmark for optical fiber communication using coherent light signal.Discovery of gas and solid state lasers gave impetus for fiber optic communication technology developments.Though these initial laters had poor lifetimes and were required to work at low temperature.Presents lasers have projected lifetimes of upto 10 years at room temperature and above.Acesssibiility of Light Emitting Diodes(LED) to transform an electrical signal into light energy and PIN ,Avalache Photo Diode (APD)to detect lightsignals and turn themback into electrical information have made fiber optic communication system simple and efficient.

b. **Elementary fiber Optic Communication System:** Fiber optic transmission system arose from a merging of two unrelated technologies, semiconductor technology and the optical wave guide technology the first one for the raw materials for light sources and detectors needed in an optical transmission system, second one is given a transmission medium ,the optical fiber. Rapid progress has been made in past two decades in both lowering attenuation in fiber and increasing the wave length that it can handle. Early fiber was in the 800-900 nm wave length region, where fibers exhibited a local attenuation minimum. After that fiber curves extended over a wider range of wave length, reflecting in 1300 m region with their attendant low chromatic dispersion and low attenuation. The latest experimental fibers can operate over a broad wave length range by providing multimode dispersion low. A single light source transmitting a single detector over a single optical fiber is increasing cost but less information. So, wave length multiplexing (WDM) system techniques used which based on a single fiber by increasing information carrying capacity. In another mode of (WDM) bi-directional transmission is being used where the multiplexing devices operate in two directions. Our future direction for optical fiber technology is towards longer wavelength.

1.2 Objective of this Thesis

In this thesis, we have analysed the coupling coefficient which measures the crosstalk caused by inter-core coupling in the homogeneous MCF. The crosstalk power and performance deterioration in terms of Bit Error Rate (BER) in an optical communication link of homogenous seven core MCF have also been evaluated and discussed.

1.3 Optical Fiber as a Waveguide

For transporting voice, video, and data high-speed communications i.e. expeditious outgiving of information, optical fiber is the most authentic transmission medium. In the arena of optical fiber, multicore fiber system is the latest technology.

A typical single optical fiber consists of a strand of ultrapure silica mixed with specific elements, the dopants. Dopants are added to adjust the refractive index of silica and thus its light propagation characteristics. The optical cable is a single strand of fiber, many miles long. It consists of several layers. The innermost layer is the silica core. The core is covered by another layer of silica with a different mix of dopants, known as cladding. The cladding is covered with a buffer coating.

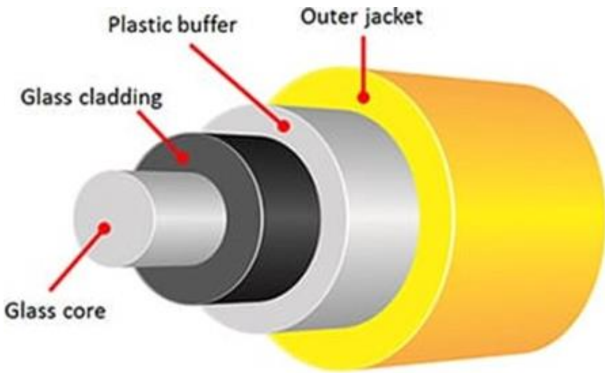

Fig: Optical Fiber Cross View

An optical wave guide is a structure that "guides" a light wave by constraining it to travel along a certain desired path. If the transverse dimensions of the guide are much larger than the wavelength of the guided light, then we can explain how the optical waveguide works using geometrical optics and total internal reflection.

An optical fiber consists of three concentric elements, the core, the cladding and the outer coating, often called the buffer. The core is usually made of glass or plastic. The core is the light-carrying portion of the fiber. The cladding surrounds the core. The cladding is made of a material with a slightly lower index of refraction than the core. This difference in the indices causes total internal reflection to occur at the core-cladding boundary along the length of the fiber.

An important aspect of a fiber optic communication is that of extension of the fiber optic cables such that losses brought about by jointing two different cables is kept to a minimum. Joining lengths of optical fiber often proves to be more complex than joining electrical wire or cable and involves careful cleaving of the fibers, perfect alignment of the fiber cores and the splicing of these aligned fiber cores. For applications that demand a permanent connection a mechanical splice which holds the ends of the fibers together could be used. Temporary or semi-permanent connections are made by means of specialized optical fiber connectors.

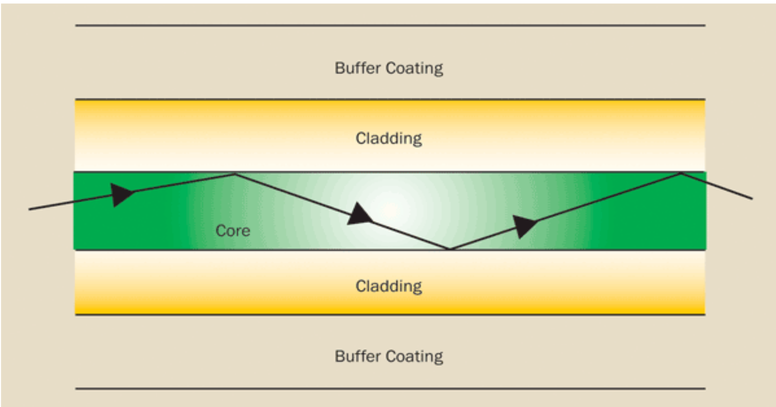

Fig:1-2: Total Internal Refraction in an Optical Fiber

Light may be confined in the middle layer by total internal reflection. This occurs only if the dielectric index of the middle layer is larger than that of the surrounding layers. In practice slab waveguides are not infinite in the direction parallel to the interface, but if the typical size of the interfaces is much larger than the depth of the layer, the slab waveguide model will be an excellent approximation. Guided modes of a slab waveguide cannot be excited by light incident from the top or bottom interfaces. Light must be injected with a lens from the side into the middle layer. Alternatively a coupling element may be used to couple light into the waveguide, such as a grating coupler or prism coupler.

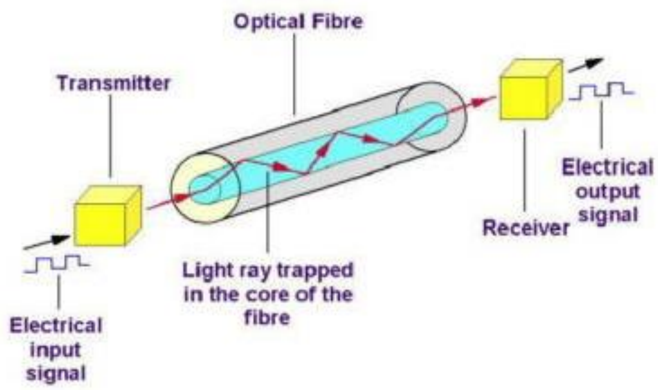

Fig:1.3: Light propagation through the optical fiber

One model of guided modes is that of a plane wave reflected back and between the two interfaces of the middle layer, at an angle of incident between the propagation direction of the light and the normal or perpendicular direction, to the material interface is greater than the critical angle .The critical angle depends on the index of refraction of the materials, which may vary depending on the wavelength of the light. Such propagation will result in a guided mode only at a discrete set of angles where the reflected plane wave does not destructively interfere with itself .

1.4 Advantages of Optical Fiber:

a. **Immunity to Electromagnetic Interference:** Although fiber optics can solve data communications problems, they are not needed everywhere. Most computer data goes over ordinary wires. Most data is sent over short distances at low speed. In ordinary environments, it is not practical to use fiber optics to transmit data between personal computers and printers as it's too costly. Electromagnetic Interference is a common type of noise that originates with one of the basic properties of electromagnetism. Magnetic field lines generate an electrical current as they cut across conductors. The flow of electrons in a conductor generates a magnetic field that changes with the current flow. Electromagnetic Interference does occur in coaxial cables, since current does cut across the conductor. Fiber optics are immune to this EMI since signals are transmitted as light instead of current. Thus, they can carry signals through places where EMI would block transmission.

b. **Data Security:** Magnetic fields and current induction work in two ways. They don't just generate noise in signal carrying conductors; they also let the information on the conductor to be leaked out. Fluctuations in the induced magnetic field outside a conductor carry the same information as the current passing through the conductor. Shielding the wire, as in coaxial cables can reduce the problem, but sometimes shielding can allow enough signal leak to allow tapping, which is exactly what we wouldn't want.

There are no radiated magnetic fields around optical fibers; the electromagnetic fields are confined within the fiber. That makes it impossible to tap the signal being transmitted through a fiber without cutting into the fiber. Since fiber optics do not radiate electromagnetic energy, emissions cannot be intercepted and physically tapping the fiber takes great skill to do undetected. Thus, the fiber is the most secure medium available for carrying sensitive data.

c. **Non Conductive Cables**: Metal cables can encounter other signal transmission problems because of subtle variations in electrical potential. Electronic designers assume that ground is a uniform potential. That is reasonable if ground is a single metal chassis, and it's not too bad if ground is a good conductor that extends through a small building. However, the nominal ground potential can differ by several volts if cables run between different buildings or sometimes even different parts of the same building.

Signal levels in semiconductor circuits are just a few volts, creating a problem known as ground loop. When the difference in ground potential at two ends of a wire gets comparable to the signal level, stray currents begin to cause noise. If the differences grow large enough, they can even damage components. Electric utilities have the biggest problems because their switching stations and power plants may have large potential differences.

A serious concern with outdoor cables in certain computer networks is that they can be hit by lightning, causing destruction to wires and other cables that are involved in the network. Certain computer companies are aware of this problem and trying to solve it by having protective devices for wire circuits to block current and voltage surges.

Any conductive cables can carry power surges or ground loops. Fiber optic cables can be made non-conductive by avoiding metal in their design. These kinds of cables are economical and standard for many indoor applications. Outdoor versions are more expensive since they require special strength members, but they can still be valuable in eliminating ground loops and protecting electronic equipment from surge damage.

d. **Eliminating Spark Hazards:** In some cases, transmitting signals electrically can be extremely dangerous. Most electric potentials create small sparks. The sparks ordinarily pose no danger, but can be really bad in a chemical plant or oil refinery where the air is contaminated with potentially explosive vapors. One tiny spark can create a big explosion potential spark hazards seriously hinder data and communication in such facilities. Fiber optic cables do not produce sparks since they do not carry current.

e. **Ease of Installation:** Increasing transmission capacity of wire cables generally makes them thicker and more rigid. Such thick cables can be difficult to install in existing buildings where they must go through walls and cable ducts. Fiber cables are easier to install since they are smaller and more flexible. They can also run along the same routes as electric cables without picking up excessive noise. One way to simplify installation in existing buildings is to run cables through ventilation ducts. However, fire codes require that such plenum cables be made of costly fire retardant materials that emit little smoke. The advantage of fiber types is that they are smaller and hence require less of the costly fire retardant materials. The small size, lightweight and flexibility of fiber optic cables also make them easier to be used in temporary or portable installations.
f. **High Bandwidth Over Long Distances:** Fiber optics have a large capacity to carry high speed signals over longer distances without repeaters than other types of cables. The information carrying capacity increases with frequency. This however, doesn't mean that optical fiber has infinite bandwidth, but it's certainly greater than coaxial cables. Generally, coaxial cables have a bandwidth parameter of a few MHz/km, where else the fiber optic cable has a bandwidth of 400MHz/km. This is an important factor that leads to the choice of fiber for data communications. Fiber can be added to a wire network so it can reach terminals outside its normal range. Fiber optic cables have a much greater bandwidth than metal cables. Optical fiber can provide data transmission performance up to 10Gbps, 40Gbps and even 100Gbps with new hardware that is now available.
g. **Low Power Loss:** An optical Fiber offers low power loss. This allows for longer transmission distances. In comparison to copper; in a network, the longest recommended copper distance is 100m while with fiber, it is 2000m. In order to increase the transmission distance, a repeater must be installed in the middle of the path to re-generate the signal. Optical fiber cable allows data to be sent far without as many repeater devices that are required by other types of cabling.
h. **Size:** In comparison to copper, a fiber optic cable has nearly 4.5 times as much capacity as the wire cable has and a cross sectional area that is 30 times less.
i. **Weight:** Fiber optic cables are much thinner and lighter than metal wires.They also occupy less space with cables of the same information capacity. Lighter weight makes fiber easier to install.
j. **Flexibility:** An optical fiber has greater tensile strength than copper or steel fibers of the same diameter. It is flexible, bends easily and resists most corrosive elements that attack copper cable.
k. **Cost:** The raw materials for glass are plentiful, unlike copper. This means glass can be made more cheaply than copper.

1.5 Review of Literature Regarding This Issue

Multicore fibers are expected as a good candidate for overcoming the capacity limit of a current optical Communication System. Between the two universally allowed research methods:

computer simulation and analytical modeling, the first one is chosen, Computer simulation or a computer model is computer program that attempts to simulate a abstract model of a particular system. Our work is perform partially with analysis and mainly with MATLAB simulation. We have parameters and other conditions with make results different. Values of this effective parameters are taken to be specified and results are evaluated for that value of parameter.

A good number of researches have already been carried out by different scholars on evaluation of the characteristics of multicore fiber. Either simulation or analytical methods were being used by them to process their works. The similar studies are shortly describe below regarding MCF and its crosswalks:

F.Y.M. Chan, A.P T Lau, and H.Y Tam [28] demonstrated Mode coupling dynamics and communication strategies for multi-core fiber systems. The propagation dynamics of 7-core multi-core fibers (MCFs) with identical and three-types of cores were analytically derived based on the coupled-mode theory. For MCFs with heterogeneous cores, it was found that even though signals from different core groups would not couple with each other, the coupling within their own group is significantly affected by the presence of other core groups. It was shown that aperiodic mode coupling in intensity modulated systems induces crosstalks which was difficult to eliminate through signal processing.

Md Mobarok Hossain Rubel and Syed Golam Mahmud [33] had worked on BER Performance Analysis for Optical Communication using DPSK Modulation. After developing an approximate form BER expression, the BER performance for different system parameters such as fiber length, gain and number of amplifier had analyzed. With the aid of analysis and simulation results the influence of different system parameters on the BER performance of an optical system using differential modulation schemes was demonstrated.

Md Jahangir and SP Majumder [29] presented an analytical approach to evaluate the Bit Error Rate (BER) performance of multicore fiber (MCF) communication system with On-Off Keying(OOK) modulation scheme. The expressions of the signal power at the output of the different cores of the MCF with excitation to any one of the cores was found out along with the crosstalk due to coupling among among the cores. Finally, the expression for Signal to Crosstalk Ratio (SCR) at the output of the excited the fiber core was found.

Md Al Amin Sajeeb, Farhat Tasnim Farin, Abdur Rahim, S P Majumder [31] presented for an optical link by using a multicore fiber (MCF) considering the effect of mutual coupling among the fiber cores which results in optical crosstalk. Analysis is carried out to find the optical crosstalk power at the output of the multicore fiber (MCF) and the photocurrents due to optical signal and crosstalk at the output of the receiver low pass filter. Crosstalk is found to be dependent on optical carrier wavelength and crosstalk is found to be minimum at certain wavelengths for a given number of cores of multicore fiber (MCF).

B. Zhu, T. F. Taunay, M. F. Yan, J. M. Fini, M. Fishteyn, E. M. Monberg, and F. V. Dimarcello [35] designed and fabricated a novel multicore fiber (MCF), with seven cores arranged in a hexagonal array. A new tapered MCF connector (TMC), showing ultra-low crosstalk and losses, is also designed and fabricated for coupling the individual signals in-and-out of the MCF. A network configuration using parallel transmissions with the MCF and TMC for passive optical network (PON) was proposed. The bidirectional parallel transmissions of 1310nm and 1490nm signals over 11.3 km of seven-core MCF with 64-way splitter for PON was demonstrated.

Wenhua Ren, Zhongwei Tan A [30] studied on the coupling coefficients for multi-core fibers. The complete analytical expressions of mode coupling dynamics for homogeneous 7-core multi-core fibers (MCFs) were obtained by using orthogonal coupled-mode theory (CMT). By using the TCF model, it was found that the coupling coefficients calculated were smaller than that calculated by formulas. Also the coupling coefficients between nonadjacent cores and self-coupling coefficients can be comparable to the coupling coefficients between adjacent cores, and consequently cannot be ignored in the analysis of strong coupling MCFs.

CHAPTER 2

PRINCIPLE OF FIBER OPTIC COMMUNICATION

2.1 Types of Optical Fiber:

a. **Mode:** A set of guided electromagnetic waves called the modes of the wave guide. Depends on propagation path or mode optical fiber is two type:

i. **Single Mode:** Single Mode cable is a single stand of glass fiber with a diameter of 8.3 to 10 microns that has one mode of transmission. Single Mode Fiber with a relatively narrow diameter, through which only one mode will propagate typically 1310 or 1550nm. Carries higher bandwidth than multimode fiber, but requires a light source with a narrow spectral width. Synonyms are mono-mode optical fiber, single-mode fiber, single-mode optical waveguide, uni-mode fiber.

Single-mode fiber gives you a higher transmission rate and up to 50 times more distance than multimode, but it also costs more. Single-mode fiber has a much smaller core than multimode. The small core and single light-wave virtually eliminate any distortion that could result from overlapping light pulses, providing the least signal attenuation and the highest transmission speeds of any fiber cable type.Single-mode optical fiber is an optical fiber in which only the lowest order bound mode can propagate at the wavelength of interest typically 1300 to 1320nm.

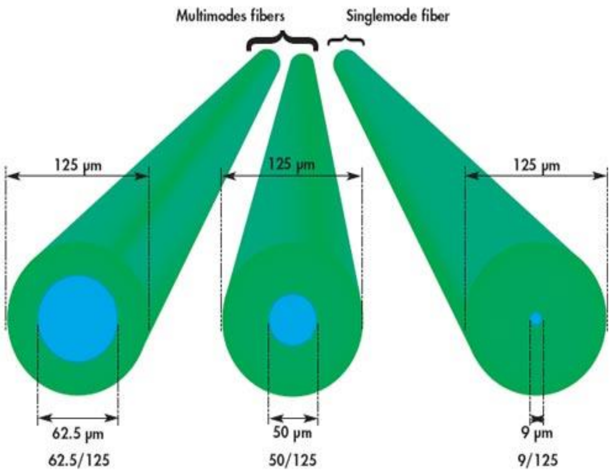

Fig 2.1: Single Mode and Multi-Mode Optical Fiber

ii. **Multi-Mode:** Multimode cable is made of glass fibers, with common diameters in the 50-to-100 micron range for the light carry component (the most common size is 62.5). POF is a newer plastic-based cable which promises performance similar to glass cable on very short runs, but at a lower cost.

Multimode fiber gives you high bandwidth at high speeds over medium distances. Light waves are dispersed into numerous paths, or modes, as they travel through the cable's core typically 850 or 1300nm. Typical multimode fiber core diameters are 50, 62.5, and 100 micrometers. However, in long cable runs (greater than 3000 feet 914.4 ml), multiple paths of light can cause signal distortion at the receiving end, resulting in an unclear and incomplete data transmission.

❖ **Advantages and Disadvantages of Single Mode fiber Cable**

Single-mode fiber cable is more suitable for long runs applications when compared with multimode fiber cable. Except for this, single-mode fiber cable also has other three advantages.

Advantages:

- ❖ Increase bandwidth capacity.
- ❖ Limited Data Dispersion & External Interference. The single input mode allows SMF to limit light scattering, which in turn reduce light waste and increase data transmission data.
- ❖ Fast Transmission Speed. Single-mode fiber cable can support data transmission speed up to 10Gbps.

Disadvantage:

Although it has better performance in long runs transmission than multimode fiber cable, single-mode fiber cables often cost more.

❖ **Advantages and Disadvantages of Multimode fiber Optic Cable**

Advantages:

- ❖ In compared with single-mode fiber cable, it is less expensive and are easier to work
- ❖ In addition, multimode fiber cable also provides high speed and high bandwidth over short distances. And they allows several mode optical signals transmitted at the same time.

Disadvantages:

However, multimode fiber cable has high dispersion and attenuation rate, the quality of optical signals is reduced as the transmission distance is getting longer. Therefore, multimode fiber cable is often used in data and audio/video applications in LANs.

b. **Refractive Index**: The refractive index of the core, n_1 is always greater than the index of cladding n_2 .by the core light is guided and the fiber consider as a optical wave guide. Here is also two type:

i. **Step-Index:** Core and Cladding material has uniform but different refractive index.

ii. **Graded Index:** Core material has variable index as a function of the radial distance from the center.

c. **Materials of Core and Cladding**

Optical fibers are composed primarily of silicon dioxide (SiO_2), though minute amounts of other chemicals are often added. Highly purified silica powder was used in the now-outmoded crucible manufacturing method, while liquid silicon tetrachloride ($SiCl_4$) in a gaseous stream of pure oxygen (O_2) is the principal source of silicon for the vapor deposition method currently in widespread use. Other chemical compounds such as germanium tetrachloride ($GeCl_4$) and phosphorus oxychloride ($POCl_4$) can be used to produce core fibers and outer shells, or claddings, with function-specific optical properties.

Because the purity and chemical composition of the glass used in optical fibers determine the most important characteristic of a fiber—degree of attenuation—research now focuses on developing glasses with the highest possible purity. Glasses with a high fluoride content hold the most promise for improving optical fiber performance because they are transparent to almost the entire range of visible light frequencies. This makes them especially valuable for multimode optical fibers, which can transmit hundreds of discrete light wave signals concurrently.

2.2 Photonics

Photonics is the technology of generating and harnessing light and other forms of radiant energy whose quantum unit is the photon. It is the technology of generating, controlling, and detecting light waves and photons, which are particles of light. The characteristics of the waves and photons can be used to explore the universe, cure diseases, and even to solve crimes. Scientists have been studying light for hundreds of years. The colors of the rainbow are only a small part of the entire light wave range, called the electromagnetic spectrum. Photonics explores a wider variety of wavelengths, from gamma rays to radio, including X-rays, UV and infrared light.

Photonics involves cutting-edge uses of lasers, optics, fiber-optics, and electro-optical devices in numerous and diverse fields of technology – alternate energy, manufacturing, health care, telecommunication, environmental monitoring, homeland security, aerospace, solid state lighting, and many others.

2.3 Photonic Crystal Fiber (PCF)

Photonic crystal fiber (PCF) is a kind of optical fiber that uses photonic crystals to form the cladding around the core of the cable.[15-16] Photonic crystal is a low-loss periodic dielectric medium constructed using a periodic array of microscopic air holes that run along the entire fiber length. In PCFs, photonic crystals with photonic band gaps are constructed to prevent light propagation in certain directions with a certain range of wavelengths. Contrary to normal fiber optics, PCFs use total internal reflection or light confinement in hollow core methods to propagate light. Light propagation in PCFs is far superior to standard fiber, which uses constant lower refractive index cladding. In PCF, on the other hand, light is trapped in the core, providing a much better wave guide to photons than standard fiber optics. The polymers used instead of glass in PCF provide the advantage of a more flexible fiber, which allows for easier and less expensive installation. Various photonic crystals conforming to various photonic lattices are manufactured depending on the required properties of the propagated light.

Photonic crystal fibers are generally divided into two main categories:

a. **Index Guiding Fibers:** Index-guiding fibers have a solid core like conventional fibers. Light is confined in this core by exploiting the modified total internal reflection mechanism.

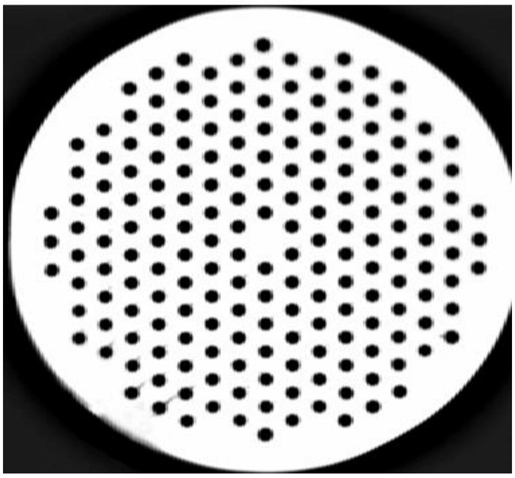

Fig:2-2: Index Guiding Fiber

b. **Photonic Band Gap Fibers:** Photonic band gap fibers have periodic microstructure elements and a core of low-index material which is also called as hollow core. The core region has a lower refractive index than the surrounding photonic crystal cladding. The light is guided by a mechanism that differs from total internal reflection in that it exploits the presence of the photonic band gap (PBG).

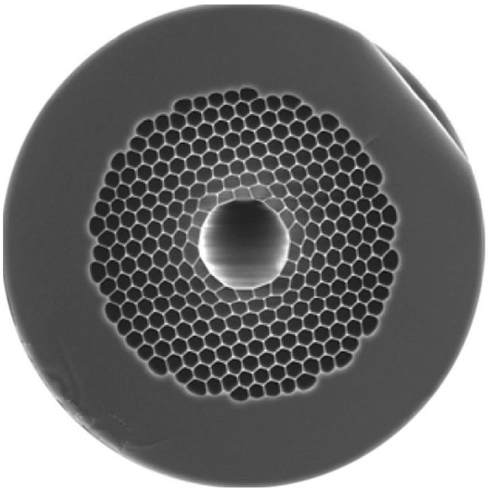

Fig:2-3: Photonic Band Gap Fiber/Hollow Fiber

Fiber-optic cables are constructed with a core and a cladding of constant refractive index difference. Light travels through the core as a result of the refraction property of light, which occurs as a result of the difference between the refractive indexes of the core and cladding. This refracted light bears much higher loss during propagation over extended distances, and thus requires repeaters and amplifiers for extended distance communications.

Applications for photonic crystal fibers include spectroscopy, metrology, biomedicine, imaging, telecommunication, industrial machining and military technology.

- **Advantages of Hollow Fiber Over Solid Core Fiber :**

Hollow-core PCF has the greatest potential for extremely low loss, because the light travels predominantly in the hollow core. Values well below 0.2 dB/km seem at least feasible. The prospect of improving on conventional fiber while greatly reducing the nonlinearities associated with a solid glass core is tantalizing. The best reported attenuation in hollow-core PCF is 13 dB/km, limited, it is believed, by the high sensitivity of the band gap to structural fluctuations that occur over long fiber lengths; wavelengths that are guided in one section may leak away in another.

2.4 The Capabilities of Multicore Fibers

The latest multicore fibers now use fibers with an overall diameter of around 200 microns. However, the total effective area of the fiber (the 'cores') is over 2% of the fiber volume compared with less than 0.5% for current G.657 fiber.

To see the real benefits we need to actually look at the bandwidth per fiber volume. If a normal, single core fiber has a capacity: volume ratio of '1', a 200 micron fiber with 14 cores has a capacity: volume ratio of ‘100’. That means the multicore fiber has essentially 100 times the bandwidth density of a monocore optical fiber of the same external diameter.

Satisfactory well transmission quality was confirmed in all cores and all wavelengths, this result is the world's largest transmission capacity of 118.5 Tera-bit/s among a standard diameter optical fiber. These achievements reveal that multi-core fiber with standard diameter can be used to realize an ultra large capacity transmission system overcoming the capacity crunch in the current SMF.

2.5 Data Bus in Optical Fiber Technology

A fiber optic data bus configuration usually contains a means by which a signal is optically transferred from one point to another via an optical transmitter through a passive link such as an optical fiber to a receiver. The receiver converts the signal from an optical signal to an electrical signal. A trans-impedance amplifier converts the signal into a voltage for processing by other electronics. Either small lenses or optical interconnections are used to couple the transmitter and receiver to the optical fiber. Optical couplers are used as power branching devices that split optical power by any ratio to other locations or paths. Cable assemblies that contain optical fiber protected by layers of fluoropolymers and terminated on either end with optical connectors are used to couple light from one point to another. Other devices such as attenuators are used to reduce the input power to the receiver. Isolators are used for providing a guard against reflections from the optical system traveling back into the optical source.

Light in a single mode fiber essentially follows a single path to reach its destination, in multimode fiber applications light takes many paths, which leads to a spreading of the pulse called dispersion. The multiple paths limit the bandwidth of a signal traveling through a multimode link. The bandwidth can be increased by creating a fiber that has an index of refraction is not constant over the cross section, but varies with a maximum at the center and dropping off until it nearly reaches the index of refraction of the cladding. The graded index core decreases dispersion, which increases bandwidth. In order to achieve a graded index fiber the core of the optical fiber must be doped with other materials such as germanium. (Although adding dopants to silica glass will increase its sensitivity to radiation, all graded index multimode fiber is doped with other materials.) Dopants used in optical fiber may be controlled in a way to allow certain wavelengths of light to pass with little loss while attenuating other wavelengths. Whereas in the past multimode communications systems typically operated at 850 nm, they now operate at the 1300 nm wavelength. In most cases, less loss is experienced at the longer wavelength. It is also true that in most cases operating at a longer wavelength with allow the fiber to perform better in a radiation environment.

CHAPTER 3

OPTICAL COMMUNICATION SYSTEM AND MEASUREMENT

3.1 Transmitter, Link Design, Receiver

a. **Transmitter**: An optical transmitter consists of a source which could be either a LASER or LED. Fiber optic communication systems require light sources must have high efficiency, low cost, longer life, sufficient power output, ability to give desired modulations and compatibility with the fiber ends. Three kinds of light sources are frequently used in fiber optic communication system, namely wide band 'continuous spectra' sources (incandescent light), Monochromic incoherent sources-Light Emitting Diode (LED), Monochromatic coherent sources (LASER).A variety of optical transmitters incorporating semiconductor sources have been developed in the wavelength range 0.8_{um}-$1.6_{um.}$In general the high bit systems (>34 Mbits/s)use lasers and it is essential to narrow the source spectrum.
In this paper Distributed Feedback Laser (DFB) used in transmitter .DFB laser is an index guiding, stripe geometry diode laser with a narrow stripe where a periodic corrugated structure or grooves is spatially etched on the surface of a passive or active waveguide which in this case lies between heterojunction layers. Whereas the narrow stripe effectively limits the transverse lasing mode to one the grating feedback from the periodic structure helps to limit the longitudinal modes.

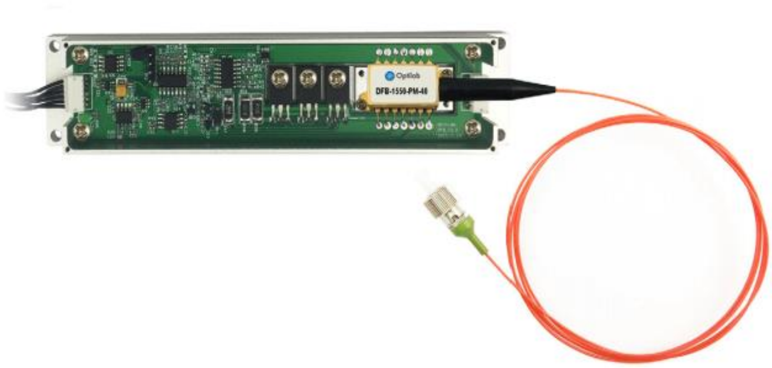

Fig 3.1: DFBLD Transmitter

b. **Link Design:** An optical fiber consists of optical source, optical fiber transmission medium, the photo detector and its associated receiver and the connectors used to join individual fiber cables to each other and to the source and the detector. The principal determining factors for the link designers to consider are, the transmission distance required Bit Error Rate (BER) and the data rate or channel band width. Because of the involvement of several factors a tradeoff is therefore required. The transmission distance up to which a fiber optic link will work well is dependent greatly on three fiber parameters, namely the Numerical Aperture (NA), core size and Attenuation. The optical power that finally falls on the detector determines the systems ultimate level of performance.NA and core size together indicates the level of optical power that can be launched into a fiber from a wide area of LED or LASER – a reliable source capable of fast operation with either analog or digital signals. Fibers attenuation determines how much power reaches the receiving end of unspliced link.

c. **Receiver**: As in case of the optical fiber receiver has three functions namely ,the conversion from optical to electrical signal then amplification and estimation of the message originally transmitted.[20] However all practical optical fiber optic communication systems use incoherent (direct) detection. whereas the ordinary radio receivers use heterodyne detection. In optical fiber communications only optical power variations are detected. The first function of receiver namely, the conversation from optical to electrical signal is achieved by the use of photo detectors together with their associated electronics circuits. The amplifiers must be such as to introduce minimum amount of noise and distortion .The receiver is a very highly sensitive low noise receiver.

Fig 3.2: APD Receiver

3.2 Data Buses, LANs and PONs

a. **Data Buses**: These are alternate of multiplexing where point to point links and are a kind of network over which a number of physically separated terminals communicate with one another by multiplexed signals. There is some variety of optical fiber data buses and these may be divided into two classes as like a Star or radial configuration and the in line or t coupler.
b. **LAN-(Local Area Network):** LAN is one type of data bus systems which is used for local business purposes. These systems are also called optical high way or subscriber loops. These are distinctive characteristics. System configuration and hardware strongly depends on the services. Presently available LAN system has the speed of transmission around 10Mbits/s.

In simple LAN systems main problem is associated with couplers or connectors. It is found that the practical limit is a cascaded of about eight couplers. But in present world LAN systems have been designed where as hundred couplers in 500 m of cable may be connected. These are Ethernet,Fibernet,Cambridge ring. Cambridge ring system is another method of implementing a LAN. This work on principle of one or more packets circulating serially in a closed loop which physically covers the area to be served. As compared to ring network Ethernet is quite reliable

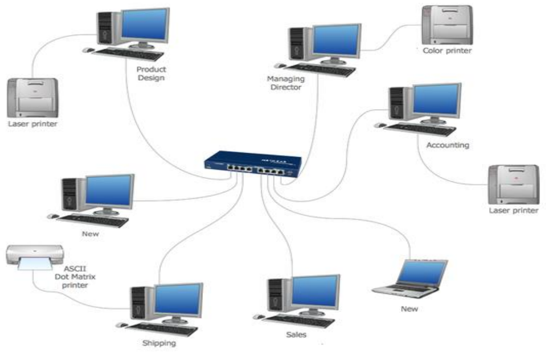

Fig 3.3: LAN Network

c. **PON:** Passive Optical Network (PON) is having no electricity to power or maintain the transmission facility. PON is very active in sending and receiving optical signals. The active parts are at both end points Splitter could be used, but is passive without repeater, the max distance traveled by signal over PON is near to 20km.The splitter enables one OLT ports to send a signal to 16-256 ONTs/ONUs at once. Because the PON uses less fiber and doesn't use electrically active parts(splitters are non-active unlike repeaters and also cost less),PON is chapter to install active optical network(AON)

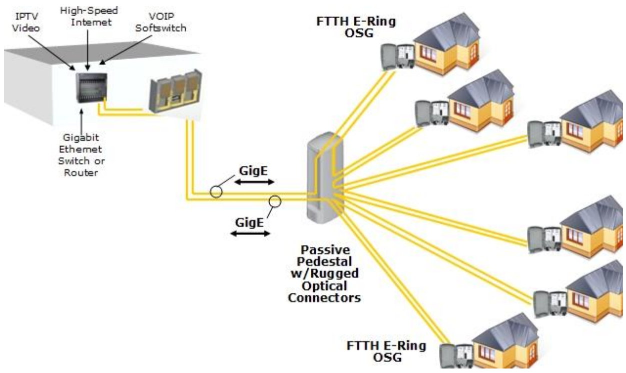

Fig 3.4 : PON Topology

3.3 ISDN,BISDN and High Speed Network

Integrated Services Digital Networks (ISDN) is a communication network that provides end-to-end digital connectivity to support a wide range of services including voice and non voice services to which users have access by al limited set of standard multipurpose users or network interfaces. [21]An ISDN is characterized by its three main features which are end to end connectivity, multiservice capability(voice, data, and video) and standard terminal interfaces. ISDN'S work with two voice channels(64 kb/s each)and one data (16kb/s)channel at the same time. These are specified by CCITT Iseries of standards. Such kind of ISDNs are also known as narrow band ISDNs.To provide communicative full motion video services broadband transmission channels are needed that are capable of supporting bit rates in excess of 2.08 Mbit/s.such as ISDNs are called broadband ISDNs. Integrated broadband communication networks,(IBCN'S)handle narrow band distributive services as well as broadband communicative services supported by BISDN.

Optical fiber provide for high speed even very high speed communication (of the order of terabit/s) links. FDDI and SONET(SDH) systems have already shown the capability of the optical fiber to be used in very high speed transmission networks. In BISDNs optical fiber are being preferred in subscriber loop to provide for all types of communication and information services .optical components most importantly switches capable of handling terabit per second through put photo detectors, etc, have already been developed. A number of opto-electronic devices have recently evolved nearly practical levels of performance, giving boost to broad band or very high speed communication technologies.

3.4 Losses of MCF

a. **Attenuation:** Attenuation means loss of light energy as the It is alsovlight pulse travels from one end of the cable to the other called as signal loss. The attenuation of an optical fiber measures the amount of light lost between input and output. Total attenuation is the sum of all losses.

   Optical losses of a fiber are usually expressed in decibels per kilometer (dB/km***)***. The expression is called the fiber's attenuation coefficient α and the expression is

$$\alpha = -\frac{10}{z[\text{km}]} \log\left(\frac{P(z)}{P(0)}\right)$$

   where P(z) is the optical power at a position z from the origin, P(0) is the power at the origin.

   For a given fiber, these losses are wavelength-dependent which is shown in the figure below. The value of the attenuation factor depends greatly on the fiber material and the manufacturing tolerances, but the figure below shows a typical optical fiber's attenuation spectral distribution.

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

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

i. **Intrinsic Material Absorption:** Intrinsic absorption is caused by interaction of the propagating light wave with one more major components of glass that constitute the fiber's material composition. These losses represent a fundamental minimum to the attainable loss and can be overcome only by changing the fiber material. An example of such an interaction is the infrared absorption band of SiO_2 shown in the above figure. However, in the wavelength regions of interest to optical communication (0.8-0.9um and 1.2-1.5um), infrared absorption tails make negligible contributions.

ii. **Extrinsic Impurity Ions Absorption*:*** Extrinsic impurity ions absorption is caused by the presence of minute quantity of metallic ions (such as Fe^{2+}, Cu^{2+}, Cr^{3+}) and the OH^- ion from water dissolved in glass.

c. **Bending loss:** The loss which exists when an optical fiber undergoes bending is called bending losses.

i. **Macro bending Loss**: Macro bending happens when the fiber is bent into a large radius of curvature relative to the fiber diameter (large bends). These bends become a great source of power loss when the radius of curvature is less than several centimeters. Macro bend may be found in a splice tray or a fiber cable that has been bent. Macro bend won't cause significant radiation loss if it has large enough radius. However, when fibers are bent below a certain radius, radiation causes big light power loss as shown in the figure below.

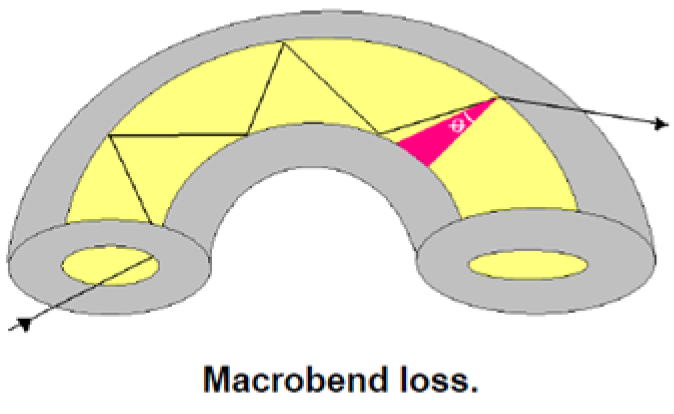

Fig 3.5 : Macrobending

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

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

Micro bending can also happen in the fiber manufacturing process. It is sharp but microscopic curvatures that create local axial displacement of a few microns (um) and spatial wavelength displacement of a few millimeters. Bends can cause 1 to 2 dB/km losses in fiber cabling process.

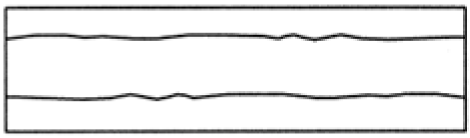

Fig 3.6 : Microbending

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

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

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

d. **Crosstalk:** Crosstalk is a disturbance caused by the electric or magnetic fields of one telecommunication signal affecting a signal in an adjacent circuit.In a telephone circuit, crosstalk can result in your hearing part of a voice conversation from another circuit. The phenomenon that causes crosstalk is called electromagnetic interference (EMI). It can occur in microcircuits within computers and audio equipment as well as within network circuits. The term is also applied to optical signals that interfere with each other. The undesired coupling from one channel to the other is referred as crosstalk. The same has been shown in the figure:

i. **FEXT (Far-End Crosstalk)**: As the one might guessed, this crosstalk is the opposite of NEXT, it appears closer to the receivers end. Assuming that attenuation weakens strength of the signal at the receivers end, FEXT is something to be considered while designing the network. Shorter cables means less attenuation, which results in higher FEXT. It is ratio of optical power from output port-1 and output port-2. The wavelength of the two ports are equal in value. Here port-2 is isolated from port-1 normally. It is expressed in dB. For WDM case, signals in two output ports will have different wavelengths. Hence here isolation term is used in place of far end crosstalk.

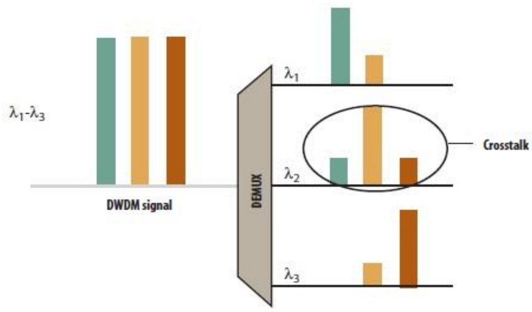

Fig 3.7 : Far End Crosstalk

ii. **NEXT (Near-End Crosstalk)**: Most commonly appears at the distance of 20-30 meters from the transmitter (60-90 feet). Reason for this crosstalk are usually poorly designed or poorly installed cables. In order to cancel the crosstalk, 10Base-T and 100Base-TX cables implement NEXT cancellation techniques by design.

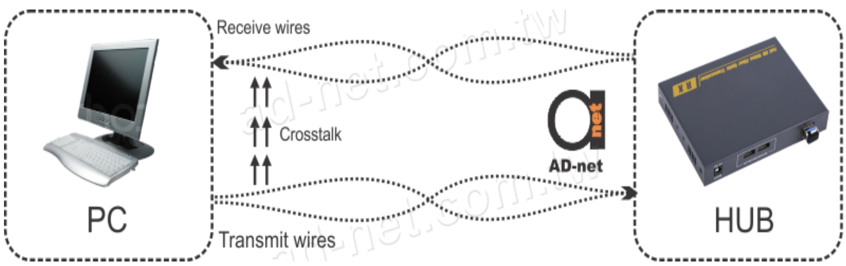

Fig 3.8 : Near End Crosstalk

e. **Dispersion**: Dispersion is the spreading out of a light pulse in time as it propagates down the fiber. Dispersion in optical fiber includes model dispersion, material dispersion and waveguide dispersion. Each type is discussed in detail below.

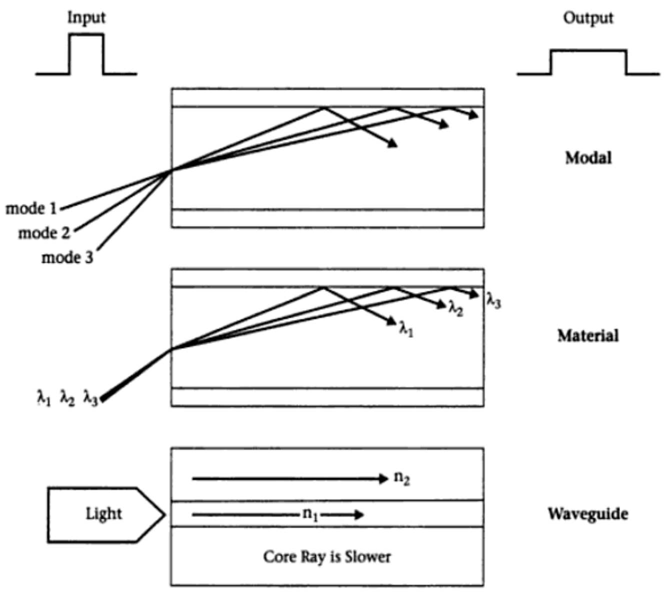

Fig 3.9 : Dispersion

i. **Material Dispersion:** Material dispersion is the result of the finite line width of the light source and the dependence of refractive index of the material on wavelength. It is shown as the 2nd illustration in the first picture. Material dispersion is a type of chromatic dispersion. Chromatic dispersion is the pulse spreading that arises because the velocity of light through a fiber depends on its wavelength.

ii. **Waveguide Dispersion:** Waveguide dispersion is only important in single mode fibers. It is caused by the fact that some light travels in the fiber cladding compared to most light travels in the fiber core. It is shown as the 3rd illustration in the first picture. Since fiber cladding has lower refractive index than fiber core, light ray that travels in the cladding travels faster than that in the core. Waveguide dispersion is also a type of chromatic dispersion. It is a function of fiber core size, V-number, wavelength and light source line width. While the difference in refractive indices of single mode fiber core and cladding are minuscule, they can still become a factor over greater distances. It can also combine with material dispersion to create a nightmare in single mode chromatic dispersion. Various tweaks in the design of single mode fiber can be used to overcome waveguide dispersion, and manufacturers are constantly refining their processes to reduce its effects.

3.5 Non Linear Loss

a. Four wave mixing: Four-wave mixing (FWM) is an intermodulation phenomenon in non-linear optics, whereby interactions between two or three wavelengths produce two or one new wavelengths. It is similar to the third-order intercept point in electrical systems. Four-wave mixing can be compared to the intermodulation distortion in standard electrical systems. It is a parametric nonlinear process, in that the energy of the incoming photons is conserved. FWM is a phase-sensitive process, in that the efficiency of the process is strongly affected by phase matching conditions.

b. Scattering: Scattering losses in glass arise from microscopic variations in the material density, from compositional fluctuations and from structural in homogeneities or defects occurring during fiber manufacture.

a. Linear scattering: It causes the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly into a different mode. This process tends to a result in attenuation of the transmitted light as the transfer may be to a leaky or radiation mode which does not continue to propagate within the fiber core, but is radiated from the fiber. With all linear process there is no change of frequency on scattering.

i. **Rayleigh scattering:** For glass fibers the foremost type of scattering is Rayleigh scattering. With this process, atoms or other particles within the fiber absorb the light signal and instantly re-emits the light in another direction. In this way Rayleigh scattering appears very much like absorption but it absorbs and redirects the light so quickly that is considered scattering.

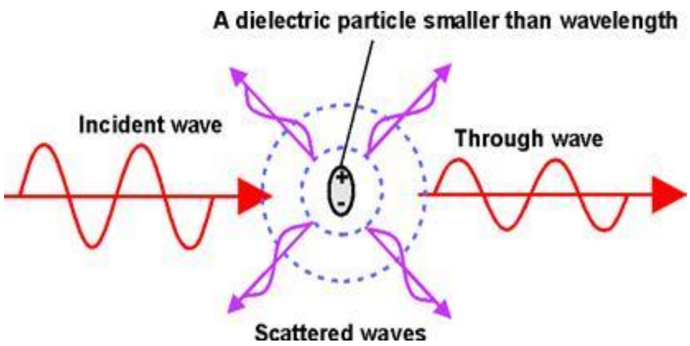

Fig 3.10: Rayleigh Scattering

ii. **Mie scattering:** Imperfections caused due to in homogeneities at the core- cladding interface which causes scattering of light. The scattering created by such in homogeneities is mainly in the forward direction and is called Mie scattering. It can be reduced by removing imperfections of glass at the time of manufacture, increasing the relative refractive index of the core and the cladding.

b. Non Linear Scattering : This scattering cause disproportionate attenuation, usually at high optical power levels. This nonlinear scattering causes the optical power from one mode to be transferred in either the forward or backward direction to the same, or other modes, at a different frequency.

i. **Stimulated Brillouin scattering (SBS):** In SBS strong optical signal generates acoustic waves. These waves produce variations in refractive index. It causes light waves to scatter in backward direction towards transmitter called as backward scatter wave which affects the forward signal leading to depletion in signal power.

ii. **Stimulated Raman scattering (SRS):** SRS is transferring of energy from short wavelengths to neighbouring high wavelength channels. If two input signal with equal power are transmitted than the former will lose its own energy and the latter will gain this energy, this limits the performance of the system.

c. **Kerr effect:** Ker effect is a change in the refractive index of a material in response to a applied electric field. This causes a variation in index of refraction which is proportional to the local irradiance of the light. The refractive index variation is responsible for the non linear fiber effects of self focusing, self phase modulation and modulation instability and is the basis for mode blocking. This effect only becomes significant with very intense beams such as those lasers.

CHAPTER 4

OPTICAL TRANSMISSION SYSTEM OF MCF

4.1 System Model With 7-Core MCF

In this thesis, 1550 nm is divided into seven outputs and connected with Tapered Multicore Optical Fiber Connector (TMC). Avalanche Photo Diode (APD) is used as the receivers. The Amplifier (AMP), Equalizer (EQ) and Low Pass Filter (LPF) are used for its normal function at the receiving end. Here we used the homogenous MCF in which all cores have same radius of 4.5 micrometer and pitch is considered 38 micrometer and cladding index is 1.4573 unless some parameter is changed for analysis.

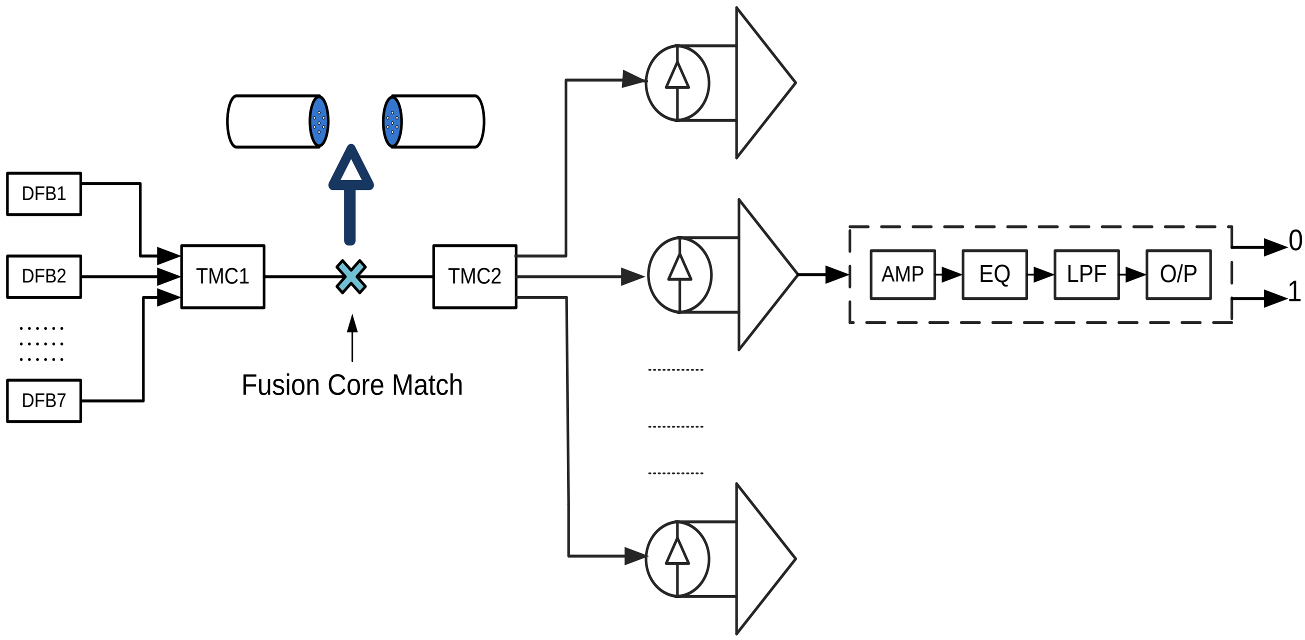

Fig: 4.1: Block diagram of a MCF Communication Link

Fig. shows a multicore fiber communication link composed of seven core homogenous multi core fiber. Some Tapered Multicore Optical Fiber Connector (TMC) is used for coupling the cores. A stable laser source DFB at 1550 nm is divided into seven outputs and connected with TMC . Avalanche Photo Diode (APD) is used as the receivers. The Amplifier (AMP), Equalizer (EQ) and Low Pass Filter (LPF) are used for its normal function at the receiving end. Here we used the homogenous MCF in which all cores have same radius of 4.5 micrometer and pitch is considered 38 micrometer and cladding index is 1.4573 unless some parameter is changed for analysis.

4.2 Analysis of Optical Link with MCF

Considering a MCF which has *n* non-identical cores (labeled core 1, 2… *n*) arbitrarily attached near the center of the cladding. The p^{th} core is identified by its radius and refractive index a_p and n_{1p} respectively while the cladding has a refractive index of n_2.Considering that each core only supports the LP01 fundamental mode and we express the amplitude of the LP01 mode of the *p*th core as $A_p(z)$. The synchronous mode coupling between all the cores of a MCF is conducted by a set of coupled mode. Couple mode equation which can be written in a matrix form as [26]

$$\frac{d\boldsymbol{A}(z)}{dz} = -\boldsymbol{CA}(z) \tag{1}$$

where, $\boldsymbol{A}(z) = [A_1(z)A_2(z)....A_n(z)]^T$ is a column vector and T denotes the transpose, z is the direction of propagation and **C** is a $n \times n$ matrix with elements C_{pq} given by[26]

$$C_{pq} = \begin{cases} jC_{pq}\exp\left[j(\beta_p - \beta_q)z\right] & p \neq q \\ 0 & p = q \end{cases} \tag{2}$$

Where β_p represents the propagation constant for the LP01 mode of core *p*. The coupling Coefficient (C_{pq}) is a measure of the special overlapping of the mode fields of core *p* and *q* over the cross-sectional area of core *q* [26].

Here we assume for a seven core homogenous MCF with $\Delta_p = \Delta$ for all p that is same relative index contrast for each core of the seven core MCF. The coupled mode equations are given by equation (1) with the matrix [26].

$$\boldsymbol{C} = j\begin{pmatrix} 0 & C_{12} & C_{12} & C_{12} & C_{12} & C_{12} & C_{12} \\ C_{12} & 0 & C_{12} & 0 & 0 & 0 & C_{12} \\ C_{12} & C_{12} & 0 & C_{12} & 0 & 0 & 0 \\ C_{12} & 0 & C_{12} & 0 & C_{12} & 0 & 0 \\ C_{12} & 0 & 0 & C_{12} & 0 & C_{12} & 0 \\ C_{12} & 0 & 0 & 0 & C_{12} & 0 & 0 \\ C_{12} & 0 & 0 & 0 & C_{12} & 0 & C_{12} \\ C_{12} & C_{12} & 0 & 0 & 0 & C_{12} & 0 \end{pmatrix}$$

Where the off-diagonal zeros correspond to pairs of cores assumed to have negligible coupling due to large inter-core distances

And the couple mode equations are given below,

$$C_{pq}=\sqrt{2\Delta_q}W_qU_pK_o\left(\frac{w_pd_{pq}}{a_p}\right)\left[a_pU_qJ_1(U_q)I_o\left(\frac{w_pa_q}{a_p}\right)\right.$$
$$\left.+a_qW_pJ_o(U_q)I_1\left(\frac{w_pa_q}{a_p}\right)\right]\left[V_pJ_1(U_q)K_1(W_p)\left(a_p^2U_q^2+a_q^2W_p^2\right)\right]^{-1} \tag{3}$$

Where, J_1 = Bessel function of first kind;

I_1 = modified Bessel function of first kind of order 1;

K_1 = modified Bessel function of second kind of order 1;

d_{pq} =distance between the centers of core p and q;

The normalized fiber parameters U_p,V_p and W_p are defined as[26]

$$U_p = a_p\left[\left(\frac{2\pi n_{1p}}{\lambda}\right)^2 - \beta_p^2\right]^{\frac{1}{2}};$$

$$V_p = a_p\left(\frac{2\pi}{\lambda}\right)\left(n_{1p}^2 - n_2^2\right)^{\frac{1}{2}};$$

$$W_p = a_p\left[\beta_p^2 - \left(\frac{2\pi n_2}{\lambda}\right)^2\right]^{\frac{1}{2}};$$

Here, a_p = core diameter

n_{1p}= core index of p-th core,

n_2 =cladding index of fiber,

λ=propagation constant,

Another fiber parameter relative index Δ with respect to core p has the expression

$$\Delta_p = \left(n_{1p}^2 - n_2^2\right)/\left(2n_{1p}^2\right)$$

The above formula can also be written

$$\Delta_p = \left(n_{1p} - n_2\right)/n_{1p}$$

Which corresponds to the relative core cladding index difference.

If p is considered as the input core , the other remaining cores are denoted by q.

As the equation (3) is a second-order differential equation, there must be two linearly independent solutions. Different variations are summarized and described in the above C_{pq} equation. It may be the concern why Bessel function is needed to determine the cross coupling. Bessel function can be applied in a system having 3 features-

a. The system must have circular cross section
b. The system must have cylindrical shape and
c. Electric field propagates through the system

The system is considered here is the multicore fiber and according to figure it fulfills all the above 3 conditions. That is why Bessel function is applied here to find the coupling coefficient.

a. Analysis for Signal , Crosstalk & Coupling Coefficient

When light is launched into core 1(center core), i.e. $A_1(0)=1$ and $A_p(0)=0$ for p≠1, analytical solution for the mode amplitude at distance z are obtained as [31]

$$A_1(z)=\left[\cos\left(\sqrt{7}C_{12}z\right)+\frac{j}{\sqrt{7}}\left(\sin\left(\sqrt{7}C_{12}z\right)\right)\right]e^{-(jC_{12}z)} \tag{4}$$

$$A_p(z)=\left[-\frac{j}{\sqrt{7}}\left(\sin\left(\sqrt{7C_{1p}z}\right)\right)\right]e^{-(jC_{1p}z)} \tag{5}$$

This is the signal which is found at the end of the multicore fiber.

The transmitted signal is given by[31]

$$E_p(t,0)=E_oe^{jw_ct} \quad ; \quad \text{when } z=0 \tag{6}$$

The signal at a distance z is given by

$$E_p(t,z)=E_oe^{jw_ct}e^{-j\beta_pz} \tag{7}$$

Due to crosstalk, signal of p^{th} core will also enter the other remaining cores. So the signal in q^{th} core is given by[31]

$$E_q(t,z) = E_o e^{jw_c t} e^{-j\beta_q z}; q \neq p \quad (8)$$

The total crosstalk signal is formed by the signal passing through all q^{th} cores except p^{th} core.[31]

$$E_{CT}(t,z) = \sum_{q=1}^{M} E_q(t,z); q \neq p \quad (9)$$

Now, signal at 1st core at z distance is given by[31]

$$E_1(z) = E_1(0)\{\cos(\beta_1 z) - j\sin(\beta_1 z)\} + \{E_2(0)\cos(C_{21}z) + E_3(0)\cos(C_{31}z) + \ldots + E_7(0)\cos(C_{71}z)\} - j\{E_2(0)\sin(C_{21}z) + E_3(0)\sin(C_{31}z) + \ldots + E_7(0)\sin(C_{71}z)\} \quad (10)$$

So, when input light signal is given to core 1, i.e. $A_1(0) = 1$

and A_p (0), p ≠ 1, then from equation (10) signal power (Pr) and crosstalk power (P_{CT}) for core 1 can be obtained as under [31]

$$P_r = |E_1(0)|^2 \sqrt{\cos^2(\beta_1 z) + \sin^2(\beta_1 z)}$$

Or, $P_r = |E_1(0)|^2$ (11)

and

$$P_{CT} = |E_2(0)\cos(C_{21}z) + E_3(0)\cos(C_{31}z) + \ldots + E_7(0)\cos(C_{71}z) + E_2(0)\sin(C_{21}z) + E_3(0)\sin(C_{31}z) + \ldots + E_7(0)\sin(C_{71}z)|^2 \quad (12)$$

Where, $C_{21}, C_{31}........C_{71}$ are the coupling coefficients between cores.

So from equation (11) and (12) signal to crosstalk ratio can be calculated.[31]

So, $(SCR)_{optical} = \frac{P_r}{P_{CT}}$ (13)

Where P_r =Received power;

P_{CT} =Crosstalk Power

Eventually signal current is obtained and that is given by

$$I_r(t) = R_d |E_q|^2 \quad (14)$$

Where, R_d is the responsibility of the photodiode.

And the crosstalk current can be found as following,[31]

$I_{CT}(t) = R_d |E_{CT}|^2$

Or, $I_{CT}(t) = R_d \left| \sum_{q=1}^{M} E_q(t,z) \right|^2$ (15)

the received optical signal with crosstalk at the input of the photo detector at a given distance z from the transmitter is given by [31]

$$e_r(t,z) = \sqrt{2GP_r(z)}e^{jw_c t} + \sqrt{2P_{CT}(z)}e^{j(w_c t - \beta z)} \quad (16)$$

Where, G is the gain of the optical pre-amplifier.

The photo current at the output of the photo detector can be expressed as: [31] $i_d(t,z) = R_d.E\left|R_e\{e_r(t,z)\}\right|^2$

$$= R_d.E\left|R_e\left\{\sqrt{2GP_{sig}(z)}e^{jw_c t} + \sqrt{2P_{CT}(z)}e^{j(w_c t-\beta z)} + \sqrt{2P_{ASE}}e^{jwt}\right\}\right|^2$$

$$= R_d.E\left|\left\{\sqrt{2GP_{sig}(z)}\cos w_c t + \sqrt{2P_{CT}(z)}\cos(w_c t - \beta z) + \sqrt{2P_{ASE}}\cos wt\right\}\right|^2$$

$$= R_d.P_{sig}(z).G + R_d.P_{CT}(z) + R_d.P_{ASE}$$

$$= I_{sig}.G + I_{CT}(t) + I_{ASE}(t) + I_{shot}(t) \quad (17)$$

Where, P_{ASE} is the spontaneous emission power the pre-amplifier is followed by photo detector and the current at the output of pre amplifier is given by [31] $I_o(t) = I_{sig}(z).G + I_{CT}(t) + I_{ASE}(t) + I_{shot}(t) + I_{th}(t)$

Where, $I_{th}(t)$ is the thermal noise due to preamplifier.

b. Calculation for Noise Variance:

The variance of the noise components can be expressed as: [29]

$$\sigma_{shot}^2 = 2eB\left(R_d.P_{sig}.G + R_d.P_{CT} + R_d.P_{ASE}\right)$$

$$\sigma_{CT}^2 = \left(R_d.P_{CT}\right)^2$$

$$P_{ASE} = \sigma_{ASE}^2 = n_{sp}(G-1)h\gamma.B_0$$

$$\sigma_{th}^2 = \frac{4KT}{R_L}.B$$

where σ_{shot} = Shot noise,

σ_{CT} = Crosstalk noise

σ_{th} = Thermal noise

R_d = Receiver responsibility

n_{sp} = spontaneous emission factor,

h= Planks constant,

ϒ= Frequency of light wave

B_o = Bandwidth of optical amplifier

B =Electrical bandwidth of the receiver.

c. Calculation for SCNR & BER:

Then the electrical signal to crosstalk plus noise ratio at the output of low pass filter is given by[29]

$$SCNR = \frac{I_{sig}^2 . G^2}{\sigma_{shot}^2 + \sigma_{CT}^2 + \sigma_{ASE}^2 + \sigma_{th}^2} \tag{18}$$

$where, I_{CT} = R_d . P_{CT}$ & $I_{sig} = R_d . P_{sig}$ .Now, for the direct detection system the BER can be evaluated from[29]

$$BER = 0.5 erfc \frac{\sqrt{SCNR}}{2\sqrt{2}} \tag{19}$$

Where, *erfc* = complimentary error function.

CHAPTER-5

RESULTS AND DISCUSSION

5.1 Introduction

The chapter presents the results obtained from the computation on the model of a seven core homogenous multicore fiber (MCF) following the theoretical analysis presented in chapter-4.

The full evaluation of chapter 4 is almost presented here with necessary figures. The simulation based results are presented here. Results have been evaluated numerically for the coupling coefficients and crosstalk due to coupling at the output of an optical link with a multicore fiver (MCF). Varying the core diameter and core to core distances changes the output of MCF. The signal plus crosstalk to noise ratio (SCNR) and the bit error rate (BER) have been determined for a given data rate. Limitation in system performance due to crosstalk is observed in terms of core diameter, core to core distance, etc. have been determined from the coupling coefficient curves and other system parameters.

5.2 Results and Discussion

Following parameters shown in table 5.1 are used for computation of the various performance results.

Table: 5.1

Parameter	**Value**
Core diameter , a_p	3.5 mirometer ~ 5.5 micrometer
Pitch, d_{pq}	20 mirometer ~ 40 micrometer
Bandwidth, B	1~30 Gbps
Cladding index , n_2	1.4573
Wavelength	1350 nm~ 1550 nm
Resistance , R	50 Ohm
Temperature, T	298 K

Parameter	Value
Signal Power, P_T	-60 dBm ~ -20 dBm
Pre – amplifier Gain , G	50
Responsivity, R_d	.85 A/m

The extraordinary demand for the huge potential of applications of Multi-core Optical Fiber (MCF) in the fields of long-haul communication links, data centres and passive optical networks has drawn considerable attention of researchers in the recent pasts . The most authentic transmission medium is optical fiber for expeditious out giving information. MCF is the latest surprise of technology in optical fiber communication. In MCF transmission in between the adjacent cores, the mode coupling distorts the signal waveform and limits the transmission execution. Extensive research works have been done on MCFs for their use in optical communications and optical fiber sensors etc. The most important issue peculiar to MCFs is to reduce the inter-core crosstalk. A coupled-mode theory (CMT) and a coupled-power theory (CPT) have been introduced to estimate the inter-core crosstalk in MCFs. Two types of crosstalk are detected in MCF. They are: intra crosstalk and inter crosstalk. Intra core crosstalk is occurred due to the coupling between the fiber modes within each core caused by the fiber deficiency such as index swerving , bends, and twist and the inter core crosstalk is caused by the mode coupling between the adjacent cores.

Here we have analyzed the coupling coefficient which measures the crosstalk caused by inter-core coupling in the homogeneous MCF. The crosstalk power and performance deterioration in terms of Bit Error Rate (BER) in an optical communication link of homogenous seven core MCF have also been evaluated and presented in this paper.

1550 nm is divided into seven outputs and connected with TMC. Avalanche Photo Diode (APD) is used as the receivers. The Amplifier (AMP), Equalizer (EQ) and Low Pass Filter (LPF)are used for its normal function at the receiving end. Here we used the homogenous MCF in which all cores have same radius of 4.5 micrometre and pitch is considered 38 micrometre and cladding index is 1.4573 unless some parameter is changed for analysis.

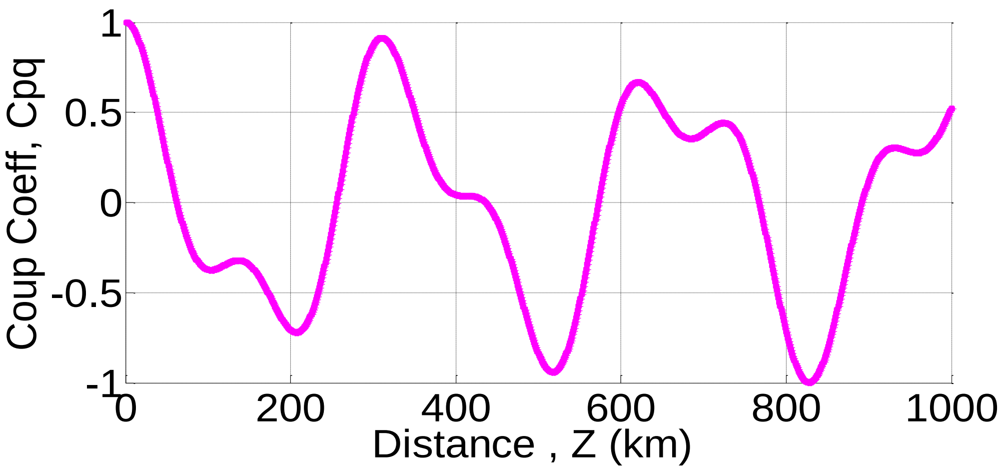

Fig.5.1. Propagation dynamics for a seven core MCF which refractive index contrast=0.39%, and a = 4.5 μm, d_{pq}= 38 μm

From equation (5), the wave shape of the mode power when light launched into core 1 of the homogeneous seven core MCF is shown in Fig.5.1. It is seen that the mode power in various cores are periodic in propagation distance, z.

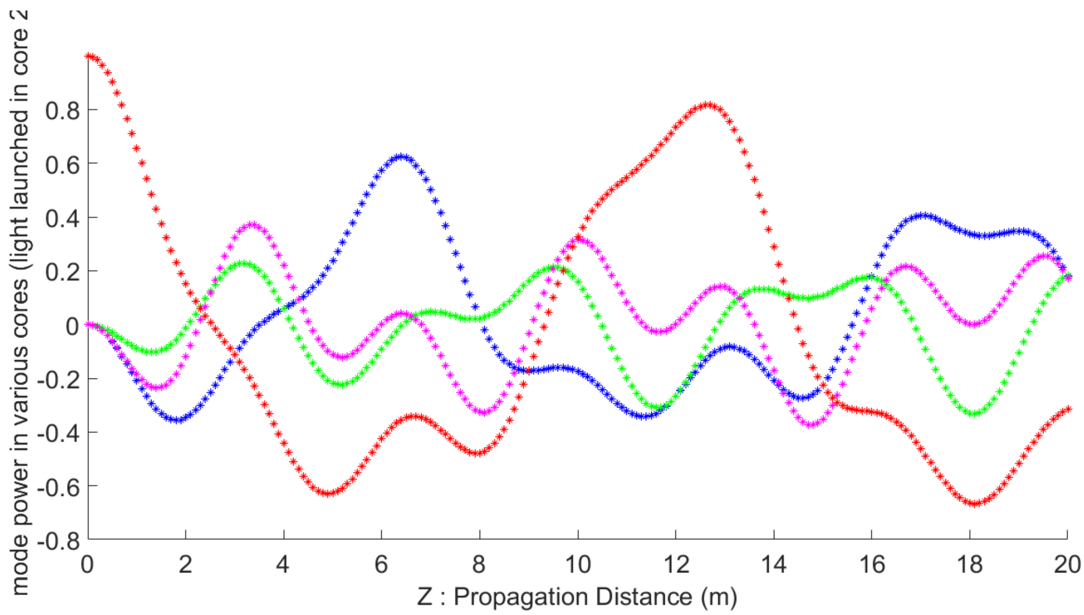

Fig.5.2. Propagation dynamics for a seven core MCF which refractive index contrast=0.39%, and a = 4.5 µm, d_{pq}= 38 µm

The propagation dynamics of a 7-core MCF when light is launched into core 2 are shown in Fig 5.2 which shows that some of the mode amplitudes are identical due to symmetry in spite of unequal coupling to different cores. It is seen that the mode power in various cores are periodic in propagation distance, z.

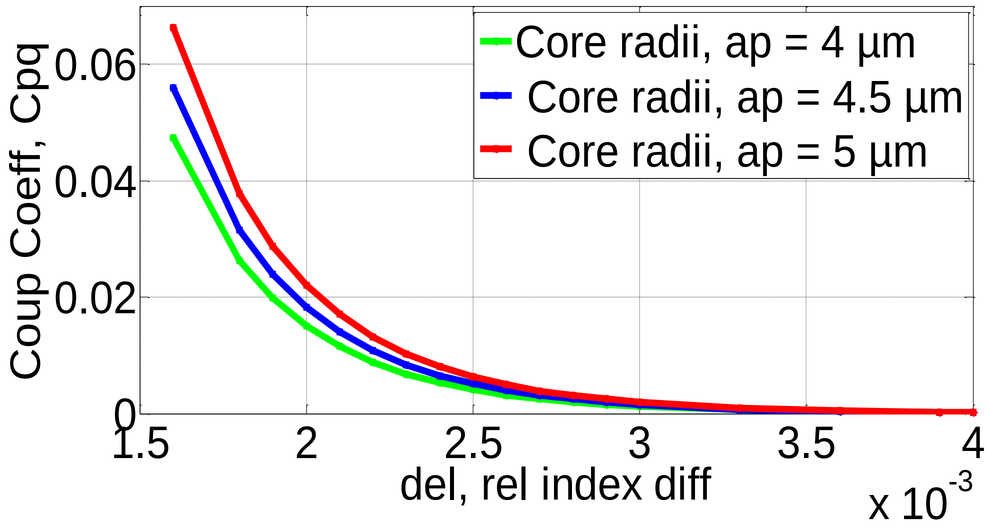

Fig.5.3. Plot of Coupling Coefficient as a function of Relative Index difference (del) with varying core radii (a_p) from 4µm to 5µm in a homogeneous seven-core MCF, where pitch, d_{pq}= 38 µm, cladding index n_2 = 1.4573.

The relationship between coupling coefficient (C_{pq}) and relative refractive index difference (Δ %) in a homogeneous seven-core MCF is determined and shown in Fig.5.3. These figure shows that the coupling coefficient decreases with the increase of the index contrast.

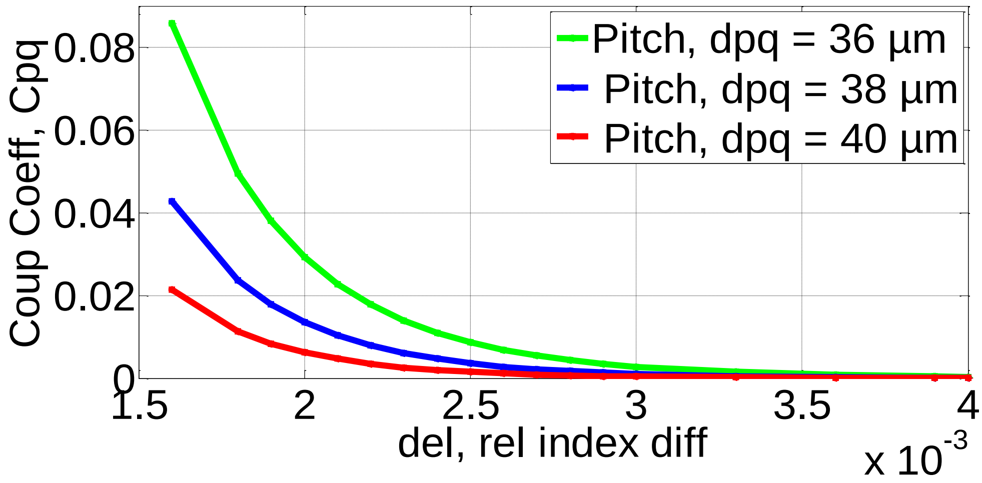

Fig.5.4. Plot of Coupling Coefficient as a function of Relative Index difference (del) with varying pitch (d_{pq}) from 36µm to 38µm in a homogeneous seven-core MCF, where core radii, a_p = 4.5 µm, cladding index n_2 = 1.4573.

Fig.5.4 shows that the coupling coefficient is inversely proportional to the index contrast and when we increase the core radii , coupling coefficient (C_{pq}) increases at the same index contrast. Fig.3.4 also shows that the coupling coefficient is inversely proportional to the index contrast and when we increase the pitch, coupling coefficient (C_{pq}) decreases at the same index contrast.

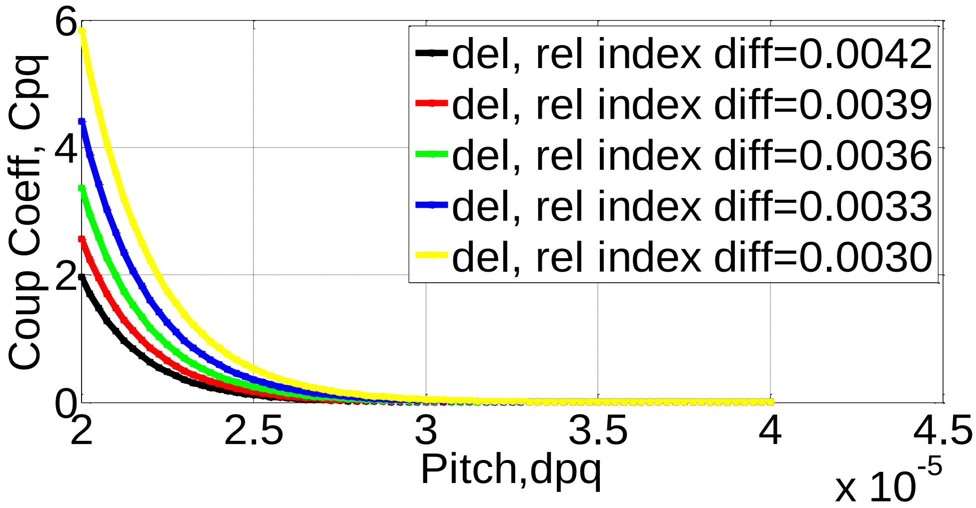

Fig.5.5. Plot of Coupling Coefficient as a function of Pitch in a homogeneous seven-core MCF with varying index contrast, where pitch d_{pq}= 38 µm, cladding index n_2 = 1.4573 and the identical core radii a_{pq} = 4.5 µm.

The relationship between coupling coefficient (C_{pq}) and Pitch (d_{pq}) while varying the index contrast in a homogeneous seven-core MCF is determined and shown below in Fig.5.5 The figure shows that the coupling coefficient is inversely proportional to the Pitch as well as the index contrast. The Fig.5.5 shows that the coupling coefficient is inversely proportional to the Pitch as well as the index contrast and when we increase the index contrast, coupling coefficient (C_{pq}) decreases at the same pitch.

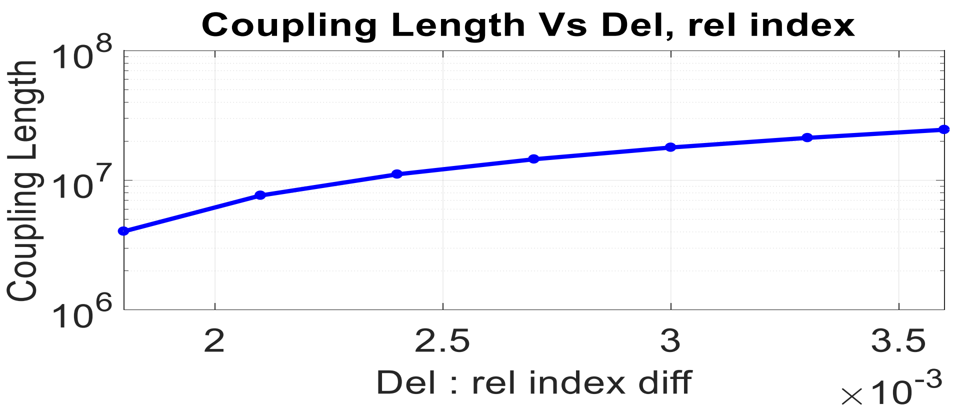

Fig. 5.6. Propagation Relationship between Coupling Coefficient and Relative Index difference in a homogeneous 7-core MCF, while light is launched into core 2.

The above figure shows that the coupling length proportional to the refractive index difference (Δ%)

The relationship between Coupling coefficient (Cpq) and relative refractive index difference (Δ%) in a homogeneous 7-core MCF is determined and shown in this Figure . The figure shows that the coupling length is proportional to the index contrast.

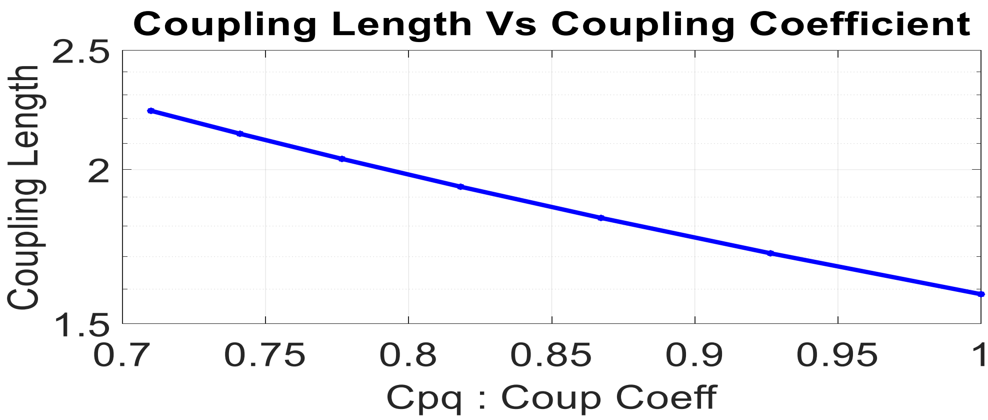

Fig. 5.7. Propagation Relationship between Coupling Coefficient and Relative Index difference in a homogeneous 7-core MCF, while light is launched

The above figure shows that the coupling length inversly proportional to Coupling Coefficient.

The relationship between Coupling coefficient (Cpq) and Coupling Coefficient in a homogeneous 7-core MCF is determined and shown in this Figure . The figure shows that the coupling length is inversly proportional to the index contrast.

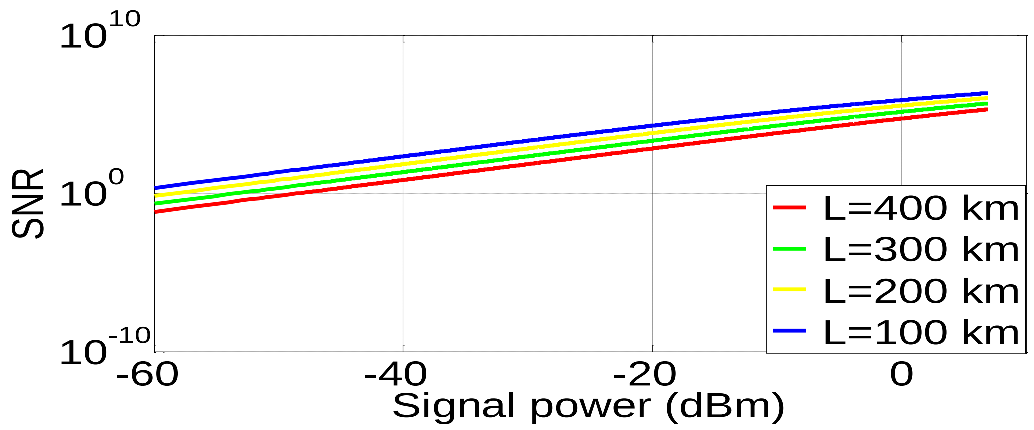

Fig. 5.8. SNR vs Input Power (varying propagation distance from 100 km to 400 km) with diff index contrast for a seven-core homogeneous MCF d_{pq}= 38 µm, cladding index n_2 = 1.4573 and the identical core radii a_{pq} = 4.5 µm (without considering crosstalk) power.

The Signal to Noise Ratio (SNR) curves with respect to various input signal power at various propagation distance in the seven-core homogeneous MCF are shown in Fig.5.8.

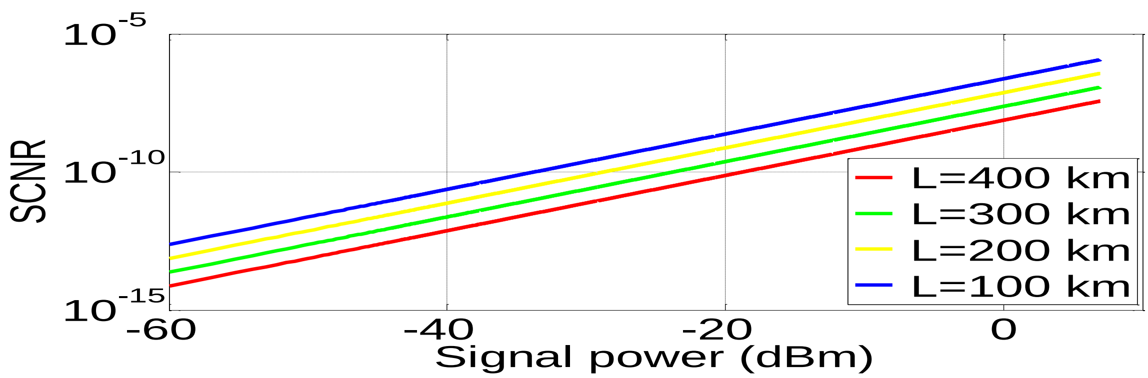

Fig. 5.9. SCNR vs Input Power (varying propagation distance from 100 km to 400 km) with diff index contrast for a seven-core homogeneous MCF d_{pq}= 38 µm, cladding index n_2 = 1.4573 and the identical core radii a_{pq} = 4.5 µm (considering crosstalk) power.

The Signal to Crosstalk Noise Ratio (SCNR) curves with respect to various input signal power at various propagation distance in the seven-core homogeneous MCF are shown in Fig.5.9.

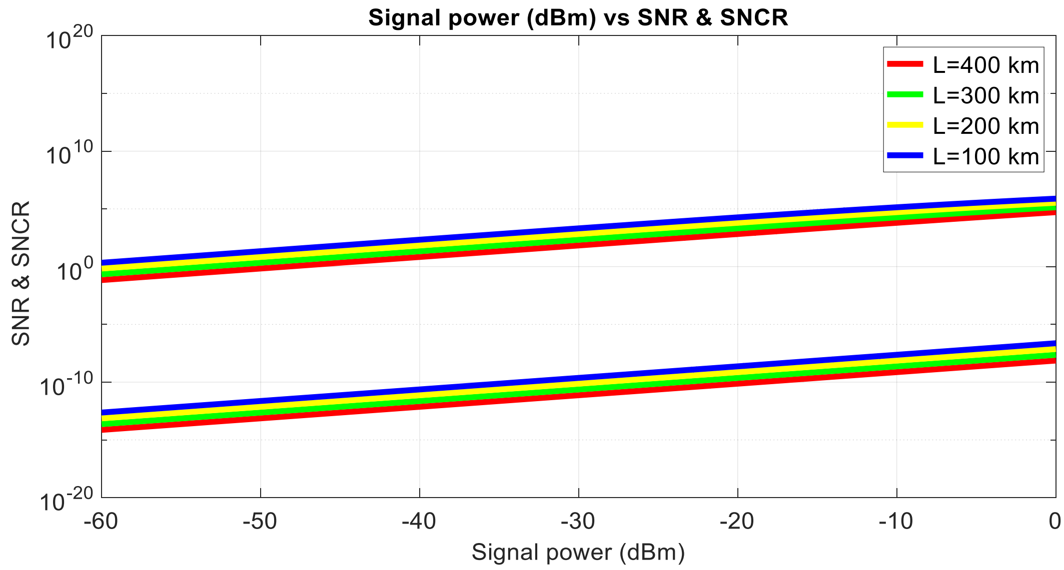

Fig. 5.10. SNR & SCNR vs Input Power (varying propagation distance from 100 km to 400 km) with diff index contrast for a seven-core homogeneous MCF d_{pq}= 38 µm, cladding index n_2 = 1.4573 and the identical core radii a_{pq} = 4.5 µm (considering crosstalk) power.

Comparing Fig.5.8 and Fig.5.9, we observed that in theFig 5.10, the Signal to Noise Ratio decreases with adding the crosstalk power.

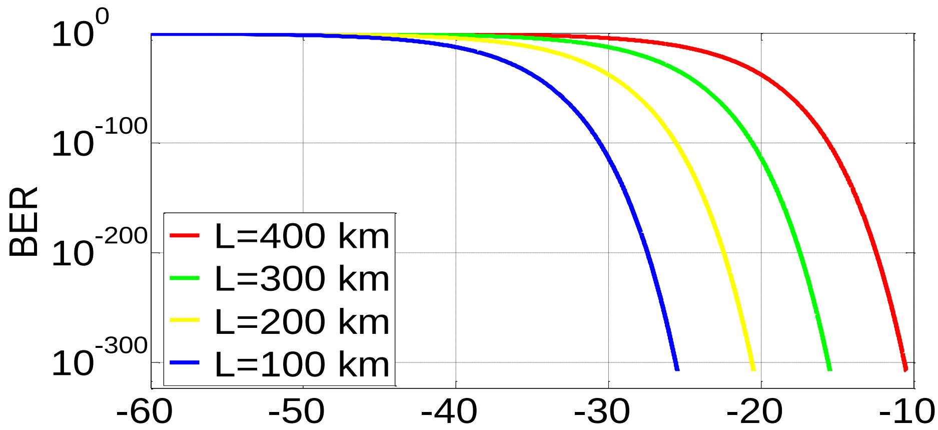

Fig.5.11. BER VS Input Power (varying propagation distance from 100 km to 400 km) with diff index contrast for a seven-core homogeneous

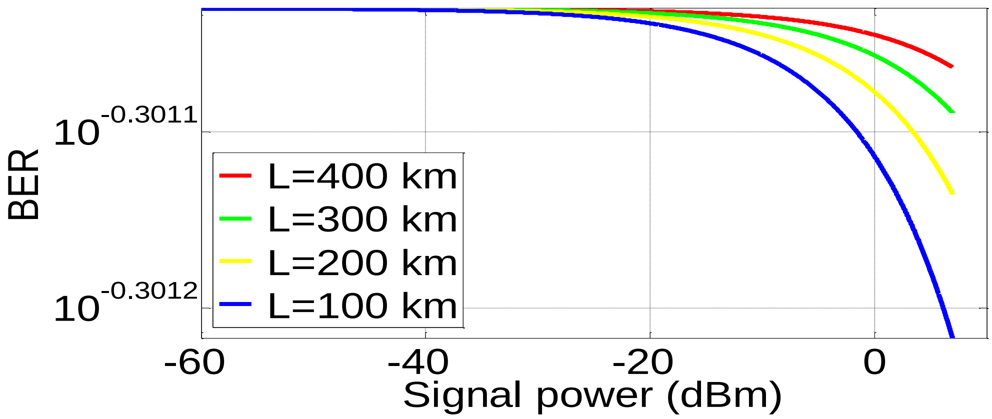

Fig.5.12. BER vs Input Power (varying propagation distance from 100 km to 400 km) with diff index contrast for a seven-core homogeneous MCF with

The above figure (Fig.5.11 and Fig.5.12) shows that BER increases after adding crosstalk power and more input power is required for longer distance to cover with same crosstalk power.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

In this paper an analytical derivation of crosstalk power due to coupling among the cores in a seven core homogeneous MCF has been done. In doing so, the coupling coefficients between Cores due to varying geometry of core pitch, core radius and relative index contrast have been determined using an established mathematical model. Analysis of performance of the MCF communication link due to crosstalk has also been carried out in terms of BER, and presented in this paper. It is noticed that significant amount crosstalk occurs due to coupling between cores for which system may suffer. So for improving the performance of channel this lower coupling
Coefficient is better option for further work in optical network. The outcome of this research will find its application to find ways to design multicore fiber system to a great extent in Optical communication and to enhance the capacity of channels.

6.2 Future Work

The present achievement indicates that a multi-core fiber with the standard diameter can be used to realize a transmission capacity of more than 100 Tera-bit/s while enabling the productivity improvement and effective use of the existing technology. This achievement is expected to open up earlier practical use of the multi-core fiber technology.

We will aim to introduce the standard diameter multi-core fiber by the early 2020s. We will also continue to contribute the realization of a future optical infrastructure which can support variety of data communication demand.

The research is multicore optical fiber may be extended further to the find the impact of Nonlinearity like dispersion, Four wave mixing, scattering effect etc. Crosstalk analysis in Heterogeneous MCF may also undertaken as a research topics. A full edged and well equipped optical communication lab may be setup in MIST to facilitate research in optical fiber systems.

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