

Investigation of Optical Multi Input Multi Output (OMIMO) transmission link using Multimode Fiber

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CERTIFICATE

I, Prashuram Prasad, hereby certify that the work which is being presented in this dissertation entitled “**Investigation of Optical Multi Input Multi Output (OMIMO) transmission link using Multimode fiber**” by me in partial fulfilment of the requirements for the award of degree of Master of Engineering in Electronics and Communication Engineering from Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of **Dr. R. S. Kaler** and refers other researcher’s works which are duly listed in the reference section.

The matter presented in this dissertation has not been submitted in any other University/Institute for the award of any other degree.

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Abstract

Optical fibers are an integral part of current networking architectures due to their ability to support extremely high data rate. The rapid growth of bandwidth requirement due to the exponential increase in end-user's bandwidth imposes new challenges to the short and medium distance networks. Theoretically the multimode fibers (MMF) exhibit a higher transport capacity limit than single mode fibers (SMF) by exploiting the various modes or groups of modes as independent communication channels with individual scattering paths. Multiple optical sources and detectors are introduced to take advantage of the spatial (modal) diversity, it is possible to recover signal transmitted using multiple transmitter over a single MMF, at the expense of greater signal processing complexity, particularly at the receiver end. The single-mode fibers (SMFs) provides high speed and long-distance optical links. However, these improvements also come with additional complexity in transmitter, receiver, alignment and packaging, thus making them costly and inappropriate for small and medium sized networks

In this thesis work we have proposed a MIMO MMF link which utilizes the transmitter and receiver diversity with spatial diversity offered by MMF, which help in improving the system performance. The modes propagating inside the MMF are used in constructing way. The 3x3 and 5x5 MIMO systems are proposed to improve the reliability of transmitted bits. The effect of changing the data rate is also observed.

The linearly polarized modes are used to achieve higher data and capacity from MMF. The maximum optical transmission range is also calculated with the help of proposed system design. The power coupling between the propagating modes and bending of MMF are investigated; the system performance is analyzed with the help of BER, received optical power, Q factor and eye diagrams. The measured result shows that MMF has great capability to support higher data and high capacity to a longer distance.

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CHAPTER 1

INTRODUCTION

1.1 Perspective

Over the years, many forms of communication systems have been developed. The basic motivations behind each new form were to improve the transmission fidelity, to increase the data rate and to enhance the transmission distance between stations. In past few decades, advances in communication technology and an increasing reliance on information exchange in society and economy have inspired and supported each other. As a result, there has been tremendous growth in wired, wireless, and optical fiber communication. Optical fibers are an integral part of current networking architectures due to their ability to support extremely high data rate. The rapid growth of bandwidth requirement caused by exponential increase in end-user's bandwidth demand with the use of multimedia-rich applications such as video/photo sharing, direct to home television services, live video streaming and cloud computing etc. imposes new challenges to the short and medium distance networks. These applications demand higher data rate transmission in the range of Giga bits per seconds [1].

In recent times, single-mode fibers (SMFs) have displaced multimode fibers (MMFs) as the choice for high speed and long-distance optical links due to their low dispersion and high data carrying abilities. However, these improvements also come with additional complexity in transmitter, receiver, alignment and packaging, thus making them costly and inappropriate for small and medium sized networks [2]. In current short range optical fiber networks i.e. local area networks (LANs) the existing infrastructure is widely based on MMF, due to easy handling and its good performance over short spans. However, as their bandwidth is limited by modal dispersion, transmission of high data rate signals even on short links requires special countermeasures. The larger core area of MMF compared to SMF results in increased tolerance to alignment mismatches, thereby enabling its use in LANs. One main drawback of the larger core of MMF is that light propagates via a larger number of modes, each with its own group velocity. As a consequence MMF has lower bandwidth than SMF. However, the bandwidth of MMF is still sufficiently larger than that of copper cables.

MMF links are widely implemented in current high-speed local area networks. They can provide the necessary bandwidth for shorter length applications at much lower expense than SMFs solutions, mainly due to the ease of optical alignment and packaging. In long-haul optical communication systems can be designed by wavelength division multiplexing of high-bitrate channels and by using Erbium-Doped Fiber Amplifiers (EDFAs) to periodically compensate the fiber loss.[3] In MMF, however, the signal on each of the fiber modes propagates down the fiber with its own distinct velocity and thus, causes inter-symbol interference (ISI). This so-called modal dispersion limits the maximum data speed for a fixed length of fiber. Thus MMF links are considered to be dispersion limited rather than noise limited. Though it seems that little can be done about the inherent modal dispersion associated with the multimode nature of fibers, researchers have achieved improvements in bandwidth-distance product of MMF using several approaches such as selective modal excitation [4], M-ary coding [5], electronic equalization [6,7] and subcarrier multiplexing (SCM) [8]. While each of these techniques has shown substantial increases in the bandwidth-distance product, they still do not exploit the MMF capacity to its full potential. Multi input-multi output (MIMO) based on MMF links is also a promising way to push the limit of overall transmission capacity [13, 14].

1.2 Motivation

In recent years it has become apparent that fiber-optics are progressively replacing copper wire as an appropriate means of communication for signal transmission. They span the long distances between local phone systems (GSM, CDMA) as well as providing the backbone for many network systems. Other system users include cable television services, university campuses, office buildings, industrial plants, and electric utility companies. A steady increase in the total internet traffic over the last two decades has not only increased the bandwidth requirement of the backbone network, the demand for bandwidth of the end-user has also increased dramatically. The capacity of optical fiber can't be utilized by a signal user, so to effectively use the available bandwidth some multiplexing technique is needed. The single mode fiber is only suitable for long haul communication networks, it is having huge bandwidth and good bit error rate. The MMF based MIMO system can be available solution

for short range optical networks. The MIMO system make is possible to have effective use of diversity in MMFs. Thus it becomes suitable for short optical communication links. This can be employed at the end of the single mode fiber. The cheaper cost of multimode fiber is additional advantage over single mode along with simple transmitter receiver design.

MMF optic cable and components are less expensive and easier to work with than their single mode counterparts. This is due largely to the fact that the multimode fiber core is larger, and alignment tolerances are much less critical than they are for single mode fibers. Because of its high capacity and reliability, multi-mode optical fiber generally is used for backbone applications in buildings complex, small offices. An increasing number of users are taking the benefits of fiber nearer to the user by running fiber to the PCs or to the zone where use can connect to the system. Standards compliant architectures which generally use star topology such as Centralized Cabling and fiber to the telecom enclosure offer users the ability to leverage the distance capabilities of fiber by centralizing electronics in telecommunications rooms, rather than having active electronics on each floor.

The applications of optical fiber communications have increased at a rapid rate, since the first commercial installation of a fiber optical system, after that some telephone companies began early on, replacing their old copper wire systems with optical fiber lines. Today's telephone companies use optical fiber cable throughout their system as the backbone architecture and as the long distance link between city phone systems. LAN is a collective group of PCs, or access systems, connected to each other allowing for shared program software or data bases. Colleges, universities, office buildings, and industrial plants etc. all make use of optical fiber within their LAN systems. Power companies are emerging groups that have started to use optical fiber cable in their communication systems. Majority of power utilities already has fiber-optic communication systems in use for monitoring their power grid systems.

1.3 Optical fiber system and Local area networks

A fiber-optic system is similar to the copper wire system that fiber-optics. The difference is that optical fiber uses light pulses to transmit information through fiber lines instead of using electronic pulses to transmit information through copper lines. Transmitters of both systems are similar. This is the place of origin for information which is to be through the optical fiber link. The transmitter accepts coded electronic pulse information coming from copper wire. It

converts that information into equivalently coded light pulses. A light-emitting diode (LED) or an injection-laser diode (ILD) can be used for generating the light pulses. Using a lens, the light pulses are funneled into the fiber-optic medium and it passes through the optical cable. The light (near infrared) is most often 850nm for shorter distances and 1,300nm for longer distances on MMF and 1300nm for SMF and 1,500nm is used for longer distances.

The manufacture of the first optical fiber with an attenuation of less than 20dB/km in achieved in 1970 [1]. The early optical communication systems were mostly uses MMF as a backbone of communication network. The advantage of a higher bandwidth, offered by SMF, however, quickly led to a shift towards its widespread use. By the early 1980's, SMF was the medium of choice, where its higher bandwidth and lower losses could be readily exploited with newly developed laser sources operating at 1310nm and eventually at 1550nm. LAN is a group of computers, access terminal and associated devices that share a common communications link wired or wirelessly in a small geographic area for example, within an office building. A network might cover a commercial building complex, or a small residential area, where link lengths between terminals are generally up to a few hundred meters.

The growing use of fiber in the LAN backbone is due to the advantage of the higher data-rates over longer link lengths as compare to other medium media. The fiber cable is able to achieve several times higher data than ordinary copper cable LAN networks for the same length of copper cable. This length benefit proves itself in the need for less repeaters than copper and the ability to operate star-type topologies where each user group may be connected directly to a centralized hub. The star topology has the advantage of requiring less cross-connect enclosures, which are costly, and is considerably easier to operate and maintain than ring-based networks. A typical network consists of a main backbone cable, which could be fiber or copper based, entering a building complex and providing access points throughout the building. The access points can be equipment such as personal computers (PCs), shared printers, scanners and telephones, which are fitted with Network Interface Cards (NICs) for connection to LANs.

The introduction of the personal computer stimulated the demand for high speed LAN connection, typically over distances of less than a kilometer. To compete with entrenched copper-based systems, fiber needed to offer not just a bandwidth advantage but also be competitive in price. To achieve this, installers started switching back to multimode fiber, where component costs were less and field terminations were easier to make. Since the development of cheap, high-speed, VCSEL laser sources in the 1990's there has been a steady resurgence of interest in multimode fiber for LAN applications.

1.4 Single mode versus Multimode fiber

The main difference between multi-mode and single-mode optical fiber is that the MMF has much larger core diameter, typically 50–100 micrometers; much larger than the wavelength of the light carried in it. Because of the large core and large numerical aperture, MMF has higher light-gathering capacity than single-mode fiber. In practical terms, the larger core size simplifies connections and also allows the use of lower-cost electronics such as light-emitting diodes (LEDs) and vertical-cavity surface-emitting lasers (VCSELs) which operate at the 850 nm and 1300 nm wavelength. Single-mode fibers used in telecommunications operate at 1310 or 1550 nm and require more expensive laser sources. SMFs exist for nearly all visible wavelengths of light. However, compared to single-mode fibers, the multi-mode fiber bandwidth–distance product limit is lower. Because multi-mode fiber has a larger core-size than single-mode fiber, it supports more than one propagation mode; hence it is limited by modal dispersion, while single mode is not.

The LED light sources sometimes used with multi-mode fiber produce a range of wavelengths and these each propagate at different speeds. This chromatic dispersion is another limit to the useful length for multi-mode fiber optic cable. In contrast, the lasers used to drive single-mode fibers produce coherent light of a single wavelength. Due to the modal dispersion, multi-mode fiber has higher pulse spreading rates than single mode fiber, limiting MMF's information transmission capacity.

Single-mode fibers are most often used in high-precision scientific research because the allowance of only one propagation mode of the light makes the light easier to focus properly.

1.5 Challenges in Multimode Fiber

Although MMF is widely deployed there are still some limitations in its utilization: modal dispersion, refractive index defects and modal noise are the most important three. Light is guided into a discrete number of electromagnetic modes in multimode fiber signal will be carried by these modes. The main challenges of MMF are listed below

- a) **Modal Dispersion:** - Each mode travels through the fiber along a different path, and will arrive at a different time according to the path taken. Therefore, the pulse tends to spread out as it travels through the fiber, and as a result, the bandwidth of the transmission will be decreased. This phenomenon is called modal dispersion.
- b) **Precise Control of The Index Profile:** - Graded index profile multimode fiber is the initial method to reduce the modal dispersion in multimode fiber. The refractive index of this kind of fiber changes gradually from the center to the edge of the core area. The reason for this change is to keep the speed of light on each possible path the same along the axis of the fiber. But since precise control of the index profile is difficult to achieve in the manufacturing process, precise control of modal dispersion is still a problem at present.
- c) **Defects in fiber fabrication:** - There are also defects in refractive index profiles in the core area caused during fiber fabrication (e.g. axial dips or peaks often found in the multimode fiber core). These defects cause the lower order modes in the multimode fiber, which travel nearer the fiber axis; to have significantly different propagation times than the higher order modes. As a result, the ideal of propagation delay equalization collapses, and the bandwidth of the transmission is degraded.
- d) **Source:** - Since traditional light emitting diodes (LED) cannot be modulated at the speed required by high-speed link, laser sources have begun to be used along with multimode fiber. The laser sources have a smaller output beam size than the LED, so only a relatively small fraction of the fiber modes are excited.
- e) **Modal Noise:** - The offset launch is implemented by using a single mode fiber launch to inject the light at a position radially offset from the multimode fiber core center, is utilized to enhance the bandwidth. This method also avoids the refractive index profile defects in the core center. Unfortunately, the employment of a laser source introduced another problem: modal noise.

1.6 Objective

The objectives of dissertation are

- 1) To analyze the performance of optical MIMO system with BER, eye diagram and received optical power.
- 2) To design and investigate the performance of 3x3 and 5x5 MIMO MMF system and measurement of different system parameters .
- 3) Enhancing the capacity of optical fiber with the utilization of linearly polarized modes in spatial multiplex system.
- 4) 5x100 Gbps data transmission using graded index multimode fiber over 50 km optical link.

1.7 Thesis organization

Chapter 2 gives a background review of MMF and MIMO system. This chapter covers the various technologies and methods develop to enhance the bandwidth-distance product of MMFs. The majority of work utilizes the spatial diversity offered by MMF to exploit the bandwidth capability of MMF. Transmitter and receiver diversity is also utilized by some authors to achieve higher data rate and high bandwidth.

Chapters 3 provide the analysis of the short range optical multiple-input multiple-output (MIMO) multimode fiber link using mode coupling effect. The various system are observed and the obtained result are compared with standard results.

Chapter 4 explains the method for enhancing the capacity of optical fiber with the utilization of linearly polarized modes in spatial multiplex system. The various capacity enhancement techniques are also discussed in the chapter.

Chapters 5 gives the system setup for 5x100 Gbps data transmission using graded index multimode fiber over 50 km optical link. The performance of system is analyzed by changing the data rate from 20Gbps to 100Gbps. The Q factor is also plotted for the designed system.

Chapter 6 concludes the all the result obtained. The main key points are heightened with merits and demerits of the proposed design. The recommendations are also given with each conclusion. The future scope related to this work is also provided in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In literature different system models are used to develop short and medium range optical MMF networks. The spatial diversity of MMF utilized to obtain larger link length with less probability of error. The majority of work is done using MMF system with parallel transmission from laser sources. The various capacity enhancement schemes are proposed by different authors. The researchers have achieved improvements in bandwidth-distance product of MMF using several approaches such as selective modal excitation, coding techniques, electronic equalization and SCM.

2.2 Research papers

N. W. Bikhazi *et al.* [15]

They proposed architecture for using MIMO techniques for a MMF broadcast channel, allowing simultaneous transmission of unique streams to different users on the same fiber while using square law detection. The resulting system throughput scales nearly linearly with the number of transmitters and receivers. The paper also proposes a training scheme appropriate for use with square law detection.

K. Appaiah *et al.*[16]

They showed that signal processing and MIMO can be effective in combating limitations of MMFs. They suggested that device design for the specific purpose of MIMO in MMFs can improve the system performance. Their paper utilizes a statistical field propagation model for MMFs to aid the analysis and designs of MMF laser and detector arrays, and which can improve data rates of the fiber. Simulations reveal that optimal device designs could possess 2-3 times the data carrying capacity of suboptimal ones.

J. M. Kahn and Keang-Po Ho. [17]

This paper shows that the strong mode coupling reduces the modal group delay spread, minimizing the complexity of digital MIMO signal processing. Similarly strong mode

coupling mitigates the mode-dependent gain of optical amplifiers, maximizing average channel capacity. This paper also shows that the statistical distributions of strongly coupled modal group delays or gains depend only on the number of modes and the variances of accumulated delay or gain, and can be derived from the eigenvalue distributions of certain random matrices. Insight into mode coupling suggests alternative approaches for MDM based on optical MIMO signal processing, which may offer reduced power consumption in short-reach direct-detection systems.

M. B. Shemirani *et al.* [18]

This paper shows that the power-coupling models are inherently unable to describe certain mode coupling effects in MMF when using coherent sources at high bit rates, such as polarization dependence of the impulse response. They develop a field-coupling model for propagation in graded-index MMF, analogous to the principal-states model for polarization-mode dispersion in single-mode fiber. This model allows computation of the fiber impulse response, given a launched electric-field profile and polarization.

In order to model both spatial- and polarization-mode coupling, the MMF is divided into numerous short sections, each having random curvature and random angular orientation. The model can be described using only a few parameters, including fiber length, number of sections, and curvature variance. For each random realization of a MMF, they compute a propagation matrix, the principal modes (PMs), and corresponding group delays (GDs). When the curvature variance and fiber length are small (low-coupling regime), the GDs are close to their uncoupled values, and scale linearly with fiber length, while the PMs remain highly polarized. In this regime, this model reproduces the polarization dependence of the impulse response that is observed in silica MMF. When the curvature variance and fiber length are sufficiently large (high-coupling regime), the GD spread is reduced, and the GDs scale with the square root of the fiber length, while the PMs become depolarized. In this regime, our model is consistent with the reduced GD spread observed in plastic MMF.

K. P. Ho and J. M. Kahn. [19]

The modal group delays (GDs) are a key property governing the dispersion of signals propagating in a MMF. An MMF is in the strong-coupling regime when the total length of the MMF is much greater than the correlation length over which local principal modes can be considered constant. In this regime, the GDs can be described as the eigenvalues of zero trace Gaussian unitary ensemble, and the probability density function (PDF) of the GDs is the eigenvalue distribution of the ensemble. For fibers with two to seven modes, the marginal PDF of the GDs is derived analytically. For fibers with a large number of modes, this PDF is shown to approach a semicircle distribution. In the strong coupling regime, the delay spread is proportional to the square root of the number of independent sections, or the square root of the overall fiber length.

In the regime of strong mode coupling, an MMF may be modeled as the cascade of many independent sections, which are described by statistically independent random matrices. The GDs are given by the eigenvalues of Gaussian unitary ensemble with zero-trace constraint. Marginal PDF's of the GDs in fibers with two to seven modes have been derived analytically. Numerical simulations of the pdf's are in excellent agreement with analytical results. In a fiber with many modes, the GD is shown to follow a semicircle distribution from free probability theory. Numerical simulations have been conducted for fibers having 16, 64 and 512 modes to compare to the semicircle distribution.

I. Li *et al.* [20]

This paper analyses the impact of real-world propagation conditions on the maximum achievable diversity performance of communication over ricean MIMO channels. They examine a MIMO channel employing orthogonal space-time block codes (OSTBCs) and study the diversity behavior of the resulting effective single-input single-output (SISO) channel. The performance criteria employed are symbol error rate, outage capacity, and wideband spectral efficiency. For general propagation conditions, they establish key quantities that determine performance irrespective of the performance criterion used. The relation between the notion of diversity order related to the slope of the average error probability versus signal-to-noise ratio (SNR) curve and diversity order related to the slope of the outage probability versus SNR curve is also discussed.

In an optical fiber, an ideal mode is an eigenvector of a propagation operator. Mode coupling enables transfer of energy from one ideal mode to another during propagation. Mode coupling can be induced by random or intentional index perturbations, bends and stresses. The pairwise coupling strength between two modes depends on a dimensionless ratio between the coupling coefficient (per unit length) and the difference between the two modal propagation constants. Hence, a given perturbation may strongly couple modes having nearly equal propagation constants, but weakly couple modes having highly unequal propagation constants. Power coupling models can explain certain effects, such as a reduced group delay (GD) spread in plastic MMF. However, most modern MMF systems use spatially and temporally coherent laser sources, and power coupling models cannot explain certain observations. Single-mode fiber (SMF) supports propagation in two polarization modes.

Polarization-mode dispersion (PMD) and polarization-dependent loss (PDL) have long been described by field coupling models, in which phase-dependent coupling of modal fields is described by complex coefficients. Field coupling models describe not only a redistribution of energy among modes, but also how eigenvectors and their eigenvalues depend on the mode coupling coefficients.

C. Qian. [21]

To characterize the strength of the overall coupling caused by random perturbations along a fiber, they consider a correlation length, over which the local eigenvectors can be assumed constant. In the weak-coupling regime, the fiber length is not much longer than the correlation length. While there may be significant coupling between modes having nearly equal propagation constants, there is limited coupling between modes having highly unequal propagation constants. Glass MMFs have tightly controlled index profiles, and even graded-index fibers up to several km long exhibit weak coupling between modes in different spatial mode groups, so the overall GD spread scales linearly with fiber length. In the strong-coupling regime, the fiber length far exceeds the correlation length, and there is significant coupling between all modes. As a result, the overall GD spread is reduced, and scales with the square-root of fiber length. Plastic MMFs have index perturbations causing strong mode coupling, which reduces the GD spread, but couples power to higher-order modes, greatly increasing the loss. They show that in long-haul MDM systems using coherent detection,

strong mode coupling reduces the GD spread to minimize signal processing complexity, and mitigates the impact of mode-dependent losses and gains.

J. M. Kahn *et al.* [22]

MMF links are widely implemented in current high-speed local area networks. They can provide the necessary bandwidth for shorter length applications at much lower expense than SMF solutions, mainly due to the ease of optical alignment and packaging. The researchers have achieved improvements in bandwidth-distance product of MMF using several approaches such as selective modal excitation, M-ary coding, electronic equalization, and subcarrier multiplexing (SCM). While each of these techniques has shown substantial increases in the bandwidth-distance product, they still do not exploit the MMF capacity to its full potential.

Wavelength-division multiplexing (WDM) based on MMF links is also a promising way to push the limit of overall transmission capacity. However, the cost associated with multi-wavelength systems is, so far, still too high to be extensively implemented for commercial use in contrast, if coherent optical transmission is used, the required length is reduced by the ratio of the RF subcarrier frequency to the optical carrier frequency. This eliminates the length requirement, making MMF channels more agreeable for MIMO operation. They also report the first demonstration of COMIMO utilizing adaptive equalization for ISI. The adaptive equalization method does not require knowledge of the channel when doing MIMO signal processing and is more amenable to real-time implementation due to its adaptively to channel variation.

C. J. Rick *et al.* [23]

In this paper, a coherent optical MIMO (COMIMO) multi-mode fiber link is proposed for enhancing the fiber information capacity. The statistical characterization of the equivalent MIMO channel and the improvement in the fiber capacity due to MIMO transmission is examined. It is shown that the equivalent channel behaves similarly to a complex Gaussian MIMO channel, suggesting that the available results on wireless MIMO communication systems can be applied to optical fiber links for capacity enhancement. The capacity enhancement is made possible through MIMO signal processing at the receiver. This

processing is performed in the digital domain through a VLSI implementation. There are two advantageous factors in support of using digital processing in optical systems. In contrast to portable wireless systems, power consumption due to increased complexity is not an immediate concern for optical systems. Furthermore, the increase in cost due to MIMO signal processing is tolerable in comparison to the high cost associated with the optical components used in the system. Moreover, VLSI implementations of signal processing algorithms benefit from Moore's law and technology scale down and represent a cost-effective approach to improve the optical system's performance.

The capacity of a 2x2 MMF system is plotted for both informed and uninformed scenarios. There is degradation in capacity in the case of simulated MIMO MMF compared to the ideal i.i.d. complex Gaussian case. This is mainly due to the fact that there is some correlation between the channel elements in H in practice. Such correlation is a result of the fact that some common guiding modes are excited by both transmitters. The capacity of the correlated optical channel approaches that of the uncorrelated channel as the SNR decreases. The elements of the equivalent baseband COMIMO MMF channel behave sufficiently close to a complex Gaussian distribution. This paves the way to apply the existing rich body of wireless MIMO communications in the literature to optical systems.

D. H. Sim *et al.* [24]

They have demonstrated that the transmission bandwidth of MMF can be drastically increased by using the mode-field matched center-launching technique. Since this technique can selectively excite the fundamental mode of MMF, it can overcome the modal bandwidth limitation inherent in MMF and achieve the SMF-like transmission characteristics. This simple analysis shows that it can achieve almost ideal mode-field matched center-launching condition simply by fusion-splicing the SMF-pigtailed transmitter to the MMF with controlled core diffusion method. As a result, more than 94% of the launched power was coupled into LP_{01} mode of the MMF. This process had an excellent repeatability. This model demonstrate the error-free transmission of 10-Gb/s and 40-Gb/s NRZ signals over 12.2 km and 3.7 km of MMF, respectively, without using any dispersion compensation technique. The bit-rate-distance product of 1.95 Tb/s.km was also demonstrated in a WDM transmission experiment of 16 10-Gb/s signals over 12.2 km of MMF.

It should be noted that, the mode-field matched center-launching technique does not require any additional optical and/or electrical components because it can be realized simply by fusion-splicing the SMF-pigtailed transmitter to the transmission MMF. They also evaluated the robustness of the MMF link implemented by using the mode-field matched center-launching technique against the mechanical perturbations such as the lateral offset between fiber connector, fiber bending, and fiber shaking in a 10-Gb/s MMF link. The results showed that the mode-field matched center-launching technique could tolerate a large offset between fiber connectors. In addition, the performance of the MMF link was hardly perturbed by the fiber bending or shaking. These results suggest that the mode-field matched center-launching technique could help the development of the next-generation MMF transmission systems operating at 10 Gb/s and beyond. In particular, this technique is suitable for upgrading the installed MMF link.

N. Bai *et al.* [25]

They successfully transmitted a 26.4 Tb/s mode-division multiplexed DWDM signal over 50-km of few-mode fiber with an inline few-mode EDFA before the receiver. Phase plates and free-space optics were used for spatial mode multiplexing and demultiplexing. The received signal was detected using three synchronized coherent receivers. They compensated mode coupling, modal group delay and chromatic dispersion using a digital $6 \times 6 \times 301$ MIMO equalizer. They also characterized the mode-dependent gain of the few-mode EDFA, as well as the differential modal group delay and dispersion characteristics of the transmission few mode fiber.

Their experiment was ultimately limited by ASE noise of the receiver's single-mode EDFAs. We attribute this to the high loss of the receiver's spatial demultiplexer. To enable longer transmission distance, it is possible to (i) use a spatial hologram to demultiplex the MDM signal without the high losses incurred by the current spatial demultiplexer, and (ii) use a higher-gain FM-EDFA to boost the MDM signal power above sensitivity. In particular, it is necessary for the gain of the FM-EDFA to be at least equal to the span loss in both mode groups of the FMF in order to enable multi-span transmission using a recirculating loop.

S. Fan and J. M. Kahn. [26]

They generalize the concept of principal states of polarization and prove the existence of principal modes in multimode waveguides. Principal modes do not suffer from modal dispersion to first order of frequency variation and form orthogonal bases at both the input and the output ends of the waveguide. They showed that principal modes are generally different from eigenmodes, even in uniform waveguides, unlike the special case of a single-mode fiber with uniform birefringence. The difference is most pronounced when different eigenmodes possess similar group velocities and when their field patterns vary as a function of frequency. This work provides a new basis for analysis and control of dispersion in multimode fiber systems.

E. J. Tyler and P. Kourtessis. [27]

This paper has described the use of SCM for data communications applications over multimode fiber. SCM can be used to provide significantly enhanced bandwidth over band limited MMF transmission systems by making use of the MMF passband. It has been shown that successful extended range transmission over MMF can be achieved using subcarrier modulation, with the subcarrier channel demonstrating improved performance compared to conventional baseband transmission. This has been achieved by developing an I&Q modem with 5.1 Gb/s per subcarrier capacity and subsequently implementing this in a full MMF link test bed.

The coherent modulation/demodulation scheme used to generate the SCM channel has then been shown to be able to overcome the power penalty associated with the excess pass band loss, allowing SCM sensitivities lower than the equivalent baseband case. This is important, as it shows the potential for penalty-free SCM link operation with capacities in excess of baseband modulation techniques. In addition, They have demonstrated a 40 5.1 Gb/s WDM/SCM system over both 500 m of worst case 62.5 m multimode fiber and 3 km of 50-m MMF. Preliminary results demonstrate the possibility of 20-GHz WDM channel spacing, which, if scaled, show the possibility of 1-Tb/s aggregate rates with a bandwidth-length product of 3 Tb/s.km.

R. E. Freund *et al.* [28]

High-speed transmission in MMF is becoming attractive for the realization of high-capacity transmission systems at low cost. This paper discusses the theoretical background of MMF transmission and gives an overview on system characterization and existing standards. An overview on high-speed transmission in multimode glass fibers was given considering latest trends in component development and system design; reach, speed and capacity extension techniques were reviewed and discussed. 40 Gb/s and 100 Gb/s MMF systems are being standardized applying space-division multiplexing on a 10 Gb/s basis, which is expected to be the lowest-cost solution at this time. Transmitter, fiber, and receiver devices, however, show up for 40 Gb/s serial transmission over distances greater than 400 m. In combination with multiplexing techniques, such as WDM, OFDM or SCM, these new devices will allow to build up Tb/s km MMF systems for next-generation local area, storage and in-house networks.

CHAPTER 3

SHORT RANGE OPTICAL MULTIPLE-INPUT MULTIPLE-OUTPUT (MIMO) MULTIMODE FIBER LINK USING MODE COUPLING EFFECT

In this chapter the performance of 3x3 and 5x5 MIMO system using multimode fiber is observed. The effect of increasing the number of transmitters, receivers, increased bending induced coupling between the propagating modes inside the multimode fiber, and total optical link length is analyzed in terms of bit error rate (BER), eye diagram and output received power. It is found that the 3x3 MIMO MMF is more robust than 5x5 MIMO MMF for higher values of bending induced coupling. It has been observed that the 3x3 MIMO MMF system performs satisfactory for the maximum link length of 27 km and for 5x5 MIMO MMF maximum link length reduces to 17 km for the bending induced coupling factor of 0.04.

3.1. Introduction:

Optical fibers are an integral part of current networking architectures due to their ability to support extremely high data rate. The rapid growth of bandwidth requirement due to the exponential increase in end-user's bandwidth demand with the use of multimedia-rich applications such as video/photo sharing, DTH TV, Live video streaming and cloud computing etc. imposes new challenges to the short and medium distance networks. These applications demand higher data rate transmission in the range of Giga bits per seconds [29]. In recent times, single-mode fibers (SMFs) have displaced multimode fibers (MMFs) as the choice for high speed and long-distance optical links due to their low dispersion and high data carrying abilities. However, these improvements also come with additional complexity in transmitter, receiver, alignment and packaging, thus making them costly and unattractive for small and medium sized networks. [30]

In current short range optical fiber networks i.e. local area networks (LANs) the existing infrastructure is widely based on multimode fiber (MMF), due to easy handling and its good performance over short spans. However, as their bandwidth is limited by modal dispersion, transmission of signals of high-modulation rates even on short links requires special

countermeasures. There is need to upgrade the transmitted capacity in the range of Gbit/s, in order to develop the near future LANs, maintaining the already installed MMFs, rather than to lay new fibers, for cost-saving reasons. Some of the proposed solutions to increase the transmission capacity of MMF are based on multiplexing methods and include wavelength division multiplexing (WDM)[31], subcarrier multiplexing (SCM) [32], and mode group-division multiplexing (MGDM)[33]. Others are based on advanced electrical processing: advanced modulation formats and electronic dispersion compensation.

Theoretically the multimode fibers (MMF) exhibit a higher transport capacity limit than single mode fibers (SMF) by exploiting the various modes or groups of modes as independent communication channels with individual scattering paths. The excitation of different modes or mode groups of the MMF by different transmit signals and separation by optical mode filtering in conjunction with multiple input multiple output (MIMO) processing at the receive side is under investigation for several years. The improved utilization of the MMF transmission capacity grown from the analogy between transmission over multiple modes and modal coupling in MMF versus the multipath and scattering phenomena occurring in wireless communication links [34], [35]. Multiple optical sources and detectors are introduced to take advantage of the spatial (modal) diversity, it is possible to recover signal transmitted using multiple transmitter over a single MMF, at the expense of greater signal processing complexity, particularly at the receiver end.

Maxim Greenberg *et al.* [36] investigated Data parallelization by means of optical (MIMO) transmission over dispersive multimode fiber (MMF), with a high degree of modal coupling. They have used analytical model for direct detection of MMF MIMO frequency-flat transmission with mutually incoherent sources. However, the effect of intermodal dispersion is not considered in the paper.

Nicolas *et al.* [37] suggested architecture using MIMO MMF for simultaneous transmission of unique streams to different users on the same fiber using square-law detection. They demonstrated increase in MMF fiber bandwidth by enabling the transmission of multiple parallel narrowband signals, one for each user, such that the impact of group delay dispersion

is minimized. This mode can be used with WDM to further enhance the throughput of MMF networks.

Bernd *et al.* [38] experimentally investigated the application of principal mode groups for the transmission of high bit rate data over OM4 graded-index multimode fiber (MMF). They have been identified eight principal mode groups as being suitable for spatially separated transmission channels at a wavelength of 1550 nm for the OM4 fiber. It has been also shown that each of the eight mode groups can be used for the transmission of 10-Gb/s data over a 5-km-long graded-index MMF.

Moshe *et al.* [39] investigated quadratic multiple-input multiple-output (Q-MIMO) channel model and used quadratic forms instead of linear channel matrices. They explored signaling formats over the Q-MIMO channel in the frequency flat regime, highlighting the unique characteristics of optical multimode fiber (MMF) systems versus their wireless counterparts. They also investigated vector amplitude modulation over MMF MIMO and study the receiver zero-forcing (ZF) technique for MMF MIMO transmission,

The vast research work has been done in the field of MMF MIMO but still the maximum length achieve is small, till date the maximum length covered is up to 5 km using GI MMF OM4 fiber with 10 Gb/s data rate. [38] In majority of research work the effect of bending occurring along with the fiber length is not considered. It is a major deciding factor of system performance it must be considered. In this paper we have proposed a MIMO MMF link with transmitter and receiver diversity with laser sources, which are couple to MMF with center launched technique. The multimode fiber with 50um core radius and 65um cladding radius is taken into consideration. The power coupling between the propagating modes and bending of MMF are investigated; the system performance is analyzed with the help of BER, received optical power and eye diagrams. The paper is organized as follows. In Section 2, the theoretical background for transmission in multimode fibers is described. Section 3 provides the details of simulation setup for MIMO MMF optical link. The section 4 provides the results and discussions. Finally section 5 concludes the paper.

3.2. Theory

In this section theoretical concept of MIMO signal transmission over multimode fiber is explained. The MMF supports propagation of multiple spatial modes, different light modes in a graded-index multimode fiber follow different path lengths along the fiber, similar to Step index MMF, However their speeds differ because the speed of guided light changes with fiber core's refractive index. So the farther the light goes from the center of the fiber, the faster its speed. So the speed difference compensate for the longer paths followed by the light rays that go farthest from the center of the fiber. This equalizing of transit times of different modes greatly reduces modal dispersion. Figure 3.1 shows the multimode fiber with 1 to N Laser sources which provides the optical spatial diversity at transmitter side. Multi-laser sources excite different modes inside the multimode fiber, modal mixing occurs in propagation through the optical fiber, and different signal are redirected to a separate detector at the output. The presence of any irregularity in the fiber such as geometrical variations or refractive index changes will lead to energy exchange between these modes. This energy exchange leads to survival of some paths in the case of MIMO system. The energy exchange between the spatial modes depends upon the bending of fiber, geometric variation in the core and cladding, intensity of spatial modes.

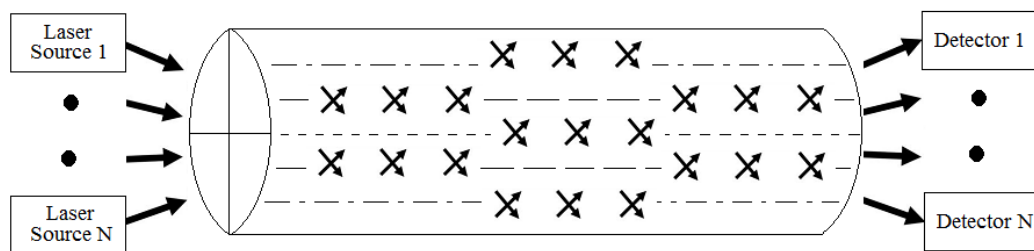


Fig. 3.1 Multimode fiber with MIMO input/output and intermodal coupling.

Let us assume for the simplicity that the number of transmitters and receivers is equal (N). Each of the transmitting lasers having similar wavelength excites slightly different mode groups (in the multimode fiber). Moreover, both the input optical coupler and output optical splitter have mode-selective properties (i.e. to the some extent they filter modes). Therefore, each connection between i^{th} receiver and j^{th} transmitter is realized by mode groups whose powers depend on the (i, j) pair. This is analogous to the multipath propagation in radio

communication. The relationship between N input signals $[s_1 \dots s_N]$ and $[r_1 \dots r_N]$ N output signals is as follows[40]:

$$\begin{bmatrix} r_1 \\ \cdot \\ \cdot \\ r_N \end{bmatrix} = \begin{bmatrix} h_{11} & \dots & \dots & h_{1N} \\ \dots & \dots & \dots & \dots \\ h_{N1} & \dots & \dots & h_{NN} \end{bmatrix} \cdot \begin{bmatrix} s_1 \\ \cdot \\ \cdot \\ s_N \end{bmatrix} \quad (1)$$

In equation (1), $[h_{i,j}]$ is the transmission matrix containing transfer coefficients between all the transmitter and receiver pairs. In general the matrix coefficients are complex; as they take into account not only amplitude changes, but also a phase shift between i^{th} transmitter and j^{th} receiver. By inverting the matrix $[h_{i,j}]$ we may recover vector $[s_i]$, however the numerical conditioning of the matrix determines SNR.

In the MIMO over multimode fiber we may express $[h_{i,j}]$ as follows [40] :-

$$h_{ij}(f) = \exp \left[- \frac{(2\pi f D L \sigma_\lambda)^2}{2} \right] \cdot \sum_{k=1}^K P_k(i,j) \exp(j2\pi f \tau_k L) \cdot 10^{\frac{-\alpha_k L}{10}} \quad (2)$$

In the equation (2), $P_k(i,j)$ is the power of k^{th} mode group, f is the carrier frequency, D is dispersion coefficient, L is the length of the fiber, σ_λ is the rms line width of the source, k is the number of mode groups propagating in the fiber, τ_k is the group delay the k^{th} mode group, α_k is the attenuation coefficient. The MIMO transmission over multimode fiber is possible, because $P_k(i,j)$ depend upon lesser, on $h(i,j)$ channel matrix, on the filtering properties of couplers splitters and slightly different conditions of each path.

3.3. Simulation setup

Simulation setup for Short Range Optical Multiple-Input Multiple-Output (MIMO) Multimode fiber link using mode coupling effect is shown in fig. 3.2. Each transmitter section consists of the data source, electrical driver, laser source and Mach-Zehnder (MZ) modulator. The data source is a NRZ format at 10Gb/s bit rate. The On-Off Keying (OOK) driver module generates an electrical signal for driving lasers and modulators. The continuous wave laser source generates the laser beam at a frequency of 193.1 THz. The input data source modulates the laser beam by using an MZ modulator. The output of the modulator is

fed to non-ideal multimode fiber coupler. The coupler couples the incoming MZ modulated signal to multimode fiber. The different various modes travel through the multimode fiber. At receiver side the optical band pass filter (OBPF) is used to select the desired range for detection of the optical signal. The OBPF is centered at 193.1THz. The PIN detector is used for converting the optical signal into electrical signal and it is followed by a LPF and signal analyzer. The signal analyzer is used for observing the eye diagram, receiver power and also for calculating BER.

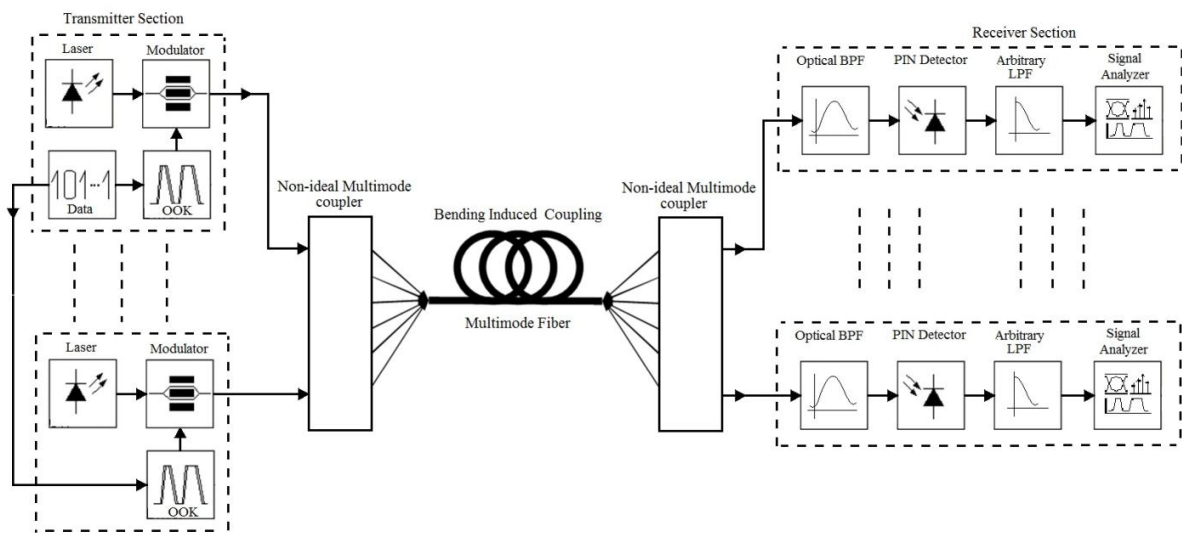


Fig. 3.2.Simulation setup for Short Range Optical Multiple-Input Multiple-Output (MIMO) Multimode fiber link using mode coupling effect

The CW laser is used in this model. The parameters for CW lasers are: emission frequency 193.1 THz, CW average power 1 mW, line width 10 MHz, noise threshold -100 dB and initial phase of 0 degree, The MZ modulator module simulates a Mach-Zehnder modulator and can also handle the frequency chirp resulting from the modulator asymmetry. The simulated bit rate is 10Gb/s with pseudorandom binary sequence. The multimode fiber has average group refractive index of 1.48, the attenuation is 0.2e-3 dB/m and core refractive index is 1.45 with core diameter of 50um. The responsivity of the PIN detector is 1 A/W, and zero dark current (approx.).

3.4. Results and discussion

The performance of Short Range Optical Multiple-Input Multiple-Output (MIMO) Multimode fiber link using mode coupling effect is determined by transmitter and receiver diversity technique. The different combination of transmitter and receiver are tested for better BER, received power and eye diagram. The robustness of the system is measured by introducing bending coefficient; which is introduced at the regular interval of 300m fiber span. The coupling between the different modes of multimode fiber is controlled by Bending induced Coupling factor (BCF). The BER versus Received power curve is plotted for different values of BCF and for different number of transmitter and receiver. Fig. 3.3 shows the BER versus Rx power curve for 3x3 MIMO MMF system.

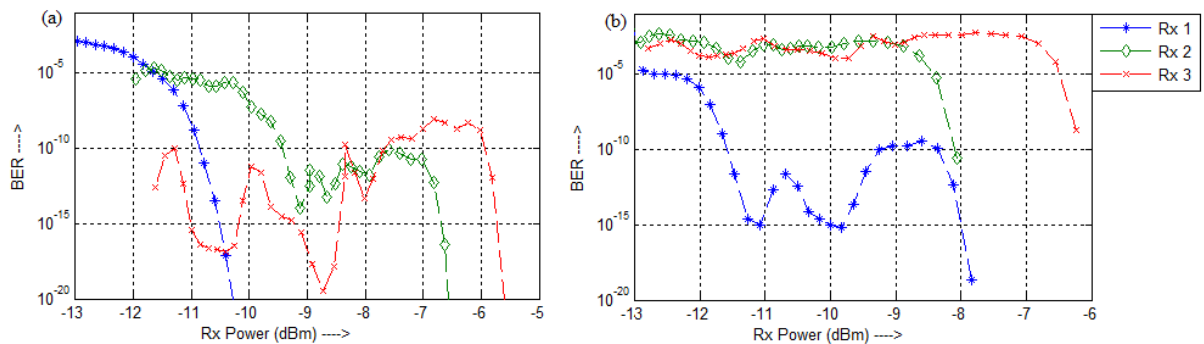


Fig. 3.3 BER versus Rx Power for 3x3 MIMO MMF with (a) BCF of 0.01 (b) BCF of 0.04

The fig. 3 shows the variation in BER of receivers as the received power changes. It can be observed that due to spatial diversity provided by transmitter, receiver and multimode fiber, the each path is having different characteristics hence difference BER is observed. As long as any one path is having BER value above the threshold the signal can be easily recovered at receiver. The figure 3(a) and 3(b) shows the characteristics for 3x3 MIMO MMF optical link for the BCF of 0.01 and 0.04 respectively. It observed that at -13dBm of received power the system with BCF of 0.04 is having BER equals to 10^{-5} whereas with BCF equals to 0.01 its value is 10^{-2} . It can also observe that the BER of Rx 1, Rx 2 is decreased in fig 3(b) with the increase in BER of Rx 3. The intermodal power coupling is the main cause for improve in BER performance.

Fig 3.4 shows the BER versus Received power characteristics for 5x5 MIMO MMF optical link. Fig 3.4(a) shows that the BER of Rx 3 is highest among the all five receivers. It is having BER of 10^{-10} with a BCF of 0.01 at received power of -11dBm. As the BCF for 5x5 system increases the performance of the system not improves as expected it is shown in fig 3.4(b) where the highest BER is 10^{-3} at received power of -11dBm. Hence it can be said that the increase in BCF is not beneficial in every scenario. For system having 3 transmitters, 3 receivers it improves the BER whereas system with 5 transmitters, 5 receivers it degrade the BER value.

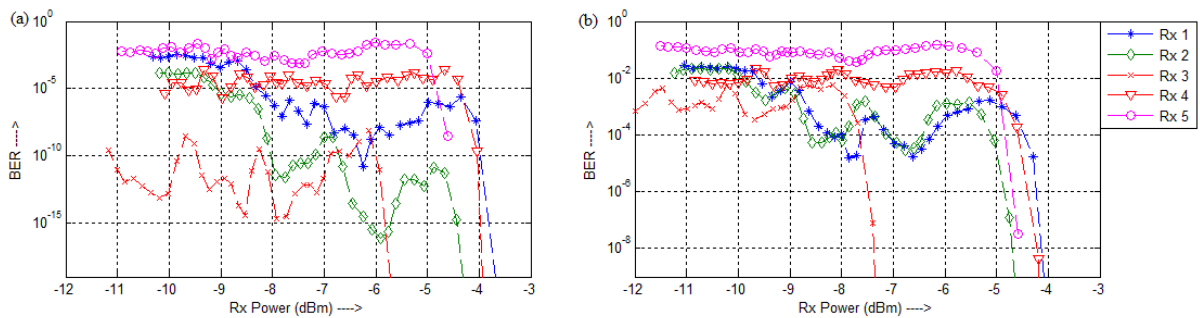


Fig. 3.4 BER v/s Rx Power for 5x5 MIMO with (a) BCF of 0.01 (b) BCF of 0.04.

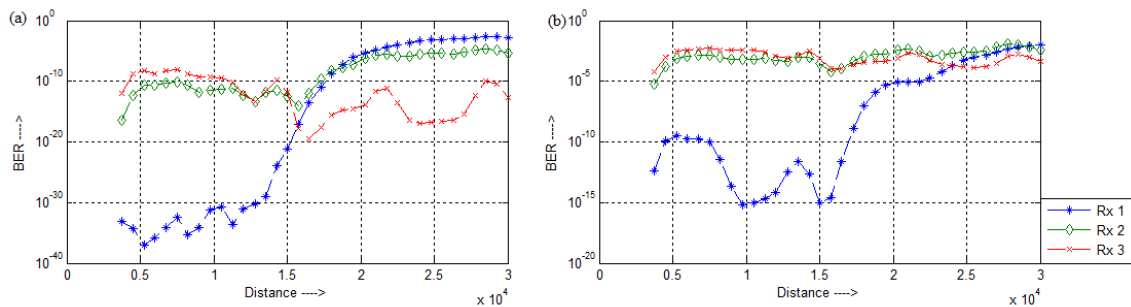


Fig. 3.5 BER versus Distance for 3x3 MIMO MMF with (a) BCF of 0.01 (b) BCF of 0.04.

The fig. 3.5 shows that the increase in BCF leads to reduction in the total link length. The BCF of 0.04 limit the maximum link length to 27 Km with a BER of 10^{-5} . The increase in BCF has worse effect on 5x5 MIMO MMF system. The maximum link length reduces to 16km for BCF equals to 0.04 indicated by fig 3.6(b) where as for the value of BCF equals to 0.01, the maximum fiber link length is about 30 km.

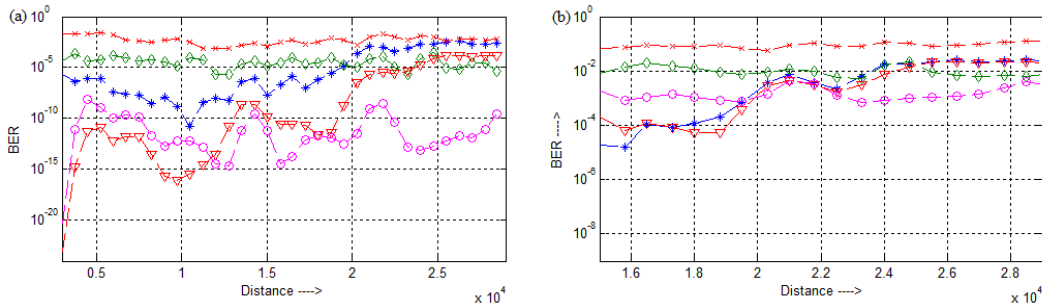


Fig. 3.6 BER versus Distance for 5x5 MIMO MMF with (a) BCF of 0.01 (b) BCF of 0.04.

The received power variation with change in fiber link length is shown on fig 3.7. The power decreases as a linear function of fiber length. There is very small difference between the power received by different receiver.

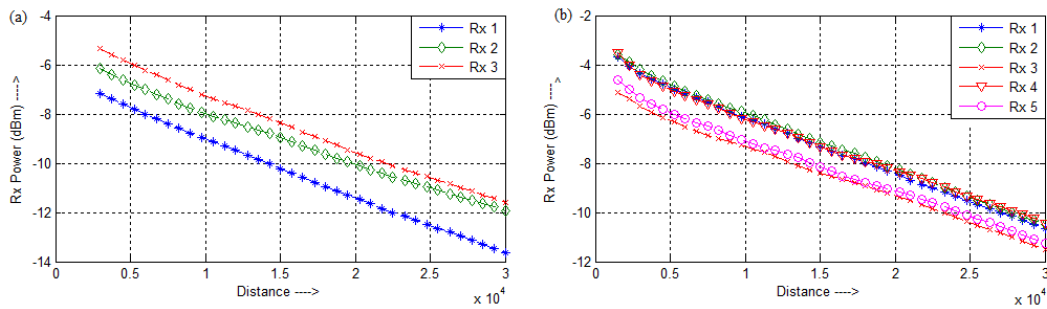


Fig. 3.7 Rx power versus fiber distance for (a) 3x3 MIMO MMF (b) 5x5 MIMO MMF optical link

The fig. 3.8 shows the eye diagram of both 3x3 and 5x5 MIMO MMF system. The first five eye diagrams from 3.8(a) to 3.8(e) are for each receiver of 5x5 MIMO MMF, the next three from 3.8(f) to 3.8(g) are for 3x3 MIMO MMF optical link. The eye diagrams of 5x5 MIMO MMF system are distorted as compare to 3x3 MIMO MMF, the main cause for high distortion are intermodal non-linearity inside the MMF, bending in MMF and coupling from neighboring propagating modes. The modes propagating as the outer side are less affected by the intermodal coupling whereas the modes propagating inside are having distorted eye diagrams.

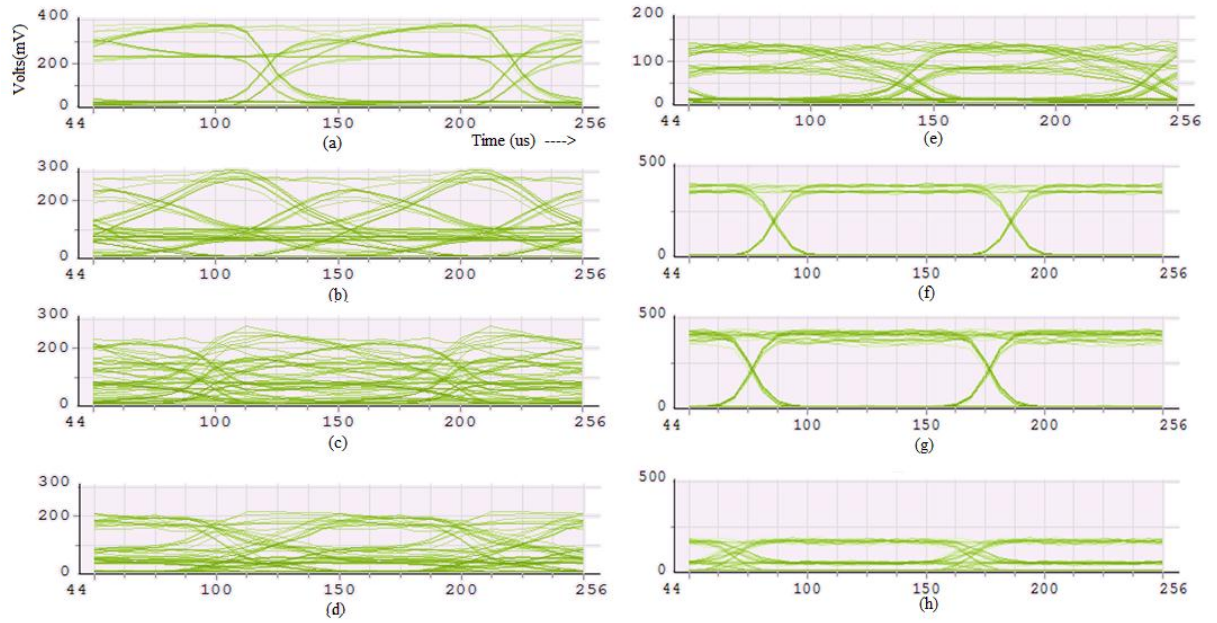


Fig. 3.8 Eye diagram for 5x5 and 3x3 MIMO MMF optical link with a bending induced coupling factor of 0.01

CHAPTER 4

ENHANCING THE CAPACITY OF OPTICAL FIBER WITH THE UTILIZATION OF LINEARLY POLARIZED MODES IN SPATIAL MULTIPLEX SYSTEM.

This chapter proposes linearly polarized (LP) multimode fiber architecture to improve the capacity of optical fiber link. The initial 10 LP modes are utilized and the modes are divided into even and odd category. The first mode group includes LP₀₁, LP₂₁, LP₃₁, LP₄₁ and LP₀₃. The measured BER is 10^{-9} for a fiber span of 66km. The BER further reduces on increasing the fiber span and reaches to 10^{-5} for total fiber span of 76km. The second LP modes group includes LP₁₁, LP₀₂, LP₁₂, LP₂₂ and LP₅₁. The measured BER is 10^{-9} for a fiber span of 67km. The BER reaches to 10^{-5} for a total fiber span of 78km. The performance is very much close to the odd mode configuration.

4.1. Introduction

The demand for high capacity has been increasing exponentially with the increases in data and voice services requirement caused by tremendous growth in number of user demanding these services. The key point in enabling high data rate communication is the enhancement of link bandwidth and reach, while keeping the system simple and low cost. In optical regime, Single-mode fiber (SMF) is the backbone of the majority of the networks due to its extremely low loss and large bandwidth. In the past decade there has been intense research to increase the transmission capacity of single mode optical fiber transmission systems which is about to reach its capacity limit [41]. On the other hand, multimode fiber (MMF) provides the necessary bandwidth for short reach links at a much lower installation and component cost compared to SMF and copper wire. The main drawback of MMF is that light propagates via a larger number of modes which causes modal dispersion hence lower bandwidth is achieved. Multimode fiber (MMF) links are widely implemented in current high-speed local area networks [1].

Theoretically the multimode fibers (MMF) exhibit a higher transport capacity limit than single mode fibers (SMF) by exploiting the various modes or groups of modes as independent communication channels with individual scattering paths. To increase the transmission capacity of MMF some methods used are wavelength division multiplexing

(WDM)[43], subcarrier multiplexing (SCM) [44], launching techniques[45]. The use of optimize semiconductor amplifier can also be used to achieve larger optical link length.[46] Few more methods are advanced electrical processing, advanced modulation formats and electronic dispersion compensation techniques. The MMF can support high data rate and bandwidth using transmission that exploit the spatial dimension.

N. Bai *et al.* [47] demonstrated a mode-division multiplexed WDM transmission system over 50-km of few-mode fiber using the fiber's LP_{01} and two degenerate LP_{11} modes. A few-mode EDFA was used to boost the power of the output signal before a few-mode coherent receiver with a 6×6 time-domain MIMO equalizer.

Adrian A *et al.* [48] investigated the suitability of Principle Modes for coherent MDM transmission as the number of eigenmodes increase in a MMF. The eigenmodes of the fibers is used as an additional degree of freedom for high data rate transmission. They have observed an exponential decay of usable PMs after reaching a local maximum.

Bernd Franz *et al.* [49] experimentally investigated the application of principal mode groups for the transmission of high bit rate data over OM4 graded-index multimode fiber (MMF). They have been identified eight principal mode groups as being suitable for spatially separated transmission channels at a wavelength of 1550 nm for the OM4 fiber. It has been also shown that each of the eight mode groups can be used for the transmission of 10-Gb/s data over a 5-km-long graded-index MMF.

However, at present, there is a lack in fiber-based or integrated optical components suitable for MDM based WDM systems. The system developed so far is very much complex requiring dedicated and costly equipment.

4.2. Theory

Fibers that carry more than one mode are called multimode fibers. There are two types of multimode fibers. One type is step-index multimode fiber and the other type is graded-index multimode fiber. The figure 1 shows the differences between these two types of multimode fibers on refractive index profile and how they guide light. Step-index multimode fibers are mostly used for imaging and illumination. Graded-index multimode fibers are used for data

communications and networks carrying signals moderate distances - typically no more than a couple of kilometers.

Modes are light intensity profiles (patterns) that propagate down the fiber maintaining their transversal field shape. Multimode fibers can support many thousands of modes. Single mode fibers support one mode. In order to accurately study optical modes, the complete Maxwell equations are to be solved. For multimode fibers, the following intuitive explanation can be given: Each mode corresponds to a light beam traveling inside the fiber core with different angles.

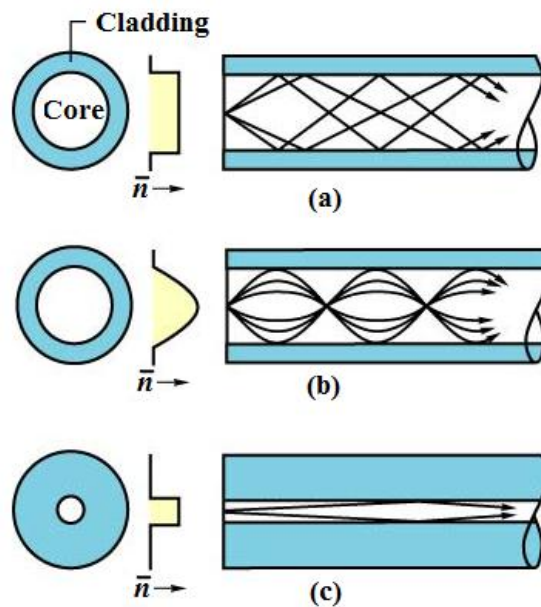


Fig.4.1. (a) step-index MMF (b) parabolic graded-index MMF (c) step-index SMF

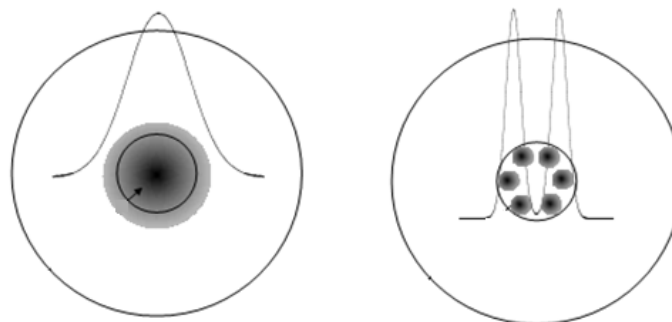


Fig. 4.2 First and second order Gaussian modes

Light travels along a multimode fiber through a series of reflections at the interface between the core and the cladding. From a geometrical point of view it would be thought that any ray angle would be possible but when electromagnetic theory is applied to the fiber it is found that only certain angles are permitted, these are known as the 'modes' of the fiber. Broadly speaking there are two types of mode, those where light passes through the axis of the fiber, known as the 'meridional' modes, and those that travel in a helical fashion, not crossing the axis, known as 'skew' modes.

A light wave is an electromagnetic wave that travels through the vacuum of outer space. Light waves are produced by vibrating electric charges. The electromagnetic wave is a transverse wave that has both an electric and a magnetic component. As an electromagnetic wave travels the vibrations occurs in more than one plane of vibration. A light wave that is vibrating in more than one plane is referred to as un-polarized light. Light emitted by the sun, by a lamp in the classroom, or by a candle flame is un-polarized light. Such light waves are created by electric charges that vibrate in a variety of directions, thus creating an electromagnetic wave that vibrates in a variety of directions. It is possible to transform un-polarized light into polarized light. Polarized light waves are light waves in which the vibrations occur in a single plane. The process of transforming un-polarized light into polarized light is known as polarization.

The index gradient causes rays which are traveling at steeper angles in the fiber, the 'high-order' modes, to catch up with rays traveling at shallow angles. This is because that, although the steeper rays have further to travel the refractive index they experience near to the core/cladding boundary is less than at the center of the core and so they travel faster in this region. It is this feature of graded-index fiber that gives it much less pulse dispersion than step-index fibers and hence superior bandwidth performance.

From an electromagnetic point of view, there are actually four different types of mode in a multimode fiber depending on the angle between the electric field vector and the axis of the fiber. For most communication fibers, however, where the refractive-index difference between the core and cladding is relatively small, the different types of mode can be grouped together into a single series of modes known as the Linearly Polarized (LP) modes.

The LP modes are normally designated by two parameters; these are the radial mode number, m , and the azimuthal mode number, n . For a particular mode ' n ' corresponds to the number of intensity peaks in the radial direction and ' $2m$ ' corresponds to the number of intensity peaks over 360 degrees in the azimuthal direction. The figure 4.3 shows the intensity distributions of some $LP_{n,m}$ modes.

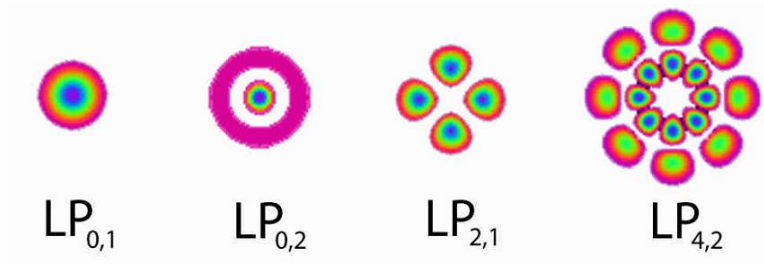


Fig. 4.3 LP mode intensity distributions.

All modes with the mode number G must fulfill the following equation. [50]

$$G = n + 2m + 1 \quad (1)$$

The mode having same group number will have the same phase constant and group delay. Table 1 gives the some of LP modes groups and table 4.2 shows the mode naming methods for LP modes.

G	Modes
3	LP_{01}
4	LP_{11a} LP_{11b}
5	LP_{02} LP_{21a} LP_{01b}
6	LP_{12a} LP_{12b} LP_{31a} LP_{31b}
7	LP_{03} LP_{22a} LP_{22b} LP_{41a} LP_{41b}
8	LP_{13a} LP_{13b} LP_{32a} LP_{32b} LP_{51a} LP_{51b}
9	LP_{04} LP_{23a} LP_{23b} LP_{42a} LP_{42b} LP_{61a} LP_{61b}

Table 4.1. Primary LP mode groups

Each mode LP with $n = 0$ comprises two degenerate modes $LP_{w,m}$, one in parallel and the other in perpendicular polarization, whereas each mode $LP_{n,m}$ with $n > 0$ comprises four degenerate modes $LP_{n,m}$ and $LP_{n,m}$ in parallel and perpendicular polarization, respectively. As can be seen in Table 4.1 the number of modes per group increases with increasing mode group number G , so that even with a high number of modes the number of groups remains relative small

Azimuthal\Radial Index Number					
	1	2	3	4	5
0	3	5	7	9	11
1	4	6	8	10	12
2	5	7	9	11	
3	6	8	10	12	
4	7	9	11		
5	8	10	12		
6	9	11			
7	10	12			
8	11				
9	12				

Table 4. 2. Naming method of LP modes

4. 3. System setup

Simulation setup for “Enhancing the capacity of optical fiber with the utilization of linearly polarized modes in spatial multiplex system” is shown in figure 4.4. Each data source represents a binary bit generator, electrical driver, laser source and Mach-Zehnder (MZ) modulator. The data source is a NRZ format at 10Gb/s bit rate. The On-Off Keying (OOK) driver module generates an electrical signal for driving lasers and modulators. The continuous wave laser source generates the laser beam at a frequency of 193.1 THz. The parameters of lase are given in table 3 shown below.

Laser parameters	
Emission frequency	193.1THz
Laser Power	1mW
Line width	10MHz
Initial Phase	0 deg.

Table 3 laser parameters specifications

The input data source modulates the laser beam by using an MZ modulator. The output of the modulator is fed to non-ideal multimode fiber coupler. The function of non-ideal coupler it to coupler the incoming light signal to fiber in such a manner that maximum light falls into numerical aperture of MMF. The falling light will induce the modes inside the MMF. The

coupler is also responsible for generation of the LP modes for multimode fiber. The different various modes travel through the multimode fiber.

The specification of MMF is given in table 4.4.

Multimode Fiber parameter	
Group Refractive index	1.48
Core Refractive index	1.45
Core diameter	50um
Attenuation	0.2 dB/km
Mode field FWHM	1.665x10e-6
Reference frequency	193.1THz

Table 4 MMF specification

At receiver side the optical band pass filter (OBPF) is used to select the desired range for detection of the optical signal. The OBPF is centered at 193.1THz. The PIN detector is used for converting the optical signal into electrical signal and it is followed by a LPF and signal analyzer. The signal analyzer is used for observing the eye diagram, receiver power and also for calculating BER.

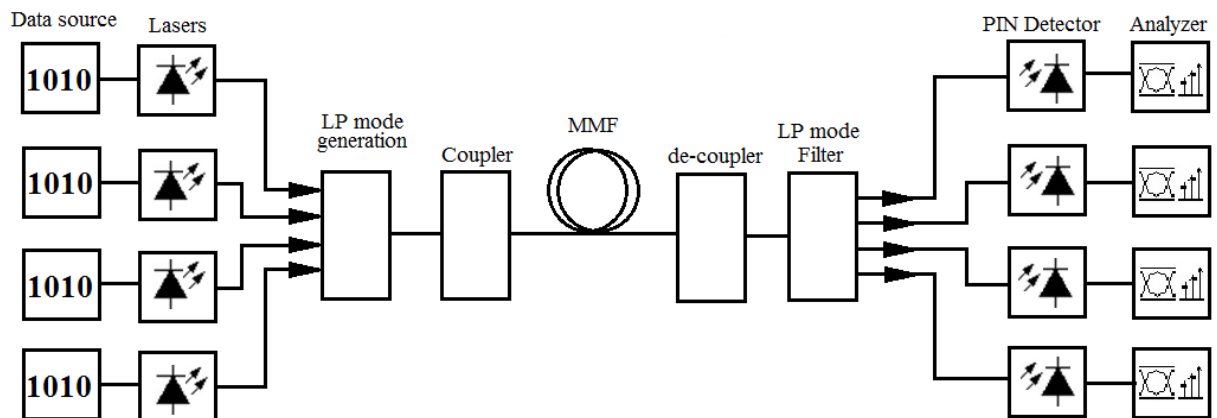


Fig. 4.4 System setup for enhancing the capacity of optical fiber with the utilization of linearly polarized modes in spatial multiplex system

4. 4. Results and discussions

The investigation of capacity enhancement of optical fiber using LP modes with spatial diversity is done with the help of BER analysis, received optical power measurement and eye

diagram. The intermodal coupling between the neighboring mode is the main cause for the distortion of signal inside the MMF. To avoid this intermodal coupling we have transmitted alternate mode leaving an empty space equal a single mode. This results lesser interference from the modes propagating with the desired signal. We have used first ten LP modes for the transmission in this system. The total modes are divided into even and odd number and two setup are used to measure BER and received optical power.

The first mode group include LP_{01} , LP_{21} , LP_{31} , LP_{41} and LP_{03} . The BER versus fiber span graph is plotted in figure 4.5. It shows that the primary mode performance better than the higher order modes. The measured BER is 10^{-9} for a fiber span of 66km. The BER further reduce and reaches to 10^{-5} for total fiber span of 76km. The received optical power versus fiber span graph is plotted in figure 4.6. It shows power decay almost linearly as fiber length increased. The modes propagating in between others modes are having a bit more power due to power coupling from the neighboring modes.

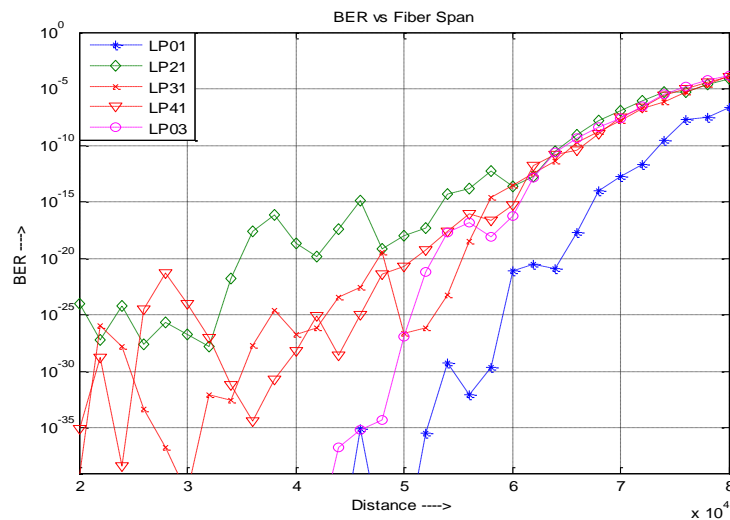


Fig 4.5 BER versus Fiber span for odd LP modes

The figure 4.5 shows the BER versus fiber span for LP_{01} , LP_{21} , LP_{31} , LP_{41} and LP_{03} . The result indicate that the primary mode LP_{01} shows higher value of BER as compare to other LP modes, whereas LP_{21} is highly effected and performs poor.

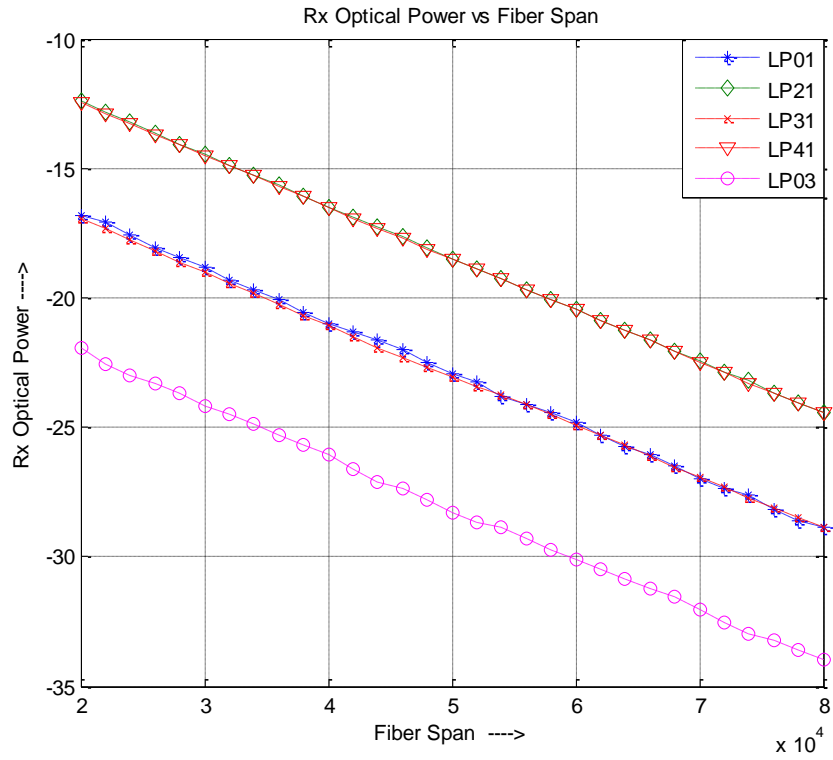


Fig 4.6. Received optical power versus Fiber span for odd LP modes.

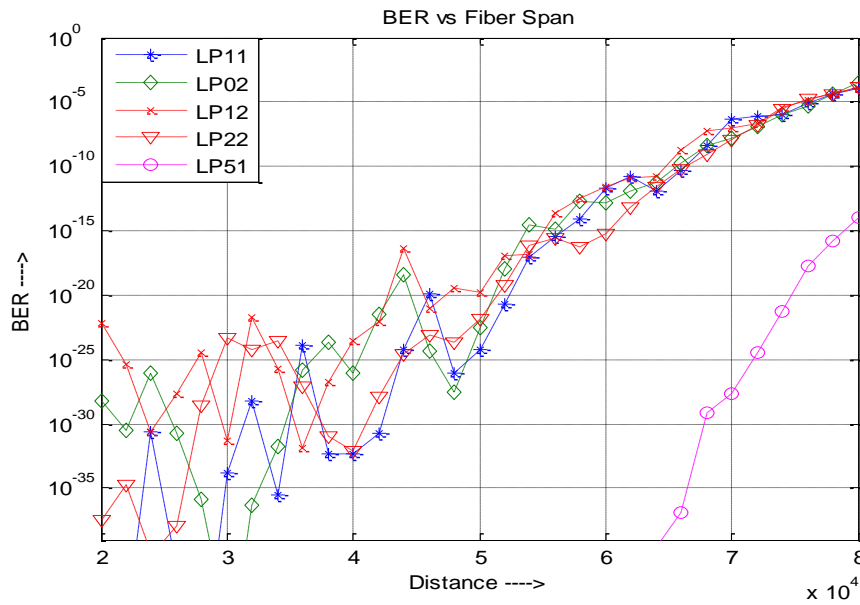


Fig 4.7 BER versus Fiber span for even mode group

The BER versus Fiber span for even modes is shown in figure 4.7. The LP modes includes are LP₁₁, LP₀₂, LP₁₂, LP₂₂ and LP₅₁. The result shows that mode LP₅₁ shows exceptional BER among others modes. The rest of modes shows almost the same value of BER.

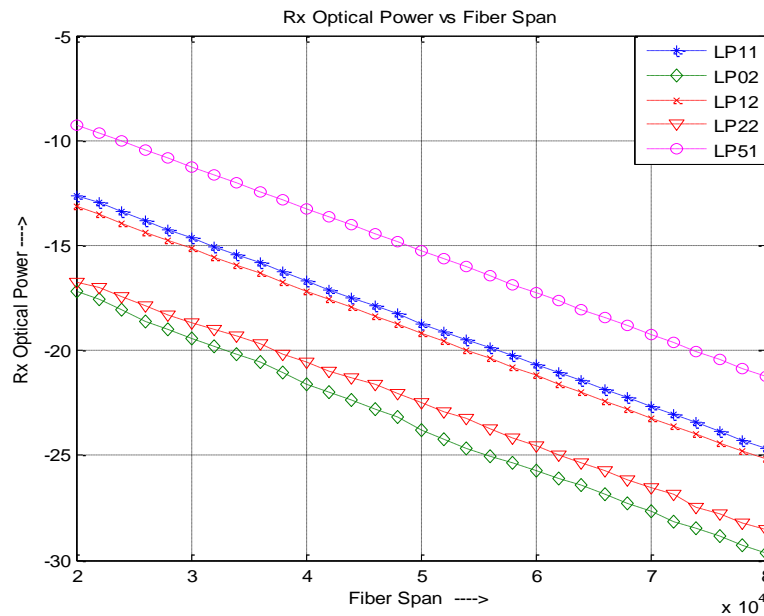


Fig. 4.8 Received optical power versus Fiber span for even mode group

The result shows that highest modes perform better than other. The other modes BER are very much closer to each other. The measured BER is 10^{-9} for a fiber span of 67km. The BER further reduce and reaches to 10^{-5} for total fiber span of 78km. The performance is very much close to the odd mode configuration. The received optical power versus fiber span graph is plotted in figure 4.8. It shows power decay almost linearly as fiber length increased. The modes propagating in between others modes are having a bit more power due to power coupling from the neighboring modes.

The eye diagrams of odd modes are shown in figure 4.9. It clearly shows that the power coupling takes place during the propagation of modes inside the MMF. At the transmitter side the LP modes are coupled to optical fiber in alternate fashion. The MMF cause generation of modes this can be seen in eye diagram shown in fig 4.9.

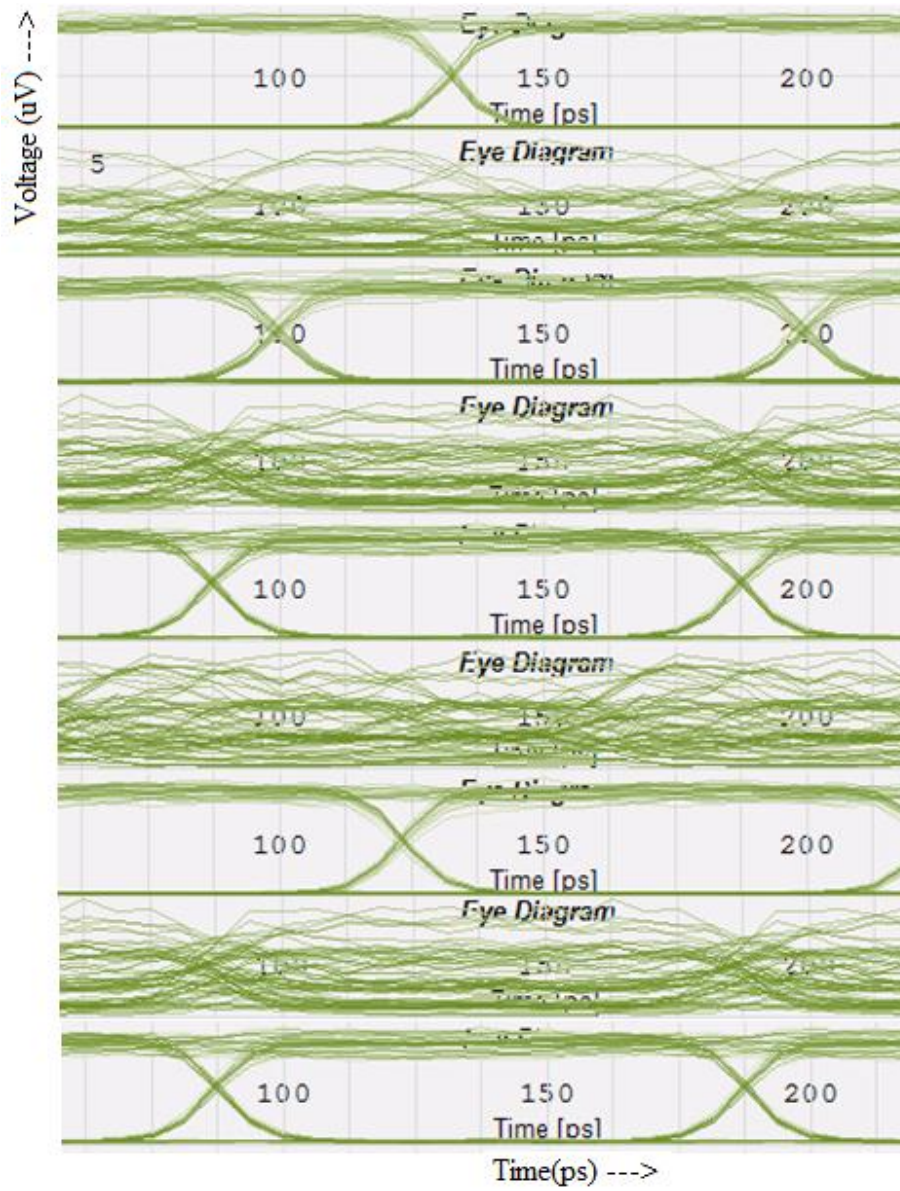


Fig. 4.9 Eye diagram of odd mode group.

CHAPTER 5

5x100 Gbps DATA TRANSMISSION USING GRADED INDEX MULTIMODE FIBER OVER 50 KM OPTICAL LINK

The higher data rate can be achieved using multimode fiber in optical transmission link. The modes of MMF can be used independently to achieve multifold increase in data rate. This chapter provides a MMF link using linearly polarized modes that can support 5 transmitter operating at 100Gbps. The result shows that at the data rate of 20Gbps the maximum fiber length with 5x5 MIMO system is up to 60km with a BER of 10^{-5} . As the data rate increases the intermodal coupling cause power transfer from one modes to another inside the MMF. The results also shows that maximum optical fiber link reduces to 50km at the data rate of 100Gbps.

5.1 Introduction

The demand for ever higher capacity data transmissions has attracted great interest in the development of high density and high-speed parallel optical communication system for a wide range of applications including internet servers, future high-performance computers, and data centers [51-53]. The small systems can be connected together to form a larger system. The task of providing and managing hundreds of individual links using either copper-based or conventional fiber cables is very much difficult. In multi-channel parallel links for high-performance super-computers and data centers applications, thousands to tens of thousands of optical links operating at 1 to 10 Gb/s may be deployed and the longest distances are typically shorter than 100 m [52].

During the Ethernet time period data rates have increased from the original 10 Mb/s to 10 Gb/s. Now, 40 Gb/s and 100 Gb/s standards have been defined, leading in the next generation of equipment and components. The researcher had already developed transmission at the gigabit Ethernet rate of 1.25 Gb/s over 550 m of MMF with long-wavelength (1300 nm) laser sources, and over 275 m at 850-nm sources [51]. These link lengths are limited by the specified bandwidth of the installed base MMF. At data rates higher than 1 Gb/s, the link lengths that can be supported become significantly reduced using conventional methods. For

example, at 10-Gb/s data rates, optical transmission link lengths are limited to less than 60 m [52]. However, as the bandwidth demand of local-area networks continues to rise, ever-faster fiber-optic links will be required in the support that aggregates the traffic of many users. Therefore, there is much interest in achieving high-speed data transmission on the currently installed MMF links.

Realization of higher transmission rates and lengths require techniques capable of overcoming primarily modal bandwidth limitations [54]. It is well known that basic wavelength-division multiplexing (WDM) techniques and multilevel coding yield improvements in the bandwidth capacity product of MMF links [55], and also that subcarrier multiplexing (SCM) can provide capacity enhancement in single and multiuser networks [56].

A. Kern et al [57] presented the monolithic design, fabrication, and properties of 850-nm wavelength AlGaAs–GaAs-based transceiver chips for low-cost bidirectional optical data transmission over a butt-coupled standard multimode fiber of a few hundred meter length. The chips with a stacked layer structure of a vertical-cavity surface-emitting laser (VCSEL) and a PIN (p-doped–intrinsic–n-doped) photodetector can well handle data rates of 9 Gb/s in back-to-back mode and 7 Gb/s over a 500-m-long 50- μ m core diameter fiber. The chips consist of PIN photodiodes and oxide-confined, top-emitting VCSELs, integrated to match 50- μ m core diameter GI MMFs. The main fabrication steps including the sophisticated selective dry- and wet-etching techniques were introduced.

C. Kromer *et al.* [58] described a quad optical transceiver for low power high density short distance optical data communication. Each channel transmits 10 Gb/s over a multimode (MM) fiber and features a link margin of 5.2 dB at a bit error rate (BER) of 10^{-12} . The transmitter and receiver amplifying circuits are implemented in an 80-nm digital CMOS process. Each driver consumes 2 mW from a 0.8-V supply, and each vertical cavity surface-emitting laser (VCSEL) requires 7 mA from a 2.4 V supply. The receiver excluding the output buffer consumes 6 mW from a 1.1-V supply per channel and achieves a trans-impedance gain of 80.1 dB. The isolation to the neighboring channels is 30 dB including the

bond wires and optical components. A detailed link budget analysis takes the relevant system impairments as losses and power penalties into account, derives the specifications for the electrical circuits, and accurately predicts the link performance.

P. Kourtessis and S. D. Walker [59] described the application of subcarrier multiplexing (SCM) to enable broadband transmission beyond the modal bandwidth of multimode fiber (MMF) optical links. The application of a quadrature phase-shift keying modem featuring novel carrier and symbol-timing recovery circuits, demonstrates significant enhancement in channel capacity. By using a 2.7-GHz pilot-tone-injected phase-locked loop (PLL) and referencing subscriber data to a pre-scaled version of the subcarrier, zero-latency carrier and data synchronization has been achieved exhibiting 675 Mb/s bit-oriented clock extraction in network terminal equipment. The novel scheme is scalable to higher aggregate rates and upgrades to existing installed-base 50 m MMF infrastructure to provide low-cost, high-capacity interconnects for storage area and campus network applications.

B. Zhu *et al.* [60] proposed a novel structure and crosstalk characteristics of a graded-index multicore fiber with seven cores arranged in a hexagonal array. A total of 70 Gb/s (7 10 Gb/s) s transmitted over a single 100-m seven-core multimode fiber (MMF) using tapered multicore fiber connectors and 850-nm vertical-cavity surface-emitting lasers, demonstrating high-speed multicore MMF transmissions for parallel optical data links. Since a pitch-matched 2-D VCSEL array is currently not commercially available, a parallel high-speed MCF transmission is conducted using novel tapered multicore connectors (TMCs) to couple signals into and out of MCF, and commercially available 850-nm VCSELs and PIN as the transmitters and receivers, respectively. For the first time, they demonstrated a total 70-Gb/s (7 10-Gb/s) transmission over 100 m of single multicore MMF for parallel optical data links. In order to demonstrate large bandwidth of this MCF, an experiment of 7x10Gb/s transmission over 550 m of seven-core MMF are also described.

In this paper we present a MMF based optical link that utilizes the modes of fiber to transmit the parallel stream of data. The n data stream increases the data rate n times which result in high capacity. The linearly polarized modes are used for transmission of data. The bending induced coupling is also considered in the optical link.

5.2 Theory

Despite the limitations, from an information theoretic viewpoint, MMF has greater capacity than its single-mode counterpart, provided one can exploit the various modes as independent communication channels. A MIMO approach where modal dispersion is exploited, rather than avoided, is a promising solution. Note that for a long time the multipath nature of wireless channels was viewed as a limiting factor to be avoided. In recent years it has been realized that the multipath nature of a channel can actually enhance throughput if it is properly exploited. If each guiding mode is regarded as a scattering path, MMF behaves similar to a wireless channel with rich multipath scattering. A similar approach could hold for the multimode nature of fiber links; it can be exploited for capacity improvement, rather than being avoided. Based on this analogy, the concept of multiple-input multiple-output (MIMO) transmission used in wireless communications can be applied to MMF channels. The feasibility of MIMO transmission over fiber has already been demonstrated in [61,62] for a 2×2 system.

Unlike in SMF, where the frequency response falls steadily toward zero, the frequency response of multimode fiber contains high-frequency components. Since the impulse response of MMF consists of a number of impulse functions that correspond to the individual modes separated in time, the Fourier transform or frequency response must contain nonzero high-frequency components. This behavior can be understood by considering the time-domain response of the fiber to a short input pulse. Such a pulse will break up into a series of pulses as different modes propagate through the fiber at different speeds. This will result in a series of pulses of various amplitudes at the output depending on the differential mode delay and mode coupling properties of the fiber. A Fourier transform of the resulting pulse train provides the frequency response, which exhibits a strong falloff near dc as the slowest and fastest modes interfere at the receiver.

The 3-dB point gives the baseband bandwidth of the fiber. Above the 3-dB bandwidth, the response is mainly determined by the dispersion between the higher order modes. Therefore, at higher frequencies, there are many delayed pulses that can interfere with one another

corresponding to transmission of the large number of higher order modes that have similar propagation times. This leads to a smoothing effect in the frequency response at such frequencies, with some background loss, giving rise to a pass band region suitable for data transmission.

5.4 System setup

The 5x100 Gbps data transmission using graded index multimode fiber over 50 km optical link system setup requires a MIMO system which is further coupled to a multimode mode fiber using multimode coupler. The system also includes design and simulation of optical coupler along with bending induced coupler. The different configurations of all these components are used to have acceptable output from the system. The system presented in this project mainly consists of a MIMO, non-ideal multimode couplers and multimode fibers. The MIMO system is having five transmitters. Each transmitter consist of continuous wave laser source, a binary source have bit rate of 10^9 bits/sec, NRZ driver, a differential Mach-Zander modulator and attenuator. Figure 5.1 shows the transmitter section of the setup.

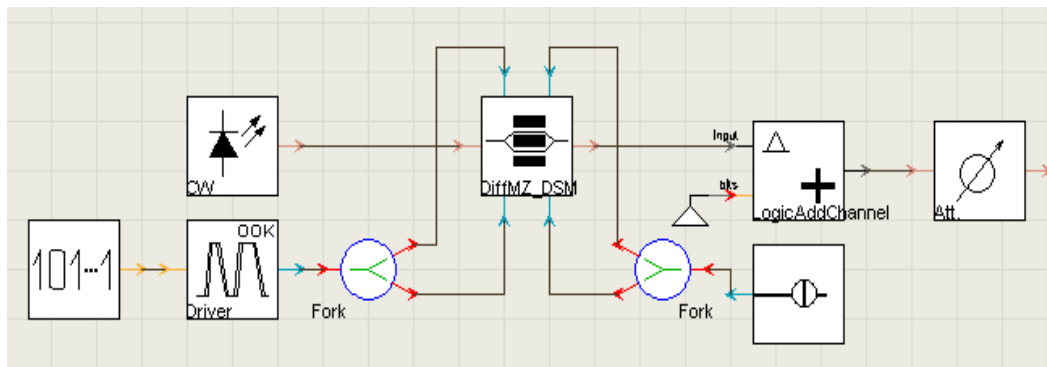


Fig. 5.1 Optical transmitter.

The complete system setup is shown in the figure 5.2. The five transmitter are coupled to MMF with the help of MMF coupler. The input signals are coupled through a bus merge along with noise source. The noise is AWGN. The coupler causes non ideal coupling of sources to the multimode fiber. This result in formation of new modes and coupling ratio defines the transfer of energy from high energy mode to other modes. . Each transmitter section consists of the data source, electrical driver, laser source and Mach-Zehnder (MZ) modulator. The data source is a NRZ format at 10Gb/s bit rate. The On-Off Keying (OOK)

driver module generates an electrical signal for driving lasers and modulators. The continuous wave laser source generates the laser beam at a frequency of 193.1 THz. The input data source modulates the laser beam by using an MZ modulator. The output of the modulator is fed to non-ideal multimode fiber coupler. The coupler couples the incoming MZ modulated signal to multimode fiber. The different various modes travel through the multimode fiber. At receiver side the optical band pass filter (OBPF) is used to select the desired range for detection of the optical signal. The OBPF is centered at 193.1THz. The PIN detector is used for converting the optical signal into electrical signal and it is followed by a LPF and signal analyzer. The signal analyzer is used for observing the eye diagram, receiver power and also for calculating BER.

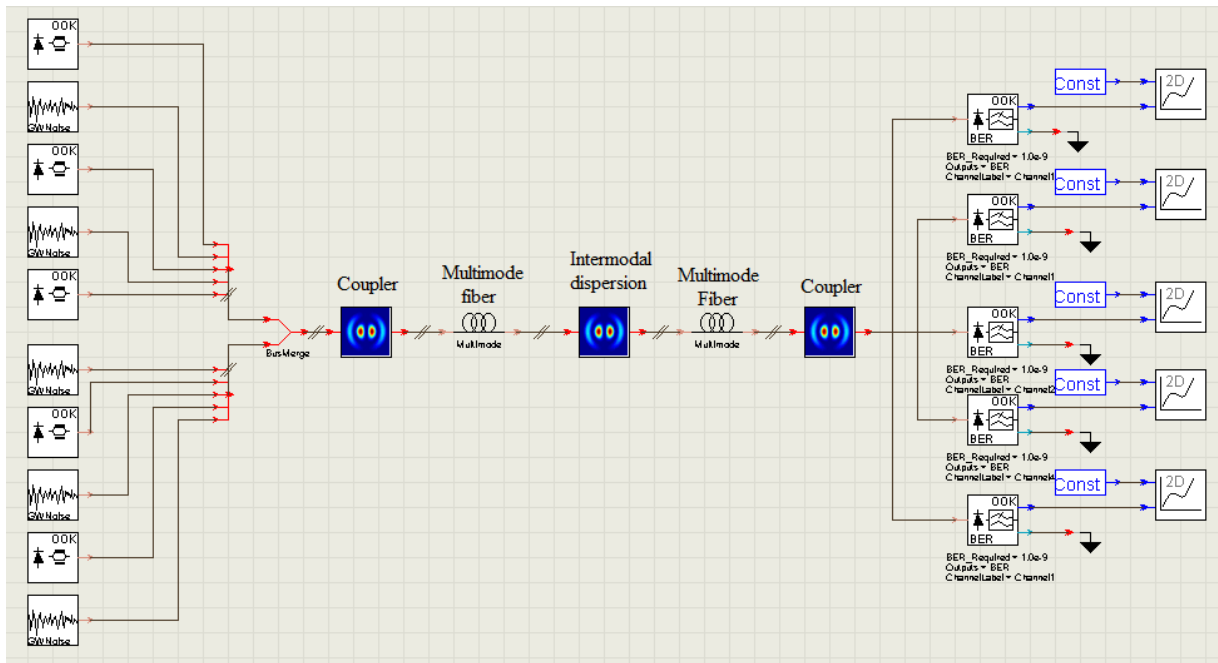


Fig. 5.2 complete system setup for 5x100 Gbps optical link

The CW laser is used in this model. The parameters for CW laser are: emission frequency 193.1 THz, CW average power 1 mW, line width 10 MHz, noise threshold -100 dB and initial phase of 0 degree, The MZ modulator module simulates a Mach-Zehnder modulator and can also handle the frequency chirp resulting from the modulator asymmetry. The simulated bit rate is 10Gb/s with pseudorandom binary sequence. The multimode fiber has average group refractive index of 1.48, the attenuation is 0.2e-3 dB/m and core refractive

index is 1.45 with core diameter of 50 μ m. The responsivity of the PIN detector is 1 A/W, and zero dark current (approx.).

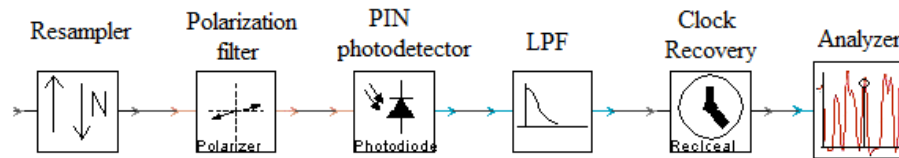
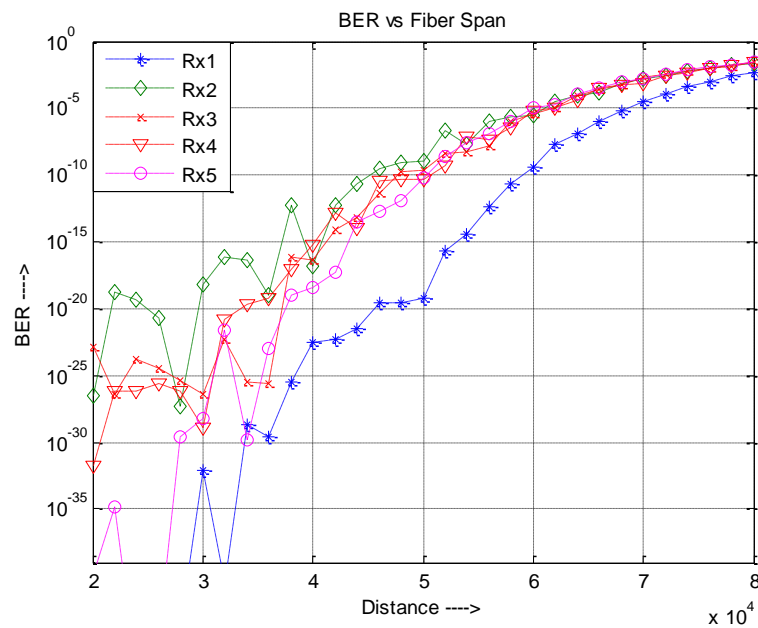


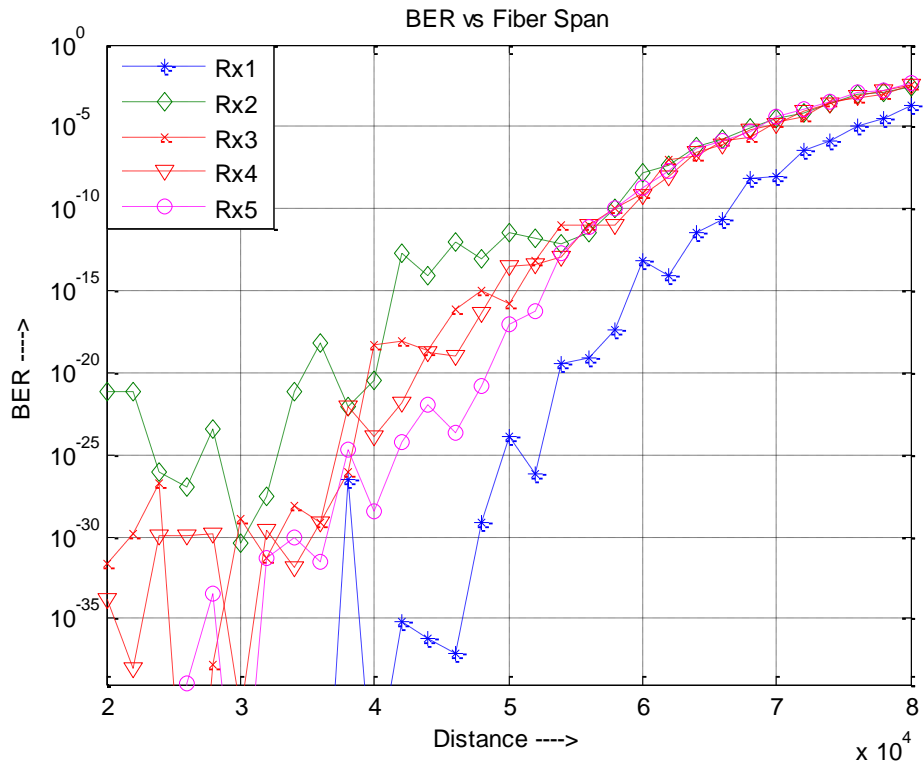
Fig. 5.3 Receiver section

5.5 Results and discussion

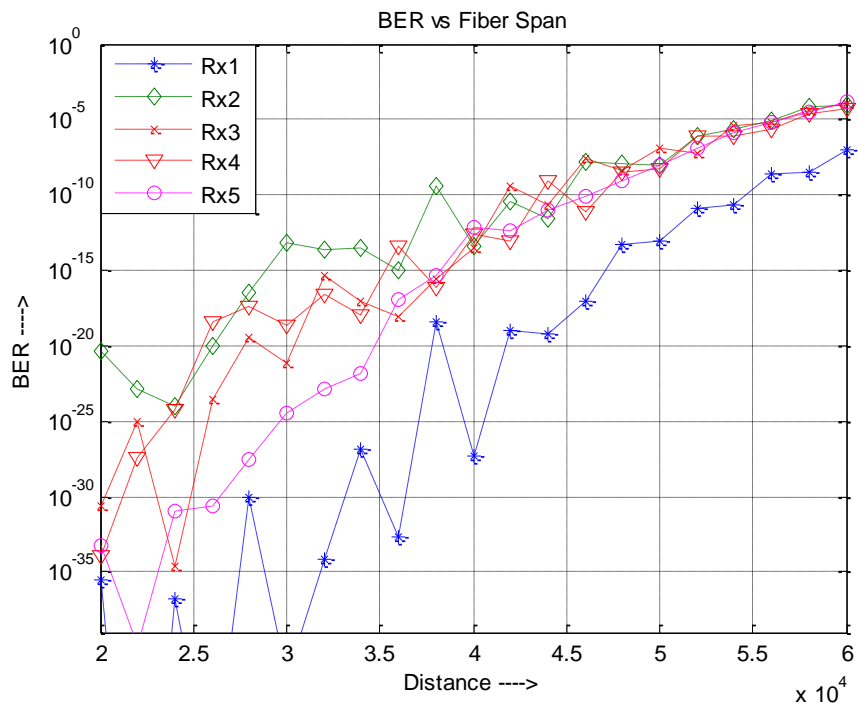
The performance of 5x100 Gbps data transmission using graded index multimode fiber over 50 km optical link is determined by transmitter and receiver diversity technique. The different data rate are tested for better BER, received power and eye diagram for different fiber span. The coupling between the different modes of multimode fiber is a critical parameter which changes the BER of the system. The BER versus Received power curve is plotted for different data rates. Fig. 5.4 shows the BER versus Rx power curve for various data rate using 5x5 MIMO system with linearly polarized transmitter.



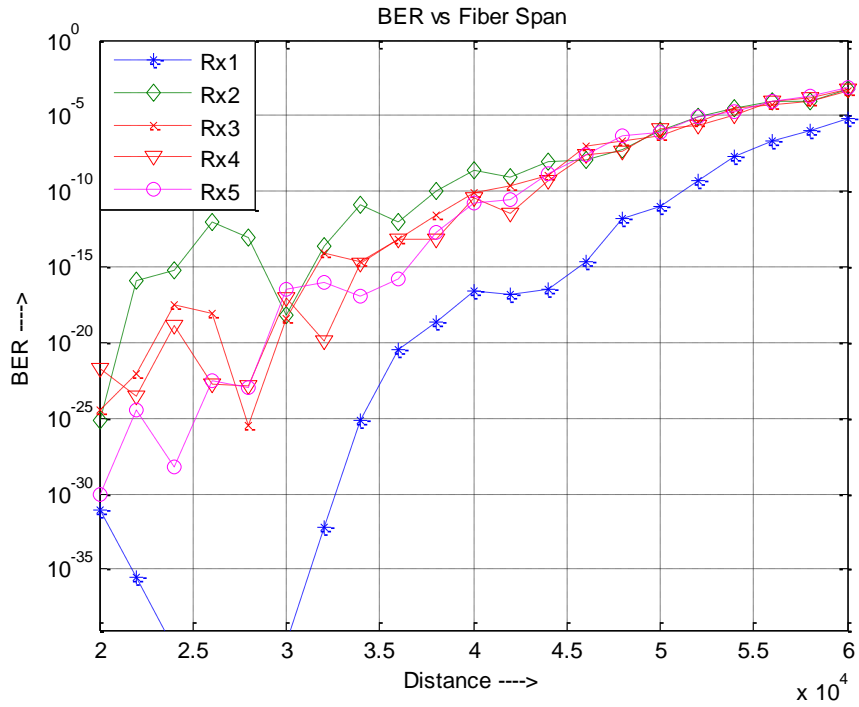
(a)



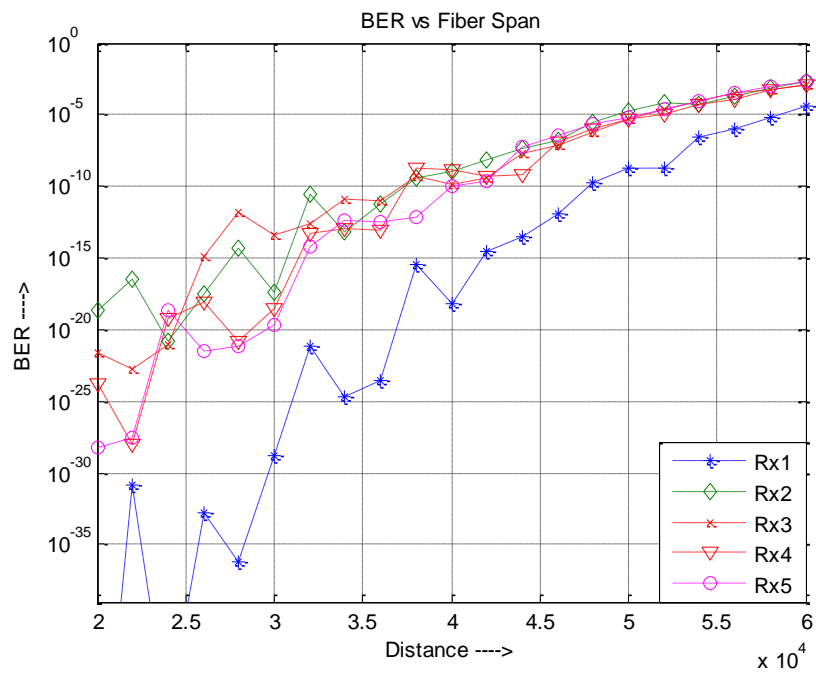
(b)



(c)



(d)



(e)

Fig. 5.4 BER v/s Fiber span for (a) 20Gbps (b) 40Gbps (c) 60 Gbps (d) 80Gbps (e)100Gbps

The results shows that as the data rate increases the maximum fiber length starts decreasing the figure from 5.4(a) to 5.4(e) shows the variation in the BER of the receiver as the data rate increases from 20Gbps to 100Gbps.

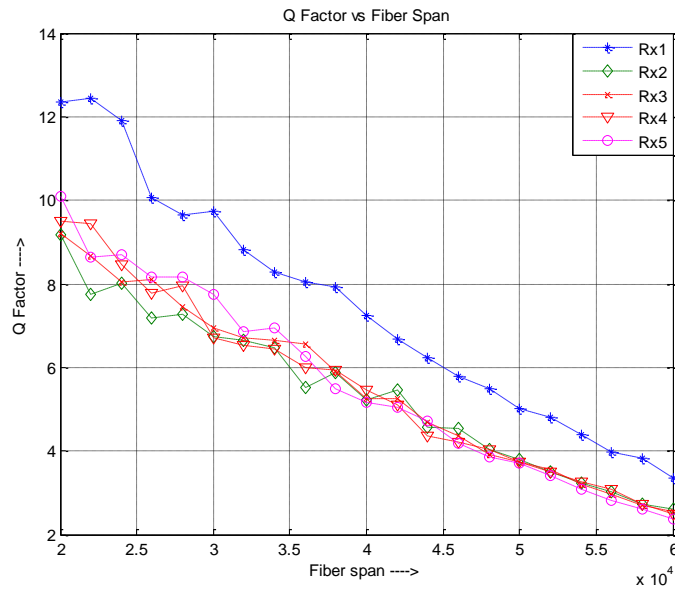


Fig. 5.5 The Q factor versus Fiber span for data rate of 100Gbps

The figure 5.5 shows the Q factor variation with the change in fiber span for a data rate of 100Gbps. The result shows that first mode in having highest Q factor. The Q factors of all other modes are quite similar to each other.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

This chapter provides the summary of the research work done in thesis. First the conclusion has been made from the result obtained and then recommendation for the future researches has been discussed. The obtained result can be summarized in the following point

1. In chapter the performance of optical multi input multi output (MIMO) using multimode fiber is analyzed. The two configurations of MIMO MMF system, 3x3 and 5x5 is introduced and the bending induced coupling is considered for the system robustness. The multimode fiber offers a high degree of spatial diversity that can be utilized for better performance of optical link. It is observed that the 3x3 MIMOMMF optical link performs better even when the bending induced coupling is higher as compared to 3x3 MIMO MMF optical link with smaller bending induced coupling. On the other hand 5x5 is more sensitive to bending induced coupling and performance better for smaller values of bending induced coupling.

Recommendation

The MIMO MMF system can be beneficial for cheaper and medium range of applications. For smaller number of users the 3x3 MIMO preferable. The 5x5 MIMO MMF is suitable for the case where chances of bending induced coupling are very much. The presence of coupling between the modes can degrade the performance of the system.

2. In chapter 4 linearly polarized modes are used to increase the capacity of the MMF. The conventional method uses LP modes in continuity which results in intermodal interference due to strong mode coupling modes. We investigate the performance of the system by transmitting only alternate LP. The LP modes are divided into even and odd groups. Results show that the performance of the system improves in LP modes are selected alternatively. The even include LP_{01} , LP_{21} , LP_{31} , LP_{41} and LP_{03} modes and the odd modes use LP_{01} , LP_{21} , LP_{31} , LP_{41} and LP_{03} modes. The results of both groups are better than system which uses

modes in continuity. The results show that maximum length that can be achieved is up to 78km with the BER value of 10^{-5} and for the BER value of 10^{-9} the length reduces to 66km.

Recommendation

The use of alternate LP mode can improve the system performance as compare to conventional LP modes selection. The BER value is less sensitive to the even and odd LP modes. The system can be easily scaled and can be scaled down. For medium size this system can be used for optical fiber link.

3. In this paper the data rate capacity of the MMF in analyzed with the help of 5x5 MIMO transreceivers. The transmitter uses five linearly polarized modes for transmission of the data on MMF. Each data path increases the data carrying capacity of MMF. The result shows that at the data rate of 20Gbps the maximum fiber length with 5x5 MIMO system is up to 60km with a BER of 10^{-5} . As the data rate increases the intermodal coupling cause power transfer from one modes to another inside the MMF. The results also shows that maximum optical fiber link reduces to 50km at the data rate of 100Gbps

Recommendation

The MIMO with LP modes is suitable for high data rate application. Five transmitters with each having a data rate of 100Gpbs can cover a distance of 50km. The intermodal coupling transfer the power in between the modes of the MMF. The BER threshold for MMF is 10^{-5} .

6.2 Future Scope

During the course of this thesis, several avenues for the continuation of this study become evident. In work we our prime objective is to design and develop a MIMO MMF based system that can support high data rate. The linear polarized modes are utilized to fulfill the current requirement. The various system parameters like BER, Received optical power, eye diagram, Q factor etc. are taken into consideration while analyzing the system performance.

However there are some other parameters involved in the system design that can further improve the system design. In this system only first 10 LP modes are taken into consideration. The higher order LP modes can be used to design a system with high data rate.

In transmission section only one type of modulation format is used. Further the power of transmitter is held constant. The transmitter parameters highly affect the system results. A high power transmitter can increase the total link and also improves the BER of the system. The receiver design can be improved with the use of optical and electrical filter as per need of the application in hand. This work does not include any combining technique at the receiver side. This can be helpful in improving the system. The nonlinearity in MMF are somewhat different in real world. The practical implementation can leads to improved system for optical transmission systems.

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