PERFORMANCE OF A CPDM-QPSK COHERENT HOMODYNE OPTICAL TRANSMISSION SYSTEM DUE TO CROSS POLARIZATION EFFECTS

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

BACHELOR OF SCIENCE
IN
ELECTRICAL, ELECTRONIC AND COMMUNICATION ENGINEERING

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December, 2017

DECLARATION

This is to certify that the work presented in this paper titled **"Performance of a CPDM-QPSK Coherent Homodyne Optical Transmission System Due to Cross Polarization Effects"** is the yield of study, analysis, simulation and research work carried out by the undersigned group of students of Electrical, Electronic and Communication Engineering (EECE),Military Institute of Science and Technology, Mirpur Cantonment, under the supervision of **Dr. Satya Prasad Majumder**, Professor, Dept. of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology (BUET).

It is hereby declared that this thesis work or any part of this has not been submitted elsewhere for the award of any degree, diploma or other qualifications.

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This thesis work titled **“Performance of a CPDM-QPSK Coherent Homodyne Optical Transmission System Due to Cross Polarization Effects”** is submitted by the group as mentioned below, has been accepted as satisfactory in partial fulfillment of the requirements for the degree B.Sc. in Electrical ,Electronic and Communication Engineering (EECE) for LEVEL-4 TERM-1&2 on December,2017.

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DEDICATION

To Our Beloved Parents

ACKNOWLEDGEMENT

We are highly grateful and indebted to our supervisor, **Dr. Satya Prasad Majumder**, Professor, Department of Electrical Electronic Engineering, Bangladesh University of Engineering & Technology (BUET), for his continuous guidance, supervision, encouragement and untiring support throughout this work.

Additionally, we would like to express our sincere thanks to all other Teachers and staffs of the Department of Electrical, Electronic & Communication Engineering, Military Institute of Science & Technology (MIST) for their co-operation and help in the successful completion of this work.

Our thanks would also go to our beloved family for their prayer, encouragement and support to achieve our goals.

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ABSTRACT

An analytical development on a Circular Polarization Division Multiplexing (CPDM) Quadrature Phase Shift Keying (QPSK) based optical transmission system with coherent homodyne detection is carried out in order to maximize the spectral efficiency of Fiber Optic transceivers by assessing the Bit Error Rate (BER) performance of the system considering the crosstalk induced by cross-polarization (XPol). Considering Maxwell-Boltzman distribution for the probability distribution function (pdf) of the misalignment angle, the average BER is derived. This analysis is extended to find the BER and Signal to Crosstalk plus Noise Ratio (SCNR) considering the power penalty due to different mean misalignment angle. Results show that the system suffers significant deterioration in BER performance and power penalty due to XPol-induced crosstalk. Penalty in signal power is found to be 6.43, 16.78, 31.99 and 76.99 dB for mean misalignment angle of 20, 30, 40 and 60 degree respectively. CPDM inherently operates QPSK to increase the bit rate within the same spectral width of the transmitter. So, the outcome of this research can be an effective candidate to upgrade the design of the existing optical polarization diversity PDM coherent transmission systems.

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LIST OF ABBREVIATIONS

FM	Frequency Modulation
FSK	Frequency Shift Keying
ASK	Amplitude Shift Keying
PSK	Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
FDM	Frequency Division Multiplexing
TDM	Time Division Multiplexing
WDM	Wavelength Division Multiplexing
PDM	Polarization Division Multiplexing
LPDM	Linear Polarization Division Multiplexing
CPDM	Circular Polarization Division Multiplexing
XPol	Cross Polarization
BER	Bit Error Rate
SNR	Signal to Noise Ratio
SCNR	Signal plus Crosstalk to Noise Ratio
LCP	Left Circular Polarization
RCP	Right Circular Polarization
PBS	Polarization Beam Splitter
CPBS	Circular Polarization Beam Splitter
SOP	State of Polarization
SE	Spectral Efficiency
DSP	Digital Signal Processing
MZ	Mach-Zehnder
MZI	Mach-Zehnder interferometer
LED	Light Emitting Diode
LD	Laser Diode
LO	Local Oscillator

IEEE	Institute of Electrical and Electronics Engineers
ETSI	European Telecommunications Standards Institute
NEXT	Near-End Crosstalk
FEXT	Far-End Crosstalk
PSNXT	Power-Sum-Near-End Crosstalk

LIST OF SYMBOLS

ϕ	Phase Shift of electric field
E_0	Electric field of output signal
E_S	Electric field of incoming signal
E_{LO}	Electric field of local oscillator
λ	Wavelength
$\Delta\phi$	Phase difference
A_S	Incoming Signal Amplitude
A_{LO}	Local Oscillator Signal Amplitude
ω_S	Incoming Signal frequency
ω_{LO}	Local Oscillator Signal frequency
S_{RCP}	Right Circular Polarized Signal
S_{LCP}	Left Circular Polarized Signal
E_{RCP}	Right Circular Polarized Electric field
E_{LCP}	Left Circular Polarized Electric field
R_d	Responsivity of the photo-diode
I	Balanced detector output photo current
η	Quantum efficiency

h	Planck's constant
ε_F	Complex fading co-efficient
ε_x	Complex crosstalk fading co-efficient
θ	Random misalignment angle
θ_m	Random mean misalignment angle
v	Operating frequency
$I_{xtalk,A}$	Crosstalk Current from Receiver A
$I_{sig,A}$	Signal Current from Receiver A
σ^2_{noise}	Total Noise Power
$\sigma^2_{thermal}$	Thermal Noise Power
σ^2_{shot}	Shot Noise Power
B	Bandwidth
T	Temperature
a_{odd}	Right Circular Polarized odd bit
a_{even}	Right Circular Polarized even bit
b_{odd}	Left Circular Polarized odd bit
b_{even}	Left Circular Polarized even bit

CHAPTER 1

INTRODUCTION

INTRODUCTION

Now we are in the twenty first century, the era of ‘Information technology’. There is no doubt that information technology has had an exponential growth through the modern telecommunication systems.

Optical circular polarization division multiplexing (CPDM) networks are very promising due to their large flexibility, spectral efficiency and the possibility to upgrade the existing optical fiber networks. We present an analytical approximation for the total crosstalk level in CPDM-QPSK coherent homodyne transmission system, which makes the component parameter optimization considerably easier.

1.1 Introduction to Optical Communication

Communication may be defined as the transfer of information from one point to another. Optical fiber is the backbone of the modern communication networks. Optical communication is the method of transmitting information from one point to another by using light as a transmission medium.

An optical communication system consists of a transmitter which encodes a message into an optical signal, a channel which carries the signal to its destination and a receiver which reproduces the message from the received optical signal. A receiver uses a photocell or photodiode to detect the light.

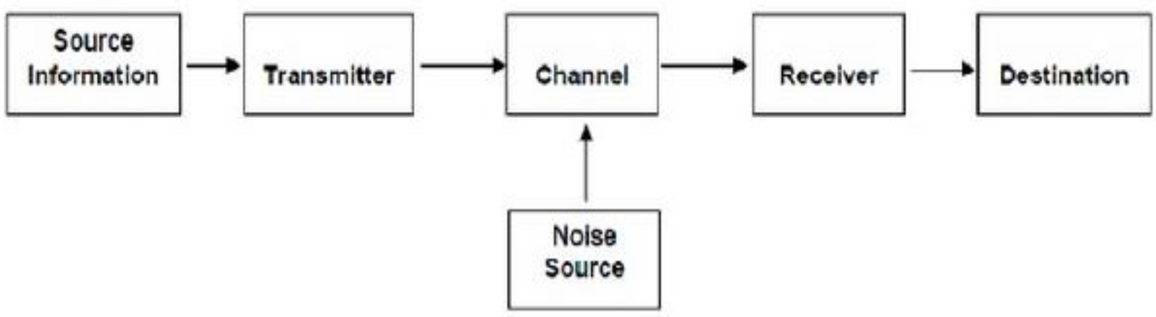

Fig 1.1: Basic block diagram of optical communication system

1.2 The History of Optical Communication

Our current “age of technology is the result of many brilliant inventions and discoveries. Optical communication has been used for thousands of years although optical physics were not understood in ancient times. The Greeks used fire and smoke signals for sending information in 800 BC. In 1790, Semaphore for telecommunication on land was invented by Claude Chappe of France. Daniel Colladon and Jacques Babinet first introduced fiber optics in Paris in the early 1840s. It was developed for the image transmission through fiber bundles. Alexander Graham Bell and Sumner Tainter invented photo-phone in which optical beam was used for the transmission of voice signals in 1880.In 1960, Theodore Maiman invented Laser for unguided optical transmission. In 1966, kao exhibited transmission of light through optical fiber.

1.3 Optical Fiber

When people talk about optical communication in the 21st century, they are referring to optical fibers. Information revolution wouldn’t have happened without optical fiber. An optical fiber is the boon of optical fiber. Optical fiber is a flexible, transparent fiber made from silica (glass) it is thin as human hair. It confines electromagnetic energy in the form of light and guides the light in a direction parallel to its axis.

Transmission is done by the process of Total Internal reflection in the core of optical fiber. This causes the fiber to act as a wave. Light signal degrades within the fiber. Signal degrades depends on the purity of the glass and the wavelength of the transmitted signal.

Joining length of optical fiber is more complex than joining electrical wire or cable. The ends of the fibers must be carefully cleaved and then spliced together either mechanically or by fusing them together with an electrical arc.

Optical fiber is the backbone of the modern communication networks. Optical fibers have wider range of application in almost all fields.

A renewed interest in optical communication was stimulated in the early 1960s with the invention of the laser.

1.4 Different Types of Optical Fibers

Based on the refractive index profile we have two types of fibers:-

a) **Step index fiber:** The refractive index of the core is constant and is larger than the refractive index of the cladding. It makes a step change at the core cladding interface as indicated in the figure.

b) **Graded index:** In fiber optics, a graded index is an optical fiber whose core has a refractive index that decreases with increasing radial distance from the optical axis of the fiber. Graded-index fibers have bandwidths which are significantly greater than step-index fibers, but still much lower than single-mode fibers.

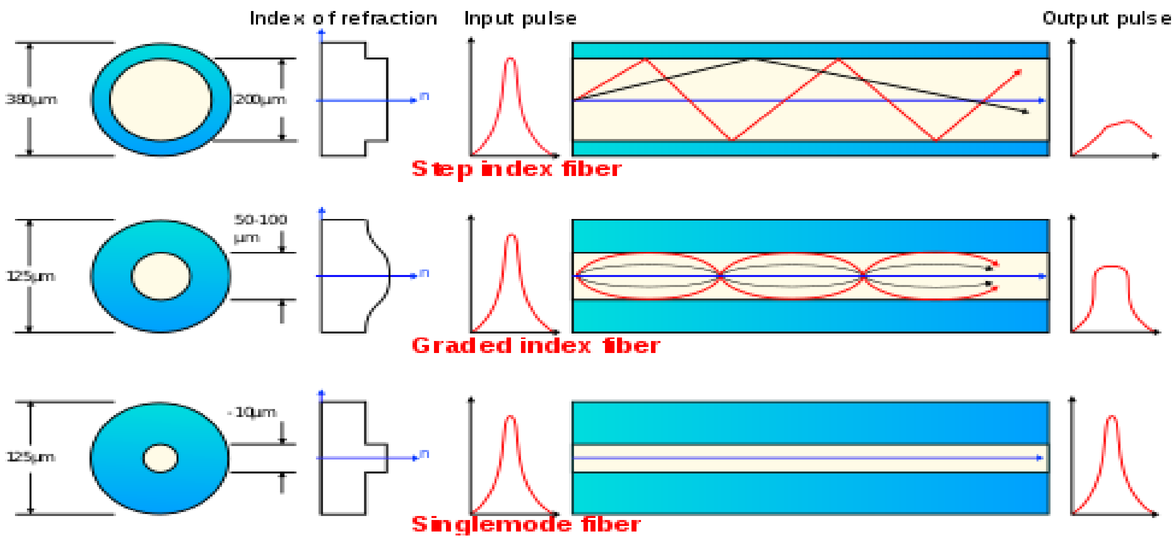

Fig 1.2: Different types of fibers

Mode:

There are another two basic types of fiber on the basis of mode. They are:

1) multimode fiber and
2) single mode fiber.

Multimode Fiber:

Each optical fiber in a multi-mode cable is about 10 times bigger than one in a single-mode cable. Multimode fiber is best designed for short transmission distances, and is suited for use in LAN systems and video surveillance. Inter modal delay causes dispersion in multimode fiber. It has bigger diameter about 50-100 µm and typically 62.5µm. Multimode Step index fiber is suitable for short distance (endoscope). Multimode graded index suitable for medium distance (LAN).

Single-mode Fiber:

The simplest type of optical fiber is called single-mode. It has a very narrow diameter about 5-10 microns. One path is used for one ray of light in single-mode. No modal delay in single-mode fiber. Single mode fiber is used for long haul and 50 times more distance than Multimode(MM).Distortion/ dispersion is less in single mode but cost is more than MM. It is suitable for long-distance telephony and multichannel television broadcast systems.

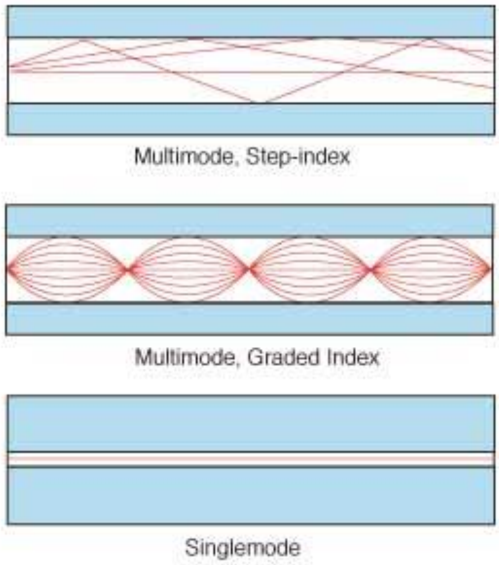

Fig 1.3: Different types of mode

1.5 Merits of Optical Fiber Communication

1. Wider bandwidth: The information carrying capacity of a transmission system is directly proportional to the carrier frequency of the transmitted signals. The optical carrier frequency range yields the far greater transmission bandwidth than the metallic cable system.

2. Low transmission loss: Due to the usage of the ultralow loss fibers and the erbium doped silica fibers as optical amplifiers, one can achieve almost lossless transmission.

3. Less signal degradation: The loss of signal in optical fiber is less than in copper wire.

3. Dielectric waveguide: Optical fiber made from silica or sometimes a plastic polymer which is an electrical insulator. It is also suitable in explosive environments. Further the optical fibers are not affected by any interference originating from power cables, railway power lines and radio waves.

4. Signal security: The transmitted signal through the fiber does not radiate. Therefore they provide a high degree of signal security. So it is widely applicable in military, banking and other secure networking.

5. Small size and weight: Optical fibers have very small diameters which are often no greater than the diameter of a human hair.

6. Long-distance signal transmission: The low attenuation and superior signal integrity found in optical systems allow much longer intervals of signal transmission than metallic-based systems. While single-line, voice-grade copper systems longer than a couple of kilometers (1.2 miles) require in-line signal for satisfactory performance, it is not unusual for optical systems to go over 100 kilometers (km), or about 62 miles, with no active or passive processing.

1.6 Optical Digital Modulation

When the information-bearing message signal is discrete-time digital, then the modulation is called digital modulation. Most commonly used digital modulations are:

a) Frequency Shift Keying (FSK)

FSK is similar to standard frequency modulation (FM) except the modulating signal is a binary signal that varies between two discrete voltage levels rather than a continuously changing analog waveform. If the frequency (f) is varied proportional to the information signal, frequency shift keying (FSK) is produced. FSK has the advantage of being very simple to generate, simple to demodulate. Significant disadvantages are the poor spectral efficiency and BER performance.

b) Amplitude Shift keying (ASK)

Amplitude Shift Keying (ASK) is a form of digital modulation that represents digital data solely as variations in the amplitude of a carrier signal. Since noise affects the amplitude of a signal, ASK is highly susceptible to noise interference, fading, and electromagnetic induction. ASK is also most susceptible to the effects of nonlinear devices, which compress and distort the signal's amplitude. It is rarely used on its own.

c) Phase Shift Keying (PSK)

If the phase of the carrier (0) is varied proportional to the information signal, phase shift keying (PSK) is produced. PSK is often used as it provides a highly bandwidth efficient modulation scheme.

d) Quadrature Phase Shift Keying (QPSK)

Quadrature phase shift keying (QPSK) is another modulation technique, and it's a particularly interesting one because it actually transmits two bits per symbol. In other words, a QPSK symbol doesn't represent 0 or 1—it represents 00, 01, 10, or 11. In QPSK, the carrier varies in terms of phase, not frequency and there are four possible phase shifts. QPSK is advantageous in terms of bandwidth efficiency. QPSK has twice bandwidth efficiency than BPSK.

QPSK Transmitter:

The QPSK Modulator uses a bit-splitter, two multipliers with local oscillator, a 2-bit serial to parallel converter, and a summer circuit. Following is the block diagram for the same. At the modulator's input, the message signal's even bits (i.e., 2^{nd} bit, 4^{th} bit, 6^{th} bit, etc.) and odd bits (i.e., 1st bit, 3^{rd} bit, 5^{th} bit, etc.) are separated by the bits splitter and are multiplied with the same carrier to generate odd BPSK and even BPSK.

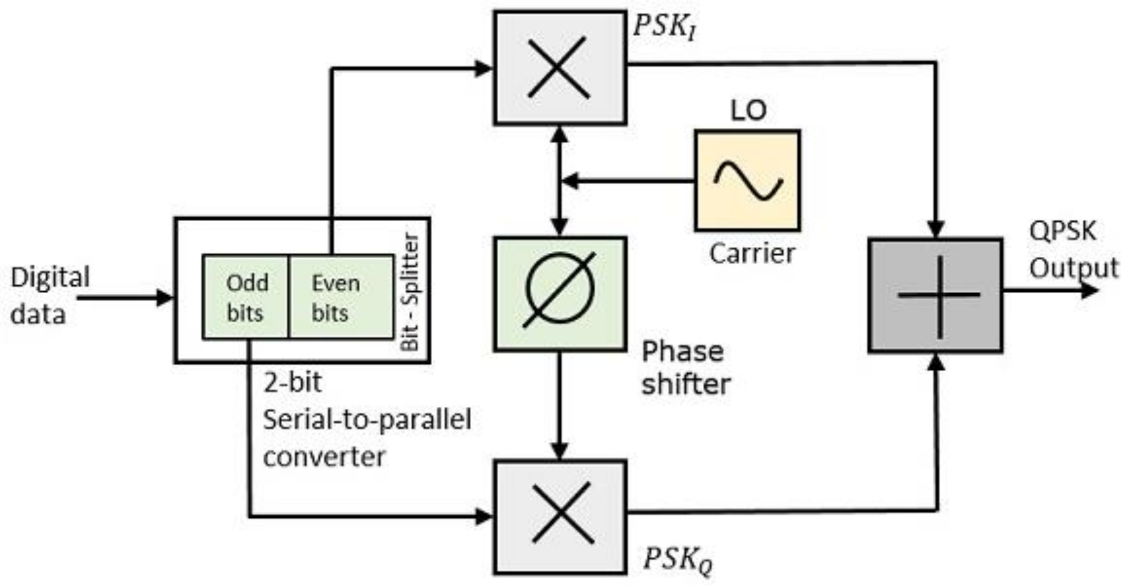

Fig 1.4: Quadrature Phase Shift Keying (QPSK) transmitter

QPSK Receiver/Modulator:

The QPSK Demodulator uses two product demodulator circuits with local oscillator, two band pass filters, two integrator circuits, and a 2-bit parallel to serial converter. Following is the diagram for the same.

The two product detectors at the input of demodulator simultaneously demodulate the two BPSK signals. The pair of bits is recovered here from the original data. These signals after processing are passed to the parallel to serial converter.

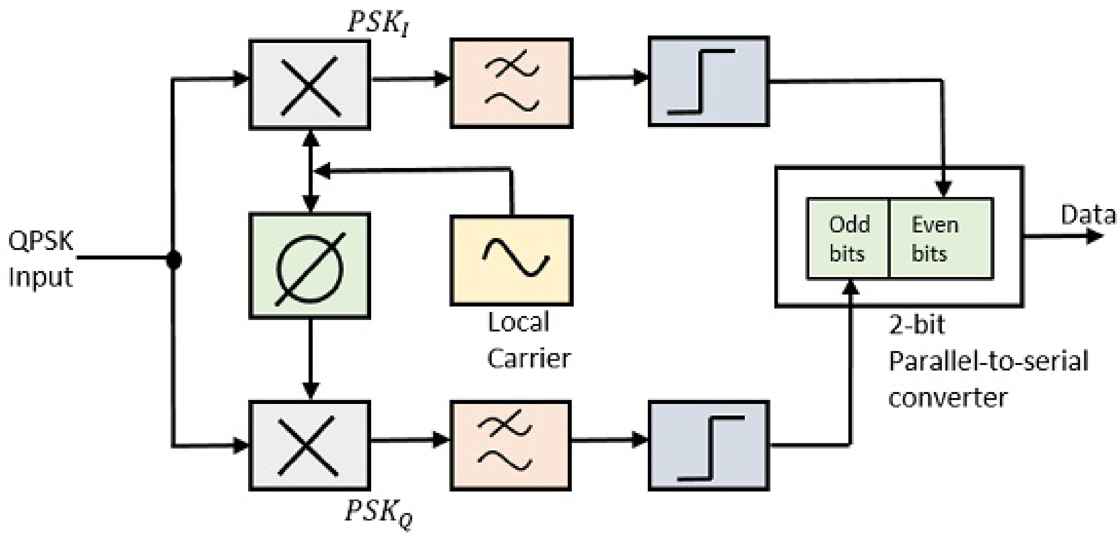

Fig 1.5: Quadrature Phase Shift Keying (QPSK) receiver

1.7 Optical Multiplexing Schemes

1.7.1 Frequency Division Multiplexing (FDM)

It is analog multiplexing technique. Signal of different frequencies are combined into a composite signal and transmitted on a single line. Bandwidth of a link should be greater than the combined bandwidths of the various channels. Each signal is having different frequency. Channels are separated by the strips of unused bandwidth called Guard Bands (to prevent overlapping).

Traditional terrestrial microwave and satellite links employ FDM. Although FDM in telecommunications is being reduced, several systems will continue to use this technique, namely: broadcast & cable TV, and commercial & cellular radio. FDM is not sensitive to propagation delay. Frequency synchronization is necessary.

1.7.2 Time Division Multiplexing (TDM)

It is the digital multiplexing technique. Channel/Link is not divided on the basis of frequency but on the basis of time. Total time available in the channel is divided between several users. Each user is allotted a particular time interval called time slot or slice. In TDM the data rate capacity of the transmission medium should be greater than the data rate required by sending of receiving devices.

The user gets full bandwidth of the channel in a particular time slot. But it is not much suitable for continues signals. Time synchronization is necessary.

1.7.3 Wavelength Division Multiplexing (WDM)

WDM is conceptually same as the FDM, except that the multiplexing and demultiplexing involve the light sources transmitted through fiber optic channels. In optical fiber communication, wavelength division multiplexing (WDM) is a technology which multiplexes multiple optical carrier signals on a single optical fiber by using different wavelengths (colors) of laser light to carry different signals. This allows for multiplication in capacity, in addition to enabling bidirectional communications over one stand to fiber.

The term wavelength division multiplexing is commonly applied to an optical carrier, whereas frequency division multiplexing typically is applied to a radio carrier.

1.7.4 Polarization Division Multiplexing (PDM)

One optical technique used to improve the efficiency of optical communication system is polarization division multiplexing (PDM). The use of PDM permits multiplying the transmission capacity, as different signals can be transmitted over orthogonal states of polarization of the same light. PDM is generally used in conjunction with advanced channel coding techniques, allowing the use of digital signal processing to decode the signal in a way that is resilient to polarization-related signal artifacts. PDM is generally used in conjunction with QPSK and DQPSK.

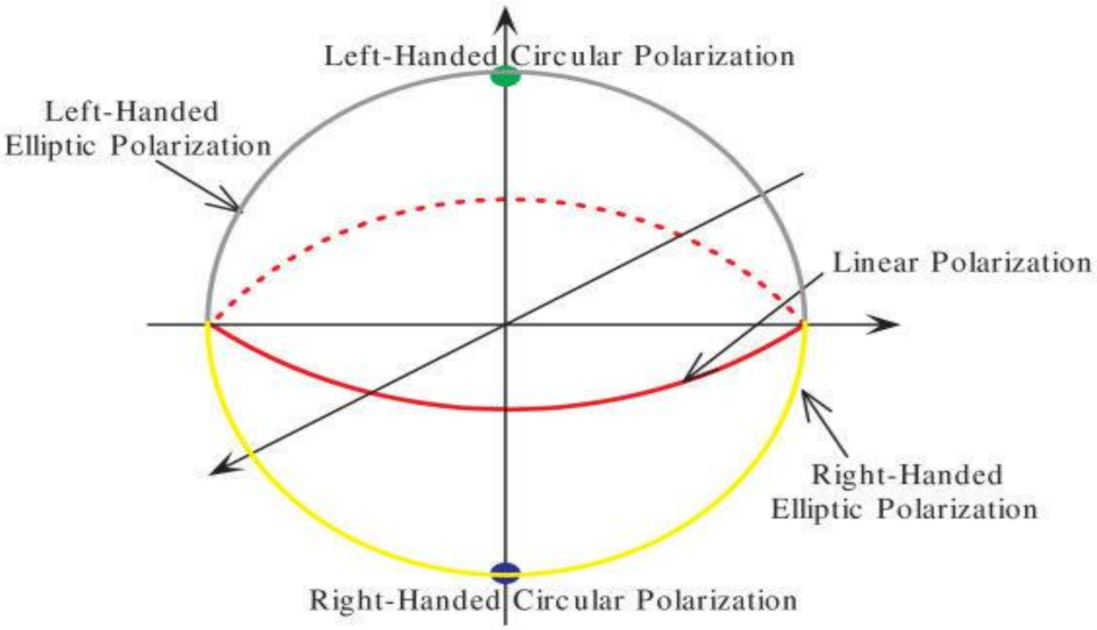

Fig 1.6: Polarization representation in Poincare-Sphere form

What if the components of the electric field are not in phase? First suppose the have the same magnitude but are a quarter wavelength out of phase, so

$$\varphi_X - \varphi_Y = \frac{\pi}{2}$$

Then,

$$\vec{E}_0 = \left(E_0, E_0 e^{i\frac{\pi}{2}}, 0 \right) = \left(E_0, iE_0 e^{i\frac{\pi}{2}}, 0 \right)$$

$$\vec{E} = \left(E_0 e^{i(kz-wt)}, iE_0 e^{i(kz-wt)}, 0 \right) \tag{1.1}$$

Taking the real part gives the actual electric field

$$\mathrm{Re}\left[\vec{E} \right] = \left(E_0 \cos(kz - wt), -E_0 \sin(kz - wt), 0 \right) \tag{1.2}$$

This is called left-handed circularly polarized light.

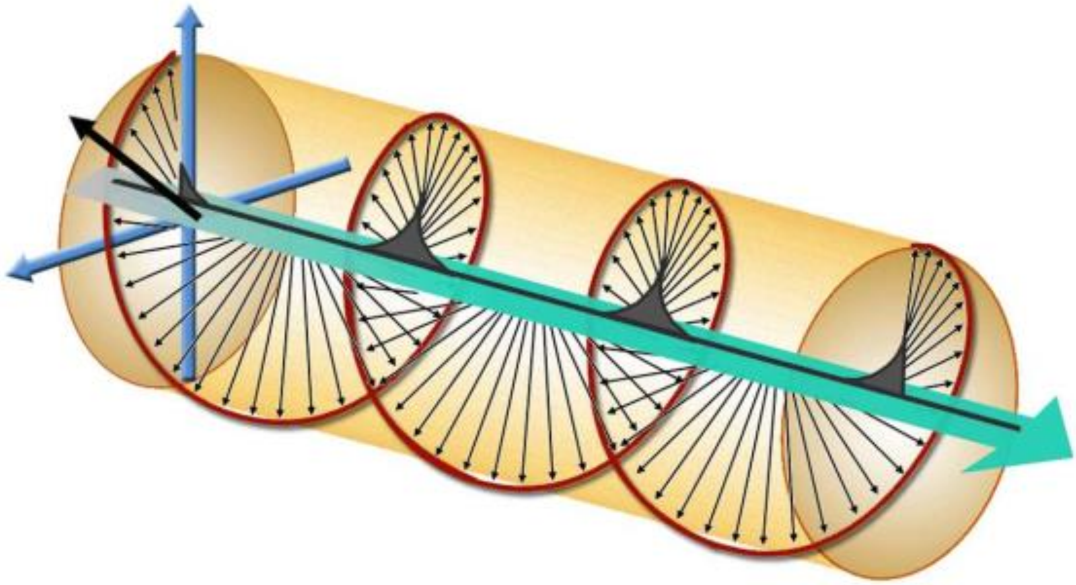

Fig 1.7: Circularly polarized light changes the direction of its polarization as it moves

Similarly, taking $\varphi_X - \varphi_Y = -\frac{\pi}{2}$ gives $\vec{E}_0 = (E_0, -iE_0, 0)$

$$\mathrm{Re}\left[\vec{E}\right] = \left(E_0 \cos(kz - wt), E_0 \sin(kz - wt), 0\right) \tag{1.3}$$

Which is right-handed circularly polarized light. In this case, at t = 0 and kz=0, the polarization points in the $\hat{x}$ direction. A quarter wave length farther, it points in the $\hat{y}$ direction, and so one. So this field rotates counterclockwise in the x-y plane. Note that when we add left and right handed polarizations we get

$$\vec{E}_0 = (E_0, iE_0, 0) + (E_0, -iE_0, 0) \tag{1.4}$$

Which is linearly polarized in the $\hat{x}$ direction. Similarly, subtracting them gives linear polarization in the $\hat{y}$ direction. Thus circular and linear polarizations are not linearly independent. Indeed, any possible polarization can be written as a linearly combination of left-handed and right-handed circularly polarized light.

Circularly polarized light has angular momentum $\pm e_0 \left|\vec{E}\right|^2 \hat{k}$, with the positive sign for left handed and the negative sign for right-handed. Linearly polarized light carries no angular momentum. This is easy to understand because it is a sum of left and right handed light. As an analogy, suppose you have two tops, one spinning clockwise and one spinning counterclockwise, the two-top system has no net angular momentum.

As mentioned before, light cannot have arbitrarily small intensity. The smallest intensity light can have is a single photon. Thus the photon itself must be polarized. A single circularly polarized photon has angular momentum $\vec{J} = \pm \frac{h}{2\pi} \hat{k}$. It may seem surprising that photons which are point like particles with no substructure can have angular momentum on their own. It is a very odd fact, but true nonetheless. Photons have spin. We say photons are particles of spin 1.

Here an important example is light from a reflection. Here the story is nearly identical, as shown in Fig 4 with the maximum polarization coming if the source is at a right angle to the viewer. In this case, the index of refraction of the two materials involved (air and lake for example) play a role and the angle is not exactly 90 degrees. Instead it is called Brewster's angle.

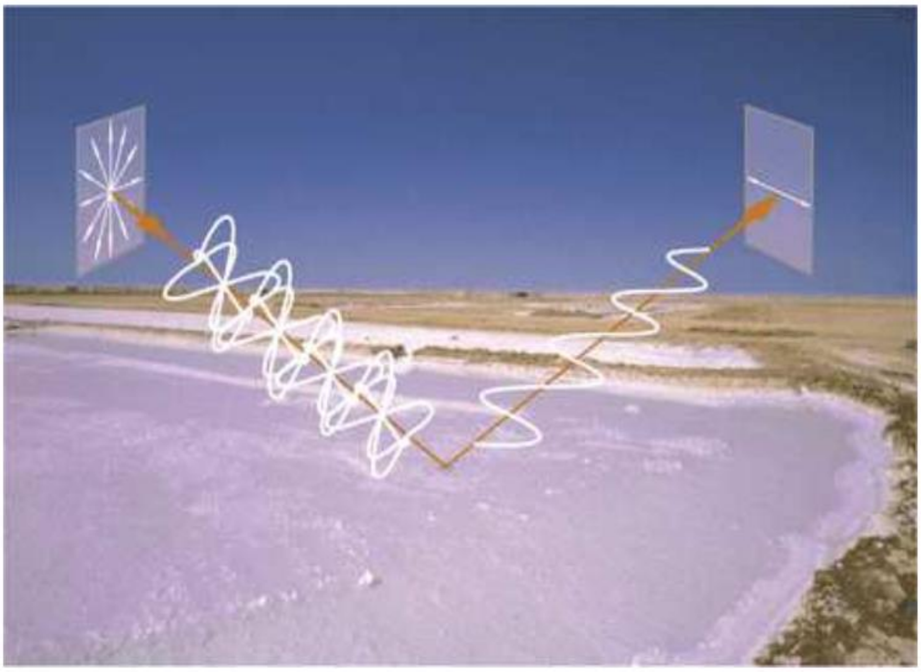

Fig 1.8: Polarization from reflection.

So reflected light is polarized. Most light around us is not polarized. So for example, if you are on a boat and light is coming in from the sky (not just the sky directly above you), and also from the water, only the light reflected off the water will be polarized. Thus if we put on polarizing sunglasses, you can filter out the reflected light, and see more clearly the things around us. Similarly, reflected light coming off the ground will be polarized horizontally. Polarizing sunglasses generally try to filter out horizontally polarized light.

1.8 Performance of Communication Link

Network performance refers to measures of service quality of a network as seen by the customer. There are many different ways to measure the performance of a network, as each network is different in nature and design. Performance can also be modeled and simulated instead of measured; one example of this is using state transition diagrams to model queuing performance or to use a Network Simulator.

The following measures are often considered important:

a. **Bandwidth:** Commonly measured in bits/second is the maximum rate that information can be transferred
b. **Latency:** The delay between the sender and the receiver decoding it, this is mainly a function of the signals travel time, and processing time at any nodes the information traverses
c. **Bit Error Rate (BER):** Error rate is the number of corrupted bits expressed as a percentage or fraction of the total sent.

$$BER = \frac{No\ of\ error\ bits}{Total\ no\ of\ bits}$$

d. **SNR:** Signal to noise ratio (SNR) is defined as the ratio of the power of a signal and the power of background noise (unwanted signal).Both signal and noise power must be measured at the same and equivalent points in a system, and within the same system bandwidth.

$$SNR = \frac{Signal\ power}{Noise\ power}$$

e. **SCNR:** For any channel shot noise, thermal noises are common. But when it is multicore fiber crosstalk and cross coupling should be brought in mind. That's why SNR formation will be modified into SCNR. It means signal to crosstalk plus noise ratio.

$$SCNR = \frac{Signal\ power}{Crosstalk\ power + Noise\ power}$$

1.9 Cross Polarization (XPol)

Cross polarization (sometimes written Xpol) is the polarization orthogonal to the polarization being discussed. For instance, if the fields from an antenna are meant to be horizontally polarized, the cross-polarization in this case is vertical polarization. If the polarization is Right Hand Circularly Polarized (RHCP), the cross-polarization is Left Hand Circularly Polarized (LHCP).

This term arises because an antenna is never 100% polarized in a single mode (linear, circular, etc). Hence, two radiation patterns of an antenna are sometimes presented, the co-pol (or desired polarization component) radiation pattern and the cross-polarization radiation pattern.

The cross polarization may be specified for an antenna as a power level in negative dB, indicating how many decibels below the desired polarization's power level the x-pol power level is.

1.10 Power Penalty

It assumes that the optical signal consists of ideal bit streams during SNR or bit error rate (BER) calculation. That is, it assumes that the bit-1 consists of optical pulse of constant energy, and there is no energy in bit-0, receiver amplifier is sharply band limited, there is no random variation in amplitude and arrival time of bit. In practice however, the bits are distorted due to various reasons and the optical signal is degraded in addition to the system noise.

To compensate for the system degradation, the signal power has to be increased to achieve the same SNR or BER performance as that of an ideal system. This increase in power is called the Power Penalty.

There are two types of signal degradation which can contribute to the power penalty.

1) Degradation during propagation in the optical fiber.

2) Degradation due to peripheral electronic and optic components in the system like the lasers, photo-detectors, couplers etc.

1.11 Receiver Sensitivity

The sensitivity of an electronic device, such as a communications system receiver, or detection device, such as a PIN diode, is the minimum magnitude of input signal required to produce a specified output signal having a specified signal-to-noise ratio, or other specified criteria.

The first receiver element is a pin or an avalanche photodiode, which produces an electric current proportional to the received power level. Since this electric current typically is very weak, a front-end amplifier boosts it to a level that can be used by the following electronics. After being amplified, the signal passes through a low-pass filter to reduce the noise that is outside of the signal bandwidth. The filter can also reshape (equalize) the pulses that have become distorted as they traveled through the fiber. Together with a clock (timing) recovery circuit, a decision circuit decides whether a 1 or 0 pulse was received.

To achieve a desired BER at a given data rate, a specific minimum average optical power level must arrive at the photo detector. The value of this minimum power level is called the receiver sensitivity. The receiver sensitivity as a function of bit rate will change for a given photodiode depending on values of parameters such as wavelength, APD gain, and noise figure.

Receiver sensitivity indicates how faint an input signal can be to be successfully received by the receiver, the lower power level, the better. Lower power for a given S/N ratio means better sensitivity since the receiver's contribution is smaller. When the power is expressed in dBm the larger the absolute value of the negative number, the better the receive sensitivity. For example, a receiver sensitivity of −98 dBm is better than a receive sensitivity of −95 dBm by 3 dB, or a factor of two. In other words, at a specified data rate, a receiver with a −98 dBm sensitivity can hear signals that are half the power of those heard by a receiver with a -95 dBm receiver sensitivity.

The minimum acceptable value of received power needed to achieve an acceptable BER or performance. It takes into account power penalties caused by use of a transmitter with worst-case values of extinction ratio, jitter, pulse rise times and fall times, optical return loss, receiver connector degradations, and measurement tolerances. The receiver sensitivity does not include power penalties associated with dispersion, or back reflections from the optical path; these effects are specified separately in the allocation of maximum optical path penalty. Sensitivity usually takes into account worst-case operating and end-of-life (EOL) conditions.

Receivers are integrated part of a long distance fiber optic communication system. A receiver includes photo detectors such as Avalanche photodiode, positive-intrinsic-negative semiconductor photodiode etc., demodulators and couplers. Receiver sensitivity is more for an optical receiver when it achieves the same performance with less optical power incident on it. The three important factors which influences receivers sensitivity are bit error rate (BER), minimum received power and quantum limit of photo detection. Bit rate is defined as the probability of incorrect identification of a bit by the decision circuit of the received. Minimum received power is a cut-off value below which receiver operation ceases. Use of avalanche photodiode improves receiver sensitivity. But excess noise factor may degrade receiver sensitivity. Quantum limit of photo detection in almost all practical optical receivers is more than 20 dB or exceeds 1000 photons.

1.12 Coherent Homodyne Optical Transmission

In optical communications there are two major kinds of detectors: direct detection and coherent detection. The direct detection is so named because the incoming signal is detected directly with the photodiode which is the element in charge of converting the optical power into a current. These detectors can only obtain the amplitude of the signal, losing its phase. With the direct detection only the amplitude of the signal can be obtained, losing its phase.

The most advanced detection method is coherent detection, where the receiver computes decision variables based on the recovery of the full electric field, which contains both amplitude and phase information. Coherent systems have several advantages over direct detection systems, but for many years it has not been developed or used due basically to two reasons: the complexity of the optical and digital systems used in coherent communications and the reasonable bandwidth provided by the direct detection, enough for the requirements of many applications.

Coherent optical communications are very much promising for gigabit optical fiber transmission to meet up the current and future demands for multimedia internet and data services. Multilevel modulation formats with high spectral efficiency (SE) supported by advanced digital signal processing (DSP) and coherent detection made it possible to raise the data rates .Coherent receivers are sensitive to the phase and SOP of the incoming signal. To cope with this problem, the configuration of coherent systems becomes much more complicated than that of IMDD systems.

It was assumed up to now that the polarization of the incoming signal was always aligned to that of LO. However, in practical systems, the polarization of the incoming signal is unlikely to remain aligned to the state of polarization (SOP) of LO because of random changes on the birefringence of the transmission fiber. One of the most serious problems of the coherent receiver is that the receiver sensitivity is dependent on SOP of the incoming signal.

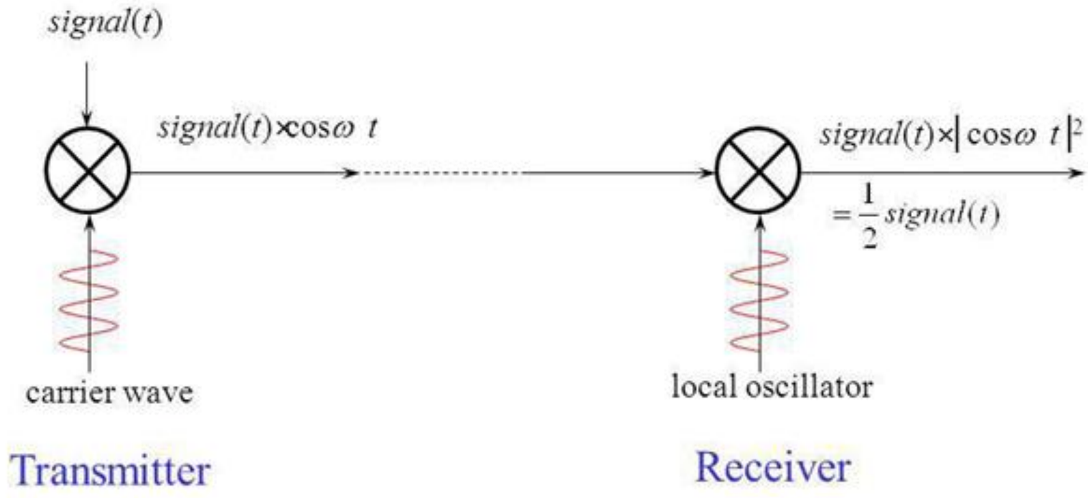

Fig 1.9: Coherent Homodyne optical transmission

Where the local oscillator frequency equals the signal frequency is called homodyne detection. For optical homodyne measurements, both waves are virtually always derived from the same laser source. The homodyne technique is phase-sensitive in the sense that the power of the heterodyne signal depends on the relative phase of signal and local oscillator, and may even totally vanish.

1.13 Circular Polarization Division Multiplexing (CPDM)

Circular polarization of an electromagnetic wave is a polarization state in which, at each point, the electric field of the wave has a constant magnitude but its direction rotates with time at a steady rate in a plane perpendicular to the direction of the wave. It is used in fiber optic communication by transmitting separate left and right circularly polarized light beams through the same optical fiber. CPDM is generally used in conjunction with QPSK and DQPSK.

The ever-growing transmission capacity demand in optical transmission systems has brought out the necessity of increasing the spectral efficiency employing different transmission techniques. CPDM-QPSK speeds up the operation and therefore it increases spectral efficiency.

1.14 Limitations of CPDM-QPSK System

Crosstalk will be one of the major limitations for the CPDM system in optical networks.

Crosstalk

Crosstalk is any phenomenon by which a signal transmitted on one circuit or channel of a transmission system creates an undesired effect in another circuit or channel. Crosstalk is critically important in CPDM-QPSK systems. When signals from one channel arrive in another they become noise in the other channel. This can have serious effects on the signal to noise ratio and hence on bit error rate.

Types of Crosstalk

Different types of crosstalk exist, depending on their source.

a) Near-End Crosstalk (NEXT): Interference that arises when signals are transmitted in opposite direction. Crosstalk is usually occurred due to poorly designed or poorly installed cables.

b) Far-End Crosstalk (FEXT): Interference that arises when signals are transmitted in same direction.

c) Power-Sum-Near-End Crosstalk (PSNXT): Power-Sum crosstalk is the value that is necessary to consider when using cables that contain more than one pair of wires in it. It is being measured by having signal in all the wire pairs except one. The one pair that has no signal will be measured. Measurements will be done from both ends of the cable separately. The procedure should be repeated for each of the wire pair there is in the cable. Worst value will be recorded as cables Power-Sum Crosstalk.

1.15 CPDM-QPSK Coherent Homodyne Transmission System

An important goal of a long-haul optical fiber system is to transmit the highest data throughput over the longest distance without signal regeneration. Given constraints on the bandwidth imposed by optical amplifiers and ultimately by the fiber itself, it is important to maximize spectral efficiency, measured in bit/s/Hz. But given constraints on signal power imposed by fiber nonlinearity, it is also important to maximize power (or SNR) efficiency, i.e., to minimize the required average transmitted energy per bit (or the required signal-to-noise ratio per bit).

The most promising detection technique for achieving high spectral efficiency while maximizing power (or SNR) efficiency, is coherent detection with circular polarization multiplexing, as symbol decisions are made using the in-phase (I) and quadrature (Q) signals in the two field polarizations, allowing information to be encoded in all the available degrees of freedom.

1.16 Previous Work on CPDM-QPSK Coherent Homodyne Transmission System

The development of CPDM-QPSK coherent homodyne transmission systems turns out to be a severe challenge for the communication engineer. The IEEE and the European Telecommunications Standards Institute (ETSI) have already started working towards the standardization of CPDM-QPSK coherent homodyne technology. It is interesting that most of the contributions on these topics are the publications in the IEEE, ICOE.

A paper is by Thomas Lee S and Hari M K, and is entitled “Circular Polarization Division Multiplexing for Faster Coherent Fiber Optic Communication Systems.” This paper proposes the use of circularly polarization division multiplexing (CPDM) in addition to the existing PDM (LPDM) in a QPSK system for enhancing bit rate of transceivers without affecting the spectral width of transmitter. This paper is based on the theoretical understanding of polarization in light and hence needs experimental validation.

1.17 Objectives of The Thesis Work

- To analyze the optical coherent homodyne CPDM-QPSK transmission system taking into consideration the influence of the crosstalk due to cross polarization induced by random misalignment of the SOPs
- To analyze the expression of the crosstalk current.
- To analyze the expression of the Signal to Crosstalk plus Noise Ratio (SCNR) at the output of a coherent homodyne QPSK receiver.
- To evaluate the performance of BER and SCNR due to Xpol-induced crosstalk and hence the system power penalty suffered for different mean misalignment angles.

1.18 Organization of The Thesis

Chapter 1 is an introductory chapter. It contains the brief discussion of optical fiber communication with the scheme of CPDM QPSK coherent homodyne system.

Chapter 2 presents the modified CPDM-QPSK system model in details. It also shows the theoretical analysis of the system. Analysis is carried out for the optical coherent homodyne CPDM-QPSK transmission system taking into consideration the influence of the SOPs. Analysis is presented to find out the expression of the Signal to Crosstalk plus Noise Ratio (SCNR) and the Bit Error Rate (BER) at the output of the coherent homodyne QPSK receiver.

Chapter 3 represents the results and discussions regarding the CPDM-QPSK system. The results show that, there is a significant deterioration in BER and SCNR performance due to the effect of cross polarization and hence the system suffers power penalty for different misalignment angles.

Chapter 4 contains the concluding remarks and scope of future works as well.

CHAPTER 2

SYSTEM MODEL AND THEORETICAL ANALYSIS

SYSTEM MODEL AND THEORETICAL ANALYSIS

2.1 System Model:

Fig 2.1 shows the block diagram of coherent homodyne CPDM-QPSK transmitter. Two orthogonal and circularly polarized input laser's electrical fields are isolated by the polarization beam splitter (PBS) at the transmitter section. Each of the circularly polarized beam are divided into two separate linearly polarized beam while passing through the PBS modules. Then the polarized signal is Quadrature phase modulated by Mach-Zehnder modulators which modulates two input signals with in-phase and quadrature components of the laser electric field.

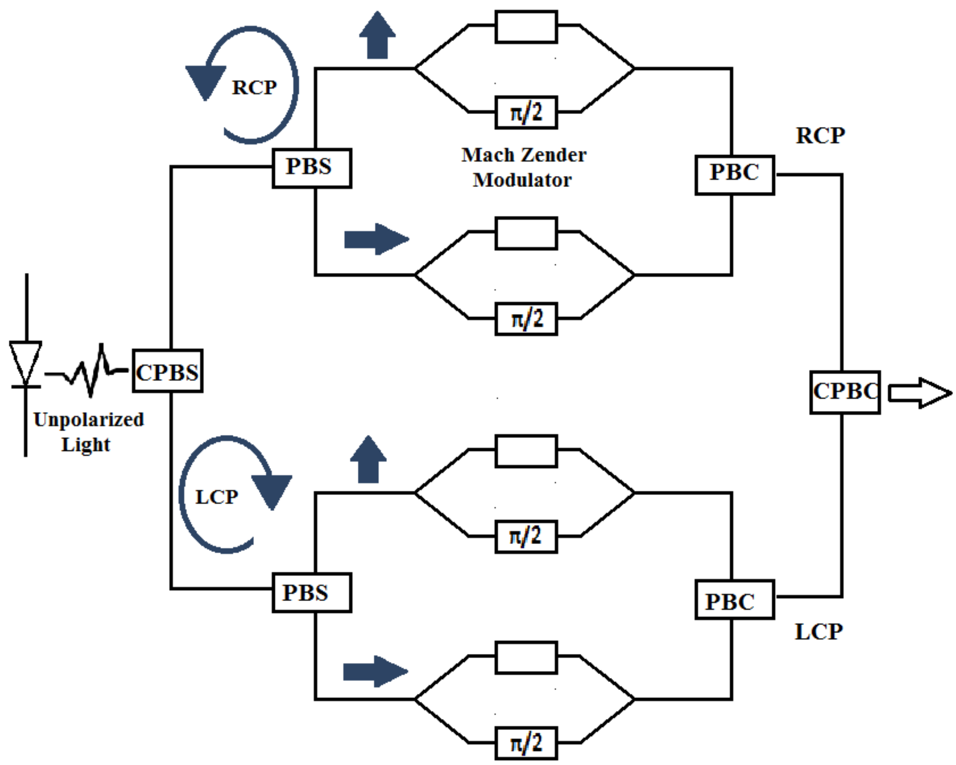

Fig.2. 1: Transmitter section with Mach Zehnder modulator

In the coherent receiver shown in Fig 2.2 the electric fields of two received signals from transmitter and light from local oscillator (LO) are split into RCP and LCP components by two separate CPBSs and again split into vertical and horizontal components by four PBSs .The output of each PBSs finally mixes with 3dB coupler and feds into QPSK demodulators. Thus the transmitted data is recovered to its original electrical signal.

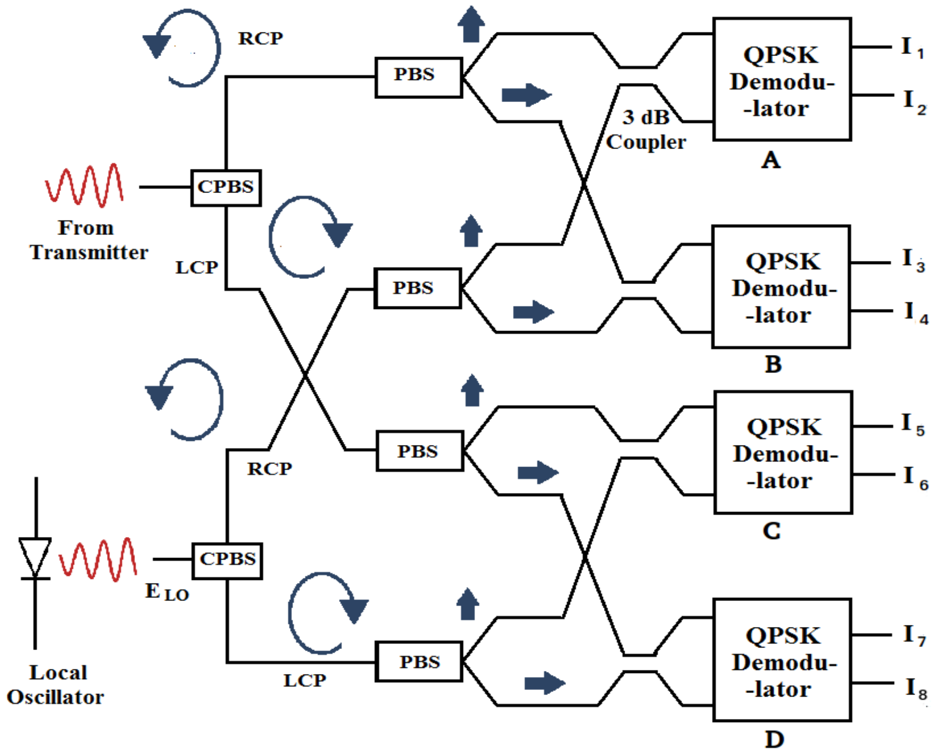

Fig 2.2: Receiver section of CPDM-QPSK transmission system.

2.1.1 Transmitter Components of The System Model:

Light Source:

Optical sources are the heart of a fiber optical data system .Optical sources are hybrid devices:-

- Converts electrical signals into optical signals
- Launches these optical signals into an optical fiber for data transmission.

These devices consist of an interface circuit, drive circuit, and components for optical source. (LEDs, ELEDs, SLEDs, LDs, etc)

Types of Sources:

There are two types of light sources used in fiber optic:

- Light Emitting diode (LED)
- LESER diode(LD)

LED (Light Emitting Diode):

Light Emitting Diodes (LEDs) are the most widely used semiconductor diodes among all the different types of semiconductor diodes available today. Light emitting diodes emit either visible light or invisible infrared light when forward biased. The LEDs which emit invisible infrared light are used for remote controls.

A light Emitting Diode (LED) is an optical semiconductor device that emits light when voltage is applied. In other words, LED is an optical semiconductor device that converts electrical energy into light energy.

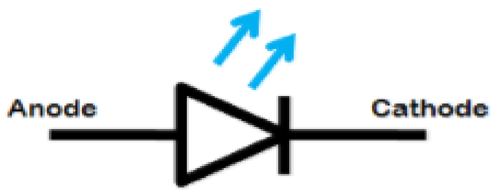

Fig 2.3: Light emitting diode

LASER:

A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The term "laser" originated as an acronym for "light amplification by stimulated emission of radiation".

LASER requires:

- Population Inversion
- Optical feedback

Population Inversion:

Under the normal conditions the lower energy level E1 of the two level atomic systems contains more atoms than the upper energy level E2. However, to achieved optical amplification it is necessary to create a non-equilibrium distribution of atoms such that the population of atoms in the upper energy level is greater than that of the lower energy level (i.e. $N_2 > N_1$). This condition is known as population inversion and achieved using an external energy source and also known as 'pumping'.

Optical Feedback:

Light amplification in laser occurs when a photon colliding with an atom in the excited energy state causes the stimulated emission of a second photon and then both these photons release two more. Continuation of this process effectively creates multiplication, and when the electromagnetic waves associated with these protons are in phase, amplified coherent emission is obtained. To achieve this laser action it is necessary to contain photons with the laser medium and maintain the conditions for coherence. This is accomplished by placing or forming mirrors at either end of the amplifying medium. Furthermore, if one mirror is made partially transmitting, useful radiation may escape from the cavity.

In our research we have used laser light source.

Mach-Zehnder Modulator:

A Mach-Zehnder modulator is used for controlling the amplitude of an optical wave. The input waveguide is split up into two waveguide interferometer arms. If a voltage is applied across one of the arms, a phase shift is induced for the wave passing through that arm. When the two arms are recombined, the phase difference between the two waves is converted to an amplitude modulation.

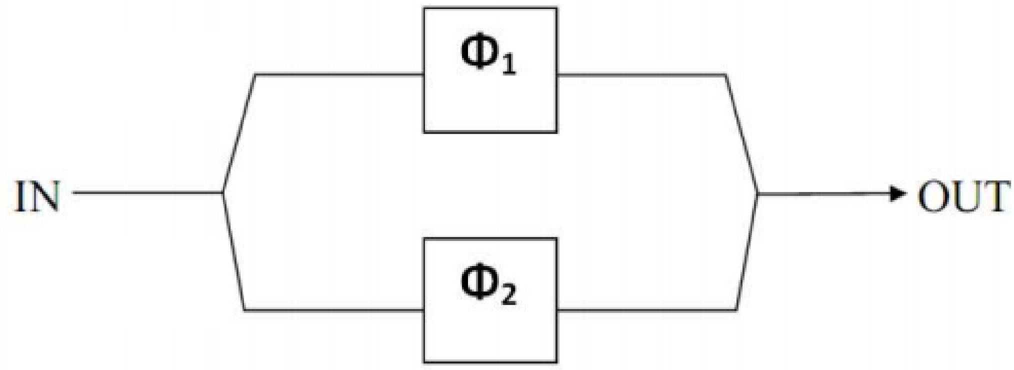

Fig 2.4: MZ Interferometer scheme

By splitting the input beam and introducing a phase shift in one of the paths, the recombined signals will interfere constructively at one output and destructively at the other.

In the central region, when the signals in the two arms come from the same light source, the outputs from these two guides have a phase difference $\Delta\phi$ given by

$$\Delta\phi = \frac{2\pi n_1}{\lambda} L - \frac{2\pi n_2}{\lambda} (L + \Delta L)$$

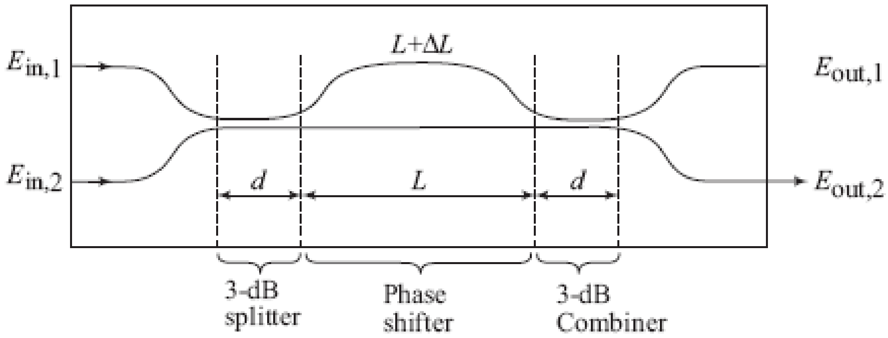

Fig 2.5: Layout of a basic 2 x 2 MZ interferometer

Using basic 2 × 2 MZIs, any size N ×N multiplexer (with $N = 2^n$) can be constructed. Each module i has a different ΔL_i in order to have all wavelengths exit at port C.

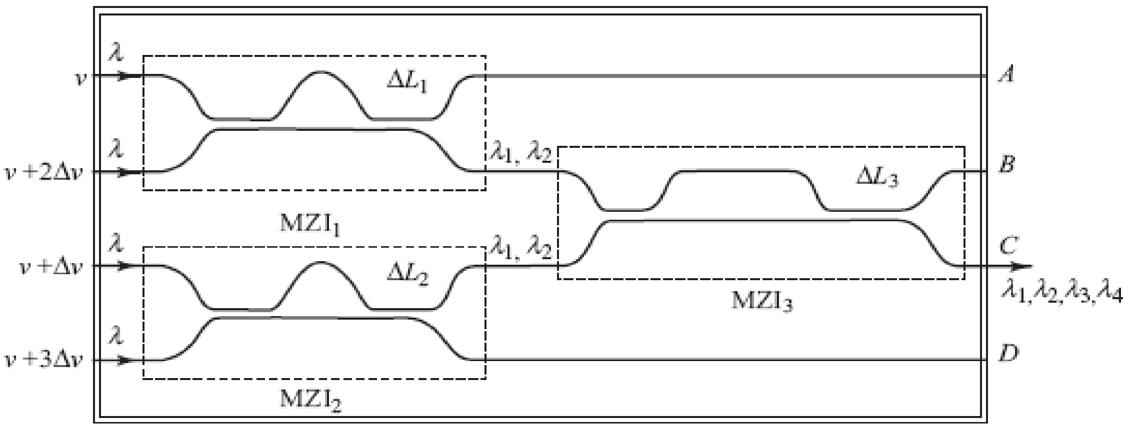

Fig 2.6: Channel wavelength multiplexer using three 2 x 2 MZI element

Beam Combiner:

A beam combiner is essentially an arrangement of beam splitters and mirrors. The function of a beam splitter is to divide the incident light into two paths, one by transmission and another by reflection. Beam splitters are coated with a material that enables the glass to reflect monochromatic light and transmit light of other wavelengths.

In order to have minimum dispersion of light, a beam combiner is constructed using a combination of three beam splitters. The coating used in the beam splitter is of great importance in reducing the dispersion and retardance of the incident light beam. Beam combiners are used in varied applications, from combining laser beams, to combining light from stars in astronomy.

Working Principle:

A beam combiner works on the same principle as a beam splitter, where a portion of the incident beam is reflected at 90°, while the rest of it is transmitted in the same direction.

Construction:

A beam combiner may be a combination of beam splitters and mirrors, or simply several beam splitters.

Application:

Some of the applications of beam combiners are listed below:

- Astronomical observations/measurements
- Laser light combination
- Nulling interferometry

Polarization Beam Combiner (PBC):

Polarization beam combining (or polarization coupling) is a technique for combining (superimposing) two linearly polarized laser beam.

Incoherent Polarization Combining:

The simpler variant is incoherent combining. For example, the output beams of two broad area laser diodes, one being vertically polarized and the other one horizontally polarized, can be sent onto a thin-film polarizer such that one of the beams is reflected, the other one transmitted, and both beams then propagate in the same direction. As a result, one obtains an unpolarized beam having the combined optical power of the input beams (neglecting some parasitic losses) and the same beam quality. Accordingly, the brightness is nearly doubled.

This technique is often used e.g. for end pumping of a solid-state laser with an increased power. It works only if the laser crystal can similarly well absorb pump radiation with both polarization directions. This is the case e.g. for Nd:YAG but not for Nd:YVO_4.

Coherent Polarization Combining:

If two mutually coherent beams are polarization combined, it is possible to obtain a linear polarization state for the output. Assuming equal input powers for the two ports, the output polarization will be rotated by 45° with respect to the polarization direction of any of the input beams. The method is one variant of coherent beam combining.

Due to the linear output polarization, coherent polarization combining can be repeated many times. It is thus a technique suitable for power scaling.

CPBC:

Circular polarization beam combiner is used for combining two circularly polarized beams. Mainly in our system model, right circular polarization (RBC) and left circular polarization (LCP) are combined while passing through CPBC module at the transmission section.

Beam Splitter:

Beam splitters are optical components used to split incident light at a designated ratio into two separate beams. Additionally, beam splitters can be used in reverse to combine two different beams into a single one. Beam splitters are often classified according to their construction: cube or plate.

Standard Beam splitters are commonly used with unpolarized light sources, such as natural or polychromatic, in applications where polarization state is not important. They are designed to split unpolarized light at a specific Reflection/Transmission (R/T) ratio with unspecified polarization tendencies.

Types of Beam splitters:

Polarization beam splitters: Polarization Beam splitters are used to split un-polarized light into two polarized parts. Polarization beam splitters are designed to split light into reflected S-polarized and transmitted P-polarized beams. They can be used to split unpolarized light at a 50/50 ratio, or for polarization separation applications such as optical isolation. Beam splitters are typically designed for 0° or 45° angle of incidence with a 90° separation of the beams, depending on the configuration.

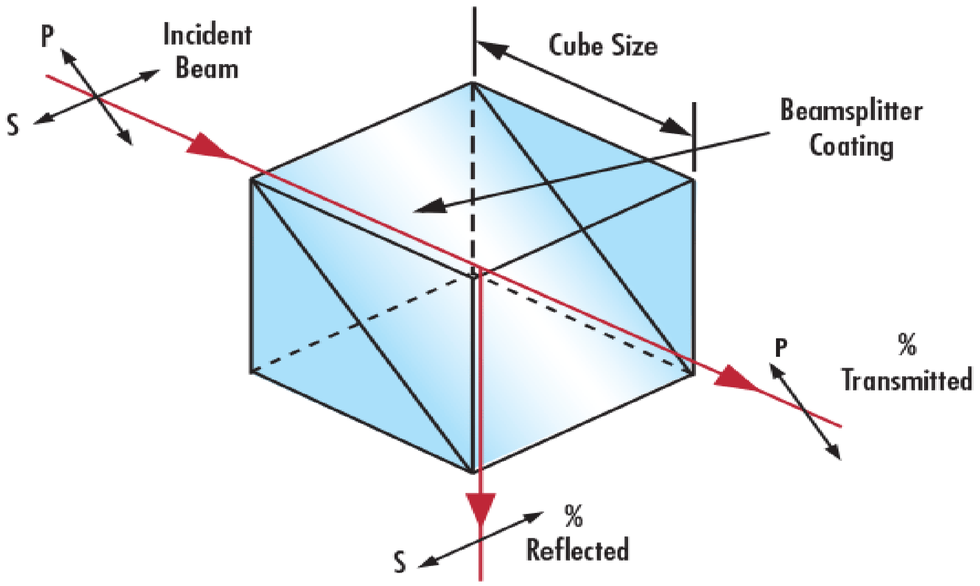

Fig 2. 7: Polarization Beam splitter

The PBS contains at least one prism having at least one major surface and having a refractive index of at least about 1.6 and a birefringent film disposed on the major surface of the prism. The birefringent film is a multi-layer film having layers of at least a first material and a second material. After uniaxial stretching, the film exhibits a refractive index difference of less than about 0.15 units in the stretched direction.

A polarization splitter, comprising a splitting medium lying between two transparent elements of defined indices, characterized in that the splitting medium comprises a periodic structure of layers of materials of different indices, having high and low indices, and having a period which is small compared with the wavelength of an incident beam, forming a uniaxial birefringent medium of optical axis perpendicular to the plane of the periodic structure, the two transparent elements being made of a material of index approximately equal to the ordinary index (n_o) of the periodic structure.

The simplest type of birefringence is described as uniaxial, meaning that there is a single direction governing the optical anisotropy whereas all directions perpendicular to it (or at a given angle to it) is optically equivalent. Thus rotating the material around this axis does not change its optical behavior. This special direction is known as the optic axis of the material. Light whose polarization is perpendicular to the optic axis is governed by a refractive index n_o (for "ordinary"). Light whose polarization is in the direction of the optic axis sees an optical index n_e (for "extraordinary"). For any ray direction there is a linear polarization direction perpendicular to the optic axis, and this is called an ordinary ray. However, for ray directions not parallel to the optic axis, the polarization direction perpendicular to the ordinary ray's polarization will be partly in the direction of the optic axis, and this is called an extraordinary ray. The ordinary ray will always experience a refractive index of n_o, whereas the refractive index of the extraordinary ray will be in between n_o and n_e, depending on the ray direction as described by the index ellipsoid.

Non-polarization Beam Splitters:

Split light into a specific R/T ratio while maintaining the incident light's original polarization state. For example, in the case of a 50/50 non-polarizing beam splitter, the transmitted P and S polarization states and the reflected P and S polarization states are split at the design ratio. These beam splitters are ideal for maintaining polarization in applications utilizing polarized light.

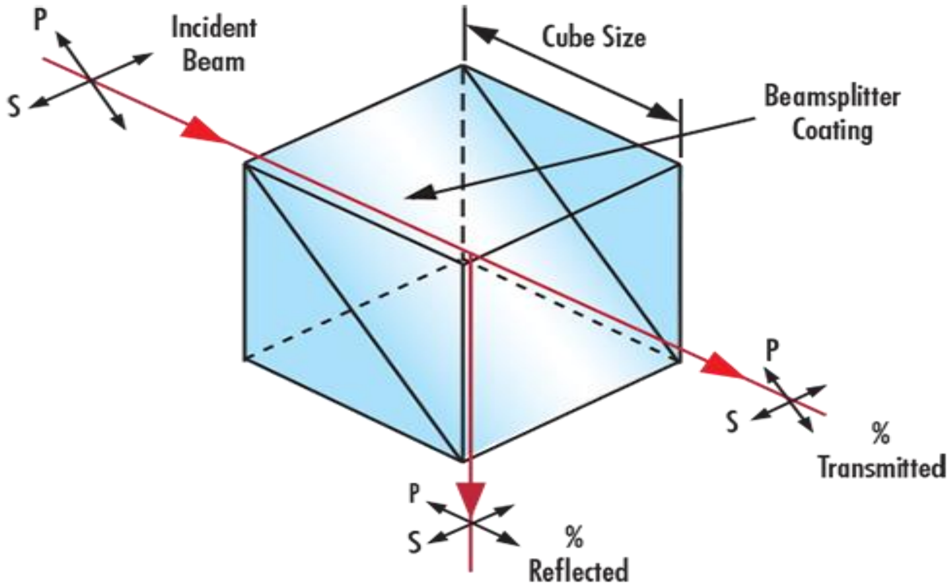

Fig 2.8: Non-Polarizing Beam splitter

Dichroic Beam splitters split light by wavelength. Options range from laser beam combiners designed for specific laser wavelengths to broadband hot and cold mirrors for splitting visible and infrared light. This type of beam splitter is commonly used in fluorescence applications.

Birefringence:

Birefringence is the optical property of a material having a refractive index that depends on the polarization and propagation direction of light. These optically anisotropic materials are said to be birefringent (or birefractive). The birefringence is often quantified as the maximum difference between refractive indices exhibited by the material. Crystals with non-cubic crystal structures are often birefringent, as are plastics under mechanical stress.

The simplest type of birefringence is described as uniaxial, meaning that there is a single direction governing the optical anisotropy whereas all directions perpendicular to it (or at a given angle to it) are optically equivalent. Thus rotating the material around this axis does not change its optical behavior. This special direction is known as the optic axis of the material. Light whose polarization is perpendicular to the optic axis is governed by a refractive index n_o (for "ordinary"). Light whose polarization is in the direction of the optic axis sees an optical index n_e (for "extraordinary"). For any ray direction there is a linear polarization direction perpendicular to the optic axis, and this is called an ordinary ray. However, for ray directions not parallel to the optic axis, the polarization direction perpendicular to the ordinary ray's polarization will be partly in the direction of the optic axis, and this is called an extraordinary ray. The ordinary ray will always experience a refractive index of n_o, whereas the refractive index of the extraordinary ray will be in between n_o and n_e, depending on the ray direction as described by the index ellipsoid.

CPBS:

Circular polarization Beam splitters (CPBS) are used to split un-polarized light into two polarized parts. Mainly in our system model, at first the input laser’s electric field is split into right circular polarization (RCP) and left circular polarization (LCP) while passing through Circular polarization Beam splitters (CPBS) module. This two orthogonal and circularly polarized input laser’s electrical fields are isolated by the polarization beam splitter (PBS) at the transmitter section.

Again, output signal from transmitter and local oscillator are split into right circular polarization (RCP) and left circular polarization (LCP) while passing through Circular polarization Beam splitters (CPBS) module.

2.1.2 Receiver Components of The System Model:

Local Oscillator:

In electronics, a local oscillator (LO) is an electronic oscillator used with a mixer to change the frequency of a signal. This frequency conversion process, also called heterodyning, produces the sum and difference frequencies from the frequency of the local oscillator and frequency of the input signal.

Local oscillators are used in the super heterodyne receiver, the most common type of radio receiver circuit. They are also used in many other communications circuits such as modems, cable television set top boxes, frequency division multiplexing systems used in telephone trunk lines, microwave relay systems, telemetry systems, atomic clocks, radio telescopes, and military electronic countermeasure (anti jamming) systems. In satellite television reception, the microwave frequencies used from the satellite down to the receiving antenna are converted to lower frequencies by a local oscillator and mixer mounted at the antenna. This allows the received signals to be sent over a length of cable that would otherwise have unacceptable signal loss at the original reception frequency. In this application, the local oscillator is of a fixed frequency and the down-converted signal frequency is variable.

A crystal oscillator is one common type of local oscillator that provides good stability and performance at relatively low cost, but its frequency is fixed, so changing frequencies requires changing the crystal. Tuning to different frequencies requires a variable-frequency oscillator which leads to a compromise between stability and tunability. With the advent of high-speed digital microelectronics, modern systems can use frequency synthesizers to obtain a stable tunable local oscillator, but care must still be taken to maintain adequate noise characteristics in the result.

3dB Coupler:

Power dividers (also power splitters and, when used in reverse, power combiners) and directional couplers are passive devices used mostly in the field of radio technology. They couple a defined amount of the electromagnetic power in a transmission line to a port enabling the signal to be used in another circuit. An essential feature of directional couplers is that they only couple power flowing in one direction. Power entering the output port is coupled to the isolated port but not to the coupled port. A directional coupler designed to split power equally between two ports is called a hybrid coupler.

Hybrid couplers are the special case of a four-port directional coupler that is designed for a 3-dB (equal) power split. Hybrids come in two types, 90 degree or quadrature hybrids, and 180 degree hybrids.

2.2 Theoretical Analysis:

If the components of the electric field are not in phase but have the same magnitude and have a quarter wavelength out of phase $\phi_x - \phi_y = \pi / 2$.

Then this is called Right circularly polarized.

When, $\phi_x - \phi_y = -\pi/2$

Then it is called Left circularly polarized light.

Right –circular: $\phi_x - \phi_y = \pi / 2$	Left –circular: $\phi_x - \phi_y = -\pi / 2$
$\mathbf{E_s} = \left(E_s, E_s e^{i\pi/2}, 0 \right) = \left(E_s, iE_s, 0 \right)$	$\mathbf{E_s} = \left(E_s, E_s e^{-i\pi/2}, 0 \right) = \left(E_s, -iE_s, 0 \right)$
$\mathbf{E} = \left(E_s e^{i(\omega t - kz)}, iE_s e^{i(\omega t - kz)}, 0 \right)$	$\mathbf{E} = \left(E_s e^{i(\omega t - kz)}, -iE_s e^{i(\omega t - kz)}, 0 \right)$
$Re[\mathbf{E}] = \left(E_s cos(\omega t - kz), -E_s sin(\omega t - kz), 0 \right)$	$Re[\mathbf{E}] = \left(E_s cos(\omega t - kz), E_s sin(\omega t - kz), 0 \right)$

Quadrature Phase modulated output combination:

: $-E_o sin(\omega t - kz)$, $-E_o cos(\omega t - kz)$ [00]

$-E_o sin(\omega t - kz)$, $E_o cos(\omega t - kz)$ [01]

: $E_o sin(\omega t - kz)$, $-E_o cos(\omega t - kz)$ [10]

$E_o sin(\omega t - kz)$, $E_o cos(\omega t - kz)$ [11]

So, the Right circular and left circular polarized signal:

$$S_{RCP}(t)=\sqrt{2P}(\ a_{odd}\cos(\omega t\text{-}kz) + a_{even}\sin(\omega t\text{-}kz)) \qquad (2.1)$$

$$S_{LCP}(t)=\sqrt{2P}(\ b_{odd}\cos(\omega t\text{-}kz) + b_{even}\sin(\omega t\text{-}kz)) \qquad (2.2)$$

Coherent Detection:

Fig 2.9 shows the configuration of the coherent optical receiver. The fundamental concept behind coherent detection is to take the product of electric fields of the modulated signal light and the continuous-wave (CW) local oscillator (LO). Let the optical signal incoming from the transmitter be

$$E_s(t) = A_s(t)exp(j\omega_s t), \qquad (2.3)$$

Where $A_s(t)$ is the complex amplitude and ω_S the angular frequency. Similarly, the electric field of LO prepared at the receiver can be written as

$$E_{LO}(t) = A_{LO}exp(j\omega_{LO}t), \qquad (2.4)$$

Where A_{LO} is the constant complex amplitude and ω_{LO} the angular frequency of LO. We note here that the complex amplitudes and ω_{LO} the angular frequency of LO. We note here that the complex amplitude A_S and A_{LO} are related to the signal power P_S and the LO power P_{LO} by $P_S = |A_S|^2 / 2$ and $P_{LO} = |A_{LO}|^2 / 2$ respectively.

Balanced detection is usually introduced into the coherent receiver as a means to suppress the dc component and maximize the signal photocurrent. The concept resides in using a 3-dB optical coupler that adds a 180° phase shift to either the signal field or the LO field between the two output ports.

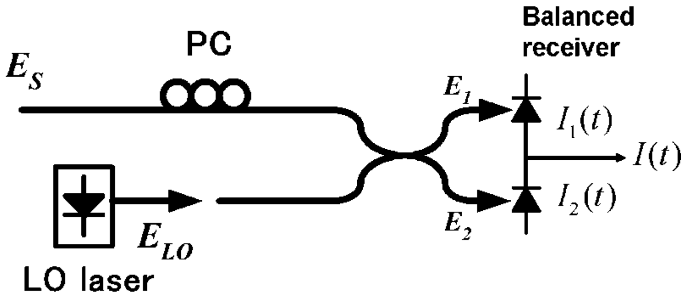

Fig 2.9: Configuration of the coherent receiver that measures the beat between the signal and LO.

$$S_{RCP}(t) = \sqrt{2P}\left(a_{odd}cos(\omega t - kz) + a_{even}sin(\omega t - kz)\right) \quad (2.5)$$

$$= \sqrt{2P}a_{odd}cos(\omega t - kz) + \sqrt{2P}a_{even}sin(\omega t - kz)$$

$$S_{LCP}(t) = \sqrt{2P}\left(b_{odd}cos(\omega t - kz) + b_{even}sin(\omega t - kz)\right) \quad (2.6)$$

$$E_{RCP} = E_{rcp1} + E_{rcp2}$$

$$E_{LCP} = E_{lcp1} + E_{lcp2}$$

Local oscillator,

$$E_{Lo}(t) = \sqrt{2P}cos(\omega_{Lo}t) \quad (2.7)$$

$$E_1 = \frac{1}{\sqrt{2}}\left(E_{rcp1} + E_{Lo}\right) \quad (2.8)$$

$$E_2 = \frac{1}{\sqrt{2}}\left(E_{rcp1} - E_{Lo}\right) \quad (2.9)$$

Output photocurrents are,

$$I_1(t) \;=\; R_d.|E_1|^2$$

$$= \frac{1}{2} R_d \left\{ \; a_{odd} E_s cos(\omega t - kz) \; + \; E_{L0} cos(\omega_L t) \; \right\}^2$$

$$= \frac{1}{2} R_d \left\{ \; a_{odd}{}^2 E_s{}^2 cos^2(\omega t - kz) \; + \; E_{L0}{}^2 cos^2(\omega_L t) \; + \; 2a_{odd} E_s E_{LO} cos(\omega t - kz) cos(\omega_L t) \; \right\}$$

$$= \frac{1}{2} R_d \{ \; \frac{1}{2} a_{odd}{}^2 \; E_s{}^2 + \frac{1}{2} a_{odd} \; E_s cos2(\omega t\text{-}kz) + \frac{1}{2} E_{Lo}{}^2 + \frac{1}{2} E_{Lo} cos(2\omega_L t)$$

$$+ \quad a_{odd} E_s E_{LO} cos(\omega t\text{-}kz\text{+} \; \omega_L t) \; + a_{odd} E_s E_{LO} cos(\omega t - \omega_L t - kz) \; \}$$

$$I_1(t) = \frac{1}{2} R_d \{ P_s + \; P_{LO} + \; 2a_{odd} \sqrt{P_S P_{LO}} \; cos(\omega_s t - \omega_L t - kz) \; \} \qquad (2.10)$$

Where,

ω=ω_s[ω_s = signal frequency]

[removing the higher frequency terms oscillating near the frequencies 2 ω_st and 2 ω_Lt]

Similarly,

$$I_2(t) = \frac{1}{2} R_d \{ \; P_s + \; P_{LO} - \; 2a_{odd} \sqrt{2P_S P}_{\;LO} \; cos(\omega_s t - \omega_L t - kz) \; \} \qquad (2.11)$$

Where,

$$R_d = \frac{ne}{hf}$$

The balanced detector output is then given as,

$$I(t) = 2R_d a_{odd} \sqrt{2P_S P_{LO}} \; cos(\omega_s t - \omega_L t - kz) \; \} \qquad (2.12)$$

Since there are random rotations of the sub-channel SOPs, the eigen mode of PBS of the receiver will be misaligned which causes signal fading and induces crosstalk between the sub channels. Taking the eigen modes of the PBS, the sub-channel electric field *Ex* will be the component of the main field along e'_x,

$$\left|e'_x\right\rangle\left\langle e'_x\right|E\rangle = \varepsilon_F E_X \left|e'_x\right\rangle + \varepsilon_X E_Y \left|e'_x\right\rangle \quad (2.13)$$

Where,

$\varepsilon_F = \left\langle e'_x \middle| e_x \right\rangle$; complex fading co-efficient

$\varepsilon_X = \left\langle e'_x \middle| e_y \right\rangle$; complex crosstalk fading co-efficient

The magnitude of ε_F and ε_X can be determined as,

$$|\varepsilon_F| = cos(\theta/2) \quad (2.14)$$

and

$$|\varepsilon_X| = sin(\theta/2) \quad (2.15)$$

Where θ is the random misalignment angle which follows the Maxwell-Boltzman probability distribution law with a mean of θ_m. The pdf of θ is,

$$p(\theta) = \frac{32}{\theta m^3 \pi^2}\theta^2 \exp\left(\frac{-4\theta^2}{\pi\theta m^2}\right) \quad (2.16)$$

The signal at the output of the PBS,

$$E_{RCP}, x = R[\varepsilon_F E_S e^{j\phi} + j\varepsilon_X E_S e^{j\phi}]$$

$$= \varepsilon_F E_s cos(\omega t - kz) - \varepsilon_X E_s sin(\omega t - kz) \quad (2.17)$$

$$E_{RCP}, _y = -\varepsilon_F E_s sin(\omega t - kz) - \varepsilon_X E_s cos(\omega t - kz) \quad (2.18)$$

Where $\varphi = (\omega t\text{-}kz)$

Similarly,

$$E_{LCP,x} = \varepsilon_F E_s cos(\omega t - kz) - \varepsilon_X E_s sin(\omega t - kz) \quad (2.19)$$

$$E_{LCP,y} = \varepsilon_F E_s sin(\omega t - kz) + \varepsilon_X E_s cos(\omega t - kz) \quad (2.20)$$

The input at the PBC is thus,

$$E_{RCP,1} = -(\varepsilon_X E_s cos\varphi + \varepsilon_F E_s sin\varphi) \; + \; (\varepsilon_X E_s sin\varphi - \varepsilon_F E_s cos\varphi) \quad (2.21)$$

$$E_{RCP,2} = -(\varepsilon_X E_s cos\varphi + \varepsilon_F E_s sin\varphi) - (\varepsilon_X E_s sin\varphi - \varepsilon_F E_s cos\varphi) \quad (2.22)$$

The output from the PBC,

$$E_{RCP} = a_{even}(\varepsilon_X E_s cos\varphi + \varepsilon_F E_s sin\varphi) \; + a_{odd}(\varepsilon_X E_s sin\varphi - \varepsilon_F E_s cos\varphi) \quad (2.23)$$

Similarly,

$$E_{LCP} = b_{even}(\varepsilon_X E_s cos\varphi + \varepsilon_F E_s sin\varphi) + b_{odd}(\varepsilon_X E_s sin\varphi - \varepsilon_F E_s cos\varphi) \quad (2.24)$$

The local oscillator signal is $E_{LO}= E_L\cos(\omega_L t)$ When the signal and the local oscillator are co-polarized, the electric fields incident on the upper and lower photo-diodes are given by the following equations:

$$E_1 = \frac{1}{\sqrt{2}}\left(E_{RCP,1} + \; E_{LO}\right) \quad (2.25)$$

$$E_2 = \frac{1}{\sqrt{2}}\left(E_{RCP,2} + \; E_{LO}\right) \quad (2.26)$$

The output photo-currents are,

$$I_1 = R_d \left|E_1\right|^2$$
$$= \frac{R_d}{2}[\ P_s + P_{LO} - 2\varepsilon_F a_{odd}\sqrt{P_s P_{LO}}\ cos(\varphi+\omega_L t)+cos(\varphi-\omega_L t)+2\varepsilon_X a_{odd}\sqrt{P_s P_{LO}} sin(\varphi+\omega_L t)+sin(\varphi-\omega_L t)\ ] \quad (2.27)$$

$$I_2 = R_d \left| E_2 \right|^2$$

$$= \frac{R_d}{2}[\ P_s + P_{LO} - 2\varepsilon_F a_{even}\sqrt{P_S P_{LO}}\ sin(\varphi+\omega_L t)+sin(\varphi-\omega_L t) +$$
$$2\varepsilon_X a_{even}\sqrt{P_S P_{LO}}\ cos(\varphi+\omega_L t)+cos(\varphi-\omega_L t)\ ] \quad (2.28)$$

Where,

Responsivity of the photo-diodes, $Rd = \eta e\ / h\nu$, in which η = quantum efficiency, ν=operating frequency, e =1.6×10^{-19}, $Ps = E_s^{\ 2} / 2$ and , P_{LO}= $\frac{E_{LO}{}^2}{2}$. Output current of the balanced photo-detector,

$$I(t)\ = I_1(t) - I_2(t)$$
$$= R_d\, \varepsilon_X \sqrt{P_s P_{LO}}(a_{odd}[sin\varphi_1\ + sin\varphi_2]\ + a_{even}[cos\varphi_1\ + cos\varphi_2])$$
$$+\ R_d \varepsilon_F \sqrt{P_s P_{LO}}(a_{even}[sin\varphi_1\ + sin\varphi_2] - a_{odd}[cos\varphi_1\ + cos\varphi_2]) \quad (2.29)$$

Here,

$$I(t)\ = I_{xtalk,A}(t)\ + I_{sig,A}(t) \quad (2.30)$$

The cross-talk and signal currents are,

$$I_{xtalk,A}(\theta,t) = R_d \varepsilon_X \sqrt{P_s P_{LO}} \left(a_{odd} \left[\sin\varphi_1 + \sin\varphi_2 \right] + a_{even} \left[\cos\varphi_1 + \cos\varphi_2 \right] \right) \quad (2.31)$$

$$I_{sig,A}(\theta,t) = R_d \varepsilon_F \sqrt{P_s P_{LO}} \left(a_{even} \left[\sin\varphi_1 + \sin\varphi_2 \right] - a_{odd} \left[\cos\varphi_1 + \cos\varphi_2 \right] \right) \quad (2.32)$$

Where,

$\varphi_1 = \omega t - kz + \omega_L t$

and

$\varphi_2 = \omega t - kz - \omega_L t$

So, combining XPol induced cross-talk for a particular BER and misalignment angle θ_m, the conditional SCNR(θ) can be determined by,

$$SCNR(\theta) = \frac{\left| I_{(sig,A)}(\theta,t) \right|^2}{I_{(xtalk,A)}(\theta,t)^2 + I_{noise}^2} \quad (2.33)$$

Where, considering only thermal and shot noise, the total noise power is

$$\sigma^2_{noise} = \sigma^2_{thermal} + \sigma^2_{shot} \quad (2.34)$$

Here,

$$\sigma^2_{thermal} = \frac{4kTB}{R_L}, \quad \sigma^2_{shot} = \sqrt{2} eBI_{sig,A} \quad (2.35)$$

The BER(θ) and the average BER can be obtained by the following formulas,

$$BER(\theta) = \frac{1}{2} erfc(\sqrt{\frac{SCNR(\theta)}{2}}) \qquad (2.36)$$

$$BER = \int_0^{\pi/2} BER(\Theta)\, p(\Theta) d\Theta \qquad (2.37)$$

CHAPTER 3

RESULTS AND DISCUSSIONS

RESULTS AND DISCUSSIONS

3.1 System Parameters

Following the analytical approach presented in section III, signal power , noise power and XPol-induced crosstalk power at the output of the coherent homodyne CPDM-QPSK receiver for a given mean misalignment angle (θ_m) are evaluated . The conditional values of SCNR(θ) are evaluated along with BER(θ) . The average BER is then determined by averaging the conditional BER over the plot of θ using Maxwell- Boltzmann distribution. The parameters used in the analytic simulation are tabulated in Table 3.1 with their appropriate values.

TABLE 3.1: Parameters used for analytical simulation

Parameter	Analytic symbol	Values with proper unit
Electronic charge	e	1.6021×10^{-19}Coul
Responsivity	R_d	0.85 or 85%
Temperature	T	300K or 27^{o}C
Boltzmann Constant	k	1.38065×10^{-23} JK^{-1}
Load Resistance	R_L	25 Ω
Bandwidth	B	5×10^{9} Hz or 5GHz

3.2 Analysis of SCNR(θ) and Received Signal Power (dBm) for Different Misalignment Angles

From the plots of SCNR(θ) vs Received signal power for different misalignment angles (θ) shown in the Fig. 3.1 , it is noticed that there is a significant degradation of SCNR from 35dB to 0dB for increasing the misalignment angle from 0^o to 90^o at a given signal power of -20dBm (for example).

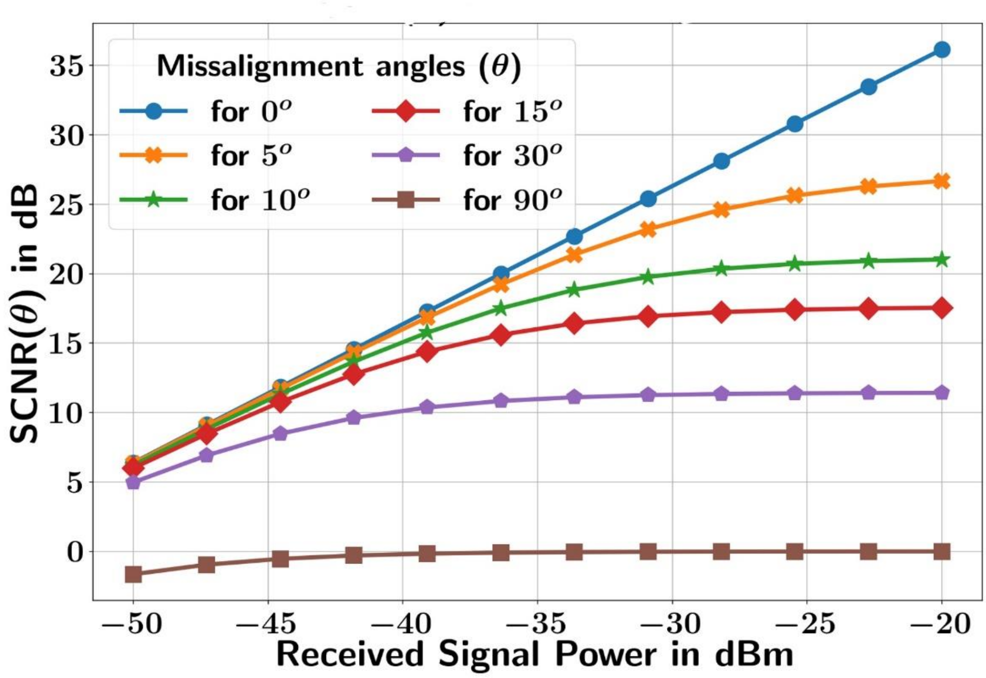

Fig 3.1: SCNR(θ) vs Received Signal power (dBm) for different misalignment angles

It is observed that SCNR is negative at misalignment angle of 90 degree as signal power is less than the overall noise power.

3.3 Analysis of BER (θ) and Received Signal Power (dBm) for Different Misalignment Angles

The plots of BER (θ) vs Received Signal power for different misalignment angles(θ) is shown in Fig 3.2. It is observed that BER increases with increase in misalignment angle at a given signal power due to XPol-induced crosstalk. This observation is more prominent in Fig 3.4

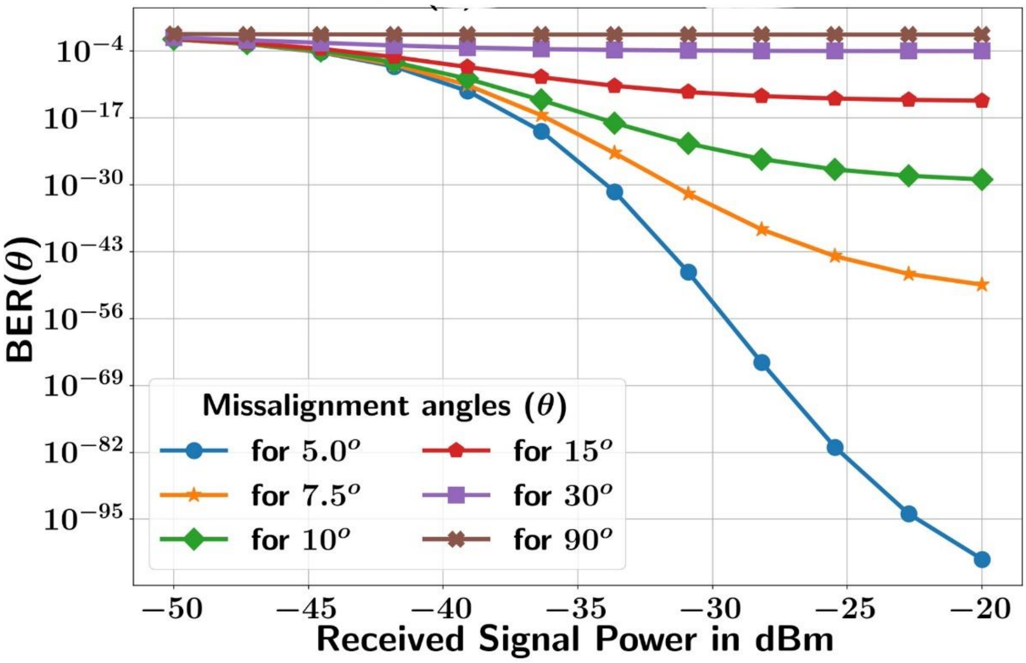

Fig 3.2: BER (θ) vs Received Signal power (dBm) for different misalignment angles

3.4 Analysis of Average BER and Received Signal Power for Different Misalignment Angles at LO Power of 1mW

In Fig 3.3 average BER is plotted as a function of Received signal power for different misalignment angles using the Maxwell-Boltzman pdf on θ. It has been found that at a given signal power -33 dBm and at local oscillator power 1.0mW the average BER increases from 10^{-14} to 10^{-1} for misalignment angles from $5^0$to 90^0. SO, it is observed that BER increases with the increase in misalignment angle at a given signal power as misalignment angle increases Xtalk power.

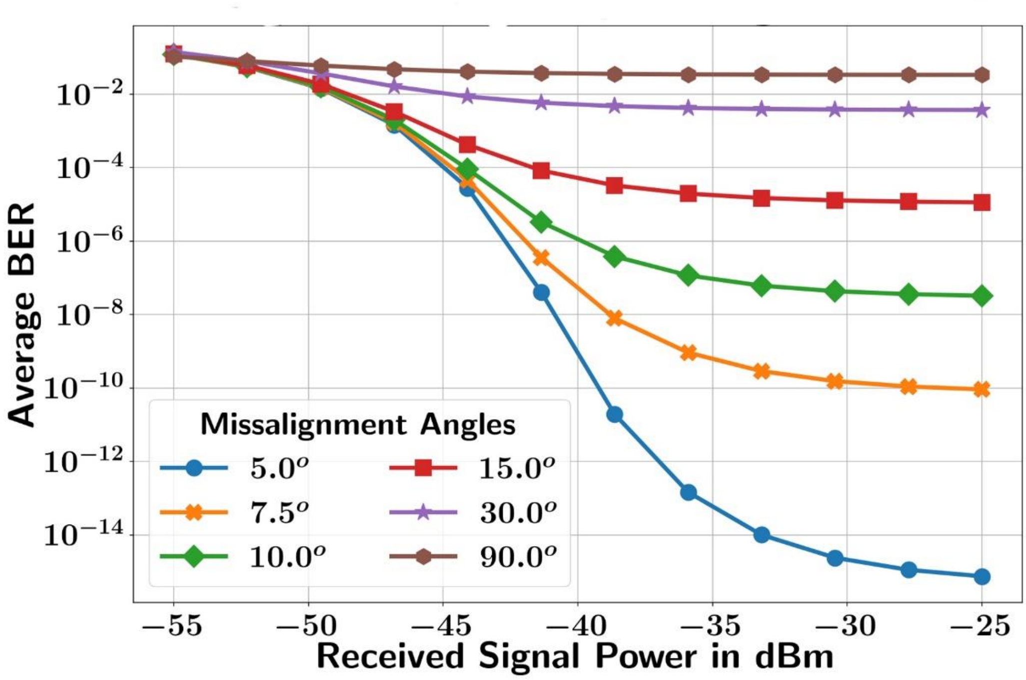

Fig 3.3: Average BER vs received signal power for different misalignment angles at LO power of 1mW

It is obvious from the equation (2.33) and (2.34), BER performance degrades due to increase in Xtalk power which is remarkably satisfied by the plots of Average BER vs Received Signal Power. For a fixed θ of 10 degrees, the conventional PDM system shows a BER of 10^{-2} at LO power of 1mW [19] whereas, CPDM shows a BER of 10^{-7} at the same condition. So, CPDM-QPSK is highly efficient in BER performance compared to the conventional PDM-QPSK coherent detection at a LO power of 1mW (0 dBm) [19] in terms of BER performance.

3.5 Analysis of BER (θ) Varying Misalignment Angles for LO power 1mW

It is observed from the Fig 3.4 that for a fixed local oscillator power 1mW with different signal power, BER increases with the increase in misalignment angle due to the effect of XPol.

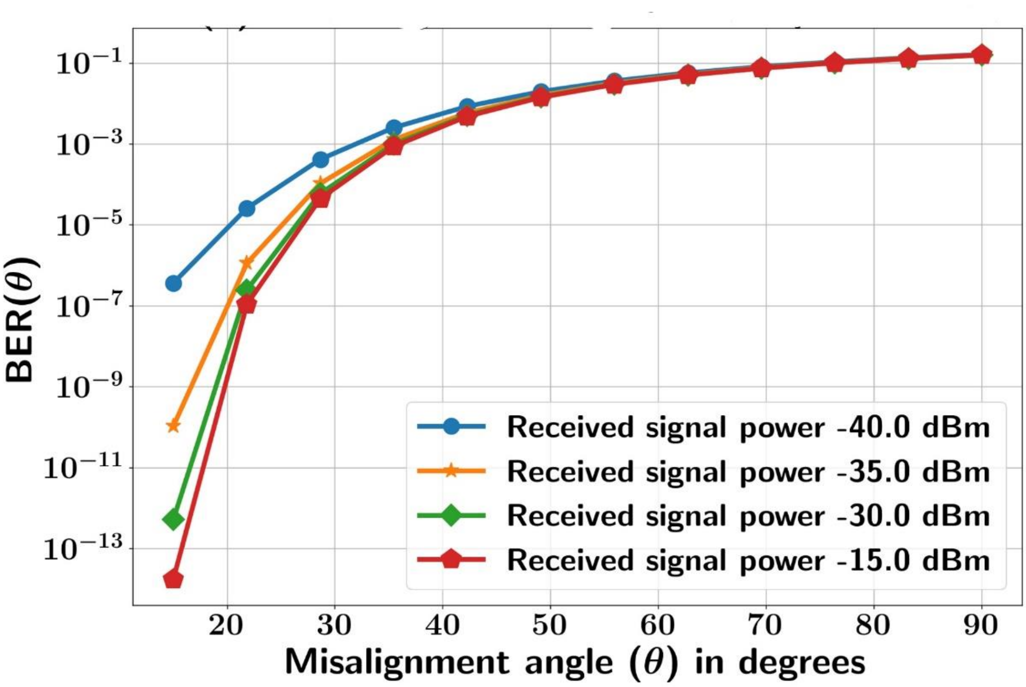

Fig 3.4: BER (θ) vs misalignment angles for LO power 1mW

3.6 Analysis of SCNR(θ) Considering Misalignment Angles for LO Power 1mW

Similar observation is found from the Fig3.5, where SCNR decreases with the increase in misalignment angle as misalignment angle exceedingly increases Xtalk power which is strongly supported by equation (2.33). In a conventional PDM QPSK system, SCNR drops by 25dB sweeping misalignment angle from 0 to 90 degrees [19] whereas in CPDM it falls only by 17dB at the same condition. So, undoubtedly the performance of SCNR of CPDM-QPSK is more efficient than conventional PDM-QPSK system [19] in terms of SCNR performance. Due to this improvement in BER and SCNR performances, CPDM QPSK system needs comparatively low incremental local oscillator power or power penalty and thus achieves higher receiver sensitivity than a typical PDM QPSK system.

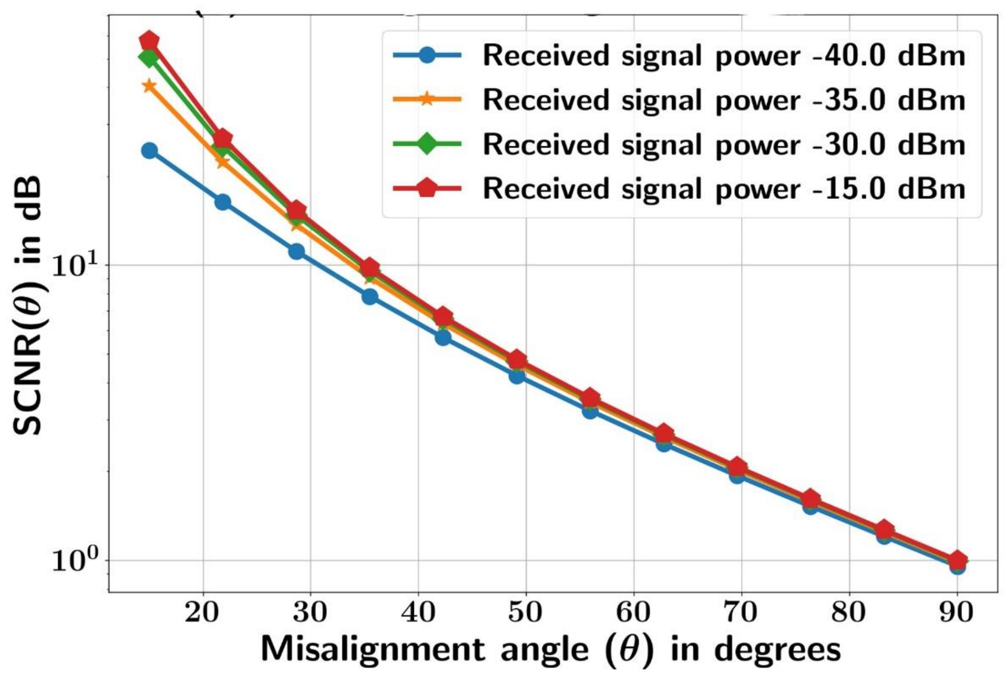

Fig 3.5: SCNR(θ) vs misalignment angles for LO power 1mW

3.7 Analysis of Average BER and Received Signal Power for Misalignment Angle 7.5 Degrees

Fig3.6 shows the plots of the average BER as a function of signal power for different values of local oscillator powers ranging from 0.1mW to 10.0mW at a misalignment angle of 7.5^0.It shows the impact of local oscillator power on the BER along with signal power as the curve shifts from right to left for increasing the local oscillator power. If the local oscillator power decreases from 10.0mW to 0.1mW, received signal power increases upto-26dBm from -45dBm at that BER of 10^{-9}.

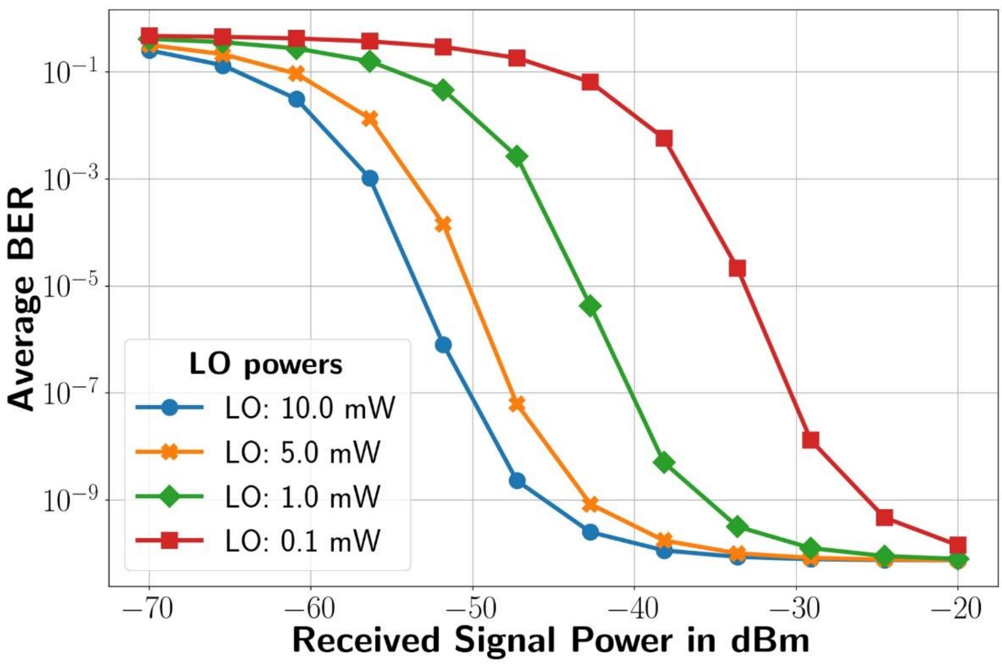

Fig 3.6: Average BER vs received signal power for misalignment angle 7.5 degrees

3.8 Analysis of Signal Power Considering Misalignment Angles

Fig 3.7 shows the impact of crosstalk on the signal power at a given local oscillator power. Signal power is constant at a given LO power when there is no crosstalk and signal power decreases with θ in the presence of crosstalk.

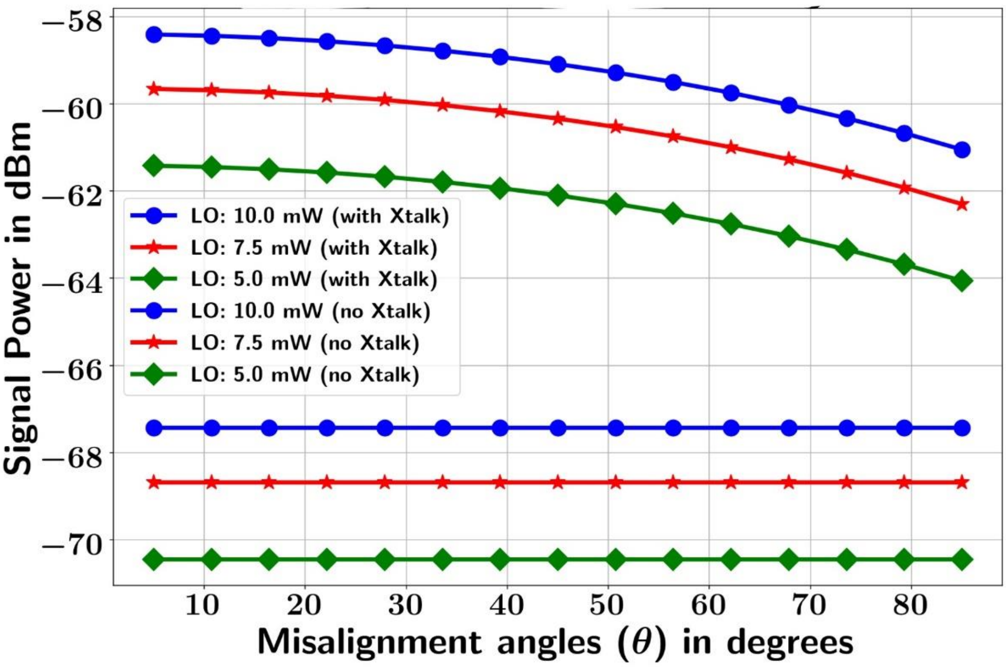

Fig 3.7: Signal power vs misalignment angles

3.9 Analysis of Power Penalty due to Misalignment Angles at BER 10^{-9}

Fig 3.8 depicts the plots of the power penalty vs misalignment angles with local oscillator power of 0.1mW, 1.0mW and 5.0mW at a given BER of 10^{-9}. It is noticed that system suffers significant power penalty due to the effect of XPol .A second order trend fits well with the scatter plots of the power penalties which introduces a square law dependency of penalty on θ. Penalties in signal power are found to be 7.43, 13.41, 18.78, 32.29 dB for misalignment angles of 20^0, 30^0, $40^0$and 60^0respectively keeping local oscillator power fixed at 1mW. The conventional PDM QPSK system shows 13.25 dB and 12.59 dB for θ of $5^0$and 7.5^0respectively at BER 10^{-9} and LO power of 1mW [19] while CPDM system shows only 2.45 dB and 3.12 dB of power penalties respectively for the same angles at the same BER and at the same LO power of 1mW.

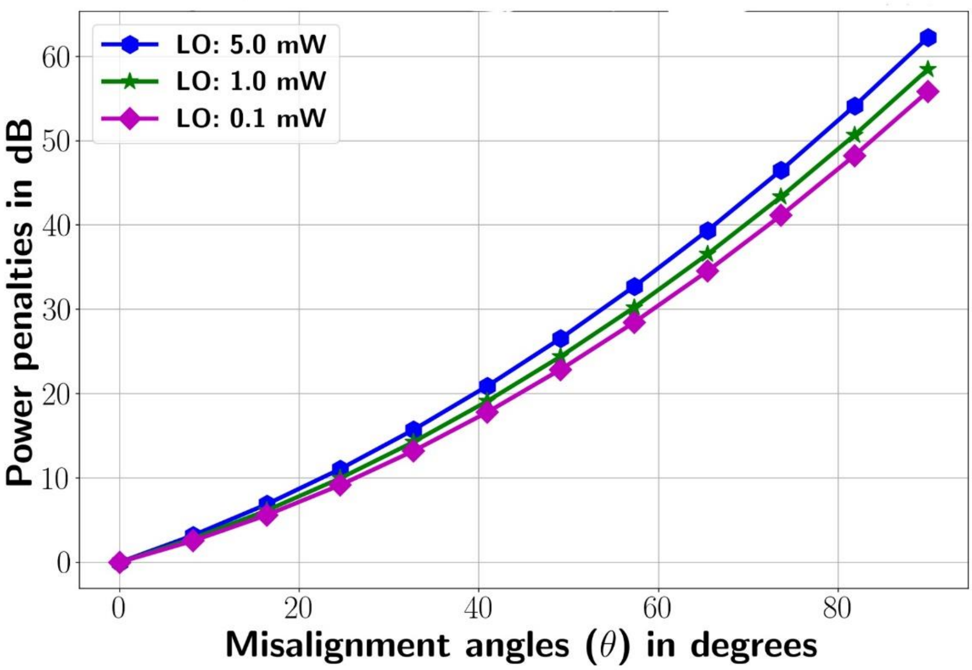

Fig 3.8: Power penalty vs misalignment angles at BER 10^{-9}

3.10 Analysis of Receiver Sensitivity Varying LO Power at BER 10^{-9}

Fig 3.9 shows the effect of local oscillator power and XPol on the receiver sensitivity. Sensitivity decreases with increase in LO power. Improving the sensitivity on the receiver (making it more negative) will allow the receiver to detect weaker signals, and can dramatically increase the transmission range. From the Fig 3.9, at a fixed LO power, the decrease of θ from $25^0$to 5^0 the sensitivity curve falls down, thus gets more negative.

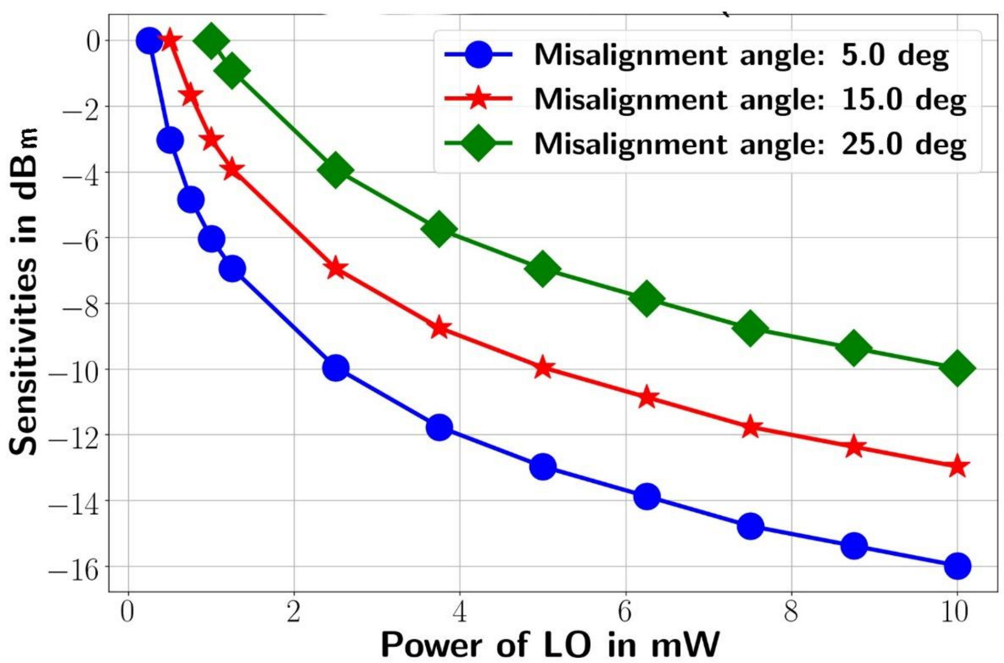

Fig 3.9: Receiver sensitivity vs LO power at BER 10^{-9}

Moreover, from Fig 3.8, the power penalty is decreasing with the decreasing of θ, therefore, the improvement in the sensitivity of receiver considerably reduces the penalties. As the power penalty of a PDM system is much higher than CPDM system, the receiver sensitivity is severely lower than later which again proves the superiority of CPDM QPSK system over the PDM one. It is clear from the above analysis that, the more misalignment angle increases, the poorer the BER performance for intrusion of Xtalk into main signal. Thus extra power is to supply to local oscillator to ensure proper differentiation of bits from the receiver signal to compensate for the power penalty at that particular BER. For this increasing LO power, receiver's sensitivity severely decreases. In the CPDM QPSK system, this situation is much less severe than the conventional PDM QPSK system accumulating in the same power of induced cross polarization.

CHAPTER 4

CONCLUSION & FUTURE WORKS

CONCLUSION AND FUTURE WORKS

4.1 Conclusion

The requirement of communication is universal. But the means of communication is updated time to time with evolution of technology. Today optical fiber communication has got wide spread popularity. It got limitation due to crosstalk and interference. Thus, fulfill the demand we need to enhance our research work to eliminate the present shortcomings. Here we try to have analytical calculation to understand which one will be good for us.

Thus an analytical approach is presented for a CPDM-QPSK coherent homodyne optical transmission system influenced by XPol-induced crosstalk to evaluate the performance in terms of BER, SCNR and power penalties suffered by the system for different misalignment angles. It is prominent from the analysis that, the system undergoes a significant degradation in BER and SCNR performance due to XPol-induced crosstalk and the system suffers power penalty for different misalignment angles which eventually reduces the sensitivity of receiver to achieve a definite BER (10^{-9}).Penalty in signal power is found to be 6.43, 16.78, 31.99 and 76.99 dB for mean misalignment angle of 20, 30, 40 and 60 degree respectively. The conventional PDM QPSK system shows 13.25 dB and 12.59 dB for θ of $5^0$and 7.5^0respectively at BER 10^{-9} and LO power of 1mW [19] while CPDM system shows only 2.45 dB and 3.12 dB of power penalties respectively for the same angles at the same BER and at the same LO power of 1mW.

SCNR decreases with the increase in misalignment angle as misalignment angle exceedingly increases Xtalk power. In a conventional PDM QPSK system, SCNR drops by 25dB sweeping misalignment angle from 0 to 90 degrees [19] whereas in CPDM it falls only by 17dB at the same condition. So, undoubtedly the performance of SCNR of CPDM-QPSK is more efficient than conventional PDM-QPSK system [19] in terms of SCNR performance. Due to this improvement in BER and SCNR performances, CPDM QPSK system needs comparatively low incremental local oscillator power or power penalty and thus achieves higher receiver sensitivity than a typical PDM QPSK system.

Thus this is far better than conventional PDM QPSK system because it is proved that, a PDM system is much less immune to this degradation than CPDM for the coherent detection of optical signals. However, the application of CPDM in optical transmission system gives an efficient way to improve the speed performance and to increase the bandwidth of fiber optic cables even more by using PBSs and CPBSs alternatively. Though the concept of QPSK is inherent in CPDM, it can be easily extended for any other modulation scheme which is another achievement over the PDM QPSK system.

4.2 Future Works

- Today's research is worthy enough to be tried at an experimental level because the benefits are too compelling. Further research can be carried out to increase spectral efficiency of CPDM-QPSK coherent homodyne transmission systems using alternate PBS and CPBSs.
- As the concept of CPDM is not limited to QPSK alone so further research can be carried out to evaluate the performance of CPDM system applying any other modulation formats.
- As the use of the circular polarization opens up a window of opportunities so future should be focused on enhancing the bandwidth of the FSO using CPDM systems.
- Work can be carried out with pre-coding techniques to minimize the effect of the deterioration of the Bit Error Rate (BER) performance on account of XPol induced crosstalk.
- Work can be carried out to mitigate the fiber nonlinearities for further improvement in maximum reach and system performance.
- Work can be carried out to overcome most of linear impairments present in CPDM optical communication systems.
- Work can be carried out to reduce the outage probability of CPDM-QPSK coherent optical systems.

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