PERFORMANCE ANALYSIS AND COMPENSATION OF POLARIZATION EFFECTS IN FIBER OPTICS COMMUNICATION SYSTEMS

A Dissertation Submitted in partial fulfilment of the requirements for the award of the degree of

Masters of Engineering

In

Electronics and Communication Engineering

Submitted by

Geetika

Roll No. : 801461008

Under the guidance of

Dr. R. S. Kaler

Senior Professor and Deputy Director

Thapar University, Patiala

ELECTRONICS AND COMMUNICATION ENGINEERING DEPARTMENT

THAPAR UNIVERSITY

(Established under the section 3 of UGC Act, 1956)

PATIALA – 147004 (PUNJAB)

July 2016

CERTIFICATE

I, Geetika, hereby declare that the work which is being presented in the dissertation entitled, **"Performance Analysis and Compensation of Polarization Effects in Fiber Optics Communication Systems"** by me in partial fulfillment of the requirement for the award of degree of M.E in Electronics and Communication submitted in Electronics and Communication Engineering Department of Thapar University, Patiala is an authentic record of my own work carried out under the supervision of **Dr. R. S. Kaler**, Senior Professor, ECED.

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

Geetika

Date: 5-July-2016 **GEETIKA**

ROLL NO: 801461008

It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

Date: 5-July-2016

Dr. R. S. Kaler
Senior Professor & Deputy Director
Thapar University

Countersigned By:-

Dr. Sanjay Sharma
Professor & Head
ECED, Thapar University

Dr. S.S. Bhatia
Dean of Academic Affairs
Thapar University

ACKNOWLEDGEMENT

To discover, analyze and to present something new is to venture on an untrodden path towards and unexplored destination is an arduous adventure unless one gets a true torch bearer to show the way. I would have never succeeded in completing my task without the cooperation, encouragement and help provided to me by various people. Words are often too less to reveals one's deep regards. I take this opportunity to express my profound sense of gratitude and respect to all those who helped me through the duration of this thesis. I acknowledge with gratitude and humility my indebtedness to **Dr. R. S. Kaler, Senior Professor,** Electronics and Communication Engineering Department, Thapar University, Patiala, under whose guidance I had the privilege to complete this thesis. I wish to express my deep gratitude towards him for providing individual guidance and support throughout the dissertation work.

I convey my sincere thanks to **Head of the Department, Dr. Sanjay Sharma** as well as **PG Coordinator, Dr. Amit Kumar Kohli, Associate Professor,** Electronics and Communication Engineering Department, entire faculty and staff of Electronics and Communication Engineering Department for their encouragement and cooperation.

My greatest thanks are to all who wished me success especially my parents. Above all I render my gratitude to the almighty GOD who bestowed self-confidence, ability and strength in me to complete this work for not letting me down at the time of crisis and showing me the silver lining in the dark clouds. I do not find enough words with which I can express my feelings of thanks to my dear friends for their help, inspiration and moral support which went a long way in successful competition of the present study.

Geetika

Roll No. 801461008

ABSTRACT

The optical communication system has become a major part of global infrastructure in past years because of its several benefits. The main objective of optical communication is to increase spectral effeciency and to utilize minimum bandwidth over long distances with minimum possible errors during transmission of signals. Spectral effeciency can be increased by using polarization multiplexing along with QPSK and QAM. Capacity can be increased by employing orthogonal polarization between adjacent WDM channels. However, depolarization of orthogonal states due to birefringence leads to degradation which limits bandwidth and capacity of systems.

The objective of dissertation is to analyze and compensate polarization effects in fiber optics communication systems and for this purpose VPI transmission maker and OptiSystem software is used which allows design of various communication systems.

Firstly, investigation of effects of second order polarization mode dispersion models on first order PMD compensator using duobinary and vestigial side band modulation is presented. Comparison of models is done in terms of bit error rate at various differential group delays for different received optical powers. These effects are studied for testing and verification of new technologies in PMD presence. Secondly, transmission analysis of 112Gbps DP-QPSK and DP-16 QAM using coherent receivers with digital signal processing is studied using optical power spectrum, OSNR tolerance, transmitter polarizing angle, different fiber lengths and constellation diagrams. These multilevel modualtion formats increases spectral effeciency and bandwidth utilization of system. Digital signal processing is used to compensate the effects of polarization demultiplexing, frequency offset and carrier phase offset. Thirdly, polarization interleaving method is proposed in DWDM systems for long haul transmission system to maintain orthogonality between adjacent channels to remove PMD and non linear effects.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

ADC	Analog to Digital Converter
ASK	Amplitude Shift Keying
BER	Bit Error Rate
CATV	Cable Access Television
CD	Chromatic Dispersion
CMA	Constant Modulus Algorithm
CPE	Carrier Phase Estimation
CRZ	Chirped return to zero
CSRZ	Carrier suppressed return to zero
CW	Continuous Wave
DC	Dual Carrier
DCF	Dispersion Compensating Fiber
DFE	Decision Feedback Equalizer
DGD	Differential Group Delay
DP	Dual Polarization
DPSK	Differential Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
DSBSC	Dual Side Band Suppressed Carrier
DSP	Digital Signal Processing
EDFA	Erbium Doped Fiber Amplifier
FOE	Frequency offset estimation
FWM	Four Wave Mixing
GVD	Group Velocity Dispersion
LO	Local Oscillator
MZM	Mach Zender Modulator
NRZ	Non Return to Zero
OOK	On Off Keying
OSNR	Optical Signal to Noise Ratio
PBC	Polarization Beam Combiner
PBS	Polarization Beam Splitter
PDG	Polarization Dependent Gain

PDL	Polarization Dependent Loss
PM	Polarization Maintaining
PMD	Polarization Mode Dispersion
POLMUX	Polarization Multiplexing
PRBS	Pseudo Random Bit Sequence
PSK	Phase Shift Keying
PSP	Principle State of Polarization
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
ROP	Received Optical Power
RZ	Return to Zero
SE	Spectral Effeciency
SMO	Simplex Method Optimization
SNR	Signal to Noise Ratio
SOP	State of polarization
SSB	Single Side Band
VSB	Vestigial Side Band
WDM	Wavelength Division Multiplexing

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
INTRODUCTION

1.1 INTRODUCTION

Since mid 90's, there has been exponential growth in Information technology through telecommunication systems. For development of high speed telecommunication and high speed systems, optical fiber communication plays an important role. In this, information between two places is exchanged by sending light signal through fiber and had brought revolutionary change in telecommunication industry. In 21st century, advantages of optical fiber over electrical transmission lead to copper wire replacement in communication system because it is a frequency of carrier which limits bandwidth of channel. Copper wire can carry signal of 1 MHz, coaxial cable can carry 100 MHz signal where as optical link can carry signal of 100 THz. In terms of capacity, fiber optical link can carry 30000 of two way voice signals.

Now a day's Optical fiber has been considered as most important communication channel. These fibers are not only used in telecommunication systems but also in Local area networks (LAN) and internet for achieving high data rates. Also no cross talk induces in optical fibers that are running along each side for large distances as in case of electrical transmission lines. The demand and use of optical fiber is growing tremendously. Telecommunication applications i.e data, video or voice transmission over long distances uses few standard designs of fiber [1]. The feasibility for using glass fibers was studied in mid 1960 and Dr. Charles Kao proposed that it would be possible to reduce attenuation of fiber to less than 20 dB/km [2]. The initial step for this development was taken in 1970's using low pass fiber [3] with semiconductor laser which were shown to be an important components in transmission systems [4] .With use of erbium doped fiber amplifiers (EDFA) in 1986, it was possible to increase distance and speed of communication systems [5]. Fig. 1.1 shows growth in fiber optic communication systems since 1974.

Therefore, fiber communication can be considered as a saviour that meets our huge bandwidth and capacity demands because of low distortion in signal, low cost, small amount of requirement of space and low usage of material [6]. With all these advantages, optical communication is becoming choice as a medium of transmission for networks of future

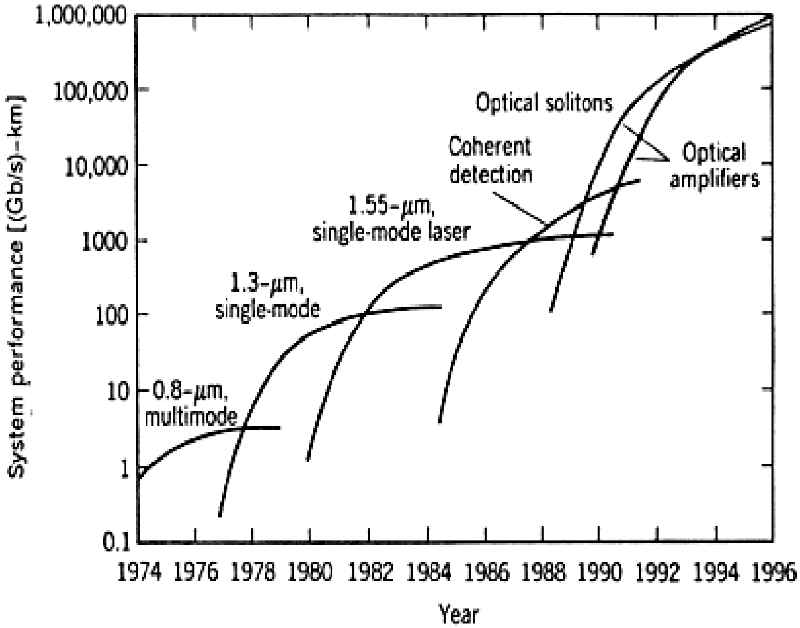


Figure 1.1: Growth in fiber optic communication system since 1974 [6].

The electronic devices can only transmit at rate of few Gb/s whereas fibers have capacities of order of Tb/s.

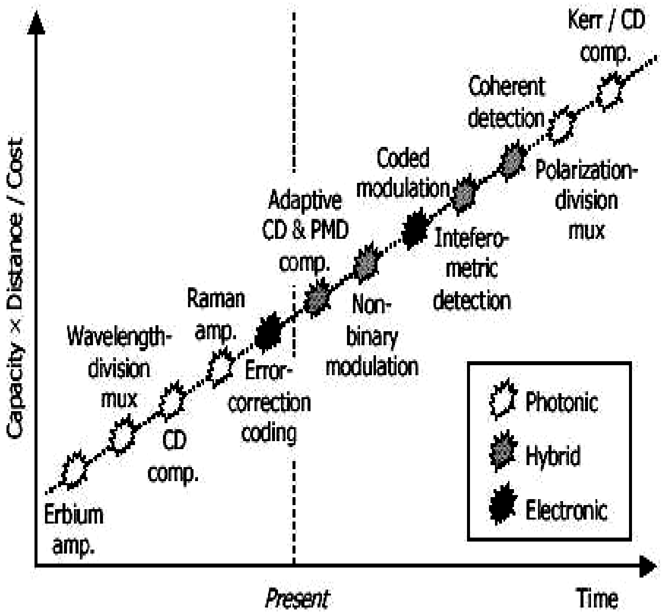


Figure 1.2: Technologies used for high capacity transmission [7].

Breakthrough in optical communication like wavelength division multiplexing (WDM) and cross connects has lead to formation of next generation optical networks. Pulses propagating through optical fiber in WDM systems offer certain degrees of freedom which include frequency, polarization state and phase. The combined use of these degrees of freedom can be considered for increasing capacity of systems. In WDM systems it is possible to increase number of channels by using orthogonal state of polarization. Also bandwidth can be increased by employing orthogonal polarization between adjacent WDM channels. However depolarization of orthogonal states of polarization due to birefringence and non linear effects degrades orthogonality of system. Hence the most important limit for spectral efficiency (SE) is due to non linear and polarization effects [7]. As shown in Fig. 1.2 improvements in SE can be obtained with polarization multiplexing of channels

1.2 POLARIZATION

In space, representation of light is given as wave of transverse nature in which wave motion is perpendicular along propagation direction. Continuous wave (CW) in which propagation direction is choosen as z is represented by E (z, t)$e^{j(w_0 t-\beta z)}$, β here refers to propagation constant, ω_0 refers to angular frequency of carrier, x, y denotes transverse coordinates. Polarization is property that represents electric field orientation E (z,t) of electromagnetic waves in plane of x, y coordinates at t time with propagation distance of z. Light is linearly polarized when phase difference between E_x and E_y is 0 or multiple of π with constant oscillation plane. And when x and y components have equal amplitudes with multiples of $\pi/2$ phase difference, then light is said to be circularly polarized and if these conditions are not satisified, light have elliptical polarization. Jones formalism provided representation of light polarization with electric field using ket 2D vector [8]

$$|s\rangle = \begin{pmatrix} s_x \\ s_y \end{pmatrix} \quad (1.1)$$

Here s_x and s_y are complex quantities and bra-ket notation is used to distinguish Jones vector from Stokes vectors .Jones vector basically have unity magnitude i.e

$$\langle s|s\rangle = s_x^* s_x + s_y^* s_y = 1 \quad (1.2)$$

Polarization can also be described by stokes formalism which have four stokes parameters. Stokes parameters for coherent light is given by [8]:

$$s_0 = s_x s_x^* + s_y s_y^* \quad (1.3)$$

$$s_1 = s_x s_x^* - s_y s_y^* \quad (1.4)$$

$$s_2 = s_x s_y^* - s_x^* s_y \quad (1.5)$$

$$s_3 = j(s_x s_y^* - s_x^* s_y) \quad (1.6)$$

Stokes vector is defined as $\hat{s} = (s_1, s_2, s_3)$ having unit length indicating polarization of field. For s_1=1, light is said to be linearly polarized along x axis, s_2=1 in linear polarization of 45^0 and s_3=1 in right circular polarization of light. The stokes vector locus which represents possible states of coherent light polarization form a sphere known as Poincare sphere providing three dimensional representation of light.

1.3 POLARIZATION MODE DISPERSION

Polarization related impairments are becoming major obstacle in increasing data rate for WDM systems. These impairments include polarization mode dispersion (PMD) in fibers, components polarization loss of passive networks and polarization gain of optical amplifiers.

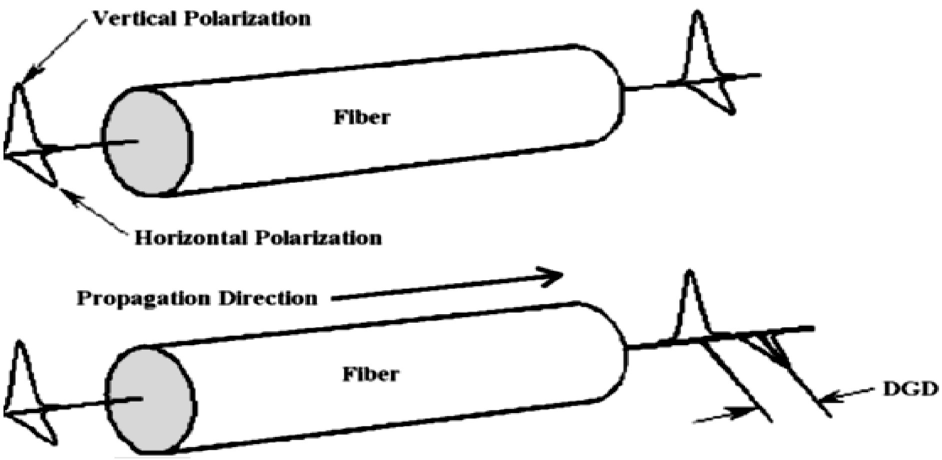


Figure 1.3: Polarization mode dispersion [9].

PMD is linear phenomenon occurring inside single mode fiber as each fiber has two propagation modes which differ from each other by their polarizations. But due to presence of birefringence, two modes have different group velocities while travelling through fiber resulting in propagation time difference which is known as Differential group delay (DGD) and randomly changing birefringence with fiber length leads to random coupling of these modes which causes receiver to unable to interpret received signal correctly. Problems manifest itself in 5Gbps and have major dislocation at 10 Gbps. It leads to signal distortion, render bits accuracy and leads to distortion of integrity of network.

The PMD value of older fibers was 100 times greater as compared to fibers of present day. But in new fibers PMD is major problem due to following factors:

a) Residual asymmetry in core of fibre

b) Slight PMD in inline discrete components for example couplers, isolators, multiplexers and modulators

Also external forces due to environment in cabling, handling leads to bending and twisting of fibers and internal forces due to thermal expansion leads to asymmetries in fiber [10].

1.4 EFFECTS DUE TO PMD

PMD leads to data loss and signal degradation. Parameters affected due to PMD are bit error rate (BER), outage probability or power penalty.

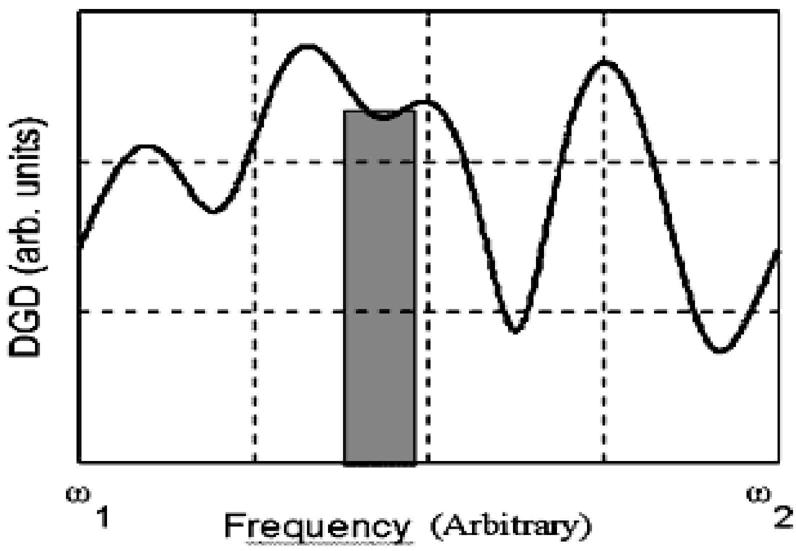


Figure 1.4: DGD variation with frequency [11].

Power penalty which is measured in decibels is amount of power attenuated before unacceptable BER. In addition to time, PMD is also affected by change in wavelength. PMD is not only problem in 40 Gbps but also in 10 Gbps optical systems. It basically disperses transmitted bits and increases BER in receiver. DGD can be measured by separation in time of polarized pulses of bits whereas separation average can be calculated from value of PMD coefficient [11].

1.5 CHARACTERIZATION OF PMD

PMD occurring in fibers used in telecommunication is stochastic or random in nature. Therefore penalties occurring due to PMD in fiber are also random in nature. Two parameters used to characterize PMD are DGD and principal state of polarization (PSP). Signal in fiber oscillate in two planes which are at right angles along each other known as PSP. For fixed value of PMD, DGD is random in nature having maxwellian probability density function (PDF). In fibers without PMD, these polarization states do not change and energy of each state reach receiver at same time. However, in PMD presence there is change in these states and their arrival times also vary. This difference in arrival time is DGD. DGD value increases with increasing fiber length as well as with increase in PMD coefficient. DGD as well as PSP both are dependent on frequency. Higher orders PMD come in existence when optical signal bandwidth is larger as compared to channel bandwidths [12].

1.6 MEASUREMENT METHODS OF PMD

Different techniques can be used for measuring PMD in fiber. Techniques dependent on polarimeter, measuring output state of polarization are convenient for measuring PSP and DGD as function of wavelength. Two of these techniques are Poincare sphere method and Jones matrix method. Techniques that are not dependent fully on polarimeter are known as fixed analyzer technique which is only able to determine one component of polarization.

Techniques for measuring PMD are

- Wavelength scanning /fixed analyzer method
- Interferometric method
- Jones matrix Eigen analysis
- Poincare Sphere method

1.6.1 Wavelength scanning method

In this, Fourier transform and extreme counting is performed. Here source and analyzer input polarizers have fixed and same value and transmission power varying with wavelength is measured for constant input power. In absence of PMD for device under test, polarized light of source will always reach analyzer with same power and at same angle. However in presence of birefringence, state of polarization revolves in cyclic manner proportional to PMD present. Then extremas can be counted and PMD can be measured [13].

1.6.2 Interferometric method

This method uses experimental setup as shown below in Fig.1.5.Interferometer here can be prismatic beam splitter, Michelson type having open beam splitter or fiber coupler. The variable delay is introduced by moving mirror between interferometric forms and then state of polarization is recombined using this delay. At end, integration is performed by detector and delay is swept using mirror. In PMD absence, measurement of autocorrelation function yields coherence time .However with PMD, coherence time and autocorrelation width increases [14].

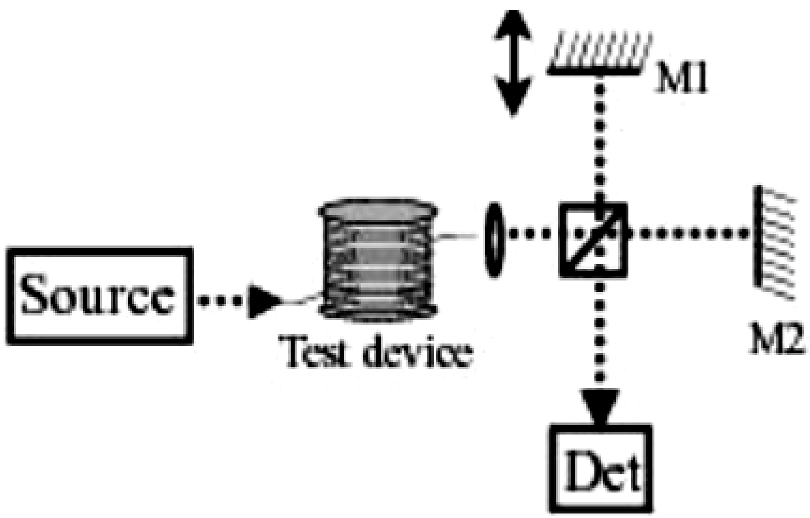


Figure 1.5: Setup for measuring PMD using interferometric method [14].

1.6.3 Poincare Sphere method

Using this techniques PMD vector can be measured by measuring output polarization state along with frequency for two input state of polarizations.
PMD vector is calculated using following equation

$$\Omega(\omega) = \frac{\frac{ds_i}{d\omega} * \frac{ds_j}{d\omega}}{\frac{ds_i}{d\omega} . s_j} \tag{1.7}$$

Here s_i , s_j are two inputs. Error in calculation occurs when one output is near to PSP. Therefore, for reducing error three inputs must be used and output can be measured by averaging these vectors

1.7 PMD EMULATORS

Important issue for designers in systems with high performance is measurement of degradation in performance due to presence of high PMD fibers. Present fibers have very low PMD value, so fibers having high value of PMD are not commercially available [9]. If they are available, they will be difficult in use to explore rapidly large number of different fibers which are required for determining PMD penalties. Thus for testing optical systems, affected due to PMD, it is important to emulate effects of first and high order PMD. PMD emulators used in communication system must have property that DGD must be maxwellian distributed at any fixed value of frequency [15]. Three most common models of PMD emulators are:

1.7.1 Fixed orientation emulators

In this type of emulators, realization is done by connection of different short polarization maintaining (PM) fibers having fixed value of angular offset after every section of fiber. But these emulators donot guarantee to produce same characteristics as that of real fiber. However they can be optimized for obtaining DGD distribution in agreement to maxwellian distribution over entire range of frequencies. But they have limited use because of large frequency range which is needed to sweep for obtaining good agreement. Also WDM systems can also be not studied using these emulators. Thus use of these emulators is limited for measuring.

1.7.2 Rotatable section emulators

In these emulators, rotatable connectors are used in between PM fibers for generating ensemble of PMD by rotation of connectors randomly. And their accuracy is dependent on number of sections of PM fiber used, large PM fibers leads to more accuracy [16]. Here rotatable connectors are used to adjust polarization axes of fibers placed adjacent to each other and length of these fibers is choosen by using Gaussian random variable. Large DGD values can be produced by changing either the wavelength with fixed angle or by rotation of angles between fibers.

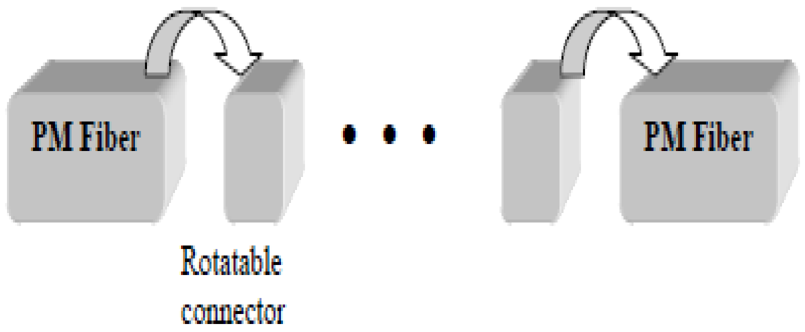


Figure 1.6: PMD emulator having unequal length PM fibers and rotatable connectors [16].

1.7.3 Variable DGD element emulators

These emulators use variable elements of DGD, microprocessors and polarization controller. DGD elements are connected along with polarization controller in between them. Polarization controllers are used for having different rotation on Poincare sphere for each DGD element [17]. Therefore, by controlling each DGD element to have maxwellian distribution and polarization controller for scattering of PMD vector, we can emulate Maxwellian distribution.

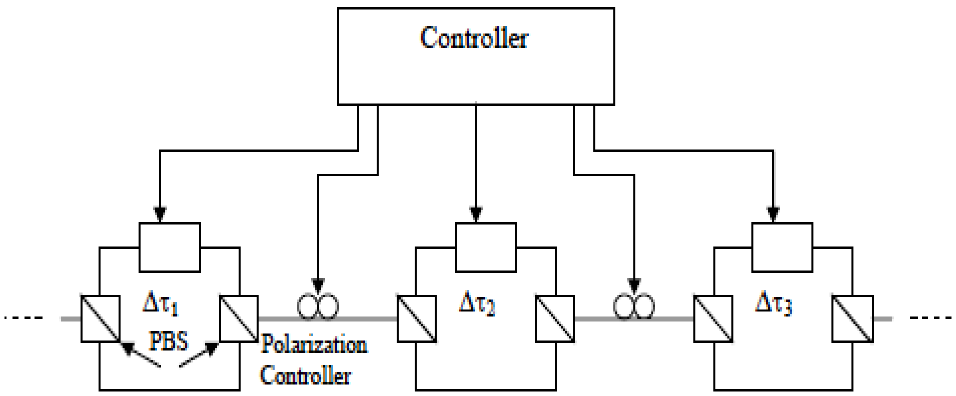


Figure 1.7: PMD emulator having variable DGD elements [17].

1.8 PMD COMPENSATION TECHNIQUES

Due to random nature of PMD, reduction of PMD impacts does not imply complete PMD cancellation but reduction in outage probability due to PMD. Compensators are classified into two categories:

1.8.1 Electrical compensators

These compensators involve electrical signal equalization before receiver but after photodiode and can be implemented in many different ways. First method which requires use of transversal filter is realized by using tapped delay line filter. In transversal filter, signal is first divided, and delayed by using constant delay stages and is then superimposed on output port. The tap filter weights are adjusted in such a way in order to maximize quality of signal. Also equalization can be done by use of decision feedback equalizer (DFE). The DFE is based on principle that once particular bit is decided as one or zero, interference caused due to this bit on future bits is subtracted before deciding future bits. This technique requires fast signal processing so that coupling of decided bit can be done in time. Other equalization way is phase diversity detection in which two photo diodes are used for detection of signals in PSP and interpret value of DGD and then suitable delay is generated in one arm [18].

Electrical compensators are robust and have improved signal against channel impairments but these are not good as that of optical compensators and also they require high speed devices

1.8.2 Optical compensators

Aim of these compensators is to reduce PMD impairments caused due to optical fiber. The block diagram of scheme is as shown which consist of adaptive element, feedback signal and control algorithm.

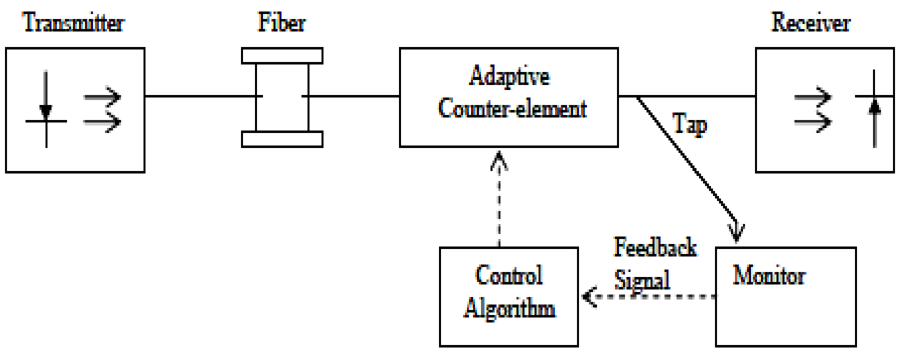


Figure 1.8: General scheme for optical PMD compensation [19].

In this core of compensator is adaptive counter element which is able to control impairments and should be tuneable. Elements having high value of birefringence for example PM fibers, Bragg grating, $LiNbO_3$ delays are used. Schemes vary in number of different elements used. In this feeback signal is provided to controlling algorithm [19]

1.9 POLARIZATION MULTIPLEXING

Approach towards multilevel modualtion formats is to use the polarization dimension of signal that is to be passed through optical fiber. In comparison with phase shift keying (PSK) and amplitude modulations, modulations using polarization multiplexing (POLMUX) has attracted only limited attention. This is due to the reason that these modulations require use of receivers that are sensitive to polarization. POLMUX also refers to as Polarization division multiplexing (PDM) or dual polarization (DP) modulation is most commonly used polarization sensitive formats for modualtion. In this two independent signals are transmitted in each of two orthogonal polarizations and is use to increase SE as compared to single polarization modualtion. This modualtion also leads to reduction of symbol rate by half in comparison with binary modulations having same bit rate [20] and leads to reduction of linear as well as non linear channel impairments. However due to birefringence of optical fiber they requires polarizations sensitive receiver for demultiplexing of two polarizations at receiver.

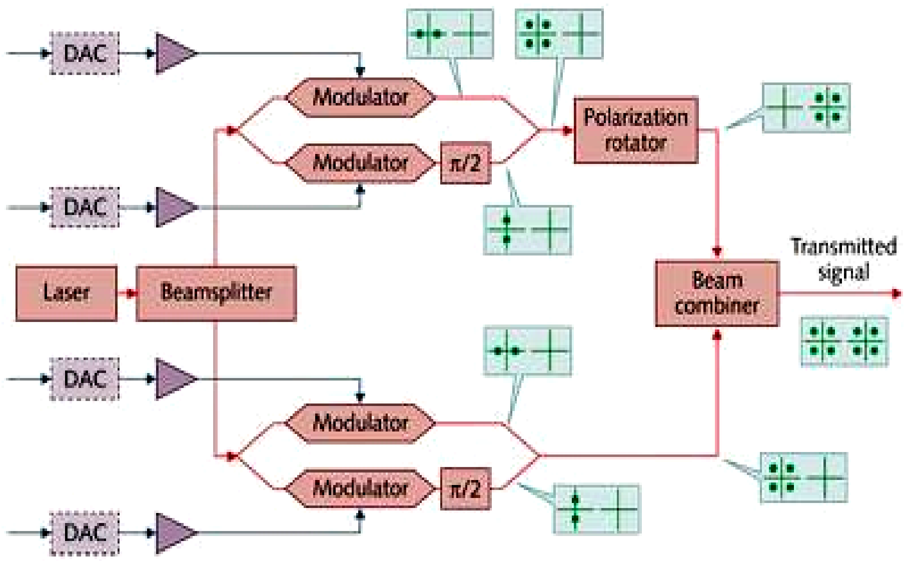


Figure 1.9: Diagram of dual polarization In phase / Quadrature optical transmitter [21].

This demultiplexing can either be done in electrical or optical domain and is more sensitive to polarization related impairments. This modualtion has been used in number of laboratory experiments for recording capacity and in field trials [21]. However they are limited to short distances. This is due to sensitivity of POLMUX to PMD related impairments in long haul transmission systems

DP is method used in multiplexing signals on electromagnetic waves using polarization of waves. It can be used in combination with phase and intensity modulated schemes for increasing spectral efficiency. Example of such modulation is DP-Quadrature phase shift keying (QPSK) which uses phase and polarization properties of optical signal. In this scheme, four mach zender modulators (MZM) are needed i.e one for each of orthogonal dimension as shown in Fig.1.9.

Demodulating these types of modulations requires mixing of received signal with that of local oscillator (LO) in coherent receiver [21]. Coherent detection results in linear relation between received optical signal and obtained electrical output. These allows mitigating channel impairments i.e chromatic dispersion(CD) and PMD in electrical domain using analog to digital converters (ADC) along with Digital signal processing (DSP).

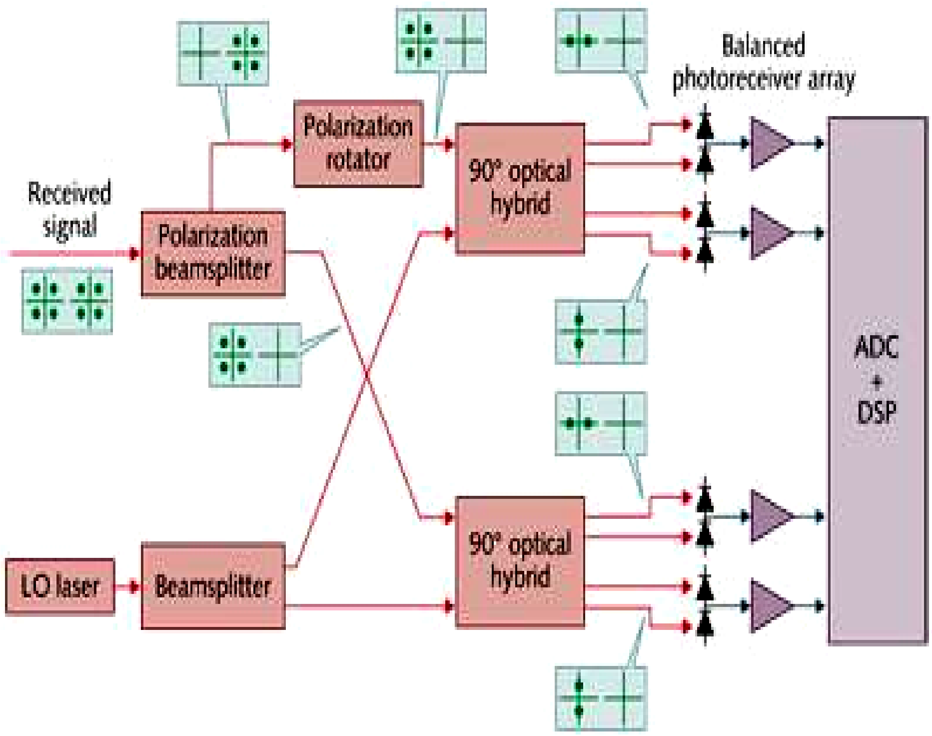


Figure 1.10: Coherent dual polarization IQ receiver [21].

1.10 POLARIZATION INTERLEAVING

In WDM systems capacity can be increased either by increasing data rate or number of channels in system, however to increase number of channels, spacing between channels have to be reduced. This reduction in spacing leads to increase in PMD and non linear effects in transmission system. Different techniques have been generated for reduction of this non linear and PMD effects. Most commonly used technique is polarization interleaving. In WDM systems, amplitude of signal at nth detector after demultiplexing is given by [22]

$$E_n = S_n + \sqrt{\gamma}\,[S_{n+1} + S_{n-1} + S_{n+2} + S_{n-2} \ldots\ldots\ldots\ldots] \quad (1.8)$$

Here S_n denotes signal amplitude of nth channel and γ is fraction of leakage of optical power in WDM due to adjacent channel interference into nth channel.

Electrical current is directly proportional with $|E_n|^2$

$$i_n(t) \propto |E_n|^2 = |S_n|^2 + \sqrt{\gamma}[S_n S_{n+1} + S_n S_{n-1} + S_{n+1} S_{n-1} S_{n+2} + \cdots \ldots\ldots\ldots]$$
$$+\gamma[|S_{n+1}|^2 + |S_{n-1}|^2 + |S_{n-2}|^2 + |S_{n+2}|^2 \ldots\ldots\ldots\ldots] \quad (1.9)$$

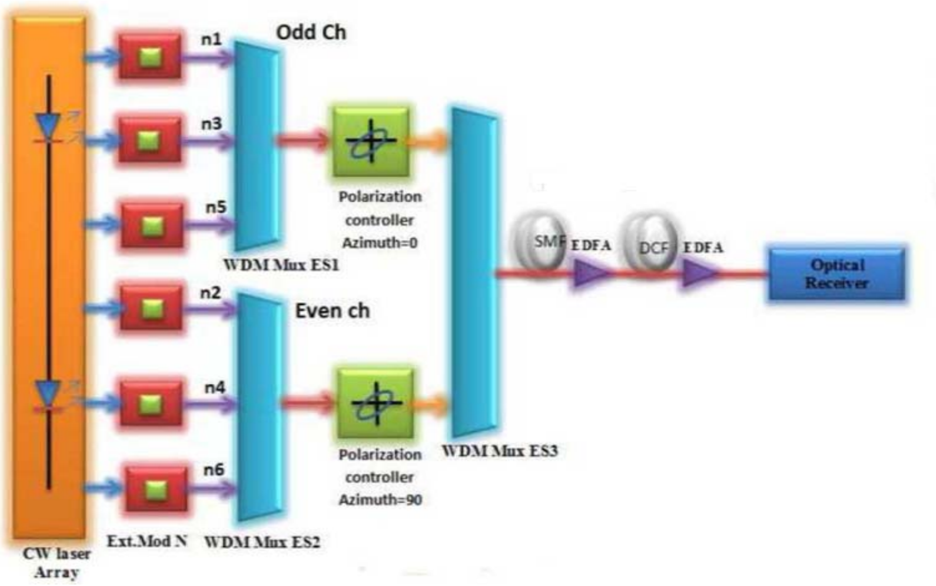


Figure 1.11: Polarization interleaving scheme in WDM system [22].

Here in this equation second term indicates interference which can be eliminated by using method of polarization interleaving and third term in equation represents power leakage. In this scheme, total number of channels of WDM Systems is divided into even and odd channels, and are then multiplexed together. Then both multiplexed channels are passed through linear polarizers before interleaving. For examples consider six WDM channels denoted as m1,m2,m3,m4 ,m5 and m6.Odd Channels m1,m3 m5 are passed through one multiplexer and even channels m2,m4 and m6 are passed through another multiplexer. Then output of both multiplexers are passed through PC which changes polarization state by changing azimuth as well as elliptical angle of signal. The polarization state of odd channels is made θ^0 where as even channel is made $\theta + 90^0$ so that adjacent channels are orthogonally polarized to each other. Then both these outputs are passed through final multiplexer. Whereas in simple WDM all channels have 0^0 polarization state [22]

1.11 OBJECTIVES OF DISSERTATION

1. To study effects of second order Polarization Mode Dispersion models on first order PMD compensator at 40 Gbps using different modualtion schemes.
2. To investigate transmission performance of 112Gbps DP-QPSK and DP-16 QAM using coherent receiver with digital signal processing in terms of optical signal to noise ratio, constellation diagrams, signal to noise ratio and polarizing angle
3. To compensate PMD in Dense Wavelength Division Multiplexing long haul system using polarization interleaving method

1.12 METHODOLOGY

The major aspect during methodology stage is simulation process which is carried out using software's VPI transmission maker and OptiSystem. VPI transmission maker accelerates design of photonic systems and subsystems for access, short range, metro and long haul transmission systems and provide technology upgrade, component substitutions strategies to be developed for existing fiber plants. The combination of graphical interface, robust simulation scheduler and optical simulation models together with flexible representation of optical signal at different abstraction degrees allows accurate modelling of transmission systems including ring, mesh networks and bidirectional link. Sampled signal modelling allows simulation of optical field in time domain enabling BER estimation and analysis of eye diagram

OptiSystem is an innovative optical simulation package that can design, test and optimize any optical link from analog video broadcasting system to intercontinental backbones. It is physical layer simulator based on modelling of fiber communication system. The extensive active and passive components include components dependent on wavelength. System performance is predicted in terms of BER and Q factor using numerical analysis for systems having noise and interference and data flow model used in simulation is component iteration data flow

1.13 OUTLINES OF DISSERTATION

Chapter 1 provides introduction to topics related to research work done during dissertation based on polarization mode dispersion, polarization multiplexing and polarization interleaving,

Chapter 2 describes literature survey based on topic of dissertation. In order to start dissertation, first step is to study papers that have been already published by other researchers. Papers related to this work are choosen and studied. With help of literature review, it became easy to perform task.

Chapter 3 compares effects of second order PMD models on first order PMD compensator at 40 Gbps using duobinary and vestigial side band modulation and is simulated using VPI transmission maker

Chapter 4 investigate transmission analysis of DP-QPSK and DP-16 Quadrature amplitude modulation in terms of optical signal to noise ratio, polarizing angle, signal to noise ratio and constellation diagrams using coherent receiver with DSP.

Chapter 5 describes method to reduce effect of PMD and non linearities in long haul DWDM systems using polarization interleaving scheme.

Chapter 6 includes the conclusion, recommendations and future prospect of research work

CHAPTER 2

LITERATURE SURVEY

As data rate in communication system increases, polarization related impairments are becoming major obstacle for upgrading present communication systems due to depolarization of light caused by birefringence in fiber. Due to these impairments large number of measurement and compensation methods has been developed by various researchers to improve performance of optical communication systems based on principle of maintaining orthogonality of light waves. The literature survey of recent polarization based techniques used in high capacity transmission systems and effects of polarization discussed by various researchers in past years is given below

Zeng [23] presented emulator based on second order PMD effects having tuneable second order PMD and fixed mean DGD for first order PMD. This emulator is based on polarization controller, fiber segment with high birefringence having fixed DGD and variable line DGD. Calculations showed that with tuning of variable DGD line, these emulators provided different second order PMD values and can be used in higher bit rate systems to test fluctuations in presence of second order PMD around mean penalties caused due to first order PMD and also to test PMD compensators to compensate both first and second order PMD effects.

Kogelnik et al. [24] described the way for determining PMD inversion to calculate pulse response i.e to determine jones matrix for studying impairments caused by PMD system, higher order PMD and construction of their models and presented discussion of second order PMD models like EMTY, planar sweep and Bruyere. These second order models has been distinguished by Eigen values and Eigen vectors. Also presented that these models can further be extended to higher order PMD by using high power rotation and concatenation rule and presented up to sixth order PMD.

Singh et al. [25] investigated performance of variable scattering section dispersion and fixed scattering section dispersion using duobinary transmitter for different PMD coefficient values at 40 Gb/s for frequency range 193 THz to 195Thz. It was observed that system performance is degraded with penalities induced by PMD. By using fixed scattering section dispersions, delay of 7 ps was observed using 200 km in received signal while this delay was compensated in case of variable scattering section dispersion. Also fluctuation of Q value was observed from 6 to 16 dB with PMD coefficients of 0.1 to 0.6 ps/km$^{1/2}$ for both cases. It was also observed that fixed scattering section have more effect of timing jitter. Therefore duobinary with variable scattering dispersion performed better than fixed scattering dispersion

Xie et al. [26] compared broadening of pulses due to different PMD models using systems with and without compensation of first order PMD. In system without PMD compensation, all PMD models i.e. Bruyere, planar sweep and EMTY have larger broadening of pulse as compared to all order model. Particularly, EMTY model have large errors, Bruyere have moderate errors whereas planar sweep is close to all order model. For system with compensation of first order PMD, EMTY model have larger pulse broadening and rest all models are comparable to all order PMD. At end, results indicated that to study PMD impairments effect, all order PMD model must be used.

Musara et al. [27] designed emulator capable of producing statistics of first and second order PMD to make it mimic for different fiber links and plants. The various PMD values can be generated by adjusting coupling angle from 0^0 to 180^0 between PM fiber having fixed fiber length and using electro optic rotators of polarization acting as half plate. The proposed emulator after the laboratory test was found to be stable and by using same setting for three days of half wave plate gave same PMD statistics and PDF for these days. Variation in halfwave plate gave random first order PMD variations as that are produced in aerial fibers.

Santosa et al. [28] analyzed correlation between second order PMD and first order PMD with temperature having different values at different temperatures. Investigation basically shows the second order PMD importance for higher values of DGD. It was observed that second order PMD have instabilities which were shown by variation along its mean value and also showed the influence of PMD as a result of stability of spectrum affected due to temperature.

Tipsuwannakul et al. [29] compared performance of two modulation formats i.e. POLMUX-RZ-D8PSK and POLMUX-RZ-DQPSK at 112 GB/s in terms of DGD, OSNR and group velocity dispersion (GVD) tolerances. The results obtained showed that POLMUX-RZ-D8PSK requires 5.5 dB higher OSNR than POLMUX-RZ-DQPSK in single channel as well as WDM transmission with 100 GHz spacing. But in DWDM systems, both modulation formats have been observed to have comparable requirement of OSNR because D8PSK have compact spectrum in DWDM systems. Also D8PSK have 15ps/nm higher GVD tolerance as compared to DQPSK because of lower baud rate .Thus POLMUX-RZ-D8PSK shows improved performance but at the cost of high OSNR requirement and increased system complexity.

Tipsuwannakul et al. [30] presented direct comparison of DP-16 QAM with duobinary- shaped DP-QPSK in WDM system with 25 GHz spacing operating at 112Gb/s with 4.1 bits/s/ Hz SE . Author compared these using different cases i.e. phase noise tolerance, back to back sensitivity and tolerance to nonlinearities using single mode fiber. From results, it was observed that in back to back sensitivity DP-16 QAM provided 1.2 dB better performances. Duobinary DP-QPSK shows 3 dB higher tolerances to non linearities at 640 km length in 3 channel WDM system .Also with optimized carrier phase estimation (CPE) length, both modulations have comparable tolerance to phase noise of laser. At end, DP-16 QAM provided better performance with less amount of transmitter and DSP complexity.

Savory [31] presented the algorithms and subsystems used in coherent receivers for optical transmission and after that discussed front end, DSP and analog to digital conversion based algorithms to relax subsystem tolerances. Then algorithms for transmission impairments compensation i.e dynamic equalization of channel, constant modulus algorithm(CMA) for DP in which several algorithms for equalizers are derived which includes radially directed, decision directed , constant modulus and trained equalizers for modualtion formats of POLMUX QPSK and 16 QAM.

Pillai et al. [32] investigated impact of end to end energy consumption in forward error correction(FEC) in long haul transmission of 100Gbps and compared energy efficiency of DP-QPSK and 16 QAM in terms of BER and different transmission distances which includes energy consumption in transmission link, transmitter, receiver and amplifier and concluded that energy consumption in receiver is more due to electrical dispersion compensation for long distances .DP-QPSK had more energy consumption than DP-16 QAM due to hard decision decoding for short distances. However, for long transmission distances, both modulations have comparable consumption of energy.

Gupta et al.[33] presented comparison between DP-QPSK and 4- QAM in terms of constellation diagram, power spectrum and optical time domain visualizer output.

From results it was observed that constellation diagram obtained from 4- QAM have 16 separate dots in each of four quadrants whereas DP-QPSK consists of many small dots in each quadrant. Also in comparison to DP-QPSK, 4 QAM have compressed power spectrum and from time domain visualizer, power of 4 QAM is constant at -15 dBm independent of time whereas DQPSK have large power fluctuations with respect to time. Therefore 4 QAM have better performance than that of DQPSK.

Ly-Gagnon et al.[34] investigated performance of 10 Gsymbol/s signal coherent optical receivers for demodulation and estimated carrier phase using DSP by locking LO phase with that of carrier. Simulation results presented that noise in phase of carrier is small by using distributed feedback lasers as compared with accurate estimation of phase. Also there was improvement in sensitivity of receiver as compared with differential detection.which increases reach of transmission system. Also 2.5b/s/hz SE was obtained using WDM system having signals with modualtion of POLMUX QPSK and 16 GHz of channel spacing. It reported that, by combining multibit per symbol, small channel spacing in WDM systems and POLMUX at transmitter, the SE of proposed system can be increased.

Abdl et al. [35] presented approach for reduction of four wave mixing (FWM) by using polarized interleaved system and behaviour of proposed system with WDM system has been analyzed. Proposed system has been evaluated for input power value of -12dBm to 0 dBm. It has been observed that FWM power increases for both cases with increasing input power. However proposed systems have more reduction of FWM power. At particular input power of -12dBm , FWM have -88 dBm power whereas simple WDM have -80 dBm power, Also at sixth channel BER of proposed system is 4.86×10^{-21} whereas for WDM is 4.43×10^{-10} with same value of input power which shows the suppressed FWM in system.

Singh et al. [36] analyzed performance of polarized interleaved with that of modified polarization interleaved systems using hybrid amplification in fiber in terms of OSNR, signal power and noise power for 8 channels with 100Ghz and 50 GHz channel spacing. Hybrid fiber amplification was used to balance between high OSNR requirements and non linear impairments of channel consisting of distributed Raman amplifier along with EDFA. Reverse dispersion fiber was used instead of dispersion compensating fiber (DCF) to reduce non linear impacts in proposed system.

Chang et al. [37] proposed dual carrier (DC) based DQPSK at 112 Gbps for cost efficient transmission of 100G systems which do not have need of coherent detection with DSP and described the scheme to update WDM systems of 10Gbps by using DC-QPSK at transmitter and receiver. Also dispersion was compensated after each span completely. Proposed system showed sufficient performance after forward error correction for transmission of error free signals.Another method in which co propagating 10.7 GB/s signals with on off keying was transmitted where two channel grids were occupied by dual carrier systems. This provided improvement in tolerance to non linearities occurred with on off keying (OOK) signals and low requirement of OSNR as compared to WDM links with 10 GB/s.

Taher et al. [38] presented simulation for various modualtion formats in optical fibers communication in presence of PMD and nonlinearities. At various values of DGD, Different modualtion schemes considered were Chirped return to zero (CRZ), carrier suppressed return to zero (CSRZ), and duobinary, return to zero(RZ), non return to zero (NRZ), DQPSK and CSRZ-DQPSK at data rate of 40 Gbps. RZ DQPSK modualtion showed best performance among all schemes. Also showed that PMD effect for some modualtion schemes decreases within increase in non linearities.From optical spectra's, it was observed that RZ-DQPSK have maximum advantage. DGD diagrams indicate that RZ-DQPSK shows better performance with all PMD values. And therefore meets requirement of higher bit rate of optical communication i.e beyond 40 Gbps.

Hirooka et al. [39] presented description and experimental demonstration regarding PMD influence and polarization dependent loss (PDL) in high speed Polarized multiplexed transmission systems. PMD and PDL effects causes rotation of PSP's leading to non orthogonality. And even when one output is constant state of polarization (SOP) i.e Constant in frequency, then other channel is frequency dependent. This leads to cross talk among polarization of polarisation multiplexing and impact was calculated at 300 km in DPSK system having 1.28 TB/s/ch. And can be avoided by minimizing bandwidth of transmitted signal and PDL minimization in long haul systems.

Kaur et al. [40] analyzed performance of modualtion techniques in cable access television (CATV) transmission system. Different modulations compared are PSK direct, 16-QAM, QPSK and PSK back to back. And concluded that all modulations have different preferences like eye opening was more in case of 16 QAM, PSK had more Q factor which means that in case of PSK, SNR is more as compared to others. Also jitter value in case of 16 QAM was less. It was concluded that 16 QAM is more preferable modualtion scheme

Yuanyuan Li et al. [41] proposed Simplex method to optimize Quality of transmission (QoT) for dispersion uncompensated systems with non identical spans in PDM-QPSK at 100Gbps. This optimization reached Q factor closed to optimal value and minimized number of EDFA. Numerical simulations showed that simplex method optimization (SMO) strategy had 1 dB more Q factor as compared with complete span loss compensation technique. Also number of EDFA needed to be adjusted was less and reduced to 2 from 8 leading to reduction in cost

Table 2.1: Literature Survey of polarization effects in past few years

TYPE	AUTHORS	WORK DONE	RESULTS
PMD emulator	Zeng	Emulator with tuneable second order PMD and fixed DGD for first order PMD	This emulator with variable DGD line provided different second order PMD values and is used to test fluctuations in presence of PMD
Second order PMD models	Kogelnik et al.	Presented discussion of second order PMD models like EMTY, planar sweep and Bruyere	Distinguished models in terms of Eigen values and Eigen vectors and extended them to higher order PMD using rotation and concatenation rule
Second order PMD models	Xie et al.	Compared models with and without first order PMD compensation	EMTY models has large errors , Bruyere had moderate errors and planar sweep in close to all order PMD model
PMD	Musara et al	Emulator for	Emulator after laboratory

emulator		producing FOPMD and SOPMD for different fiber links and plants	test was found to be stable and by varying half wave plate , first order PMD can be varied
Polarization multiplexing	Tipsuwannakul et al	Compared DP-16 QAM with duobinary- shaped DP-QPSK in WDM system	DP-16 QAM provides 1.2 dB better performance in back to back sensitivity. Duobinary DP-QPSK shows 3 dB higher tolerance to non linearities and comparable tolerance to phase noise
Polarization multiplexing	Pillai et al.	Compared energy efficiency of dual polarization QPSK and 16 QAM in terms of bit error rate and different transmission distances	DP QPSK have more energy consumption than DP16 QAM due to hard decision decoding for short distances. However, for long transmission distances, both modulations have comparable consumption of energy
Polarization multiplexing	Gupta et al.	Compared DP-QPSK and 4- QAM in terms of constellation diagram, power spectrum and optical time domain visualizer output.	4 QAM have compressed power spectrum and from time domain visualizer, power of 4 QAM is constant at -15 dBm independent of time where as DQPSK have large fluctuations which indicate that 4 QAM have better performance.
Polarization Interleaving	Abdl et al.	Presented approach for reduction of four wave mixing by using polarized	Proposed systems have more reduction of FWM power. At particular input power of -12dBm, FWM have -88 dBm

		interleaved system and compared with simple WDM system. for input power value of -12dBm to 0 dBm.	powers whereas simple WDM have -80 dBm power. BER of proposed system was 4.86×10^{-21} whereas for W DM was 4.43×10^{-10} with same value of input power

CHAPTER 3

ANALYSIS OF SECOND ORDER PMD MODELS USING VESTIGIAL SIDE BAND AND DUOBINARY MODULATED DATA

In this chapter, the performance of 40 Gbps vestigial side band (VSB)/ Duo binary modulation with PMD models i.e. EMTY, Bruyere and Planar sweep models have been investigated using deterministic PMD emulator module on first order PMD compensator. System performance is checked at different received optical powers (ROP) for various DGD values. It is observed that planar sweep with VSB shows better performance than other i.e EMTY, and Bruyere model .We achieved BER of $2.22e^{-23}$,$1.4e^{-22}$, and$1.4e^{-18}$ with VSB modulated data for planar sweep, Bruyere and EMTY model at DGD 15ps, respectively. Second order Bruyere model also gives us good agreement in system. The proposed system shows that VSB have more tolerance to PMD effects as compared to duo binary modualtion.

3.1 INTRODUCTION

PMD is considered as major limiting factor in long link and high speed communication having bit rate of 40 Gb/s and higher. Due to random nature of PMD, it is difficult to eliminate, so can be minimized by the use of correct modulation schemewor. PMD emulation is important because designers of network use these emulators for testing and verification of new technologies in presence of PMD, mainly for systems that cannot use dispersion compensators. The PMD emulator effects are important whether PMD compensators are present or not in system having attributes i.e. desired statistics, stability and repeatability [15]. Second order PMD is important issue for performance of system therefore PMD emulators should not only produce first order, but second order effects also. Modulation formats have attracted attention in present years as an effective way for increasing transmission capacity of communication using single-mode fiber links. Optical modulation formats like DQPSK [42], duobinary, single side band (SSB) [43] and VSB [44] are spectrum efficient that makes them more immune to dispersion. In VSB one side band is passed completely whereas vestige of other side band is retained making them bandwidth efficient. Nelson et al. [45] investigated the performance of NRZ data at 40Gbps in

POLMUX system which include first order PMD and showed that with PM, sensitivity of PMD increases due to crosstalk. Liu et al. [46] analyzed that penalties of PMD are dependent on many factors namely at modulation format and characteristics of receiver and investigated OOK, DPSK and DQPSK modulation formats by method of importance sampling. Harjit singh et al.[25] evaluated performance of duobinary transmitter at 40 Gbps for different scattering dispersion and PMD coefficient values of single mode fiber and analyzed that the variable scattering dispersion have improved performance with duobinary system as compared to fixed scattering dispersion. Chongjin Xie et al. [26] compared performance of different order PMD models for systems without and with first-order PMD compensation. Previously proposed work involves only study on effects of PMD second order models using NRZ modulation only. Also PMD penalties using DPSK, DQPSK and OOK modulation format has been investigated. Alternative to these formats, vestigial side band and duobinary modulation can also be used to study effects of second order PMD models

In this chapter, we have investigated the performance of second order polarization mode dispersion models on first order PMD compensator using VSB and duo binary modulation formats. After introduction, this chapter has been organized as follows: Section 3.2 describes theoretical analysis of second order PMD models and modualtion formats followed by section 3.3 describing simulation setup while Section 3.4 describe the results and discussion. In section 3.5 conclusions is drawn.

3.2 THEORETICAL ANALYSIS

3.2.1 Second order PMD models

PMD is linear electromagnetic wave propagation phenomena that occur in single mode fiber. These fibers support two modes of propagation distinguished by their polarization. By using PSP model, PMD can be defined by using PMD vector [47]:

$$\vec{\tau}=\Delta\tau.\hat{p} \qquad (3.1)$$

Where $\Delta\tau$ denotes DGD and $\hat{p}$ represents unit vector in direction of slow PSP and are constants and independent of frequency.

The Second order PMD vector is defined as [47]:

$$\tau_{\omega}=\frac{\partial\tau}{\partial\omega}= \Delta\tau.\hat{p}_{\omega} + \Delta\tau_{\omega}.\hat{p} \qquad (3.2)$$

The term $\Delta\tau.\hat{p}_w$ defines depolarization of PSP and $\Delta\tau_\omega.\hat{p}$ indicates polarization chromatic dispersion (PCD) (i.e. change in chromatic dispersion due to polarization).PMD can also be described by 2×2 jones matrix (U) [47].Second order models are constructed using different realizable elements having unitary *U* matrix to have similarity with first order PMD and second-order PMD vectors of Model and fiber.

Various second order PMD models are:

a) EMTY model:

The EMTY model with Jones matrix denoted by *U* have two sections of different rotational power is [26]:

$$U=U_2U_1 = exp\left(-j\frac{\emptyset_2}{2}\hat{r}_2.\bar{\sigma}\right).exp\left(-j\frac{\emptyset_1}{2}\hat{r}_1.\bar{\sigma}\right) \tag{3.3}$$

Where $\emptyset_1 = \Delta\tau\Delta\omega$, $\hat{r}_1=\hat{p}$ and $\emptyset_2 = |\vec{\tau}_\omega|$ and$\Delta\omega^2/2$,$\hat{r}_2 = \vec{\tau}_\omega/|\vec{\tau}_\omega|$. Here U_1 *and* U_2 denotes jones matrix, and this model only includes PCD.

b) Bruyere model:

Bruyere model consist of three elements in diagonal of *U* matrix in distinction with diagonal model of first-order PMD and also uses frequency dependent matrices [26].

$$U = \begin{Bmatrix}\cos k\Delta\omega & -\sin k\Delta\omega\\ \sin k\Delta\omega & \cos k\Delta\omega\end{Bmatrix}\begin{Bmatrix}\exp(-\emptyset/2) & 0\\ 0 & \exp(-\emptyset/2)\end{Bmatrix}\begin{Bmatrix}\cos k\Delta\omega & \sin k\Delta\omega\\ -\sin k\Delta\omega & cosk\Delta\omega\end{Bmatrix} \tag{3.4}$$

Where $\emptyset = \Delta\tau\Delta\omega + \Delta\tau_\omega\Delta\omega^2/2$ and k=$|\hat{p}_\omega|/4$. Bruyere model have both depolarization of PSP as well as PCD.

c) Planar sweep model:

The planar sweep model that emulates only PSP depolarization produce a vector that forms a circle on sphere known as Poincare sphere along with *Δω*. and minimizes higher orders of PMD [26].

$$U = \begin{pmatrix}\exp(-j\frac{\hat{p}_{\omega\Delta\omega}}{2} & 0\\ 0 & \exp(j\frac{\hat{p}_{\omega\Delta\omega}}{2}\end{pmatrix}\begin{pmatrix}\cos\frac{\Delta\tau_{1\Delta\omega}}{2} + j\frac{\hat{p}_w}{\Delta\tau_1}sin\frac{\Delta\tau_1\Delta\omega}{2} & -j\frac{\Delta\tau}{\Delta\tau_1}sin\frac{\Delta\tau_{1\Delta\omega}}{2}\\ -j\frac{\Delta\tau}{\Delta\tau_1}sin\frac{\Delta\tau_{1\Delta\omega}}{2} & cos\frac{\Delta\tau_{1\Delta\omega}}{2} - j\frac{\hat{p}_\omega}{\Delta\tau_1}sin\frac{\Delta\tau_1\Delta\omega}{2}\end{pmatrix} \tag{3.5}$$

Where, $\Delta\tau_{1=}\sqrt{\Delta\tau^2 + \hat{p}_\omega{}^2}$includes only PSP depolarization.

3.2.2 Duobinary and Vestigial side band modulation

In optical fibers, information is transmitted using different characteristics namely polarization, amplitude and phase of carrier signal and different modulations are distinguished by using these attributes. Duobinary modualtion is used to provide high spectral effeciency and tolerance to impairments. It is basically a combination of amplitude shift keying (ASK) and PSK modulations and is considered as multilevel system of transmission in which bits are encoded in phase and have reduced spectral width [48]. This modualtion uses less than R/2 bandwidth for R bits /s. In this modualtion, two 1's have π phase shift between them having odd number of 0's in between them. Modulated signal in electrical form is formed by addition of delayed data with 1 bit in present bit of data leading to formation of three level signals and can also be formed by passing original binary data from low pass filter. Here modulated signal is formed by passing electrical signal from MZM and can be demodulated by using optical detection receiver. VSB modulation is compromise between SSB and dual side band suppressed carrier (DSBSC). This is formed by using selective filtering as that in case of SSB modulation. As in SSB, transmission of speech signal is suited because of energy gap between spectrum in zero and few hertz of frequency. But in case of television signals, where signal also contains low frequencies, lower and upper side bands meet. To overcome this limitation, VSB is used which passes one side band completely whereas trace of another side band is passed and have effeciency same as that in case of SSB modulation [44]

3.3 SIMULATION DESCRIPTION

Proposed simulation setup for PMD emulator is represented in Fig.3.1. The transmitter consists of duobinary and VSB modulator. The modulated signal is then passed through the PMD emulator which includes effect of Bruyere, planar sweep and EMTY models of second order PMD followed by attenuator.Here deterministic emulator is used which produces particular DGD value at particular frequency.After attenuator, the PMD compensator is used which compensate first order PMD is completely compensated for studying second order effects of PMD. And then output is analyzed using various analyzers which measures corresponding eye diagrams, BER and ROP.

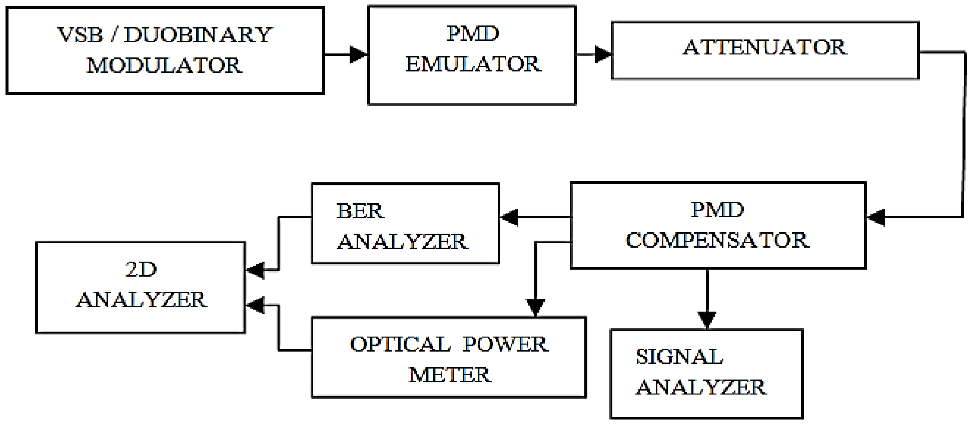
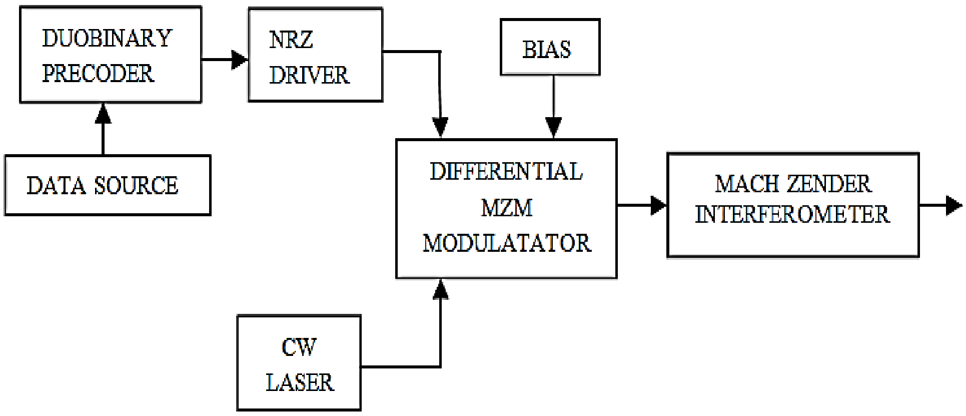
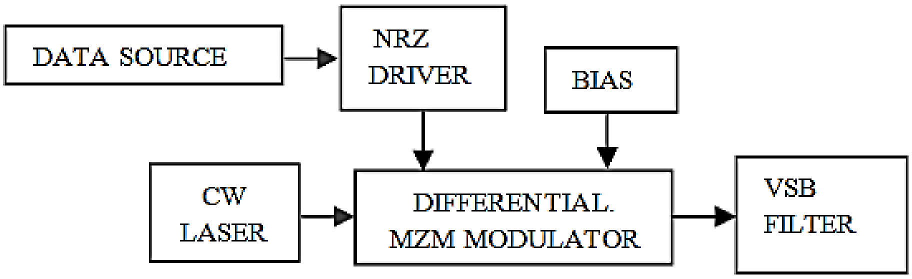


Figure 3.1: Block diagram of PMD emulator setup.

The internal structure for Duobinary and VSB is represented in Fig. 3.2 . Fig 3.2(a) reprsent internal block diagram for duobinary modulation.The data source produces a Pseudo random bit sequence(PRBS) having 40 Gbit/s bit rate that is encoded by duo binary encoder consisting of 1 bit delay line.



(a)



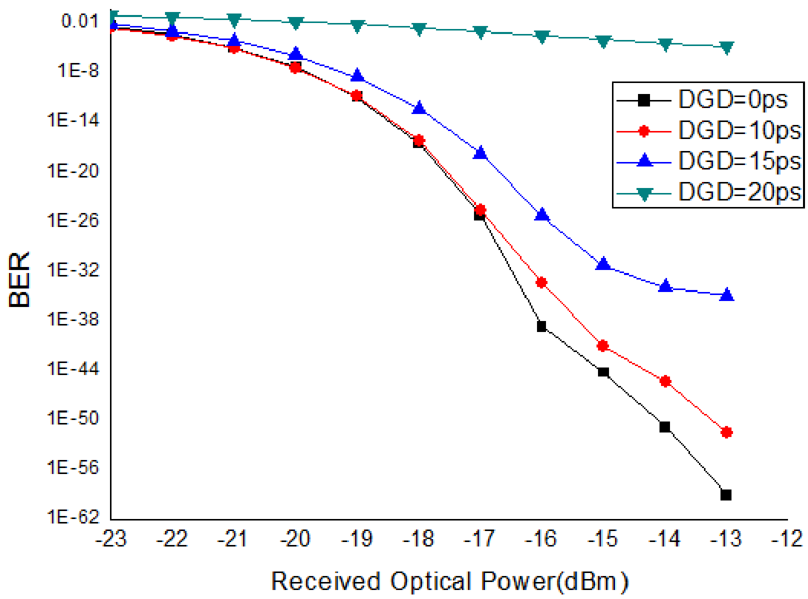
(b)

Figure 3.2: Internal block diagram for (a) Duobinay (b)VSB modulation.

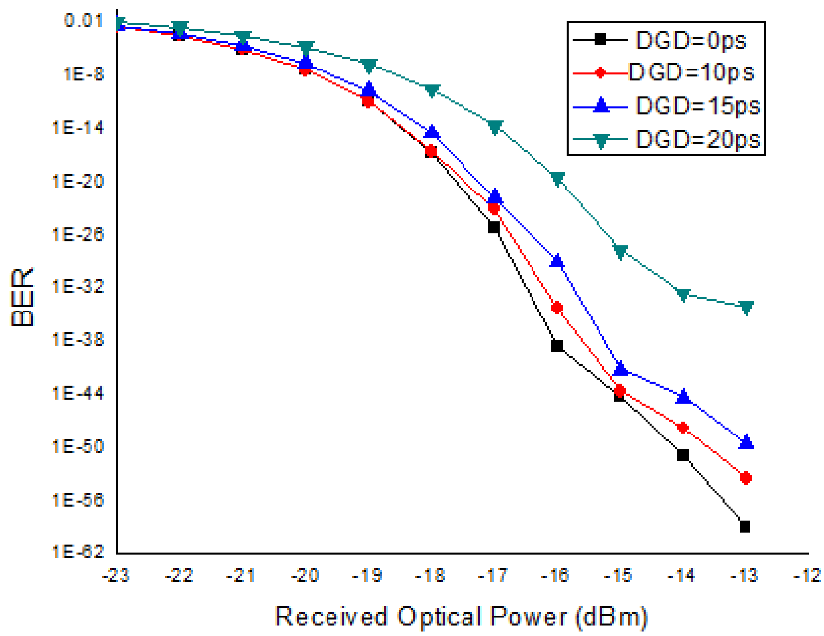
And the delay output is then added to original signal to produce zero mean three level signals. Then duobinary encoded data is converted into NRZ signal. After that signal passes through differential MZM modulator having extinction ratio 35 dB and biased at minimum transmission followed by Mach zender interferometer. Fig 3.2 (b) shows the VSB modulation. In this , 40Gb/s data produced by data source is first modulated by using differential MZM with 35 dB extinction ratio and is then passed through VSB filter which is Gaussian band pass filter with 200Ghz bandwidth to remove unwanted frequencies.

3.4 RESULTS AND DISCUSSIONS

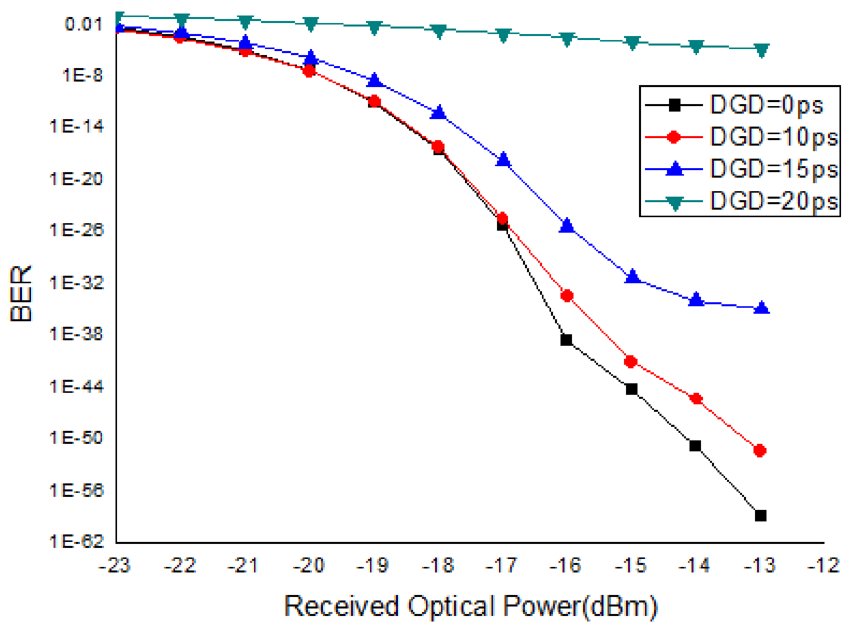
The proposed setup of PMD emulator is simulated using VPI transmission maker.Fig 3.3 and 3.4 graphically shows the variation of BER against ROP. The variation of BER from -23dBm to-13dBm with step of 1 dBm at DGD values of 0ps,10ps, 15ps and 20ps with duobinary and VSB modulated data for second order PMD models. From the results, we observed that VSB modualted data with second order PMD models have low BER for all received optical power at all DGD values as compared to duobinary modulated data which shows that VSB modualted data shows more tolerance to PMD effects. We have also achive that, VSB with planar sweep model shows less second order effects in comparison with bruyere and EMTY model. For instance, BER value is $2.22e^{-23}$,$1.4e^{-22}$, and$1.4e^{-18}$ for planar sweep, bruyere, EMTY model with VSB at 15ps DGD for -17dBm, respectiely.



(a)



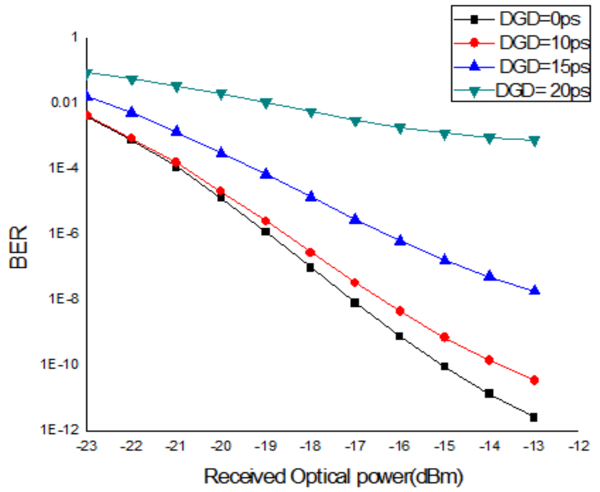
(b)



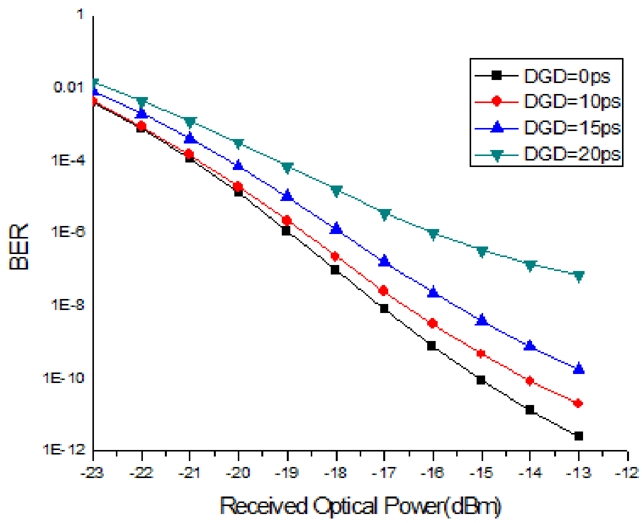
(c)

Figure 3.3: Graphical representation for BER against Received optical power for VSB: (a) EMTY model (b) Bruyere model and (c) Planar sweep model.

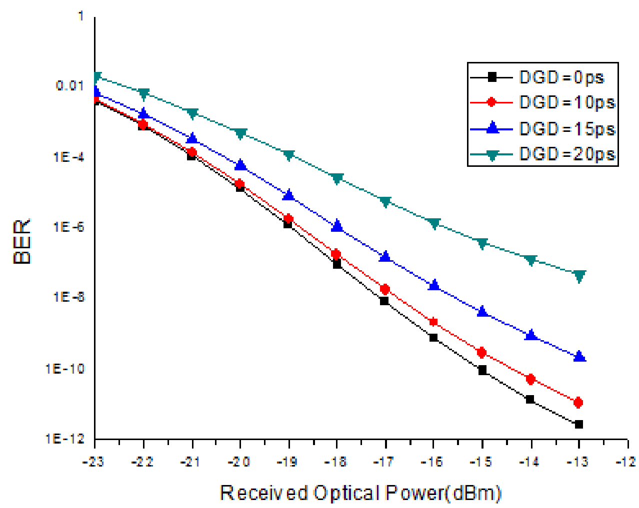
And the BER is $1.4e^{-18}$,$1.44e^{-07}$ and$1.66e^{-07}$ for planar sweep, bruyere, EMTY model with duo-binary at15ps DGD for -17dBm respectiely. Fig 3.5 and 3.6 shows the eye diagrams for VSB and duobinary modulated data using second order PMD models.An eye diagram shows the signal quality and fast advanced signal transmission.



(a)

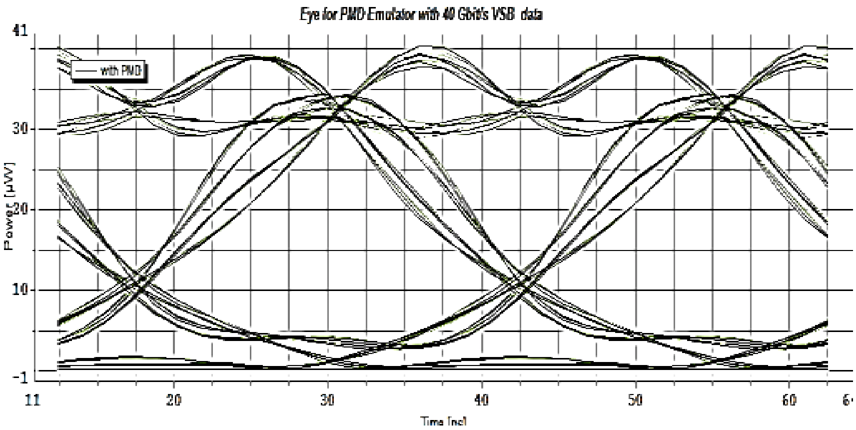


(b)

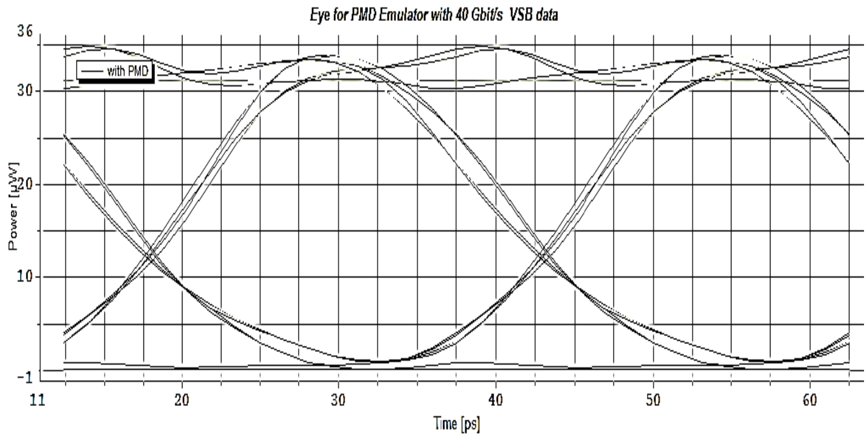


(c)

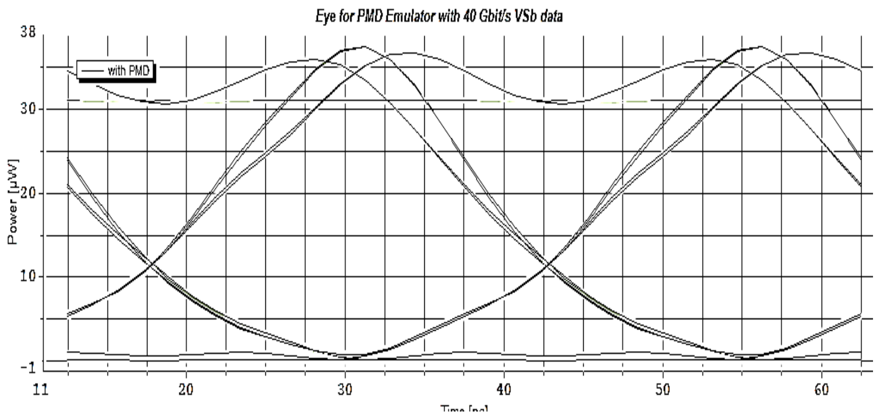
Figure 3.4: Graphical representation for BER against Received optical power for Duo binary: (a) EMTY model (b) Bruyere model and (c) Planar sweep model.



(a)



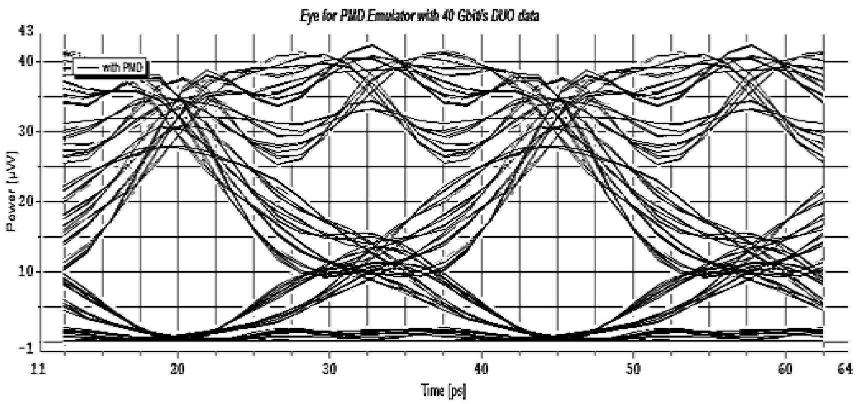
(b)



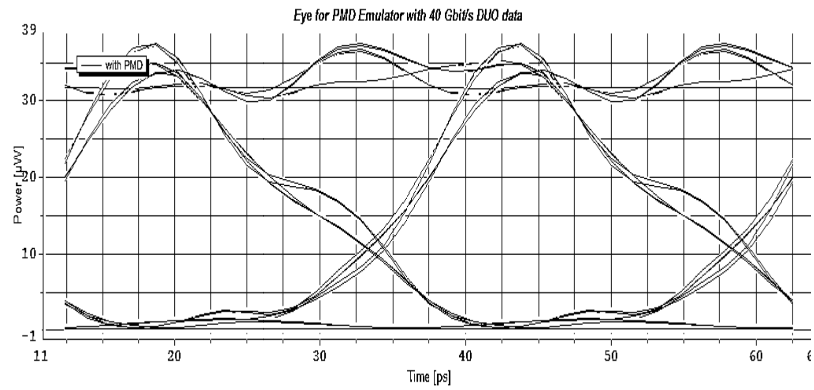
(c)

Figure 3.5: Eye diagram with VSB for: (a) EMTY model (b) Bruyere Model and (c) planar sweep Model.

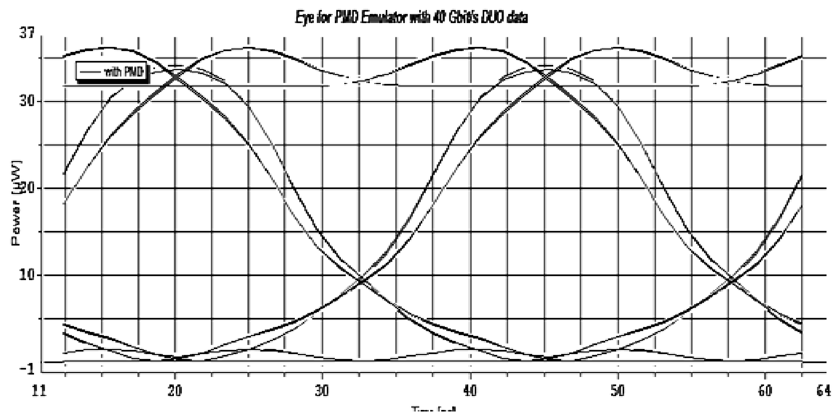
The closure of eye diagram represents distortion in the signal waveform due to noise and intersymbol interference. In this way, an open eye diagram corresponds to minimum signal distortion.



(a)



(b)



(c)

Figure 3.6: Eye diagram with duobinary modulated data for: (a) EMTY model (b) Bruyere Model and (c) planar sweep model.

3.5 CONCLUSION

Investigation of induced PMD impairments with second order models for VSB and Duo binary modulated data using deterministic PMD emulator has been carried out. PMD emulation is important because designers of network use emulators for testing and verification of new technologies in PMD presence, mainly for systems which cannot use PMD compensators. From the results we have concluded that planar sweep model for both cases i.e VSB and duobinary shows better performance than other models. Further, we have also shown that using VSB we have achieved better performance than duo binary. We have achieved BER of $2.22e^{-23}$,$1.4e^{-22}$ and$1.4e^{-18}$ with VSB modulated data for planar sweep, Bruyere and EMTY model at DGD 15ps, respectively. Second order Bruyere model also gives us good agreement in proposed system. The proposed system also shows that VSB have more tolerance to PMD effects as compared to duo binary.

CHAPTER 4
TRANSMISSION ANALYSIS OF 112 Gbps DP-QPSK AND DP-16 QAM

In this chapter, the performance of 112 Gbps DP-QPSK and DP-16QAM multilevel modulation formats in terms of SNR for different fiber lengths, polarizing angle and OSNR tolerance is analyzed. Then mitigated channel impairments using DSP for dispersion compensation, polarization demultiplexing, frequency offset estimation (FOE) and CPE in coherent receiver. It is observed that DP-16 QAM have more SNR as compared to DP-QPSK at all fiber lengths and system performance degrades when polarizing angle is increased from 0^0 to 20^0 due to polarization mismatch in transmitter. Also for particular BER of 10^{-3}, DP-QPSK shows 4 dBm more OSNR tolerance than DP 16 QAM and received constellations after DSP are ideal which shows the mitigated channel impairments

4.1 INTRODUCTION

From last few years, there has been a continuous challenge to accommodate the higher bit rate for designers in optical networks to meet the demands of internet traffic [49].Therefore, there is a need to identify schemes which can achieve high SE by using three characteristics of optical field i.e. Phase, intensity and polarization to transmit information [50] which requires use of multilevel modulation formats. POLMUX in which two signals having same wavelength are transmitted in two orthogonal polarization along with DQPSK/ 16 QAM can be used for data rate of 100 Gbps or above due to their narrow spectrum and tolerance to channel impairments[51]. DP enables doubling the number of bits transmitted keeping the symbol rate same as compared to single polarization signal i.e. it doubles the SE. But this requires polarization demultiplexing after transmission at receiver to separate x and y polarizations leading to complexity of receiver. But PMD tolerance of dual polarization modulation is still more as compared to that of binary modulation formats.

The ADC having high speed and the advances in DSP for coherent receiver have made it possible to mitigate random changes in polarization of fiber in the electronic domain. This can be achieved by the use of coherent receivers. Coherent detection with DSP provides new capabilities such as enabling the use of highly spectrally efficient modulation formats and mitigating a wide variety of transmission impairments [52].

Using DSP, 100 Gbit/s optical systems having long-range transmissions can be realized by using compensators for dispersion, algorithm for polarization demultiplexing and recovery estimation of phase based algorithms. Stefan Wabnitz et al. [53] analyzed performance of DP-QPSK system with coherent receivers in presence of fiber impairments and estimated the error and outage probability using importance sampling due to the PMD and other impairments. Thomas Duthel et al. [54] investigated the performance of polarization multiplexing RZ-DQPSK and discussed applications of coherent receivers, DSP impact and sampling with 1 or 2 sample/bit. Maxim Kuschnerov et al. [55] discussed algorithms for DSP with coherent receivers i.e for freqeuncy domain equalization, time recovery followed by polarization demultiplexing. M.S.Faruk et al. [56] described filter to compensate IQ imbalances in coherent receivers.

Unfortunately, these investigations are limited to different type of dispersion compensation; it can be further improved by using DSP scheme i.e polarization demultiplexing, CPE and FOE. In this we extended the previous reported investigations by compensating the dispersion such as PMD In further comparison in terms of OSNR tolerance and variation in degree of polarization which affects BER of system is studied.

Broadly, this chapter starts with introduction after which theoretical analysis is presented in Section 4.2, followed by Section 4.3, which describes the simulation setup and section 4.4 describing results and discussion. In Section 4.5 conclusion is drawn

4.2 THEORETICAL ANALYSIS

4.2.1 Coherent detection

Modulated signal in coherent receivers which carry information in both amplitude and phase is given by[57]

$$E_s(t) = A_s(t) exp(i\omega_s t + \emptyset_s)] \quad (4.1)$$

Here ω_s denotes frequency of carrier and $\emptyset_s$ is carrier phase and A_s(t) represents amplitude of signal. Local Oscillator optical field is given as

$$E_{LO}(t) = A_{LO}(t)\exp[i(\omega_{LO}t + \emptyset_{LO})] \quad (4.2)$$

Where ω_{LO},$\emptyset_{LO}$, A_{LO} are frequency , phase and amplitude of local oscillator.

Here DP Quadrature coherent detection is used having 90^0 hybrid for detection of DP-QPSK and DP -16QAM. In this two 90^0 hybrid is used with four photo diodes for detection of orthogonally polarized signals. Firstly both signals are splitted into two polarized branches with help of PBS. Then in phase and quadrature signals obtained after detection are given by [57].

$$E_{xI}(t) = 2P_x(t)cos[\Delta\omega t + \Delta\emptyset] \quad (4.3)$$

$$E_{xQ}(t) = 2P_x(t)sin[\Delta\omega t + \Delta\emptyset] \quad (4.4)$$

$$E_{yI}(t) = 2P_y(t)cos[\Delta\omega t + \Delta\emptyset] \quad (4.5)$$

$$E_{yQ}(t) = 2P_y(t)sin[\Delta\omega t + \Delta\emptyset] \quad (4.6)$$

These equations represent amplitude of signals after balanced detection

4.2.2 Digital signal processing

Coherent detection using DSP enables compensation of channel impairments occurring in fiber. In this, various algorithms are implemented. Firstly CD compensation is performed using Fast Fourier transform over block of samples. Then sampling using specific sampling frequency is required for clock recovery. After that polarization detection is used to detect signal in each polarization which emulate polarization state of received signal. For this FIR filter with butterfly structure is used. In end phase and carrier recovery is done to remove mismatch between carrier signal and LO which is performed using viterbi-viterbi algorithm [57]

4.3 SIMULATION DESCRIPTION

Fig 4.1 depicts the block diagram of proposed system. The system is divided into different parts, which consists of DP QPSK/ 16 QAM transmitter followed by optical transmission link. At receiver side coherent detection along with signal processing block is used and then detection along with decoding is done to calculate error. Transmission link consists of EDFA, SMF and Gaussian optical filter .We have used pre- post EDFA with inline SMF. EDFA have 16dB gain, SMF have 16.75 ps/nm/km dispersion and PMD coefficient of 0.05 ps/sqrt (km) followed by band pass Gaussian optical filter with bandwidth 50GHz.

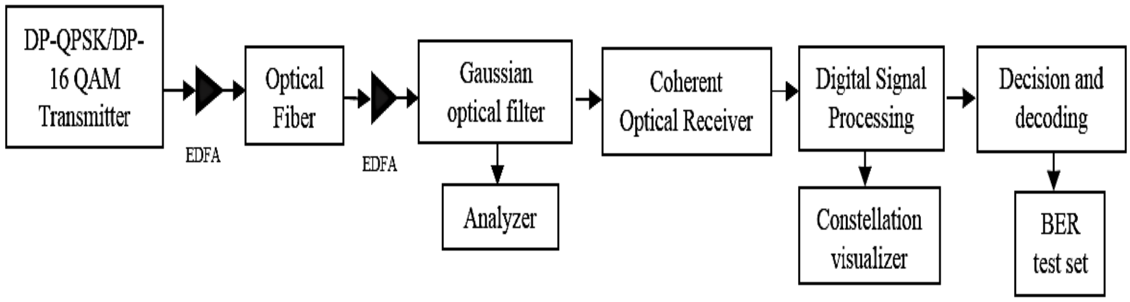
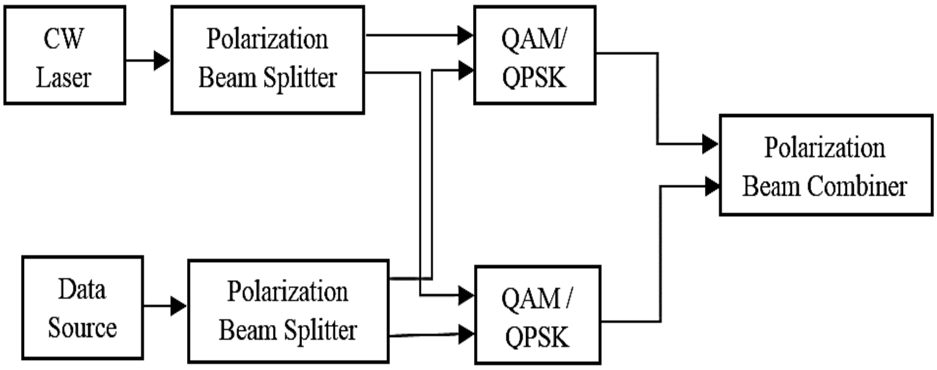


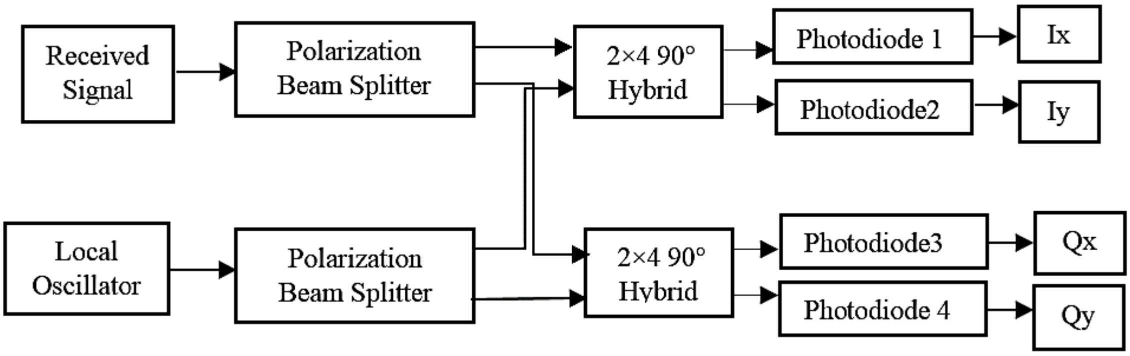
Figure 4.1: System setup for DP-QPSK and DP-16QAM transmission system.

Fig. 4.2(a) illustrates the block diagram of 112 Gbit/s DP-16 QAM and DP-QPSK transmitter.In this setup the CW laser with input power 10dBm and wavelength 1550 nm is used. Further, the laser is splitted by polarization beam splitter (PBS) into two polarizations with orthogonality between them. The PRBS with 112Gbps bit rate is fed to PBS, where it is splitted into two parallel sequences using serial to parallel converter and is then modulated by 16 QAM/QPSK modulators. The 16 QAM/ QPSK modulator consist of QAM/QPSK sequence generator and generate Mary sequences. At the end both 16QAM/QPSK modulated signals are combined using polarization beam combiner to form DP-QPSK/16QAM signal. Fig 4.2(b) depicts DP-QPSK/QAM coherent receiver. In coherent receiver, the incoming optical signal with random polarization and a LO signal are first splitted having two orthogonal polarizations using PBS. The electric field is detected in each polarization by allowing incoming signal to interfere with LO in 90° hybrid followed by four pair of balanced detectors.

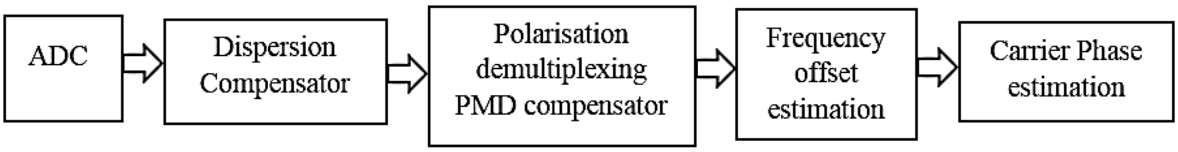
Further, the outputs from receiver show I and Q components along x, y polarization. Fig 4.2(c) shows the internal components of DSP. The four signals are passed through DSP module for compensation of channel impairments. Firstly, signals are passed through third order Bessel filter and then are converted in digital signal using ADC which samples the in-phase and quadrature component of polarizations. Then the accumulated dispersion is compensated using transversal digital filter with 181 taps in frequency domain.



(a)



(b)



(c)

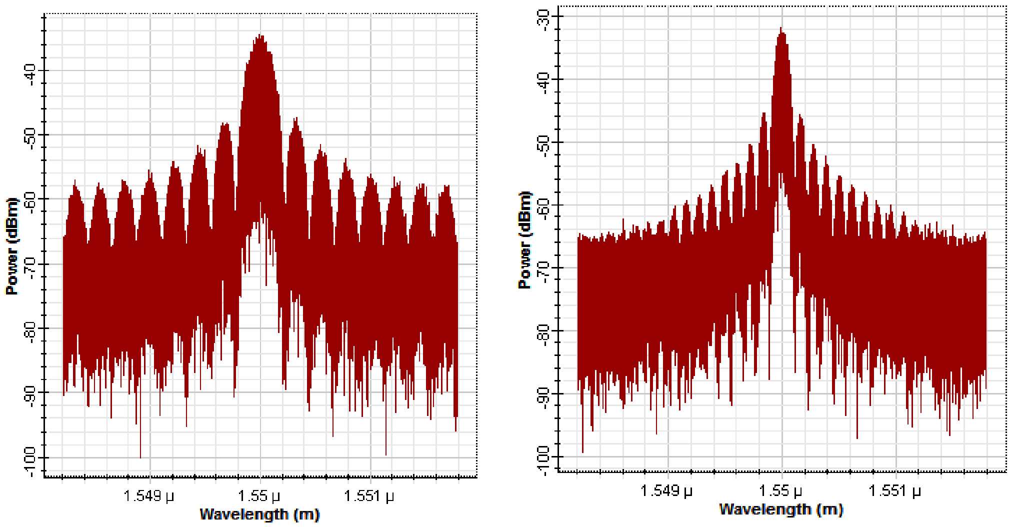
Fig.ure 4.2: Internal block diagram of: (a) DP QPSK /16QAM transmitter (b) Coherent receiver (c) Digital signal processing.

After that, the dual polarized signal is demultiplexed using blind channel equalization. In addition to de-multiplexing, it is also capable of compensating effects like PMD, PDL and CD. And is implemented by use FIR filter with nine taps arranged in a structure of butterfly. The filter performs jones matrix inverse of the channel and coefficients of the tap filter are updated by using CMA having step size 10^{-06} and 15 number of iterations. Then offset frequency is estimated between the transmitter and the LO followed by phase estimation with help of Viterbi –Viterbi algorithm. Finally, estimation of symbol at end and decoding is performed. If frequency offset left

uncompensated it causes rotation in constellation diagram, then decoding will not be done properly. Therefore it is desirable that the transmitter laser and the LO must have very limited offset frequency between them.

4.4 RESULTS AND DISCUSSIONS

Fig. 4.3 represents optical power spectrum for DP-QPSK and DP-16 QAM after optical fiber. From the spectrum we observed that, using DP-16QAM, we have achieved more optical power with acceptable range.

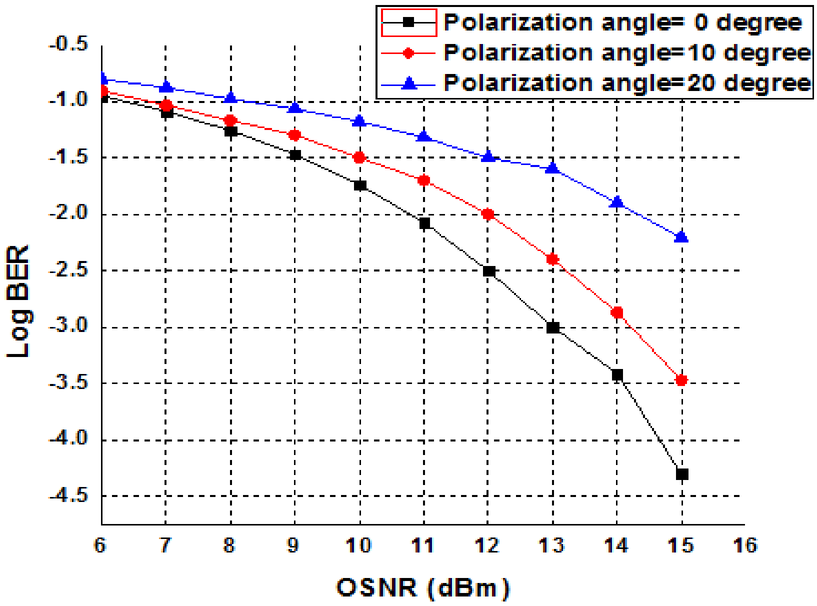


(a) (b)

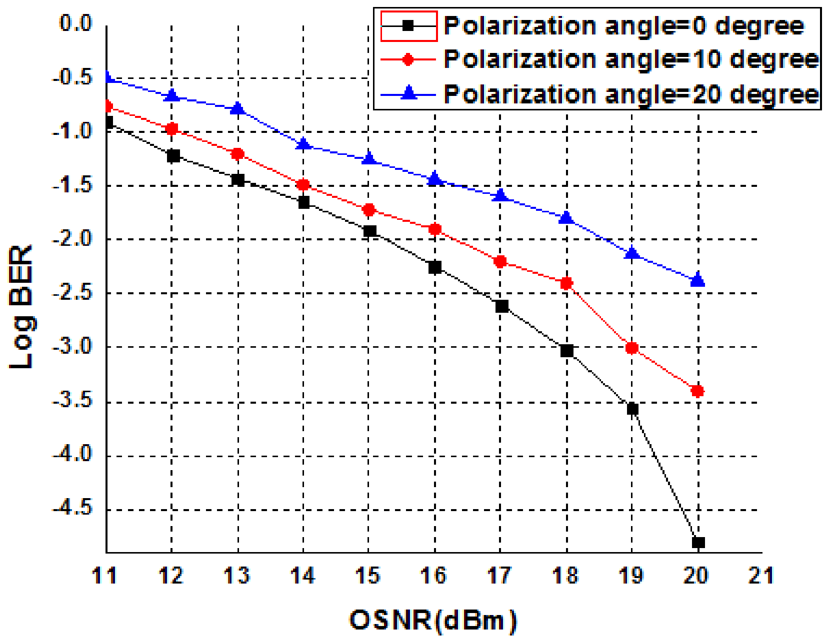
Figure 4.3: Optical power spectrums for: (a) DP –QPSK   (b) DP-16 QAM.

The system is investigated at polarization angle of 0^0, 10^0 and 20^0 at transmitter side. It is observed that when polarization angle increases from 0^0 to 20^0, Log BER increases from -4.3 to -2.21 in case of DP-QPSK and -1.91 to -1.26 in case of DP-16 QAM. This degradation in performance is due to polarization mismatch in transmitter. Fig. 4.5 shows plot of SNR for different fiber lengths. We can observe that DP-16 QAM have more SNR as compared to DP-QPSK for same fiber length i.e SNR in case of DP-16 QAM is 24.26 whereas in DP-QPSK is 19.6 at 200 km fiber length. Fig 4.6 shows graphical representation of Log BER values for different OSNR. It was observed that for BER of 10^{-3}, DP-16 QAM requires OSNR of 18 dBm whereas DP-

QPSK requires 14 dBm OSNR which shows that DP-QPSK shows 4 dBm more OSNR tolerance than DP-16 QAM. Constellation diagrams represent relation between quadrature amplitude value and in phase amplitude value.



(a)



(b)

Figure 4.4: Log BER as function of Optical SNR at different polarization angle for: (a) DP- QPSK (b) DP-16QAM.

From Fig 4.7(a) and 4.8(a) we observed that after compensation of dispersion, sampling points of constellation diagram are distributed unevenly along circular ring which rolls along antilock wise and clock wise direction.

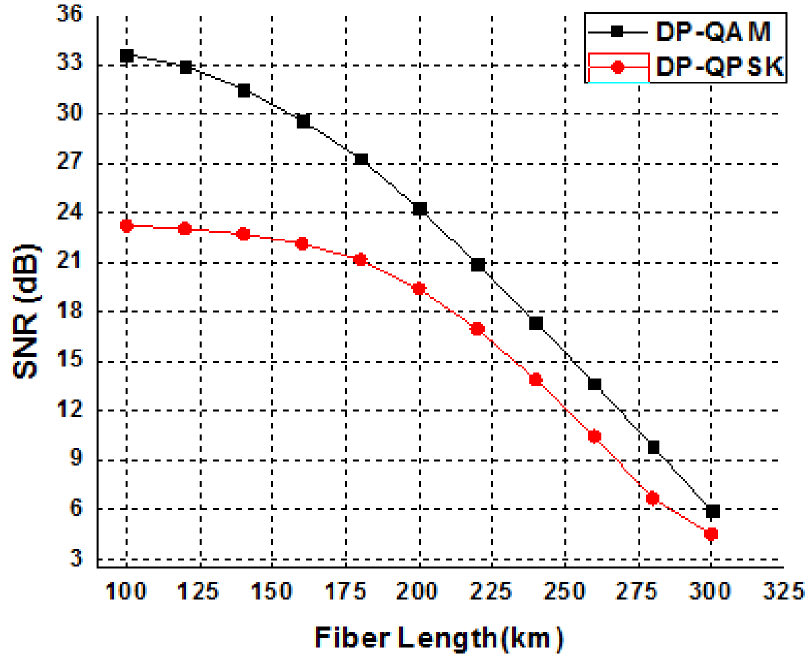


Figure 4.5: Graphical representation of SNR for different fiber lengths using DP-QPSK and DP-16 QAM

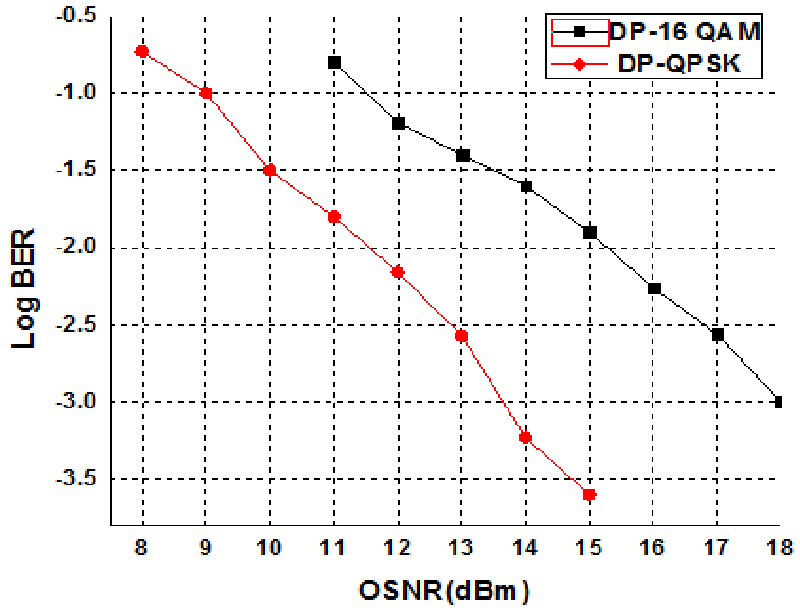
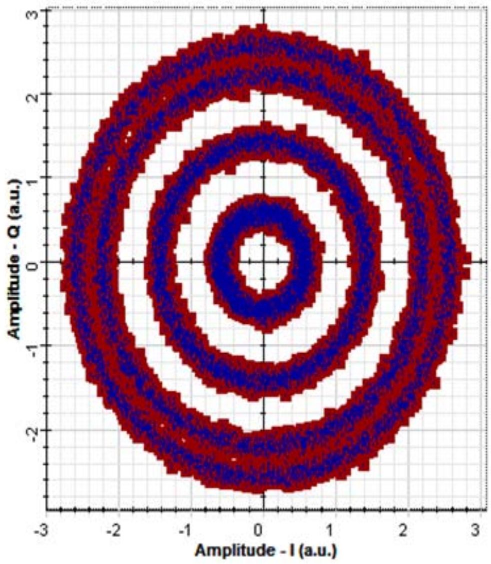
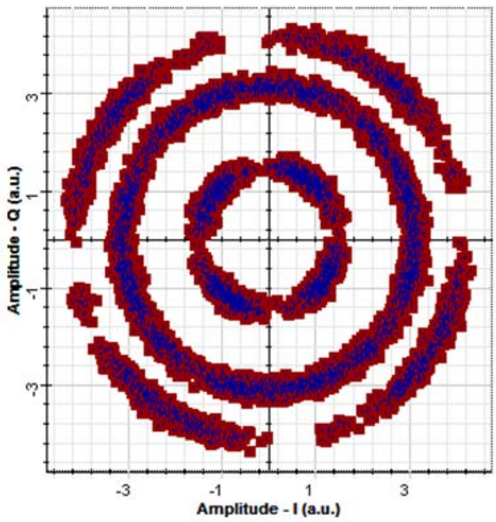


Figure 4.6: Graphical representation of BER for different OSNR values using DP-QPSK and DP-16 QAM.

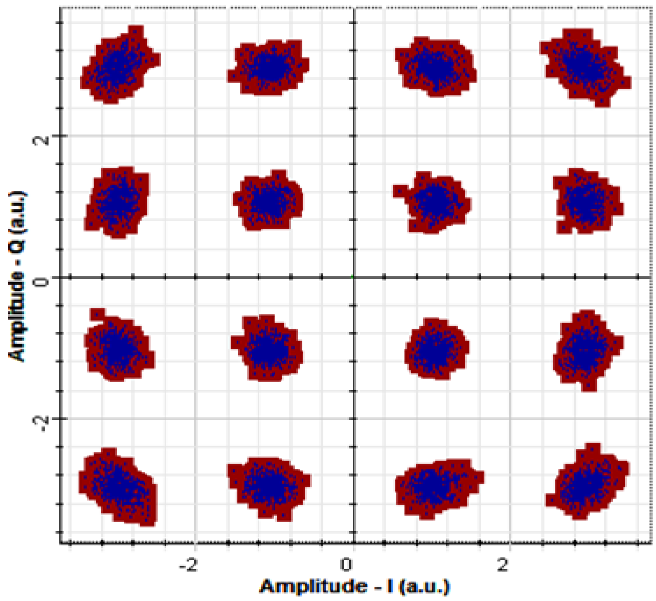
Figure 4.7 (b) and 4.8 (b) shows that after FOE, phase noise is still heavy which cause rotation of constellation diagram.



(a)



(b)



(c)

Figure 4.7: Received constellation diagrams for DP-16 QAM after (a) Dispersion compensation and polarization demultiplexing (b) Frequency offset estimation (c) carrier phase estimation.

From Fig.4.7(c) and 4.8(c) we observed that distribution of sampling points is concentrated and far from center and has reasonable noise

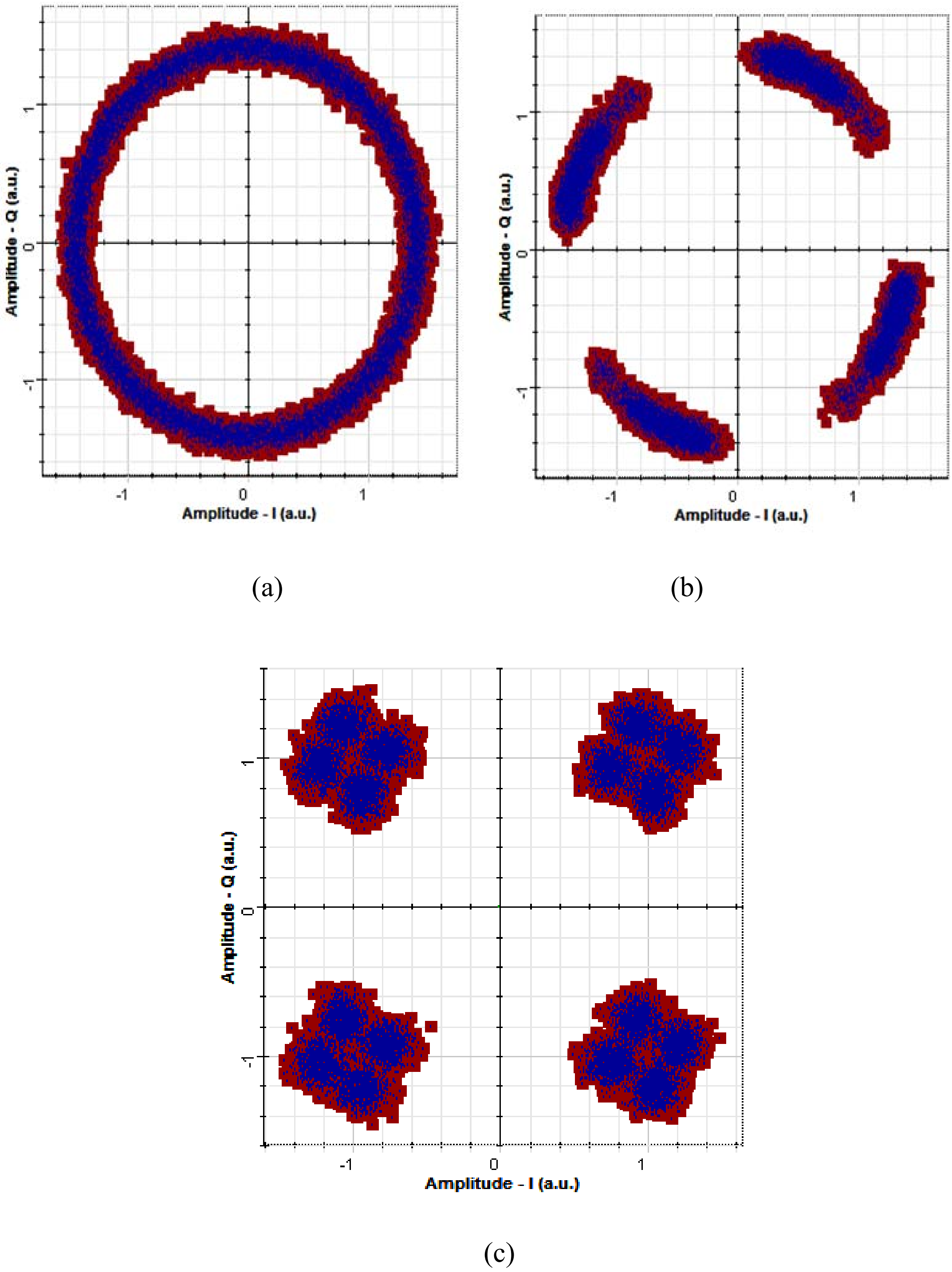


Figure 4.8: Received constellation diagrams for DP-QPSK after (a) Dispersion compensation and polarization demultiplexing (b) Frequency offset estimation (c) carrier phase estimation.

4.5 CONCLUSION

The performance of 112 Gbps DP-QPSK and DP-16 QAM multilevel modulation formats has been investigated. Further, mitigated channel impairments using DSP in terms of compensation of dispersion, demultiplexing of polarizations, FOE and CPE for optical transmission. It was observed that DP-16 QAM have more SNR as compared to DP-QPSK at all fiber lengths of system and BER increases gradually with increase in polarizing angle from 0^0 to 20^0 due to polarization mismatch in transmitter. It was observed that for BER of 10^{-3}, DP-QPSK shows more tolerance of 4dBm OSNR than DP 16-QAM and received constellations after DSP are ideal for both modulations which shows the mitigated channel impairments.

CHAPTER 5
POLARIZATION INTERLEAVING IN LONG HAUL DWDM SYSTEMS

In order to achieve long haul transmission distance in dense wavelength division multiplexing (DWDM) systems, PMD non-linear impairments affecting system performance have to be minimized. This chapter proposed polarization interleaving strategy for 40 Gbps DWDM systems to remove PMD,3rd order nonlinearity between neighbouring channels by adjusting state of polarization using linear polarizers. Proposed system has acceptable value of Q factor at all fiber lengths i.e Q factor of polarization interleaved system is 16 and conventional DWDM system is 3.2 at 720 km fiber length. Then comparison of three different electrical filter i.e Gaussian, rectangular and Bessel filter at receiver is performed for different optical fiber lengths which shows that Bessel filter have improved performance. At particular instance, Q factor for Bessel, Gaussian and rectangular filters are 12, 9.9 and 8 for 864 km fiber length

5.1 INTRODUCTION

WDM have significant role in high capacity optical transmission systems which allows large amount of data to be transferred through optical fiber with different wavelengths. To increase capacity of fiber optics communication in WDM systems, most effective technique is to increase number of channels or bit rate per channel in WDM systems [58]. Optical light passing in WDM system offers some degree of freedoms i.e phase, state of polarization and frequency. However these systems suffer from undesirable effects which influence efficiency of system and leads to degradation in performance of system due to non-linearities. Severe degradation occurs when there are large numbers of channels in WDM systems [59] .In addition to non linear effects, depolarization of wave due to random birefringence degrades orthogonality of polarized signals and are difficult to demultiplex at receiver.

There are three polarization effects that lead to impairments in the long-haul optical fiber transmission systems: PMD, PDL and polarization dependent gain (PDG). Q. Lin et al.[60] investigated PMD effects due to cross phase modualtion in WDM systems. Haider. J. Abdl et al. [35] presented approach for reduction of FWM by using polarization interleaved system and behaviour of proposed system with WDM system was analyzed. D. van den Borne et al. [61] mitigated non linear penalties in 2×10 Gbps polarized multiplexed NRZ system by polarization interleaving of channels

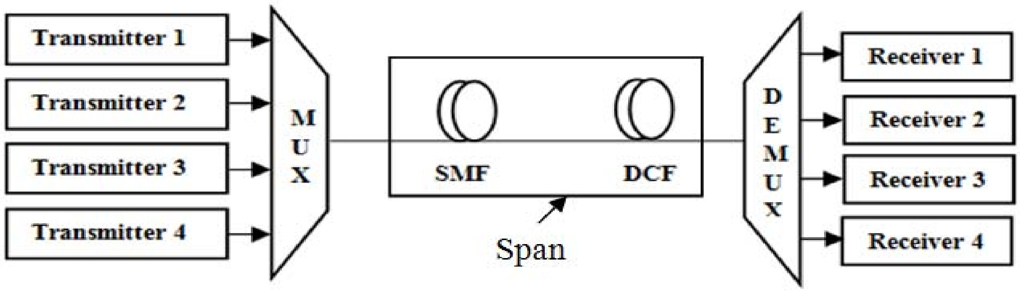
Previously proposed architectures involve transmission of signal at a short distance and compensated FWM in WDM systems. It can be extended further to mitigate PMD effects and non linearities in DWDM systems. In this chapter, polarization interleaving techniques has been used to reduce PMD as well as non linearities. After introduction chapter is sorted out as follows section 5.2 describes theoretical analysis, in section 5.3 system setup of proposed framework is discussed. In section 5.4, results and discussion is clarified and conclusion is drawn in section 5.5.

5.2 THEORETICAL ANALYSIS

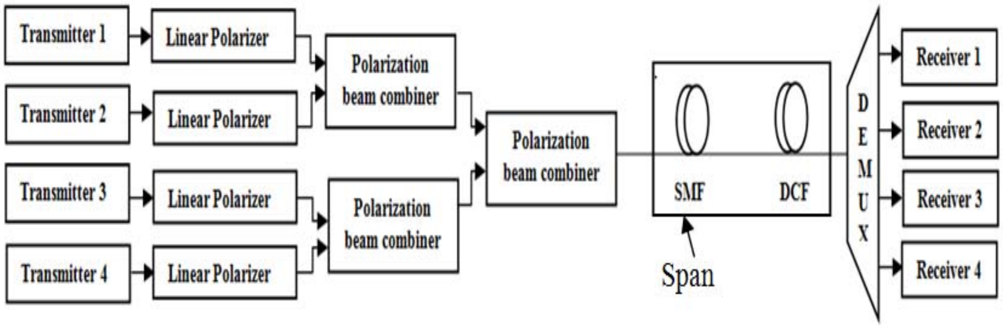
In wavelength division multiplexing systems, different wavelengths of light are produced using array of lasers and are then multiplexed in fiber. After transmission, combined signal is demultiplexed at receiver by distributing optical power to each port equally and are recovered using tuneable filter at receiver. Since mid 90's DWDM emerged with 16 to 40 channels having spacing of 100-200 GHz. After that emerged as systems where they were capable of carrying 64-160 channels at 50 or 25 GHz and are used for enhancing data capacity of system. This allows transmission of different audio, data and video signals transmitted over fiber to enhance performance.

5.3 SIMULATION DESCRIPTION

Fig.5.1 shows block diagram of polarization interleaved DWDM and conventional DWDM system. In polarization interleaving, channels are divided into odd and even channels, further it passed through linear polarizers to change the state of polarization of channels in such a way that adjacent channels are orthogonal to each other i.e odd channels are passed through linear polarizer with angle 45^0 while even channels through linear polarizer of 135^0. After that channels are combined through PBC then passed through optical transmission link consisting of loop spans with optical fiber of 40 km having dispersion 16.75 ps/nm Km, attenuation 0.2 dB/Km, followed by dispersion compensating fiber with dispersion of -80 ps/nm km. When conventional DWDM system is used the fiber length is set to 8km, and all channels have same state of polarization. The length of optical fiber is varied by varying number of loop spans of transmission link. We have used a DCF for decreasing the overall dispersion of the fiber link. After propagation through optical fiber, signal is passed through receiver and analyzed using BER analyzer

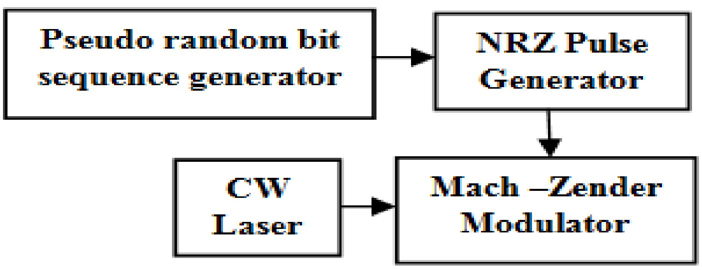


(a)

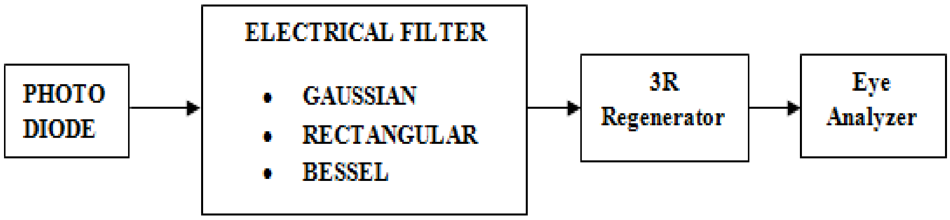


(b)

Figure 5.1: Block diagram of: (a) Conventional DWDM system (b) Proposed polarization interleaved system.



(a)



(b)

Figure 5.2: Internal block diagram of: (a) Transmitter (b) Receiver of each channel in proposed system

Fig 5.2 shows internal block diagram for transmitter and receiver of system. In transmitter CW laser array of four lasers is considered producing carriers with 1 THz spacing. These CW lasers are connected with MZM which is also connected to NRZ pulse generators and at receiver side, demultiplexer is used to separate multiplexed signals and is then detected through photodiode followed by electrical low pass Bessel filter and after that eye diagram analyzer is used to measure system performance.

5.4 RESULTS AND DISCUSSIONS

Figure 5.3 show optical power spectrum of conventional DWDM system (a) after multiplexing and (b) after propagation distance of 720 km. It is observed that spectrum is distorted and broadened after propagation through fiber representing induced nonlinearities and PMD.

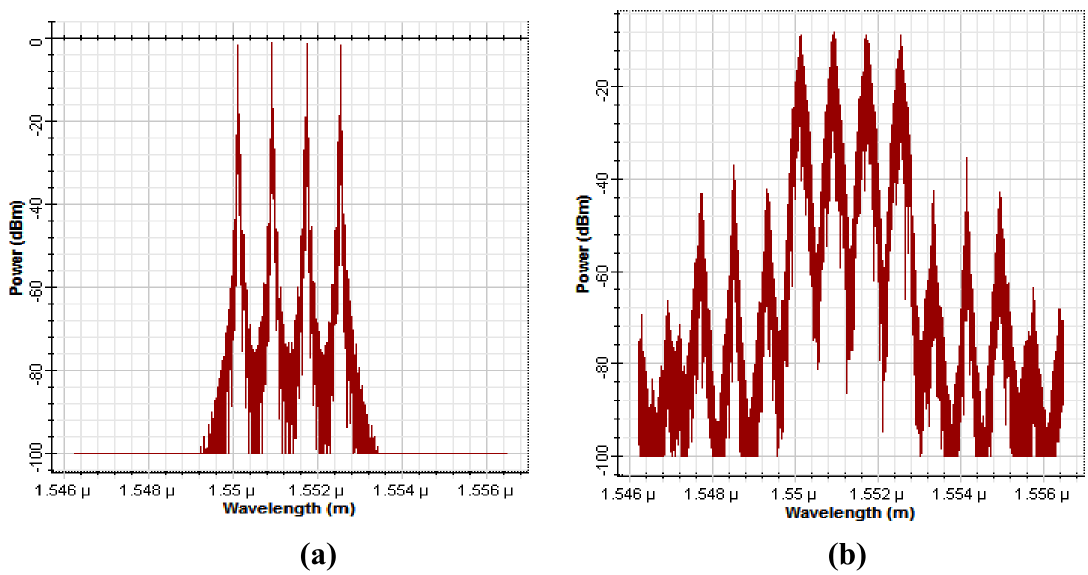


Figure 5.3: Optical spectrum for conventional DWDM system after: (a) Multiplexing (b) Propagation distance of 720 km.

Fig 5.4 (a) and (b) represents optical power spectrum for polarized interleaving system. Both spectrums are same representing mitigation of PMD, nonlinearities in received signal.

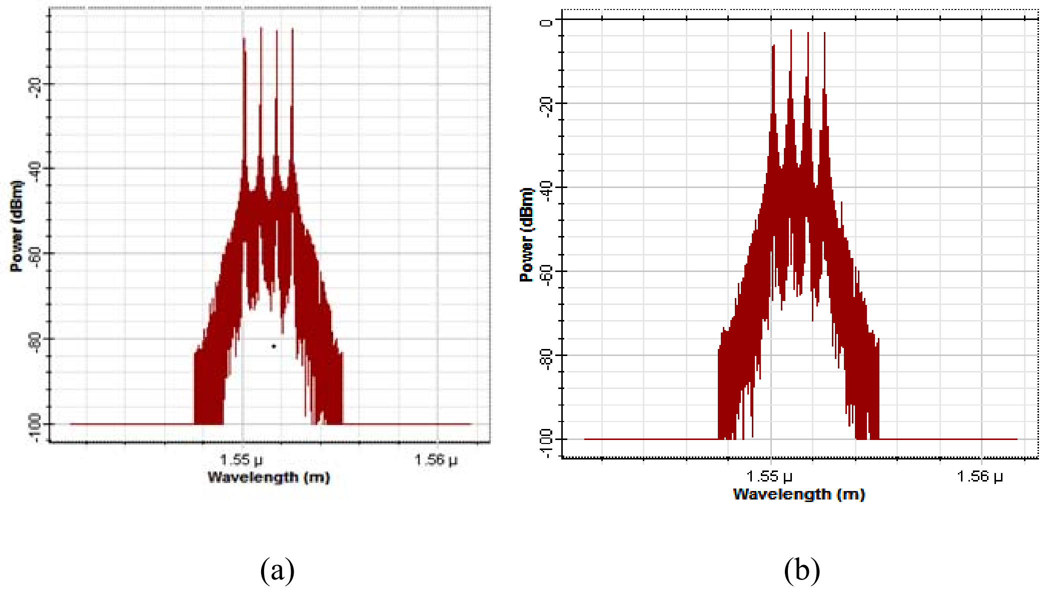


Figure 5.4: Optical spectrum for polarization interleaved DWDM system after: (a) multiplexing (b) propagation distance of 720 km.

Fig.5.5 represents Q factor as a function of fiber length for both conventional DWDM and polarized interleaved DWDM system.

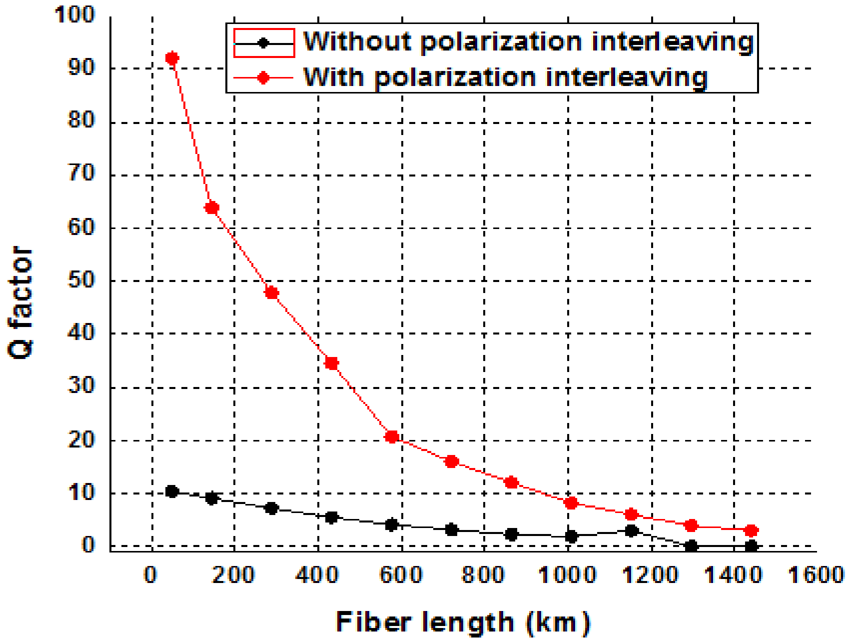


Figure 5.5: Graphical representation of Q factor with varying fiber length with and without polarization interleaved system.

From graph, we observed that signal quality increases with polarization interleaving, which leads to increase in transmission distance. In this case, we have achieved long haul distance of 1440 km with acceptable range. For particular fiber length i.e 720 km, proposed system have Q factor of 16 whereas conventional DWDM have Q factor of 3.5.At receiver side we have proposed different type of electrical filter Gaussian, rectangular and Bessel filter and compared the results to each other as shown in Fig. 5.6. It is observed that Bessel filter shows better performance as compared to rectangular and Gaussian filter.

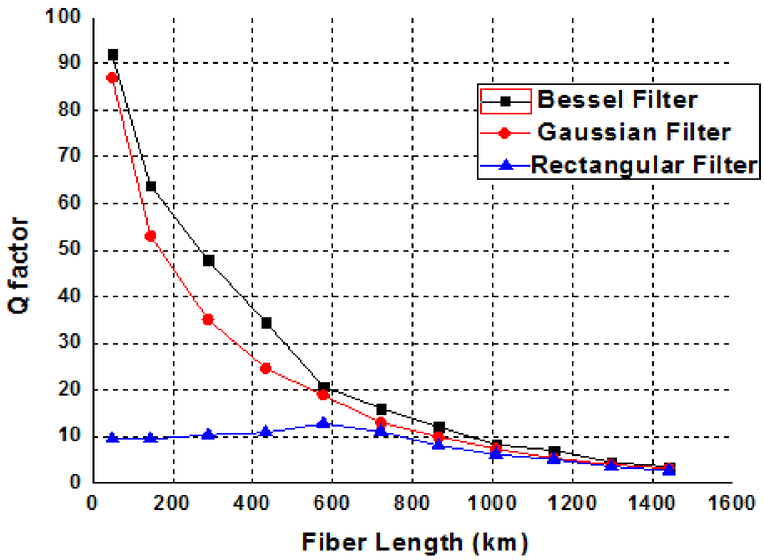
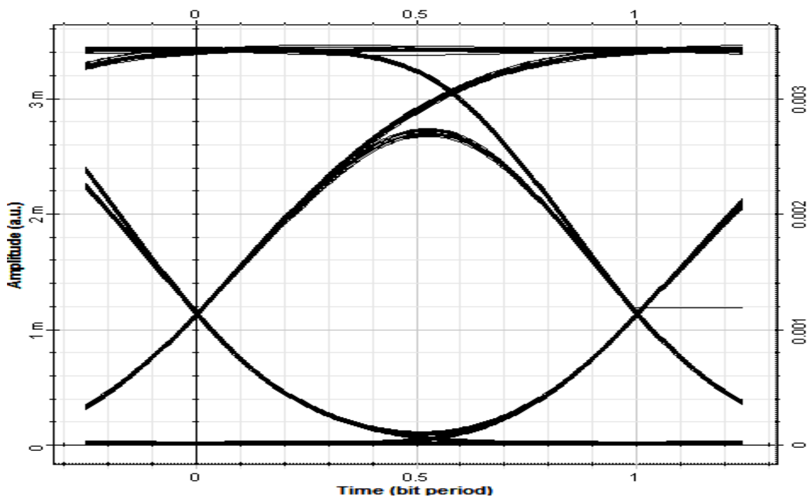
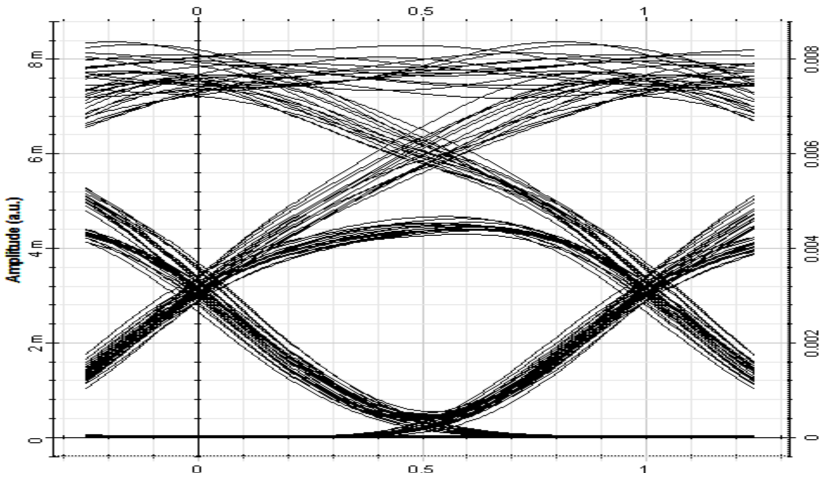


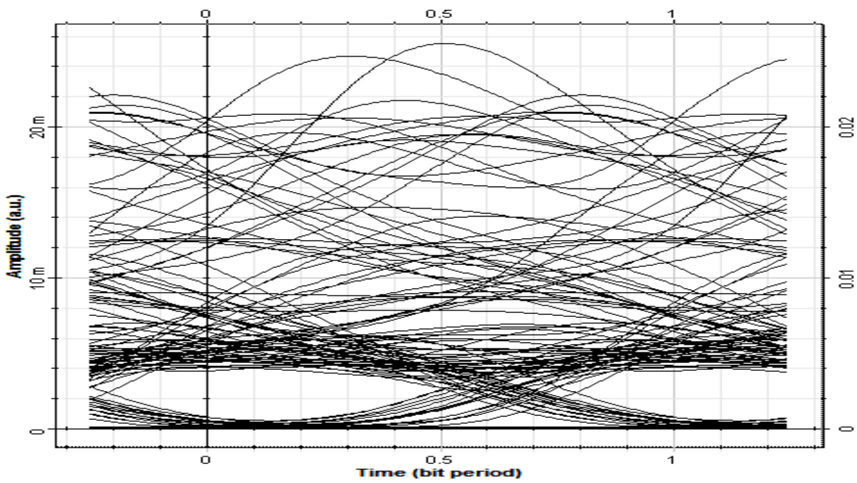
Figure 5.6: Graphical representation of Q factor with varying fiber length for Gaussian, Bessel and rectangular filter.



(a)



(b)

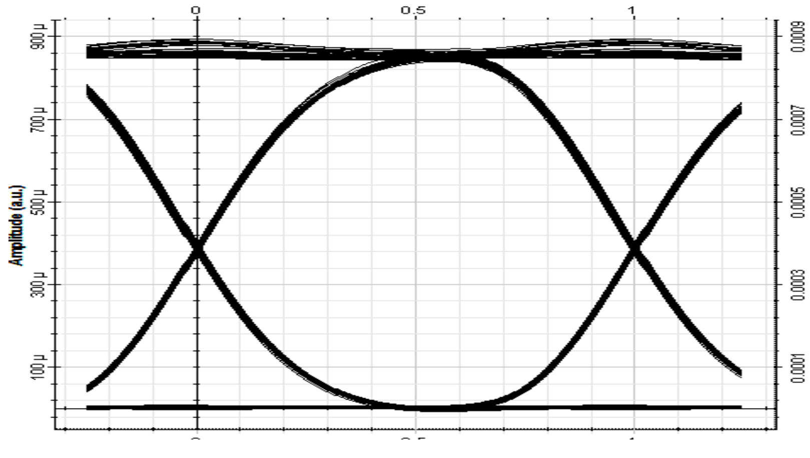


(c)

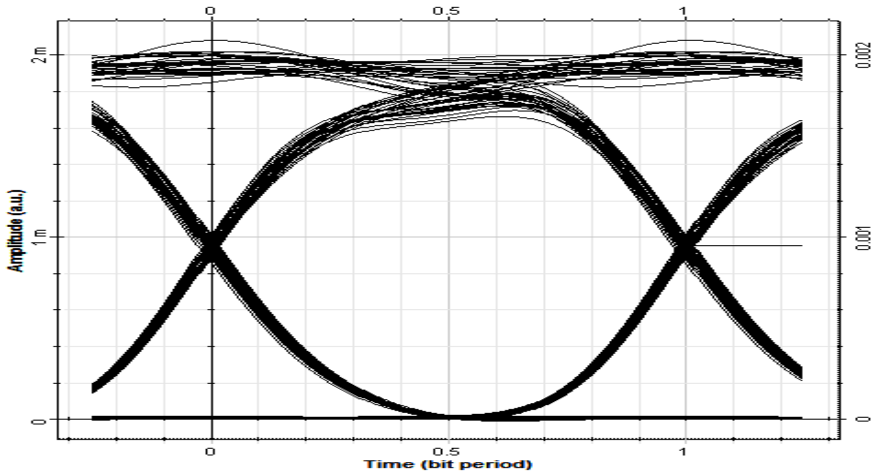
Figure 5.7: Eye diagram for conventional DWDM system at: (a) 48km (b) 576 Km (C) 1152 km.

After Bessel filter, Gaussian filter shows good performance and rectangular filter shows worst performance. At particular instance, Q factor for Bessel, Gaussian and Rectangular are 16, 12.9 and 11 at 720 Km fiber length.

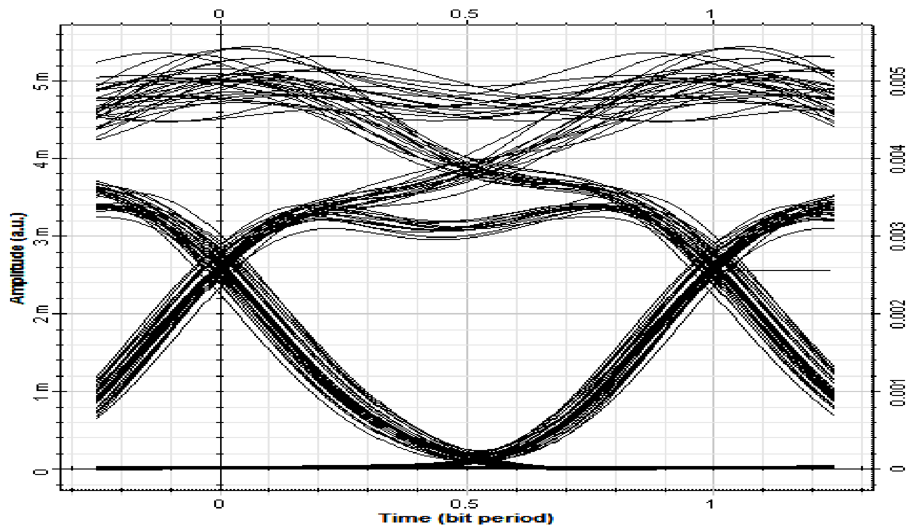
From Fig. 5.5 and 5.6 it can be observed that the proposed system provides high quality factor on polarization interleaving with Bessel filter. For further clarity the eye diagrams over the system has been observed with and without polarization. An eye diagram shows the signal quality amid fast advanced signal transmission. The closure of eye diagram represents distortion in the signal waveform due to noise and inters-symbol- interference. In this way, an open eye diagram corresponds to minimum signal distortion.



(a)



(b)



(c)

Figure 5.8: Eye diagram for polarization interleaved system at: (a) 48km (b) 576 Km (c) 1152 km.

Fig. 5.7 and 5.8 show the eye diagrams for uplink signal at a fiber length of 48km, 576km and 1152 km. When polarization interleaving is used in system, than we achieved better eye opening for long haul transmission as compared to conversational system.

5.5 CONCLUSION

The performance of polarization interleaved DWDM system is analyzed and compared with conventional DWDM system to mitigate the nonlinearities and PMD over fiber. It is observed that proposed system (with polarization interleaving) have more Q factor than conventional DWDM for particular fiber lengths and transmission distance of 1440 km was observed with acceptable value. Also different electrical filter is compared to each other for best suitability with system setup. And Bessel filter shows better performance than Gaussian and rectangular filter at different length of optical fiber. It can be concluded that using polarization scheme, we can send the data at high speed on long distance with good quality of signal.

CHAPTER 6

CONCLUSION, RECOMMENDATION AND FUTURE SCOPE

This chapter provides result and conclusion of defined objectives of research work that is done is dissertation.

6.1 CONCLUSION

The obtained results in thesis are concluded as follows:

1. The performance of second order PMD models using VSB and duobinary modulations has been discussed at 40 Gbps on first order PMD compensator. Performance of proposed system was observed with BER at various received optical powers using different DGD values and it was observed that planar sweep model with VSB modulation shows better performance than EMTY and Bruyere model. BER for EMTY, Bruyere and planar sweep with VSB at 15ps have values of $1.4e^{-18}$, $1.4\ e^{-22}$ and $2.22e^{-23}$.Also Bruyere model performed better after planar sweep model. It was concluded that VSB modulation provided more tolerance than duobinary modualtion for different PMD models.
2. DP-QPSK and DP-16 QAM at 112 Gbps using coherent receiver with DSP has been analyzed in terms of OSNR tolerance, SNR for different fiber lengths, different polarizing angles and constellation diagrams. It was observed that DP-16 QAM had more SNR value than DP-QPSK for fiber length. From the results, it was observed that BER increased linearly with increase in polarizing angle from 0^0 to 20^0 due to mismatching in polarization at transmitter. It was also reported that DP-QPSK at BER of 10^{-3} had 4 dBm more tolerance in comparison with DP-16 QAM and using DSP.
3. Polarization interleaving scheme for mitigation of PMD and non linearities in DWDM long haul transmission system was analyzed and compared with conventional DWDM system. Then comparison between three electrical filters i.e Bessel, Rectangular and Gaussian was done and it was observed that Bessel filter shows improved performance than others at all fiber lengths and transmission distance of 1440 km was achieved with proposed system. It was observed that proposed system provided 16 Q-factor and conventional system provided 3.2 Q-factor for 720 km fiber length.

6.2 RECOMMENDATIONS

The proposed PMD emulator setup can be used by network designers for studying second order PMD effects in communication systems that cannot afford to use PMD compensators in them.

Polarization multiplexing in combination with modualtion schemes has higher bit rates i.e above 100Gbps. So these formats are recommended to be used for obtaining high capacity and SE in communication systems

DWDM systems with polarization interleaving in transmitter is recommended to acheive longer transmission systems and to avoid the effect of depolarization occurring due to interference between adjacent channels in WDM systems

6.3 FUTURE SCOPE OF WORK

During course of dissertation, several areas for which continuation of study can be done come into picture. The worthwhile topics are discussed below:

1. The proposed setup of emulator can further be used for studying PMD effects using multilevel modualtion formats
2. Number of channels and channel spacing in dual polarization and polarization interleaved systems can be increased or decreased varied to study their impact on transmission distance
3. Fiber non linearities such as Stimulated Raman Scattering and Stimulated Brillouin Scattering can also be considered in fiber system to measure overall performance of system

REFERENCES:

[1] Vivek Alwayn, "*Optical Network Design and Implementation*" published by Cisco Press, 2004.

[2]F. P Kapron, D.B Keck and R.D. Mauirer, "Radiation losses in glass optical waveguides," *Applied Physics Lett*ers, vol. 17, no.10, pp. 423-425, 1970

[3] S. B Poole, D.N Payne, R.J Mears, M.E Fermann and R.I Laming , " Fabrication and characterization of low pass optical fibers containing rare earth ions ," *Journal of Lightwave Technology*, vol. 4 ,no. 7, pp. 870-876, 1986.

[4] Hayashi, M. B. Panish, P.W Foy and S. Sumski, "Junction Lasers which operate continuously at room temperature," *Applied Physics Lett*ers , vol. 17, no. 3, pp. 109-111, 1970

[5]J. M. Kahn and Keang-Po Ho, "Spectral Efficiency Limits and Modulation/Detection Techniques for DWDM Systems," *IEEE Journal of selected topics in quantum electronics*, vol. 10, no. 2, pp.259-272, 2004

[6] B. Mukherjee, "*Optical communication networks,"* McGraw-Hill, 1st edition, 1997.

[7] Z. Pan, Q. Yu, A. E. Willner and Y. Arieli, "XPM-induced polarization-state fluctuations in WDM systems and their mitigation," *Optical Fiber Communication Conference, IEEE,* pp. 379-381, 2002

[8] Kaminow and P. Ivan., "Polarization in optical fibers," *IEEE Journal of Quantum Electron*ics, vol. 17, pp. 15-22, 1981

[9] M. Z Jamaludin, A. F Abas, A.S. M. Noor and M. K. Abdullah, "Issues On Polarization Mode Dispersion (PMD) For High Speed Fiber Optics Transmission," *J. Sci. Technol.* , vol. 12, no. 2, pp. 98-106, 2005.

[10]J. P Gordon and H. Kogelnik., "PMD fundamentals: Polarization mode dispersion in optical fibers," *Proceedings of the National Academy of Sciences*, vol. 97, no. 9, pp. 4541-4550, 2002.

[11] I. Yoon and B. Lee, "Change in PMD due to the combined effect of PMD and PDL for a chirped Gaussian pulse," *Optics express*, vol. 12, no. 3, pp. 492-501, 2004.

[12] A. Eyal and M.Tur, "Characterization and measurement of the polarization properties of optical systems in the presence of PMD and PDL," Optical *Fiber Communication Conference, Optical Society of America*, 2005.

[13]B. Batagelj, P. Ritosa, T. Korosec, "Measurement of PMD with a Fixed Analyzer Measurement Technique," *48th International Symposium ELMAR, Zadar, Croatia IEEE,* pp.379-382, 2006.

[14] B.E Olsson, M. Karlsson, and P. A. Andrekson, "Polarization Mode Dispersion Measurement Using a Sagnac Interferometer and a Comparison with the Fixed Analyzer Method," *IEEE photonics technology letters*, vol. 10, no. 7, pp.997-999, 1998.

[15] A. E Willner and M.C Hauer, "PMD emulation," *Journal of optical and fiber communication reports*, vol. 1, no. 3, pp. 181-200, 2004.

[16] I.T. Lima Jr, E. Ibragimov, C. R. Menyuk, and A. E.Willner, "Comparison of polarization mode dispersion emulators," *Journal of Light wave Technology*, vol. 19, no. 12, pp. 1872-1881, 2001

[17] J.H. Lee, and Y.C. Chung, "Statistical PMD emulator using variable DGD elements," *Optical Fiber Communication Conference and Exhibit*, *IEEE*, pp. 375-376, 2002

[18] D. Penninckx and S. Lanne, "Reducing PMD impairments," *Optical Fiber Communication Conference and Exhibit,* vol. 2, pp. TuP1-TuP1, *IEEE,* 2001.

[19]F. Buchali and H. Bülow, "Adaptive PMD Compensation by Electrical and Optical Techniques," *Journal of Lightwave Technology*, vol. 24, no. 4, pp. 11- 60, 2004

[20] S. Bigo, Y. Frignac and G. Charlet., "10.2 Tbit/s (256 x 42.7 Gbit/s PDM/WDM) Transmission over 100km Teralight Fiber with 1.28 bits/s/Hz Spectral Efficiency," *Optical Fiber Communication Conference*, *Anaheim, California United States, OSA,* 2001.

[21] N. E. Hecker, E. Gottwald and K. Kotten., "Automated Polarization Control Demonstrated in a 1.28 Tbit/s (16x2x40Gbit/s) Polarization Multiplexed DWDM Field Trail," *27th European Conference on Optical Communication*, *IEEE,* vol.1, pp.86-87, 2001.

[22] S. P. Singh and N. Singh, "Nonlinear effects in optical fibers: origin, management and applications," *Progress in Electromagnetic Research*, vol. 73, pp. 249–275, 2007.

[23] K. Zeng, "A PMD emulator with tuneable second-order PMD and constant mean first-order DGD," *IEEE Photonics Technology Letter*, vol. 15, no. 8, pp.1150 -1152, 2003.

[24] H. Kogelnik, L. E. Nelson, and J. P. Gordon, "Emulation and Inversion of Polarization-Mode Dispersion," *Journal of lightwave technology*, vol. 21, no. 2, 2003

[25] H. Singh and A. Sheetal, "Impact of PMD induced penalties on 40Gb/s duobinary optical communication system for fixed and variable scattering section dispersion," *Optik- international Journal for Light and Electron Optics*, vol. 17, no. 123, pp. 1520-1524, 2012

[26] C. Xie and L. Moller, "Comparison and assessment of different polarization mode dispersion models," *Optical Fiber Communication Conference*, *Optical Society of America,* 2005.

[27] V. Musara, W. T. Ireeta, S. K. Fosuhene, L Wu and W.R. Leitch, "Polarization mode dispersion emulator: Fixed polarization maintaining Fibre sections and rotatable polarization on orientations," *Optik -International Journal for Light and Electron Optics* , vol. 123 ,no. 3, pp. 228-234, 2012

[28] A. B. dos Santos, T. V. N Coelho, M J Pontes and D. Discini, "A deeper analysis of the second order polarization mode dispersion in optical communications systems," *Optik- International Journal for Light and Electron Optics*, vol. 125, no. 21,pp. 6436-6440,2014.

[29] E. Tipsuwannakul, M. Sköld, M. Karlsson, and P. A. Andrekson, "Comparison of 112-Gb/s PM-RZ-DQPSK and PM-RZ-D8PSK in Terms of OSNR Requirement and Transmission Impairments," *Journal of Lightwave Technology*, vol. 32, no. 18, 2014.

[30] E. Tipsuwannakul, J. Li, M. K. and P. A. Andrekson, "Performance Comparisons of DP-16QAM and Duobinary-Shaped DP-QPSK for Optical Systems With 4.1 Bit/s/Hz Spectral Efficiency," *Journal of Lightwave Technology*, vol. 30, no. 14, pp. 2307-2314,2012

[31] S. Savory, "Digital coherent optical receivers: algorithms and subsystems," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 16, no. 5 pp. 1164-1179, 2010.

[32] B. S. G Pillai , B. Sedigh, , K. Guan, , N. P. Shieh, W. Anthapadmanabhan, K. J Hinton and R. S Tucker, "End-to-end energy modelling and analysis of long-haul coherent transmission systems," *Journal of Lightwave Technology,* vol. 32, no. 18, pp. 3093-3111, 2014

[33] A. Gupta, K. S. Bhatia and H. Kaur, "Comparison of QAM and DP-QPSK in a coherent optical communication system,"*Optik- International Journal for Light and Electron Optics,* vol. 125, no. 20, pp. 5940-5942, 2014.

[34] D. S. L Gagnon, S. Tsukamoto, K. Katoh and K. Kikuch, "Coherent Detection of Optical Quadrature Phase-Shift Keying Signals With Carrier Phase Estimation," *Journal of lightwave technology*, vol. 24, no. 1, p.12, 2006.

[35] H. J. Abd, M.H. Mansoori, N.M. Din, F. Abdullah and H.A. Fadhil, " Priority-based parameter optimization strategy for reducing the effects of four-wave mixing on WDM system ,"*Optik -International Journal for Light and Electron Optics*, vol. 125, no.1 ,pp. 25-30, 2014.

[36] S. P. Singh, A.K.Sharma, N. Singh, "Crosstalk reduction in WDM systems using hybrid amplification technique," *Optics Communications*, vol. 285, no. 19, pp. 3931 3934, 2012

[37]S. H. Chang , H. S. Chung, J. C. Lee, K. Kim and J. H. Lee, "Transmission of 112 Gb/s dual-carrier DQPSK signal over 10 Gb/s-based WDM optical links," *Optical fiber technology* , vol. 19, no. 2 ,pp. 67-74, 2013

[38] K. A Taher, S. P. Majumder , and B.M A. Rahman, "Performance of different modulation formats in 40 Gb/s optical systems in the presence of polarization mode dispersion and nonlinear effects," *International Conference on Electrical Engineering and Information & Communication Technology (ICEEICT), IEEE,* pp.1-4, 2014.

[39] T.Hirooka, T. Hirano, Y. Tomiyama, P. Guan and M. Nakazawa, "PMD-induced crosstalk in ultrahigh-speed polarization-multiplexed optical transmission in the presence of PDL," *Journal of Lightwave Technology*, vol. 29, no. 19, pp. 2963-2970, 2011.

[40] A.Kaur, K.S Bhatia, S.Singh, S. Kaur and A. Sharma, "Different types of modulation analysis used for CATV transmission system." *Optik-International Journal for Light and Electron Optics*, vol. 125, no. 20, pp. 5952-5955, 2014

[41] Y. Li, G. Gao, J. Zhang, S. Chen, X. Yu and W. Gu, "Simplex-method based transmission performance optimization for 100G PDM-QPSK systems with non-identical spans," *Optical Fiber Technology*, vol. 23, pp. 48-52, 2015

[42] R. Griffin and A. Carter, "Optical differential quadrature phase shift key (oDQPSK) for high capacity optical transmission", *Optical Fiber Communication conference and Exhibit, California, USA,* paper WX6, pp. 367- 368, 2002

[43] M. Sieben, J. Conradi and D. Dodds,"Optical single sideband transmission at 10 Gb/s using only electrical dispersion compensation", *IEEE Journal of Lightwave Technology*, vol. 17, no. 10, pp. 1742-1749, Oct. 1999.

[44]Tiago G. Silveira, António, L. J. Teixeira, Ana P. S. Ferreira and Paulo M. N. P. Monteiro,"All-Optical Vestigial Sideband Generation Using a Semiconductor Optical Amplifier", *IEEE photonics technology letters* , vol. 18, no. 21, 2006

[45] L.E. Nelson, T.N. Nielsen, and H. Kogelnik, "Observation of PMD-induced coherent crosstalk in polarization-multiplexed transmission", *IEEE Photonics Technology Letters*, vol. 19, no.13, pp. 738–740, 2001.

[46] H. Liu, X. Zhang, and K. Chen, "Comparison of polarization-mode dispersion tolerances in polarization-multiplexing systems with different modulation format", *Optics Communications*, vol. 259, pp. 640–644, 2006

[47] R. Menyuk, and A. Galtarossa, "*Polarization mode dispersion*", Springer, 2004

[48] P.Šalík, Č. Filip and R. Rastislav, "Duobinary Modulation Format in Optical Communication System," *Advances in Signal Processing*, vol. 3, no. 1, pp. 1-7, 2015

[49] B. Kantarci and H. Mouftah, "Bandwidth distribution solutions for performance enhancement in long-reach passive optical networks", *IEEE Communications Survey and Tutorials*, vol. 9, pp. 1–20, 2011

[50] A.H. Gnauck, G. Charlet, P. Tran, P.J. Winzer, C.R. Doerr, J.C. Centanni, E.C. Bur-rows, T. Kawanishi, T. Sakamoto, and K. Higuma,"25.6-Tb/s WDM transmission of polarization-multiplexed RZ-DQPSK signals,"*IEEE Journal of Lightwave Technology*, vol. 26, pp. 79–84, 2008

[51] P. J. Winzer, A. H. Gnauck, C. R. Doerr, M. Magarini and L. L. Buhl, "Spectrally efficient long-haul optical networking using 112-Gb/s polarization-multiplexed 16-QAM," *Journal of Lightwave Technology*, vol. 28, no. 4, pp. 547–556, 2010

[52] M.G. Taylor, "Coherent detection method using DSP for demodulation of signal and subsequent equalization of propagation impairments", *IEEE Photonics Technology Letters*, vol. 16, no. 2, pp. 674–676, 2004

[53] S. Wabnitz, "Importance Sampling analysis of PMD outages in PDM-QPSK coherent non-linear transmissions," *IEEE Photon Technology Letter,* vol. 25, no. 3, pp. 264-267, 2013

[54] C. R. S. Fludger, T. Duthel, D. V. D. Borne, and C. Schulien, Ernst Dieter Schmidt, Torsten Wuth, J. Geyer, E. D. Man, G. D. Khoe and Huug de Waardt,

"Coherent Equalization and POLMUX-RZ-DQPSK for Robust 100-GE Transmission," *Journal of Lightwave Technology*, vol. 26, no. 1, pp. 64-72, 2008

[55] M. Kuschnerov, F.N. Hauske, K. Piyawanno and B. Spinnler, "DSP for coherent single carrier receiver", *Journal of Lightwave Technology*, vol. 27, no. 16, 2009

[56] X. Xie, F. Yaman, X. Zhou and G. Li., "Polarization demultiplexing by independent component analysis", *Photonics Technology Letters*, *IEEE*, vol. 22, no. 11, pp. 805-807, 2010

[57] D. Godard, "Self-recovering equalization and carrier tracking in two dimensional data communication systems," *IEEE Transactions on communications,* vol. 28, no. 11, pp. 1867 - 1875, 1980.

[58] S. Singh and R. S. Kaler, "Novel Optical Flat Gain Hybrid Amplifier for Dense Wavelength Division Multiplexed System", *IEEE Photonics Technology Letters,* vol. 26, no. 2, pp. 173-176, 2014

[59] S. P. Singh, A. K. Sharma and N. Singh, "Crosstalk reduction in WDM systems using hybrid amplification technique," *Optics Communications*, vol. 285, pp. 3931-3934, 2012

[60] Q. Lin and G. P. Agrawal, "Effects of Polarization-Mode Dispersion on Cross-Phase Modulation in Dispersion-Managed Wavelength-Division-Multiplexed Systems," *Journal of lightwave technology,* vol. 22, no. 4, 2004

[61] D. van den Borne, S. L. Jamen, G. D. Khoe and H. de Waardt, "Polarization interleaving to reduce inter-channel nonlinear penalties in polarization multiplexed transmission," *Optical Fiber Communication Conference*, *Anaheim, California United States*, vol. 3, pp. 6-11, 2005

LIST OF PUBLICATIONS

[1] Geetika, R.S Kaler and Gurpreet Kaur, “Investigation of second order PMD models on first order PMD compensator with 40 Gb/s VSB data,” accepted in International conference on Sciences, Engineering and Technology Innovations, CT Institute of technology, Shahpur , 2016

[2] Geetika, R.S Kaler and Gurpreet Kaur, “Comparative analysis of 40 Gbps duobinary and VSB modulated data using second order PMD models on first order PMD compensator,” communicated to Optoelectronics and Advanced Materials - Rapid Communications (OAM-RC).

[3] Geetika, R.S Kaler and Gurpreet Kaur, “Transmission analysis of 112Gbps Dual polarization QPSK/ 16 QAM using coherent receiver with digital signal processing,” communicated to National Academy of science letters.

[4] Geetika, R.S Kaler and Gurpreet Kaur, “Mitigation of polarization mode dispersion over dense wavelength division multiplexing long haul system using polarization interleaving,” communicated to Optica Applicata.