SIMULATION ANALYSIS OF POLARIZATION MODE DISPERSION AND COMPENSATION TECHNIQUES

Thesis submitted in the partial fulfillment of requirement for the award of degree

of

MASTER OF ENGINEERING

IN

ELECTRONICS AND COMMUNICATION ENGINEERING

Submitted by

Kapil Kashyap

Roll No. 801061010

Under guidance of

Dr. Hardeep Singh

Assistant Professor, ECED

T.U. Patiala

ELECTRONICS AND COMMUNICATION ENGINEERING DEPARTMENT

THAPAR UNIVERSITY

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

PATIALA – 147004, INDIA

JUNE-2012

DECLARATION

I, Kapil Kashyap hereby certify that the work which is being presented in the thesis entitled "Simulation Analysis of Polarization Mode Dispersion and Compensation Techniques" by me in partial fulfillment of the requirements for the award of degree of Master of Engineering in Electronics and Communication Engineering from Thapar University (Deemed University), Patiala, is an authentic record of my own work carried out under the supervision of Dr. Hardeep Singh.

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

19/6/12

Kapil Kashyap

Roll No. 801061010

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

19/06/2012

Dr. Hardeep Singh

Assistant Professor, ECED

(Dr Rajesh Khanna)

Professor and Head ECED

Thapar University, Patiala

(Dr. S.K. Mohapatra)

Dean Academic Affairs

Thapar University, Patiala

ACKNOWLEDGEMENT

I would like to give special thanks to my guide **Dr. Hardeep Singh** Assistant Professor **ECED**, Thapar University, Patiala, for his advice, kind assistance, and invaluable guidance. It has been a great honor to work under him.

I am also thankful to **Dr. Rajesh Khanna**, Prof. & Head, Electronics and communication Engineering Department, for providing us with adequate infrastructure in carrying the work.

I am also thankful to **Dr. Kulbir Singh**, P.G. Coordinator, Electronics and communication Engineering Department for the motivation and inspiration that triggered me for the report work.

I would also like to thank all the faculty members of ECED for their intellectual support and also special thanks to my friends who constantly encouraged me to complete this work. I am also thankful to the authors whose work I have consulted and quoted in this work.

Kapil Kashyap

Roll no. 801061010

Abstract

The topic of thesis is “Simulation Analysis of Polarization Mode Dispersion (PMD)” in Fiber optics communication. The work can be divided into three parts which deals with major aspects of PMD: characteristics, transmission and compensation.

Polarization-mode dispersion (PMD), in single-mode optical fibers, is a phenomenon that a limit the bit-rate-distance product of amplified, lightwave communication systems. However, compensation is complicated due to the random nature of PMD. Therefore, adaptive compensation techniques are required. We modified the PMD compensation system that was earlier developed and made it robust and bit-rate independent. The impact of PMD in transmission systems has also been investigated..

By simulation we analyze the affect of PMD on the fiber optic system. At high bit rate PMD has a great effect on the system. As the bit rate increases the dispersion due to two modes. This is due to polarization. The intent of which is that of making the performance of a coherent optical receiver insensitive to the polarization transformations occurring along the optical fiber, without resorting to polarization compensation or control. The principle on which polarization spreading operates is that of spreading the signal power over different states of polarization, some classes of spreading waveforms satisfying the above condition, the derivation of the structure and performance of optimum receivers in Gaussian noise. In this thesis we discuss the compensation techniques of PMD and make their simulation set-ups to compensation the orders of the PMD according to those set-ups.

The various factors which can be varied can be discussed in these thesis e.g. BER, equivalent Q factor and Electrical power. The graphs show that as the PMD of the fiber increases, the BER can be increased. And the Q factor and electrical power decreased. The effect on the output can be studied through the eye diagrams. As the eye is open that means the output is that much. The enclosing of the eye shows the effect of the PMD on the system.

LIST OF FIGURES

FIGURE	DESCRIPTION	PAGE
1.1	Increase in the bit rate –distance (B-L) product since 1850	1
1.2	Progress in optical fiber communication since 1974	2
1.3	Cross-Sectional defects of Optical Fibers	8
1.4	Polarization Mode Dispersion	9
1.5	The local birefringence in an optical fiber changing the polarization state of the light	11
1.6	Occurrence of PMD at distance L	12
1.7	Dispersion compensation methods	18
1.8	Various dispersion compensating techniques	20
1.9	Dispersion compensation schemes in multi-span systems	22
3.1	Simulation Setup for PMD variation effects	30
3.2	Eye Diagram at PMD = 0 *ps*/ *km*	31
3.3	Eye Diagram at PMD = 60 *ps*/ *km*	32
3.4	Eye Diagram at PMD = 120 *ps*/ *km*	32
3.5	Eye Diagram at PMD = 180 *ps*/ *km*	33
3.6	Q Value at Different values of PMD	34
3.7	Eye Opening at Different values of PMD	34
3.8	Eye Closure at Different values of PMD	35
3.9	Electrical Power at Different values of PMD	35
3.10	A NRZ simulation setup for PMD compensation using PMD	36

emulator and VDGD: Variable Differential Group Delay with an average PMD of 10 ps. VDGD

3.11(a)	Dispersion verses Equivalent Q before emulation	46
3.11(b)	Dispersion verses Equivalent Q after emulation.	47
3.12(a)	Dispersion verses BER before emulation	48
3.12(b)	Dispersion verses BER after emulation	48
3.13(a)	Dispersion verses electrical power before emulation.	49
3.13(b)	Dispersion verses electrical power after emulation.	50
3.14(a)	Eye opening with PMD before emulation	51
3.14(b)	Eye opening with PMD after emulation	51
3.15(a)	Q value with PMD before emulation	52
3.15(b)	Q value with PMD after emulation	52
3.16(a)	Eye closure with PMD before emulation	53
3.316(b)	Eye closure with PMD after emulation	54
4.1	Simulation set-up for first order pre-compensation	56
4.2	Simulation set-up for first order post-compensation	57
4.3(a)	PMD verses equivalent Q factor	58
4.3(b)	PMD verses BER	58
4.3(c)	PMD verses electrical power	59
4.3(d)	Eye diagram at 10 $ps/\sqrt{km}$	69
4.3(e)	PMD verses eye opening	60
4.3(f)	PMD verses eye closure	60
4.4(a)	PMD verses equivalent Q factor	61

4.4(b)	PMD verses BER	62
4.4(c)	PMD verses electrical power	62
4.4(d)	Eye diagram at 10 $ps/\sqrt{km}$	63
4.4(e)	PMD verses eye opening	63
4.4(f)	PMD verses eye closure	64
4.5(a)	PMD verses equivalent Q factor	65
4.5(b)	PMD verses BER	65
4.5(c)	PMD verses electrical power	66
4.5(d)	Eye diagram at 10 $ps/\sqrt{km}$	66
4.5(e)	PMD verses eye opening	67
4.5(f)	PMD verses eye closure	67
4.6(a)	PMD verses equivalent Q factor	68
4.6(b)	PMD verses BER	69
4.6(c)	PMD verses electrical power	69
4.6(d)	Eye diagram at 10 $ps/\sqrt{km}$	70
4.6(e)	PMD verses eye opening	70
4.6(f)	PMD verses eye closure	71
4.7(a)	PMD verses equivalent Q factor	72
4.7(b)	PMD verses BER	72
4.7(c)	PMD verses electrical power	73
4.7(d)	Eye diagram at 10 $ps/\sqrt{km}$	73
4.7(e)	PMD verses eye opening	74
4.7(f)	PMD verses eye closure	74

4.8(a)	PMD verses equivalent Q factor	75
4.8(b)	PMD verses BER	76
4.8(c)	PMD verses electrical power	76
4.8(d)	Eye diagram at 10 $ps/\sqrt{km}$	77
4.8(e)	PMD verses eye opening	77
4.8 (f)	PMD verses eye closure	78

LIST OF ABBREVIATIONS

CD	Chromatic Dispersion
CPM	Cross Phase Modulation
DM	Dispersion Management
DOF	Degree of Freedom
DOP	Degree of Polarization
DGD	Differential Group Delay
DDGD	Deterministic Differential Group Delay
DCF	Dispersion Compensating Fiber
EDFA	Erbium Doped Fiber Amplifier
FBG	Fiber Bragg Grating
FWM	Four Wave Mixing
OSNR	Optical Signal to Noise Ratio
PDG	Polarization Dependent Gain
PDL	Polarization Dependent Loss
PMD	Polarization Mode Dispersion
PMF	Polarization Maintaining Fiber
SOA	Semiconductor Optical Amplifier
SOP	State Of Position
SRS	Stimulated Raman Scattering
SBS	Stimulated Brillouin Scattering
SPM	Self Phase Modulation
SMF	Single Mode Fiber
TDM	Time Domain Multiplexing
WDM	Wavelength Division Multiplexing
XPM	Cross Phase Modulation

Chapter 1

INTRODUCTION

The growth of telecommunication technologies has been phenomenal since the past century and a half. From the early telegraph to the present day high speed optical systems, there has been a constant upward surge in the data rates and the system capabilities.

The feasibility of using glass fiber for optical communication was seriously studied in the mid-1960s. Dr. Charles Kao and others proposed that it would be possible to reduce fiber attenuation to less than 20 dB/km. The first step towards this development were taken in the early 1970's when a low pass optimal fiber [1, 4], together with an improved semiconductor Laser [2] were shown to be promising key components in optical transmission systems. Even though the fiber loss has been reduced to 0.2 dB/km over the years.

It was not until the advent of Erbium Doped Fiber Amplifier (EDFA) in the late 1980's [3], that chromatic dispersion in the fiber become main limiting factor in the optical transmission systems rather than fiber losses.

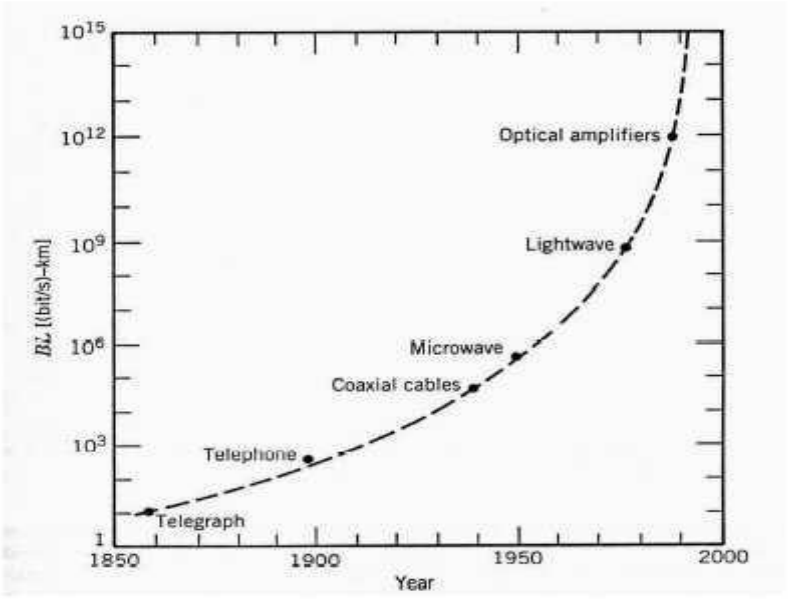


Figure 1.1: Increase in the bit rate –distance (B-L) product since 1850 [1]

The mid 1980s saw telecommunication carriers like Sprint establish extensive fiber optic backbone networks. With the advent of the optical amplifier, or specifically the Erbium

Doped Fiber Amplifier (EDFA) in 1986, it has been possible to increase the span and speed of optical fiber based communication operate, proved to be an important factor in fixing the wavelength of operation of present day fiber optic systems. Figure (1.1) shows the increase in the bit-rate distance product since 1850. Figure (1.2) depicts the growth of fiber-optic systems since 1974.

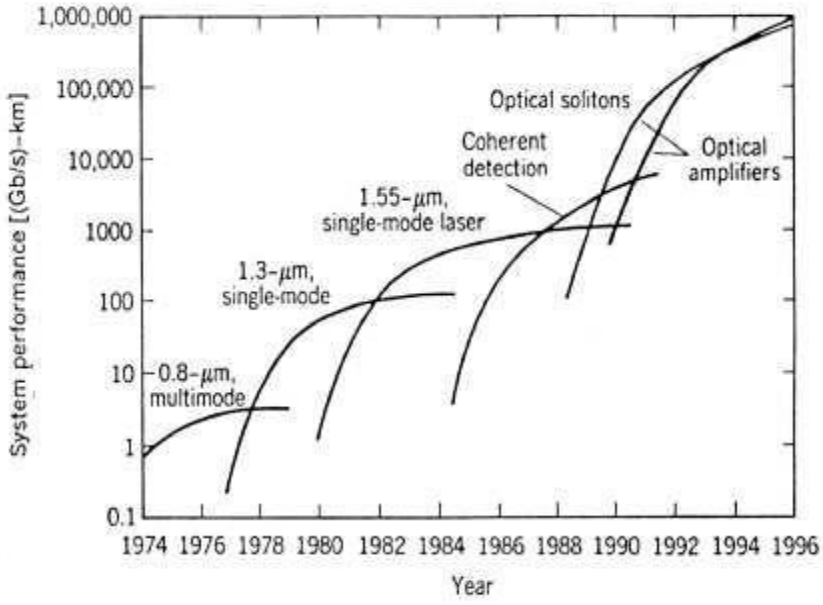


Figure 1.2: Progress in optical fiber communication since 1974

The EDFA band is wide enough to support many wavelengths simultaneously. This led to the development of Wavelength Division Multiplexed (WDM) systems or the simultaneous propagation of several wavelengths of light through a fiber. Each wavelength can carry a different data stream. In the 1990s systems the EDFA band, or the range of wavelengths over which the EDFA can, the demand for bandwidth, especially with the growth of the internet, fueled a rapid increase in the data rates.

As the number of channels and data rates rose, certain phenomena such as chromatic dispersion and nonlinearities began to show up as obstacles. Using special fibers called dispersion compensating fibers and other novel devices could effectively compensate for chromatic dispersion, being deterministic in nature. Nonlinearities could also be minimized with careful power budget consideration. With all these measures, the upward surge of the data rate would have seemed unstoppable. However, at very high data rates (above 10 Gbps)

even minute phenomena have to be taken into consideration to ensure error-free transmission. Examples of such phenomena are polarization-dependent broadening and polarization-dependent loss of the optical signal. The optical fiber has some inherent properties like birefringence, which leads to what is called polarization-mode dispersion (PMD). The following paragraphs will provide the definition of PMD and will discuss why PMD plays an important role in the design of high speed fiber-optic telecommunication systems.

In the more than 15 years since the introduction of the early concepts[4,5], the fundamentals of polarization mode dispersion (PMD) in optical fibers have become an important body of knowledge basic for the design of high-capacity optical communication systems. PMD effects are linear electromagnetic propagation phenomena occurring in so-called ‘‘single-mode’’ fibers. Despite their name, these fibers support two modes of propagation distinguished by their polarization. Because of optical birefringence in the fiber, the two modes travel with different group velocities and the random change of this birefringence along the fiber length results in random coupling between the modes. With current practical transmission technology the resulting PMD phenomena lead to pulse distortion and system impairments that limit the transmission capacity of the fiber. Excellent reviews are available [6], covering the practical aspects and applications of PMD concepts to fiber transmission systems and the effects of PMD on nonlinear fiber transmission. In this review we aim to complement these surveys and to collect and synthesize the fundamental concepts and theory of PMD, interweaving and linking the principal laws and key formulas that appear scattered in various places in the literature. We will explore the connection between frequency domain and time-domain analyses and the isomorphic relation between the three-dimensional (3-D) view using real-valued 3-D Stokes vectors and the two-dimensional (2-D) view using complex- valued 2-D Jones vectors. Isomorphic pairings of operators such as these have been widely used elsewhere in physics such as in mechanics [6], in quantum mechanics [7], and even in the unification of quantum theory and general relativity. We borrow this methodology for our purposes.

In high-speed optical communication systems working at data rates of 10 Gbps and beyond, signal distortion caused by polarization mode dispersion (PMD) is a major limitation of the transmission distance. This leads to degradation in system performance [8]. Especially

in upgrading of existing transmission lines, high PMD of 'old' fibers is a serious problem. The PMD of installed fibers fluctuates with time due to environmental influences, for example changes in temperature and stress [9]. Therefore, adaptive PMD compensation during system operation is indispensable [10]. To remove the system degradation caused by the fiber PMD, several optical and electrical PMD compensation techniques have been proposed and discussed in the literature. A detailed description of PMD compensation systems, working in optical domain, structures and requirements for automatic compensation, is given in [11]. Another way to mitigate signal distortions is to use electrical signal processing techniques [12]. Based on the concept of transversal filters, an analog tapped delay line equalizer was used the first time for mitigation of signal distortions caused by PMD [13]. An adaptive compensation system realized with an electronic SiGe Equalizer IC, including a 4-tap transversal filter operating at 10 Gbps, is described in [14]. Overall, electrical signal processing has become an alternative for PMD compensation due to possible compact and cost-effective implementation of the equalizer in the receiver electronics [8] and the need of individual compensation in WDM systems. In order to be able to compensate PMD in the optical domain, a suitable equalizer structure must be found. For signal distortions caused by first and higher order PMD, compensators consisting of a several number of differential group delay (DGD) sections must be used. Each section is separated by an adjustable polarization transformer, which leads to a very complex equalization algorithm and is not clearly presented until now [15, 16].

PMD can cause several undesirable effects that could be obstacles to high speed telecommunication through optical fibers. Such effects are not limited to digital communication systems but affect analog communication systems as well. With the evolution of specialized manufacturing methods, PMD in present day, telecommunication grade fibers is kept very low (< 0.1ps/km). Still no matter how good the fiber may be, at some bit-rate-length product, PMD will be an issue. Hence, there is need to investigate strategies for PMD mitigation. Over the years, research groups from around the globe have proposed and/or demonstrated different strategies for PMD compensation. In this chapter an overview of these strategies shall be given. Their relative merits and demerits will also be mentioned. Following that, methods to increase the tolerance of a fiber-optic communication system to PMD, will also be discussed.

The increasing demand for bandwidth is driving most telecommunications operators toward the deployment of large-capacity transmission systems. Systems based on 10-Gb/s channel rates are being deployed, and suppliers have announced plans for channel rates as high as 40 Gbps. Polarization mode dispersion represents a major impairment for high bit-rate systems, producing pulse broadening and distortion, thus leading to performance degradation [17].

Polarization mode dispersion in optical fiber stems from the breakup of circular symmetry in the core and cladding. Ideally, this symmetry renders the fiber perfectly isotropic; i.e., non birefringent. The fiber's index of refraction is independent of the orientation of the electric field or, equivalently, the polarization of the light. Light propagation in single-mode fibers is governed by two orthogonally polarized fundamental modes, which, in the case of ideal fibers, are degenerating (indistinguishable).

In this thesis we have analyze the effect of the PMD on different bit rates and how we compensate it by using polarization controller. This all we have done with the help of the software called OptSim. OptSim includes the most commonly used components for the engineering of electro-optical systems, with particular emphasis on WDM and digital CATV systems. It also supports innovative optical approaches such as quasi-RZ and dispersion-managed soliton systems. During simulation OptSim will exchange signals using the documented OptSim signal format.

OptSim is a stand-alone product that comes with a Windows-like user interface and on-line HTML help. You do not need additional tools or expensive frameworks to realize the full power of OptSim. OptSim is extremely easy-of-use, allowing non-experts to set up the most complex simulations in a matter of minutes by using drag-and-drop icons and editing parameter values for each component. In my thesis with the help of this software, I analyze the effect of the PMD on the output electrical power.

Twenty first century is the era of 'Information technology'. There is no doubt that information technology has had an exponential growth through the modern telecommunication systems. Particularly, optical fiber communication plays a vital role in the development of high quality and high-speed telecommunication systems. Fiber optic communication is a way of exchanging the information between to places by sending the light signal through the optical fiber cable. Fiber optic communication brought the revolutionary change in the telecommunication industry and played a major role in the

advent of information age. In the twenty first century, its advantages over electrical transmission cause the replacement of copper wire with the optical fiber in the communication system. Now the optical fiber is the most common type of channel used in communication system, but the other types of waveguides are also used within the communication system. Today, optical fibers are not only used in telecommunication links but also used in the Internet and local area networks (LAN) to achieve high signalling rates. The core advantages of optical fiber such as low loss, which allows long distances between amplifiers and its high data carrying capacity as that of thousands of electrical links would be required to carry that much data. Also no cross talk introduces in optical fibers running alongside each other for long distances as introduces in some types of electrical transmission lines. The use and demand for optical fiber has grown tremendously and optical-fiber applications are numerous. Telecommunication applications are widespread, ranging from global networks to desktop computers. These involve the transmission of voice, data, or video over distances of less than a meter to hundreds of kilometers, using one of a few standard fiber designs in one of several cable designs [18].

But in the fiber optic communication system linear and nonlinear characteristics of fiber put limitations over high speed data transmission in the communication system. The Linear characteristics include attenuation, chromatic dispersion (CD), polarization mode dispersion (PMD), and optical signal-to-noise ratio (OSNR). The nonlinear characteristics include self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), stimulated Raman scattering (SRS), and stimulated Brillouin scattering (SBS). Nonlinear fiber effects such as self- and cross-phase modulation combined with the group velocity dispersion result in intensity distortion of the propagating signals in WDM links, limiting the maximum transmission distance. The transmission distances can be increased by optimizing the dispersion map to reduce the impact of nonlinearities. Further the maximum transmission distance is limited by the dispersion or spreading of optical pulses as they travel along the fiber.

1.1 Polarization Mode Dispersion

The polarization related impairments have become a major obstacle to the increase transmission rates in WDM systems. Such impairments include polarization mode dispersion

(PMD) in optical fibers, polarization dependent loss (PDL) in passive optical components, polarization dependent modulation (PDM) in electro optical modulators, and polarization dependent gain (PDG) in optical amplifiers.

Polarization Mode Dispersion, or PMD, is an important linear phenomenon occurring inside optical fibers, which can cause the optical receiver to be unable to interpret the signal correctly, and results in high bit error rates. PMD can dramatically decrease the fiber optic network's performance, particularly those networks operating at high data rates. The technology for years had been made a free ride as it grew from 90 Mbps to 270 Mbps to 435 Mbps to 2.5 Gbps [19]. A problem began to manifest itself in 5 Gbps systems and threatens major dislocation at 10 Gbps networking. For the first time, the fiber-optics industry was faced with a networking killer. It can distort signals, render bits inaccurate, and destroy the signal integrity of the network.

1.1.1 Polarization Mode Dispersion (PMD) Overview

While the phenomenon of Polarization Mode Dispersion (PMD) has been known for years, it has only been recently that it has posed a serious, realistic problem for optical networks. PMD's negative effects result in a limitation of a networks bandwidth or length that is, of course, undesirable to say the least. It is important to understand however, that with proper measurement and management, the negative effects of PMD may be minimized or eliminated altogether.

The older fibers had the PMD value 100 times greater than that of the present day fibers. But in the new fiber the PMD remains the major problem because of the following reasons:

i. There is still a small residual asymmetry in the fiber core as shown in figure (1.3).

ii. Slight PMD exists in the discrete in line components such as isolators, couplers, Erbium Doped Fibers, modulators and multiplexers.

In addition to this, internal forces induced by thermal expansion and external forces induced by the environment through handling and cabling, such as bending and twisting, add slight non symmetrical stress fields inside the fiber core. As laser light is generally highly polarized, the digital bits that they emit contain light that is also highly polarized.

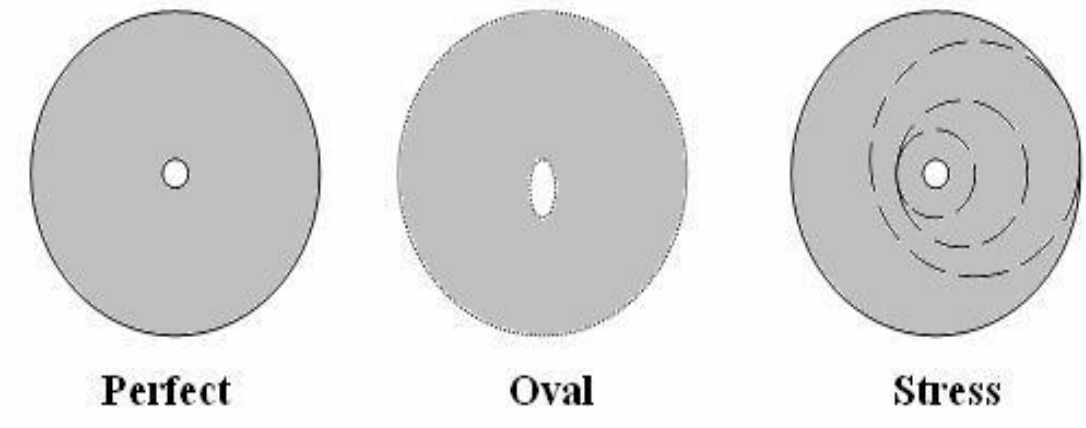


Figure 1.3: Cross-Sectional defects of Optical Fibers

Couple this with the birefringence present in the fiber and the result is that different components (polarizations) of the digital bits travel at different velocities [20]. In other words some of the light in the bit travels faster and some of the light travels slower. This causes the digital bit to spread in time; this is termed dispersion. Moreover, the residual birefringence is not constant along the length of the fiber but changes with distance in a random way, not only in amount, but also in its local principal axes. So in the best conditions, PMD still significantly limits the deployment of high bit rate systems. For a given fiber, PMD is supposed to be fixed. However, this is not the case in real communication systems because environment fluctuations cause PMD to vary randomly in time. Therefore, it is important to understand the statistical properties of pulse propagation induced by PMD.

A single-mode fiber is designed to support only one mode of propagation of light. The principal advantage of letting light propagate along only one mode is that inter-modal dispersion can be avoided. Inter-modal dispersion happens as a result of relative delay between the light propagating in the various modes in a multi-mode fiber. In single-mode fibers, as there is only one mode available for light propagation (theoretically), intermodal dispersion is nonexistent. Single mode optical fiber and components support one fundamental mode, which consists of two orthogonal polarization modes. This asymmetry introduces small refractive index differences for the two polarization states. This characteristic is known as birefringence. The birefringence causes one polarization mode to travel faster than the other, resulting in a difference in the propagation time, which is called the differential group delay (DGD).

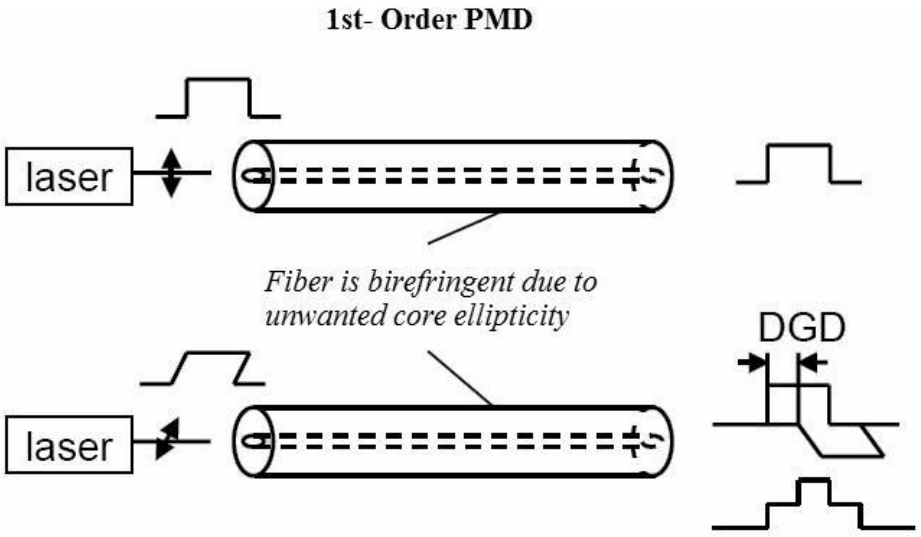


Figure 1.4: Polarization Mode Dispersion

DGD is the unit that is used to describe PMD. DGD is typically measured in picoseconds. A fiber that acquires birefringence causes a propagating pulse to lose the balance between the polarization components. This leads to a stage in which different polarization components travel at different velocities, creating a pulse spread as shown in Figure (1.4). PMD can be classified as first-order PMD, also known as DGD, and second-order PMD (SOPMD). The SOPMD results from dispersion that occurs because of the signal's wavelength dependence and spectral width. If the fibers were perfect, the state of polarization (SOP) of the light signal transmitting in the fiber would remain constant and the effects of the PMD, PDL, PDM, and PDG could be easily eliminated.

Unfortunately, the SOP of light propagating in the length of slandered communication fiber varies along the fiber due to random birefringence induced by the thermal stress, mechanical stress, and irregularities of the fiber core. Generally, at the output end of fiber the light polarized, with varying degrees of ellipticity, and with the major elliptical axis at the arbitrary angle. Worst of all, the induced birefringence changes with temperature, pressure, stress and other environmental variations, making polarization impairments time dependent.

The single mode fibers manufactured in mid 1990s have the property that has become more problematic as the bit rates and span lengths increases. This all was due to the imperfectly rounded fiber core. As the core of a fiber should have a perfect cylindrical shape,

but in practice it is not possible to have ideally cylindrical shape because of change in core diameter randomly while drawing the fiber, so because of this physical limitation the PMD occurs [20]. So as it is impossible to manufacture the perfectly symmetrical and rounded fiber, the researchers got success to produce more symmetrically rounded fiber. But the problem of PMD still exists with a small coefficient of 0.1 $ps/\sqrt{km}$ [21].

1.1.1.1 Refractive Index

Light within a medium travels at a slower speed than in the vacuum. The speed at which light travels in the medium is determined by its refractive index. In an ideal situation, the refractive index would not depend on the wavelength of the light. However, this is not the case which results in different wavelengths travelling at different speeds within an optical fiber. Environmental conditions, such as variations in temperature can change the refractive index of the optical fiber. As temperature increases, so will the refractive index, however, the increase is not uniform over all wavelengths resulting in differing wavelength speeds. In addition, stress, such as the pressure experienced by a submarine cable, can affect the refractive index of an optical fiber. When pressure is exerted on the optical fiber the refractive index decreases. The amount of the decrease is also a function of the wavelength [22].

The refractive index of an optical fiber can have a different value across the horizontal and vertical axis of the fiber core. This difference in the refractive index results in the two orthogonal states of polarization (vertical and horizontal) travelling at different speeds through the fiber. The result is a Differential Group Delay, measured in ps / km , between the two states of polarization (vertical and horizontal axis) and possibly intersymbol interference. This effect is known as Polarization Mode Dispersion (PMD). A typical design rule is that DGD should not exceed 10% of the bit rate for an NRZ signal. This implies that as the bit rate increases, the acceptable amount of DGD decreases. Meeting this design rule can be challenging since PMD is a result of geometric irregularities of the fiber core, temperature changes and stress placed on the fiber, making PMD unpredictable and statistical in nature.

1.1.1.2 Birefringence

The birefringence in optical fiber can be expressed as a difference in the refractive index, and hence propagation constant , for the orthogonal polarization modes

$$\Delta\beta = \beta_s - \beta_f = \frac{\omega n_s}{c} - \frac{\omega n_f}{c} = \frac{\omega \Delta n}{c} = \frac{2\pi}{\lambda}\Delta n \qquad (1.1)$$

Where ω is the angular frequency of the light, c is the speed of the light in vacuum and $\Delta n = n_s n_f > 0$ is the refractive index difference between the slow and fast axis, while λ is the wavelength of the light in vacuum. The difference can also change the state of polarization (SOP) of the light as it travels along the fiber as illustrated in the figure (1.5). Two orthogonal polarization states exist (eigenstates) that are unaffected by the birefringence. Any polarization state can be decomposed into the two eigenstates. In the uniformly birefringent segment, the eigenstates corresponds to the well defined birefringence axes.

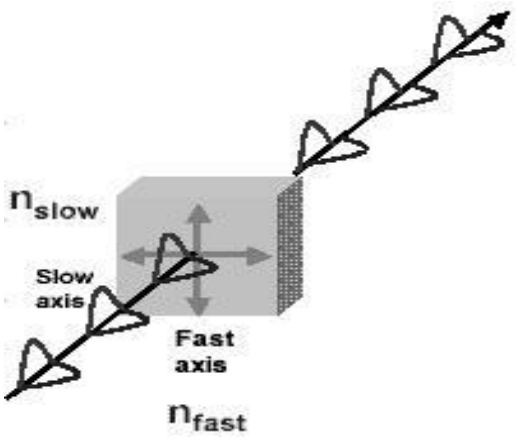


Figure 1.5: The local birefringence in an optical fiber changing the polarization state of the light

The phase retardation between the two orthogonal fields due to birefringence causes the polarization to evolve in a periodic manner and the period of this variation is referred to as the beat length, $L_\beta = \frac{\lambda}{\Delta n}$ **.** For standard single mode fiber Δn is typically 10^{-7} , which leads to a beat length to around 15 m at the wavelength 1550 nm. The difference in phase velocity indicated by equation is usually accompanied by a difference in the local group velocity and by a subsequent splitting of pulses that travel through the fiber. This group velocity difference gives rise to a differential group velocity (DGD), Δt is a random variable that has a Maxwellian probability density function (pdf). Figure (1.5) shows the pulse

splitting that arises due to the birefringence. In long fibers, the birefringence is combined with random polarization mode coupling and the PMD grows with the square root of the fiber length. The degeneracy can be lifted if, through a loss of the circular symmetry, any amount of anisotropy is introduced, leading to some birefringence [23, 24]. This is the general case of real fibers, where the loss of symmetry originates in the fiber manufacturing process from noncircular waveguide geometry (geometrical birefringence static) or in deployed fiber from non symmetrically distributed mechanical stress (stress birefringence time varying) [25].

1.1.2 How PMD Occurs

When light travels down a single mode fiber toward the receiver, it has two polarization modes that follow the path of two axes. They move toward the receiver at right angles to each other. When the core of the fiber that bounds the light is asymmetrical, the light travelling along one polarization axis moves slower or faster than the light polarized along the other axis. This effect can spread the pulse enough to make it overlap with other pulses or change its own shape enough to make it undetectable at the receiver as shown in figure (1.6).

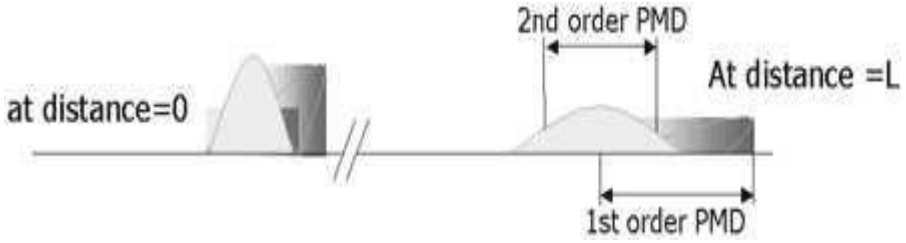


Figure 1.6: Occurrence of PMD at distance L

As figure (1.6) shows, the optical pulse and its constituent photons travel from the source, or transmitter, at distance 0, along the single-mode optical fiber. At some distance after PMD has affected the pulse, the polarized energy is separated by some time. This time is known as differential group delay (DGD). DGD is the fundamental measure of PMD and is measured in picoseconds (10-12 seconds). If DGD is severe, the receiver at some distance *L* cannot accurately decode the optical pulse, and bit errors can result. The optical eye pattern of a PMD-limited signal exhibits the effects of DGD by "closure" of the eye. The effect of the eye closure is caused by the separation of the polarized axes of photons, as the DGD

becomes higher, separation becomes greater, and optical pulses start to interfere with each other.

PMD is not an issue at low bit rates but becomes an issue at bit rates in excess of 5 Gbps. PMD is noticeable at high bit rates and is a significant source of impairment for ultra-long-haul systems. PMD compensation can be achieved by using PMD compensators that contain dispersion-maintaining fibers with degrees of birefringence in them. The introduced birefringence negates the effects of PMD over a length of transmission. For error-free transmission, PMD compensation is a useful technique for long-haul and metropolitan-area networks running at bit rates greater than 10 Gbps. The PMD value of the fiber is the mean value over time or frequency of the DGD and is represented as $ps/\sqrt{km}$. A 0.5-dB power margin is typically reserved to account for the effects of PMD at high bit rates.

1.1.3 PMD Characterization

There are two parameters that characterize the PMD: principal states of polarization and differential group delay. Signals oscillate through fiber along two planes at right angles to each other, called the principal states of polarization. For a fixed PMD, DGD is a random variable that has a Maxwellian probability density function (pdf). In a PMD free fiber, polarization states do not change and the energy in each state arrives at the receiver at the same time. In the presence of PMD, however, the states change and the arrival time of one state varies with respect to arrival time of the other. This time difference is Differential Group Delay (DGD). Since asymmetry causes PMD, DGD increases with both the fiber's PMD coefficient and its length. At some distance PMD effects become so great that regeneration is necessary unless the effect of PMD is mitigated. To find the "peak value" typically multiply the statistical average DGD. That is the value above which less than 1%, of delay values are likely to exist. Regeneration distance is inversely proportional to the square root of the channel rate.

For a length of fiber, at every frequency, there is a pair of input polarization states called the PSPs. A PSP is that input polarization state for which the output state of polarization is independent of frequency over a small frequency range. Using the PSP concept, PMD can be characterized as a vector represented as [26]:

$$\vec{\tau} = \Delta\tau\hat{P} \tag{1.2}$$

The PMD vector is a vector in three-dimensional spaces (Stokes space). The length of the vector ($\Delta\tau$) is the DGD and the direction of the vector ($\hat{P}$) is along the axis that joins the two output PSP points in Stokes space [26, 27].

Excellent reviews are available [28], covering the practical aspects and applications of PMD concepts to fiber transmission systems and the effects of PMD on nonlinear fiber transmission. In this review we aim to complement these surveys and to collect and synthesize the fundamental concepts and theory of PMD. PMD can cause several undesirable effects that could be obstacles to high speed telecommunication through optical fibers. Such effects are not limited to digital communication systems but affect analog communication systems as well. With the evolution of specialized manufacturing methods, PMD in present day, telecommunication grade fibers is kept very low (<0.1 $ps/\sqrt{km}$). Still no matter how good the fiber may be, at some bit-rate-length product, PMD will be an issue.

1.2 Dispersion Mapping

The advent of optical repeaters based on erbium-doped fiber amplifiers (EDFAs) has opened the new era of optical transmission technologies, allowing us to use wavelength division-multiplexing (WDM) technologies with simple, compact, and economical approaches [29]. In fact, the demonstrated capacity for long-haul optical transmission has been growing remarkably, and more than a thousand fold increase in capacity has been achieved over the past ten years. The price we have to pay for such success is the combat with the accumulated impact of fiber nonlinearity, interplaying with the chromatic dispersion of the transmission fiber, which grows with transmission distance and, therefore, becomes significant for ultra-long-haul systems. Dispersion-management technologies have been invented to overcome such inherent problems in optically amplified transmission systems [30].

The transmission of optical signals in an optical communication system may be limited by optical effects such as chromatic dispersion. Optical signals may be transmitted as pulses of light in an optical fiber. When light propagating within an optical fiber undergoes chromatic dispersion, the light is delayed within the optical fiber. The delay causes spreading of the light pulses, which may affect the performance of the system. The specific amount of dispersion that an optical signal undergoes varies depending upon the wavelength of the optical signal. The extent to which dispersion varies as a function of light wavelength is often

referred to as dispersion slope. Various dispersion management techniques have been used to reduce dispersion and to manage dispersion slope by reducing dispersion at individual channel wavelengths. Dispersion management is particularly important in wavelength division multiplexed (WDM) optical communication systems transmitting multiple channels at multiple wavelengths.

Dispersion can be minimized when the signals are placed symmetrically around the fiber's zero-dispersion wavelength $\lambda_D = 0$, but then FWM will increase and severely degrade system performance. Since higher dispersion will eliminate FWM, therefore, two solutions to suppress FWM include: 1) placing all wavelengths away from, and on only one side of $\lambda_D = 0$: and 2) utilizing alternating fiber segments with positive and negative dispersion values in a dispersion-managed system in which there is always an absolute dispersion value exists along the link, but the total accumulated dispersion is 0. In both these cases, each WDM channel accumulates a different amount of dispersion because of the spectrally dependent dispersion slope of the fibers. Additionally, each channel experiences SPM/XPM which interacts with the GVD, resulting in further degradation. To combat dispersion and nonlinearities, each WDM channel can separately be either pre-compensated, post-compensated or dual-compensated (using a combination of pre and post-compensation) in total accumulated dispersion [31].

1.2.1 Origins of Nonlinearities

A number of nonlinearities arises in the optical fibers which are the causes of the various unwanted effects in the optical fiber.

1.2.2 Optical Kerr Effect

The optical Kerr effect or AC Kerr effect is the case in which the electric field is due to the light itself. This causes a variation in index of refraction which is proportional to the local irradiance of the light. This refractive index variation is responsible for the nonlinear optical effects of self-focusing and self-phase modulation. This effect only becomes significant with very intense beams such as those from lasers. In fact, phase modulation due to intensity dependent refractive index induces various nonlinear effects, namely, self-phase modulation (SPM), cross-phase modulation (CPM), and four-wave mixing (FWM).

1.2.2.1 Self Phase Modulation (SPM)

Phase modulation of an optical signal by itself is known as self-phase modulation (SPM). SPM is primarily due to the self-modulation of the pulses. Generally, SPM occurs in single-wavelength systems. At high bit rates however, SPM tends to cancel dispersion. However, consideration must be given to receiver saturation and to nonlinear effects such as SPM, which occurs with high signal levels. SPM results in phase shift and a nonlinear pulse spread. As the pulses spread, they tend to overlap and are no longer distinguishable by the receiver. The acceptable norm in system design to counter the SPM effect is to take into account a power penalty that can be assumed equal to the negative effect posed by XPM. By the SPM-impact new spectral components are generated in the optical signal spectrum resulting in a spectral broadening.

1.2.2.2 Cross Phase Modulation (XPM)

Cross-phase modulation (XPM) is a nonlinear effect that limits system performance in wavelength Division Multiplexed (WDM) systems. XPM is the phase modulation of a signal caused by an adjacent signal within the same fiber. XPM is related to the combination (dispersion/effective area). XPM results from the different carrier frequencies of independent channels, including the associated phase shifts on one another. The induced phase shift is due to the walkover effect, whereby two pulses at different bit rates or with different group velocities walk across each other. As a result, the slower pulse sees the walkover and induces a phase shift. The total phase shift depends on the net power of all the channels and on the bit output of the channels. Maximum phase shift is produced when bits belonging to high-powered adjacent channels walk across each other.

1.2.2.3 Four Wave Mixing (FWM)

FWM can be compared to the intermodulation distortion in standard electrical systems. When three wavelengths ($\lambda 1$, $\lambda 2$, and $\lambda 3$) interact in a nonlinear medium, they give rise to a fourth wavelength ($\lambda 4$), which is formed by the scattering of the three incident photons, producing the fourth photon. This effect is known as four-wave mixing (FWM) and is a fiber-optic characteristic that affects WDM systems. The effects of FWM are pronounced with decreased channel spacing of wavelengths and at high signal power levels. High

chromatic dispersion also increases FWM effects. FWM also causes interchannel cross-talk effects for equally spaced WDM channels.

1.2.2.4 Stimulated Scattering

When light is incident on material it undergoes various scattering process. Most of the scattering is elastic, and the scattered wave has the same frequency as the incident wave. However, this scattered light is, in general, at some arbitrary angle to the forward direction of propagation. Hence, if one measures the transmitted light in the forward direction, there is a reduction in intensity as a result of the scattering into other directions. This loss is known as Rayleigh scattering loss. The frequency shifts can be small (approximately 1 cm^{-1}) or large (greater than 100 cm^{-1}). When the frequency shift is small, the process is known as Brillouin scattering. The larger frequency shifts characterize the regime of Raman scattering. Stimulated Brillouin scattering (SBS) is due to the acoustic properties of photon interaction with the medium. When light propagates through a medium, the photons interact with silica molecules during propagation. The photons also interact with themselves and cause scattering effects such as SBS in the reverse direction of propagation along the fiber. In SBS, a low-wavelength wave called Stoke's wave is generated due to the scattering of energy. This wave amplifies the higher wavelengths. The gain obtained by using such a wave forms the basis of Brillouin amplification. The Brillouin gain peaks in a narrow peak near the C-band. SBS is pronounced at high bit rates and high power levels. The SRS refers to lower wavelengths pumping up the amplitude of higher wavelengths, which results in the higher wavelengths suppressing signals from the lower wavelengths. One way to mitigate the effects of SRS is to lower the input power. In SRS, a low-wavelength wave called Stoke's wave is generated due to the scattering of energy. This wave amplifies the higher wavelengths. The gain obtained by using such a wave forms the basis of Raman amplification. The Raman gain can extend most of the operating band (C- and L-band) for WDM networks. SRS is pronounced at high bit rates and high power levels.

1.2.3 Dispersion Compensation in Optical Transmission Lines

Depending on the place and realization where the dispersion compensation is made in a system, it can be distinguished between three compensating methods: a) pre-chirp techniques

at the transmitter side b) dispersion compensation in the transmission line (inline compensation) and c) dispersion compensation at the receiver side (Fig. 1.7).

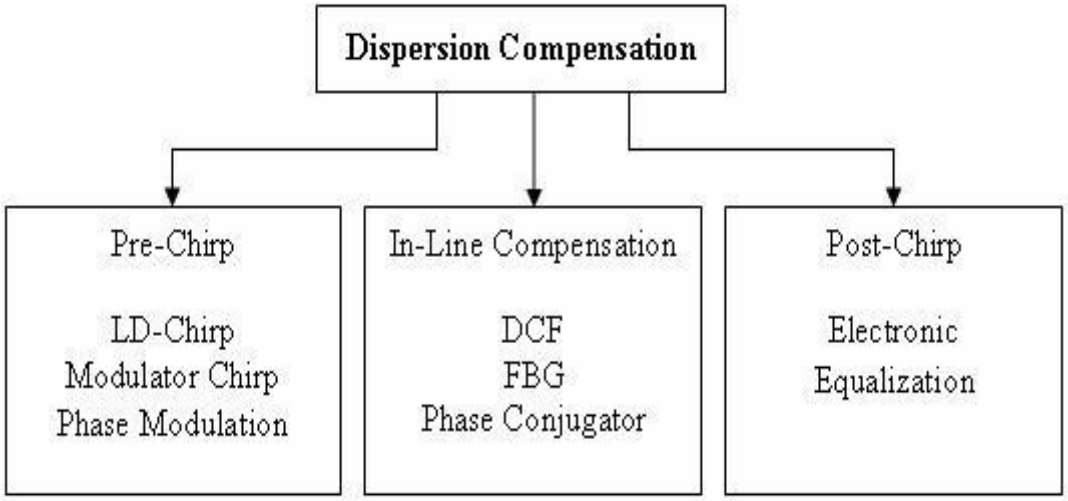


Figure 1.7: Dispersion compensation methods

The idea behind the pre-chirping at the transmitter side is the implementation of chirp with the opposite sign to the fiber chirp in order to counter the GVD effects in the fiber. The main implementation area of this technique is cost effective, optical short-reach systems (e.g. MANs) with smaller channel bit rates, but in combination with other dispersion compensation techniques (e.g. in-line compensation) it can enable a performance improvement even in high-bit rate transmission systems over long distances [32]. In-line dispersion compensation represents the key enabling technology for the realization of long-haul transmission systems. The dispersion compensation is realized in the optical domain without electro-optical conversion of the signal, enabling better compensation of the signal because the optical phase is maintained. The post-chirp techniques at the receiver side are characterized by the compensation of the chromatic dispersion in electrical domain. This compensation method is cost effective, and in combination with in-line compensation, enables an enhanced transmission performance.

1.2.3.1 In line Compensation Devices

Implementation of in-line compensation devices in the transmission line affects the transmission performance of the system because of the interaction of dispersion map with

transmission disturbances (e.g. ASE-noise, nonlinearities). The following dispersion compensating devices are used for the realization of in-line dispersion compensation:

Dispersion Compensating Fiber (DCF) represents the most widely used in-line dispersion compensation technique in today's transmission systems. The DCFs are characterized by a large negative dispersion and a small core diameter. The large negative dispersion values can be achieved by variation of the fiber profile by doping the fiber cladding (e.g. by fluorine), introducing an increase in the refractive index difference between the core and cladding. The demands on DCFs are a large negative dispersion (- 70-300 ps/nm), low insertion losses, low polarization dependent (PDL) losses, a low polarization mode dispersion (< $\sqrt{0.05}$ ps/km), a large effective area (A_{eff}) and a negative dispersion slope. The DCFs can be used for simultaneous compensation of several channels, but due to imperfections in slope compensation, a small amount of residual dispersion remains especially in outer channels.

Fiber Bragg Grating (FBG) modules are fabricated by implementing refractive index changes in the fiber core. The regions with different refractive indices are called gratings. Depending on the distance between the gratings known as grating period, which can be realized as constant or varying (chirped), the shorter wavelengths will be reflected before the longer ones. The consequence is pulse compression and dispersion compensation. FBGs represent a promising technology for the realization of dynamic dispersion compensation in tuneable dispersion compensators. The advantages of FBGs are large nonlinear tolerance and lower device loss. The main FBG drawback is an increased device complexity because of the implementation of optical circulators and large ripples in insertion losses (IL) and group delay (GD).

Phase Conjugator is utilizes the concept known as mid-span spectral inversion (MSSI). The principle of MSSI is the spectral inversion of the optical signal spectrum in the middle of the transmission span by applying an active component (e.g. semiconductor laser) or highly nonlinear fiber (e.g. nonlinear phase-conjugating mirror). The short wavelengths of the signal are interchanged with the longer wavelengths making use of a nonlinearity based phase conjugation. This concept enables a full compensation of dispersion and dispersion slope, but it is less practical for the implementation in the transmission systems because of its complexity. For the system used in this work, conventional DCF based compensation devices

are implemented because of the fact that they represent the state-of-the-art technology in today's optical communication systems.

1.2.3.2 Dispersion Compensating Schemes

Depending on the placement and the combination of in-line compensation devices in the transmission line, several different dispersion compensation schemes can be realized (Fig. 1.8). Common for all dispersion compensation schemes enabling the full dispersion compensation is that the compensation of the accumulated dispersion in the transmission fiber has to be performed according to the following rule:

$$D_{SMF}.L_{SMF} + D_{DCF}.L_{DCF} = 0 \tag{1.3}$$

WhereD_{SMF}, D_{DCF} are the chromatic dispersion values of transmission and compensating fibers, respectively, and L_{SMF}, L_{DCF} the lengths of these fibers. This rule can be fulfilled by placing DCFs in different positions within a transmission line. Typically, a transmission line consists of several cascaded spans. Depending on the realization of the span infrastructure, it can be distinguished between three basic dispersion compensation schemes: pre, hybrid and post-compensation figure (1.9).

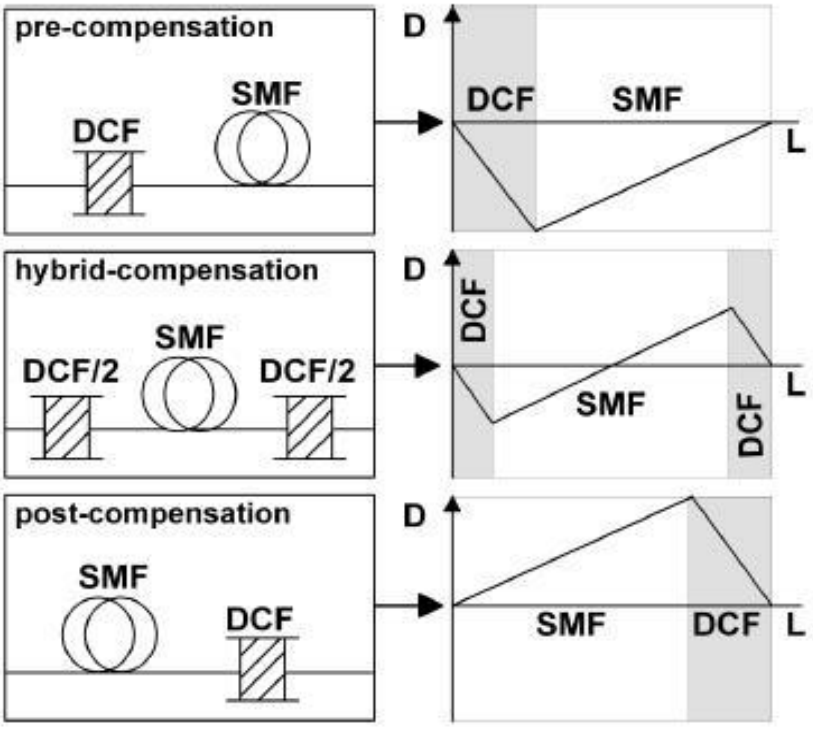


Figure 1.8: Various dispersion compensating techniques

In pre- and post-compensation the DCFs are placed before or after the SMF fiber. In hybrid-compensation 50% of the SMF dispersion is compensated before the SMF and the other 50% is compensated afterwards. The system behaviour can be quite different for the different schemes because of the influence of dispersion compensation on the linear and nonlinear effects. This influence varies for different channel data rates making a system upgrade becoming a critical issue.

The full dispersion post-compensation scheme provides full compensation and signal shape regeneration after each span. This scheme is interesting for the practical implementation because the optical signal form is maintained after each span and the signal can be easily accessed or detected. The nonlinear characteristics of this scheme are rather poor, because the walk-off between adjacent channels in the system vanishes after each span resulting in an increased impact and accumulation of inter-channel nonlinearities (e.g. XPM), depending on the local dispersion of the transmission fiber. The nonlinear tolerance of this scheme can be improved by implementation of the pre chirp at the transmitter side. A similar effect can be achieved by pre-compensation (under-compensation) of chromatic dispersion along the transmission line. Depending on the amount of under-compensation, the accumulated residual dispersion varies from span to span. The drawback of this approach is the necessity of additional or tuneable dispersion compensation at the end or within the transmission line, if some channel has to be dropped or switched. This can be critical in systems with higher channel bit rates (>10Gbps) because of a reduced dispersion tolerance.

A more exotic compensation scheme, are known as compact dispersion compensation or hybrid-compensation where dispersion compensation of the total accumulated system dispersion is realized directly after the transmitter and before the receiver. The advantage of this approach is that the impact of nonlinearities in the transmission line can be significantly suppressed, because the pulses are fully dispersed during propagation. This scheme is less relevant for the practical implementation, because the optical channels cannot be accessed within the transmission line.

The compensation of only β_2 (chromatic dispersion) alone is insufficient for the compensation of accumulated dispersion in high speed transmission systems, because of the existence of dispersion slope, which results in a wavelength dependent residual dispersion.

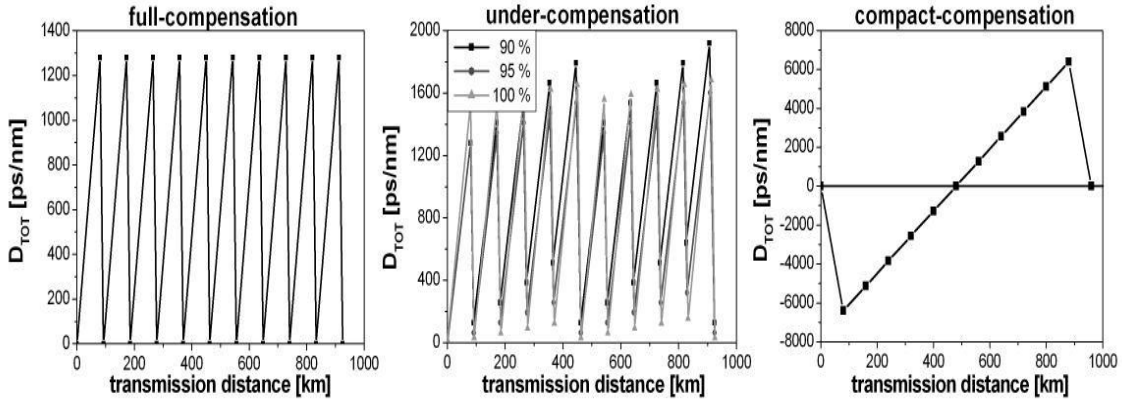


Figure 1.9: Dispersion compensation schemes in multi-span systems

Theoretically, the complete slope compensation could be realized if the DCF slope (S_{DCF}) can be tailored to:

$$S_{SMF}.L_{SMF} + S_{DCF}.L_{DCF} = 0 \qquad (1.4)$$

The fiber nonlinearities like SBS (Stimulated Brillouin Scattering) and SRS (Stimulated Raman Scattering) also put the limitation on the input power up to a threshold value. Because the optical waveguides do not always behave as completely linear channel whose increase in output optical power is directly proportional to the input optical power [9]. The nonlinearities produces the effects which in case of scattering cause disproportionate attenuation, usually at high power levels. This effect causes the optical power from one mode to be transferred in either the forward or backward direction to the same, or other modes, at a different frequency. It depends critically upon the optical power density within the fiber and hence become significant above threshold power levels. It causes the distortion in the information with increase in input power.

1.3 Objectives of the thesis

The various objectives are discussed below.

. To study the effects of the variation of PMD on the system performance in terms of eye opening, eye closing and electrical power, Q factor and BER.

. To analyze different PMD compensation techniques such as pre- and post-compensation techniques. To analyze the effect of using the emulator before and after transmission.

. To investigate bit error rate (BER) performance of PMD with fiber channels that how the BER varies with the variation of the PMD.

· To analyst the equivalent Q factor of the system with PMD. As the PMD increases the equivalent Q factor decays

· To analyze the effect of the PMD on the system with the help of eye diagrams. The eye becomes closure as the output of the system decreases. This shows that the output decrease due to the effect of the PMD. When the eye is maximum open then that means the output is maximum. This is at 0 PMD and the eye is maximum closed at maximum PMD, in our simulation part we take maximum PMD is 10 ps/$\sqrt{km}$.

· To analyze the effect of the PMD on the electrical power at the output of the system.

These objectives can be shown and discussed in chapter 3 and 4 for different compensation techniques.

1.4 Thesis Organization

This chapter includes the brief introduction to the optical communication with brief history about the basics of PMD i.e. what are its causes, its effects, how we measure PMD and how we compensate it by different compensation techniques. In chapter 2 we have approximately discussed 17 papers and discuss what schemes can be used for the PMD compensation and now how we compensate PMD by using these techniques. In chapter 3, we have discussed about system modeling in the optsim. Here we make a model of a PMD compensator system by using polarization emulator for four channels at different bit rates. We have analyzed the results by using delay or after applying PMD emulator. In chapter 4, we studied the different compensation techniques and how we apply them on the first order compensation of the PMD. This chapter shows the different compensation schemes on compensation of polarization mode dispersion. This chapter also shows the compensation of ordering of the PMD and shows the effect of the PMD on the various parameters of the system. Finally the fifth chapter gives the conclusion of the thesis work.

Chapter 2

LITERATURE REVIEW

The polarization related and nonlinear impairments have become a major obstacle to increase the transmission rates in WDM systems. The work done by different authors is reviewed is given below.

2.1 Polarization Mode Dispersion

G.J. Foschini and C. D. Poole [33] gave their ideas towards the small deviations from perfect circular symmetry in the core region of single mode fibers cause the optical pulses to become broadened as they propagate and causes inter symbol interference. They had also identified the three dimensional polarization vectors and characterize the polarization effects in narrowband sources. They specify the solution of Poole's stochastic dynamical equation for the evaluation of the polarization dispersion vector with fiber length. Their work represented a close interplay of theory with experiment and simulation. They determined the properties of the three components of the dispersion vector, probability density of the components of the derivative of the dispersion vector, relative strength of the first order and second order effects and the square root of the fiber length dependence on the magnitude of the dispersion vector.

Daniel Mahgerefteh, Curtis R. Menyuk [34] dealt with the effect of first order PMD compensation on pulse broadening in the fiber with randomly varying birefringence. They had shown the demand of bandwidth of higher bit rates in older installed fibers where PMD is a limiting factor. PMD in standard telecommunication fibers can be compensated to first order by using the concept of principle state of polarization. At the receiver the pulse is decomposed into two waveforms polarized along the two principle states for the optical link and their delay is removed. Compensation sharpens the probability distribution function of the pulse duration by a factor that decreases with increasing polarization dispersion. They also shows that the small randomly varying birefringence of fibers tends to depolarize optical signals and randomize their phase.

M. Wegmuller, S. Demma, C. Vinegoni and N. Gisin [35] analyzed the impact of first and second order polarization mode dispersion, they also found that the principal states vectors can lead to important fluctuations around the mean penalties induced by the first

order PMD. They found that the approaches which try to mimic a standard fiber as closely as possible; the emulator presented gives constant but user adjustable values for differential group delay (DGD) and the ratio of first to second order PMD. Once it is set, the ratio is conserved while the DGD can be easily varied within the range of 0-300 ps. This allows investigating the low probability events of large DGD and second order PMD important for system outage.

According to the paper given in [36], Ling-Wei Guo, Ying-Wu Zhou, Zu-Jie Fang gave their ideas towards the pulse broadening of optical signals in a single mode fiber was studied theoretically in presence of PMD, PDL, Chromatic dispersion and spectral chirping. Analytical expressions were derived for the parameters of the pulse broadening characteristics without simplification assumption w.r.t. the pulse shape and to the order of dispersion. Analysis and simulation shows that it is compatible with the previous theories and more capable of dealing with pulse broadening and distortion in complicated cases, which is the key problem in the high speed optical communication networks. They also found the effect of polarization dependent loss (PDL) in the exploration of polarization mode dispersion.

Andrew J. Stark, Yu-Ting Hsueh, Steven Searcy, Thomas F. Detwiler,, Cheng Liu and Mark M. Filer in [37] analyzed a nonlinear penalty threshold that contains the total nonlinear phase shift is examined as a criterion for scaling fiber optic links. We investigate 112 Gb/s PDM-QPSK hybrid optical networks consisting of either TrueWave (G.655) or All- Wave (G.652) fiber. We establish experimental and simulation environments with robust absolute matching in both linear and nonlinear regimes. We identify both XPM and SPM penalties in 0% and 100% inline dispersion compensation schemes for the two different fiber types. Both experimental and simulation results reveal that 0% inline-compensated links operate with larger nonlinear threshold for increasing span count and readily yield simple design rules.

Md Zaini Jamaludin, Ahmad Fauzi Abas, Ahmad Shukri Muhammad Noor and Mohamad Khazani Abdullah in [38] analyzed the first and second order PMD characteristics. They found that a pulse spread of up to 15% of the pulse width is allowed depending on the receiver sensitivity penalty tolerated the system. PMD measurement is also discussed considering Interferometric, Jones- Matrix Eigen analysis (JME) and Fixed Analyzer techniques, from the perspective of field and laboratory applications. They performed the simulation based on realistic parameters of a fiber optic link and the results show that at a 40

Gbps transmission rate, a fiber optic with a PMD coefficient of 0.5 ps / km can only support up to a 10 km distance.

Sonja Zentner Pilinsky, Zvonimir sipus, and Lubomir Sumichrast described in [39] that Polarization mode dispersion (PMD) occurs in the optical fibers due to circular asymmetries of the fibers core. In the paper, they gave the mathematical description of PMD and some simulations examples of PMD's deleterious impact on high bit-rate transmission systems. PMD can be described locally as fibers birefringence and globally, the birefringence is combined with random polarization mode coupling. They have demonstrated the deleterious effect of PMD on high bit-rates through the simulation. The solution to PMD problem is either to install new, fibers with low PMD, or to try to compensate PMD on already installed fibers.

In [40] G.P Aggarwal provides the background material and the mathematical tools needed for understanding the various nonlinear effects. Starting from the Maxwell's equation, the wave equation in a nonlinear dispersive medium is used to discuss the fiber modes and to obtain the basic propagation equation. The main effect of GVD and dispersion induced broadening is also explained in detail. This book also explains the nonlinear phenomenon of SPM occurring as a result of intensity dependence of the refractive index. Study of higher optical solitons is introduced together with the inverse scattering method used to solve the nonlinear Schrödinger equation. Also focus other nonlinear effects such as XPM, SRS, and SBS. During the description of theory SBS Dr. Aggarwal describes the important features such as the brillouin threshold, pump depletion, and gain saturation.

Fan Zhang, Christian A. Bunge, Klaus Petermann and Andre Richter [41] has presented a numerical study of the performance of 40 Gbps return-to-zero differential phase-shift keying (RZ-DPSK) transmission with different dispersion maps. The optimum dispersion mapping for RZ-DPSK format are discussed and compared with those for on-off keying (OOK). Two pseudo-linear transmission systems, one using standard single-mode fiber and the other nonzero dispersion-shifted fiber, are investigated, respectively. IFWM-induced optical signal-to-noise ratio (OSNR) penalty in RZ-DPSK systems with different dispersion maps by considering nonlinear phase noise – which cannot be studied in terms of OSNR penalty by estimating the bit error rate (BER) via a semi-stochastic method based on the numerical solution of the nonlinear Schrodinger equation.

Ruben S. Luís, Daniel Fonseca, António Luís Jesus Teixeira, and Paulo Monteiro in [42] presented an alternative approach to minimize the impact of fiber nonlinearities in optical single-sideband systems at 10 Gbps using electrical dispersion pre-compensation by adding optical post-compensation while maintaining low accumulated dispersion. Numerical simulation had been used to show that the dependence of the system performance on the dispersion compensation scheme resembles a pseudo linear transmission regime, although it is not considered as such in the strictest sense. A launched power increase of 3 dB is achieved when compared to full electrically pre compensated systems. A feasible implementation of the optical transmitter is considered, which imposes a maximum transmitted modulation depth. It is reported by them that low modulation depths result in an asymmetric optimum dispersion compensation map.

L.S. Yan, Q. Yu., A.E. Willner, X. Steve Yao [43] gave their ideas towards the compensation of higher order polarization mode dispersion using polarization controller This paper demonstrated the higher order polarization mode dispersion compensation scheme using a polarization controller and phase delay after transmission through the fiber as well as traditional first order compensator at the receiver. The effectiveness of this approach is experimentally demonstrated for 10 Gbps NRZ transmission link of an averaged PMD of 50 ps. After first order PMD compensation, the residual power properties due to higher order effects no longer have any correlation with the link first order PMD whereas the penalties strongly correlated to the second order link PMD.

T. Merker, N. Hahnenkamp, P. Meissner [44] showed the comparison of PMD-compensation techniques at 10 Gbps Using an Optical First-Order Compensator and Electrical Transversal Filter in their paper. This paper present, for what is believed to be the first time, a direct comparison of two basically differently working polarization mode dispersion compensation techniques, the first-order compensator working in optical domain and an adjustable transversal filter working in electrical domain. Based on numerical simulations we show the efficiency of both equalizers in presence of first- and higher order PMD applying a transmission at 10 Gbps. Furthermore they showed the applicability of spectral filtering for penalty signal extraction in presence of higher order PMD and give an overview of adaptive blind channel equalization.

R.Gowri Manohari and T.Sabapathi [45] deals with the effects and compensation of Polarization Mode Dispersion (PMD), which has found to be a considerable attention in high data rate systems, now-a-days. In general, a small amount of PMD is to be considered in high data rate systems, since it limits the data rate. Unlike the chromatic dispersion phenomenon, the PMD is found to be a time varying and an unstable phenomenon. Thus compensation of PMD is required since it distorts the signal and broadens the pulse in a statistical manner. In this paper we analyze the PMD effects by varying the length and birefringence of the fiber and compensate the effect of PMD using the OPTSIM simulation for 10, and 40 Giga bits per second (Gb/s) transmission systems. Here the Compensation of PMD is done by an optical compensation method called Deterministic Differential Group Delay (DDGD) and the results have been simulated and analyzed.

Chapter 3

SYSTEM MODELING OF PMD

Optima are a high-end optical system simulator for professional engineering and cutting-edge research of WDM, CATV and other emerging optical systems. OptSim is designed to combine the greatest possible accuracy and modeling power along with extreme ease-of-use on UNIX and Windows NT operating systems. OptSim includes the latest simulation algorithms to guarantee the highest possible accuracy and real-world results.

Optima include the most commonly used components for the engineering of electro-optical systems, with particular emphasis on WDM and digital CATV systems. It also supports innovative optical approaches such as quasi-RZ and dispersion-managed soliton systems. This component library is in a state of continuous improvement through on-going research performed in exclusive cooperation with world class simulation specialists at the Polytechnic University of Turin and other major optical technology centers.

We can generate an external executable, using any program language like C, C++, FORTRAN, Pascal, etc. that models your own component. During simulation OptSim will exchange signals using the documented OptSim signal format. OptSim is a stand-alone product that comes with a Windows-like user interface and on-line HTML help. You do not need additional tools or expensive frameworks to realize the full power of OptSim. OptSim is extremely easy-of-use, allowing non-experts to set up the most complex simulations in a matter of minutes by using drag-and-drop icons and editing parameter values for each component.

OptSim is exclusively developed, marketed, and supported worldwide by RSOFT Design Group, and entirely focused on productivity tools for telecom and datacom engineering and components. OptSim 3.5-1 goes forward allowing the fully featured OptSim-MATLAB co-simulation. This tool functionality is supported by the inclusion of the CCM, the Custom Component for MATLAB co-simulation: users can write their own MATLAB routine, define it as a CCM and then run it within an OptSim simulation. Custom Component for using with MATLAB (CCM) is a special OptSim component whose behavior during the simulation is described by an external MATLAB routine.

Polarization mode dispersion has emerged as a key limitation at 10 Gbps and 40 Gbps systems that use even the newest types of fibers due to none zero PMD. Moreover, the system degrading effects caused by PMD are characterized as random stochastic processes that change with many environmental effects. So, it becomes necessary to compensate the effects of the polarization mode dispersion (PMD). We can make a setup in OptSim (software of optical fiber communication) to compensate the PMD occurs in the fiber during transmission. This setup can be shown below and some information about the components which can be used in this setup can be explained below.

3.1 Simulation Setup for PMD Variation

The figure (3.1) shows the structure for the analysis of PMD variation in optical link having 4 channels. The PMD is varied in four steps from 0 to 180 $ps/\sqrt{km}$. The transmitter and receiver section are connected by the dispersive fiber link. The transmitter section consists of data source, modulator driver, laser source and modulator. Data source produces a pseudo-random sequence of bits at a rate of 2.5 Gbps. The output of data source is given to modulator driver which produces a NRZ (Non return to zero) format pulse train. The transmitted signal is formed by modulating the light carrier by the NRZ data source. The light carrier is generated by Lorentzian laser source at the 1550 nm wavelength.

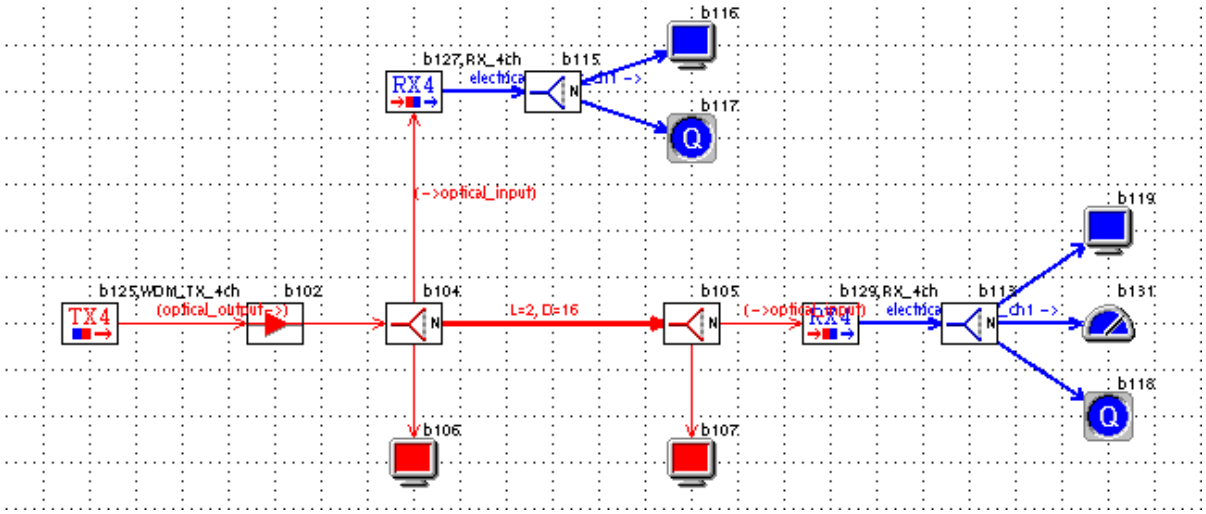


Figure 3.1: Simulation Setup for PMD variation effects.

The transmitter output is boosted up by the fixed gain Erbium Doped Fiber Amplifier (fixed_output_power). There are two types of optical amplifiers; Semiconductor Optical Amplifier (SOA) and the Erbium Doped Fiber Amplifiers (EDFA). Due to its high gain characteristics EDFA are used these days. The shape of the gain graph is flat having a gain of 25 dB. The noise figure value is set at 4.5 dB. The transmission medium used is a standard single mode fiber (L=2, D=6) of 2 km length. The receiver used is the system is the PIN (Receiver, PIN) receiver, which uses the PIN (p-intrinsic-n) diode as a detector. The pin photodiode simulated had 70% quantum efficiency. The dark current was simulated at 0.1 nA. The output of the receiver is given to the measurement devices which are fed through the electrical splitter, the electrical scope and the Q estimator. The optical spectrum of the signal is observed from optical spectrum analyzer (input and output) by splitting the signal from fiber link with the use of optical splitters. To analyze the effects due the variation of PMD on the specified parameters, the PMD is taken as global parameter.

3.1.1 Results and Discussions

The figures shown below are the results obtained for the different values of Polarization Mode dispersion for channel number 4.

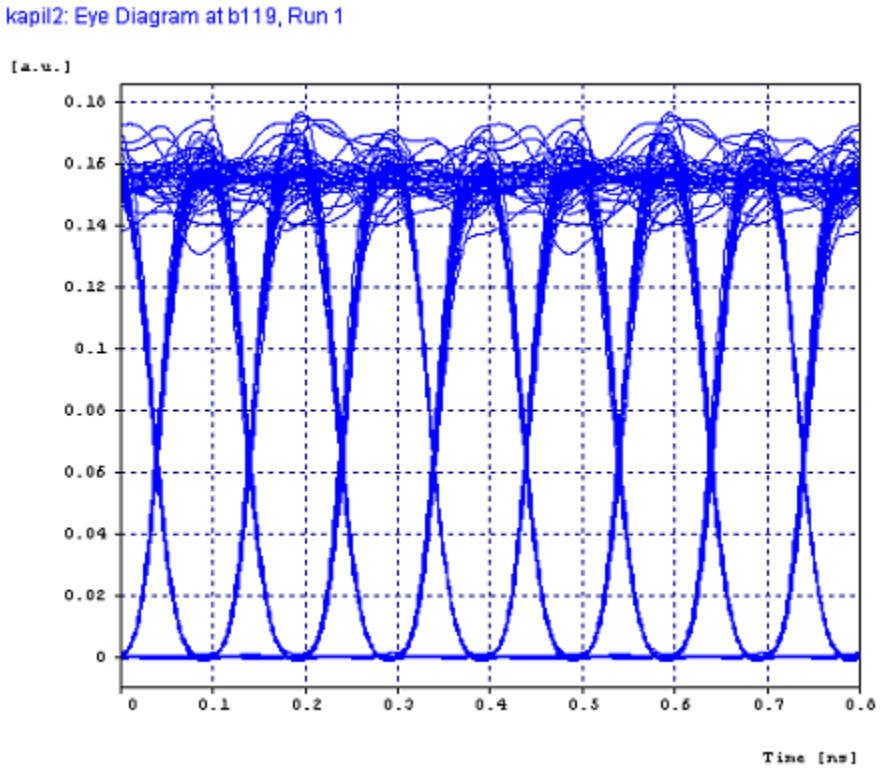


Figure 3.2: Eye Diagram at PMD= 0 $ps/\sqrt{km}$

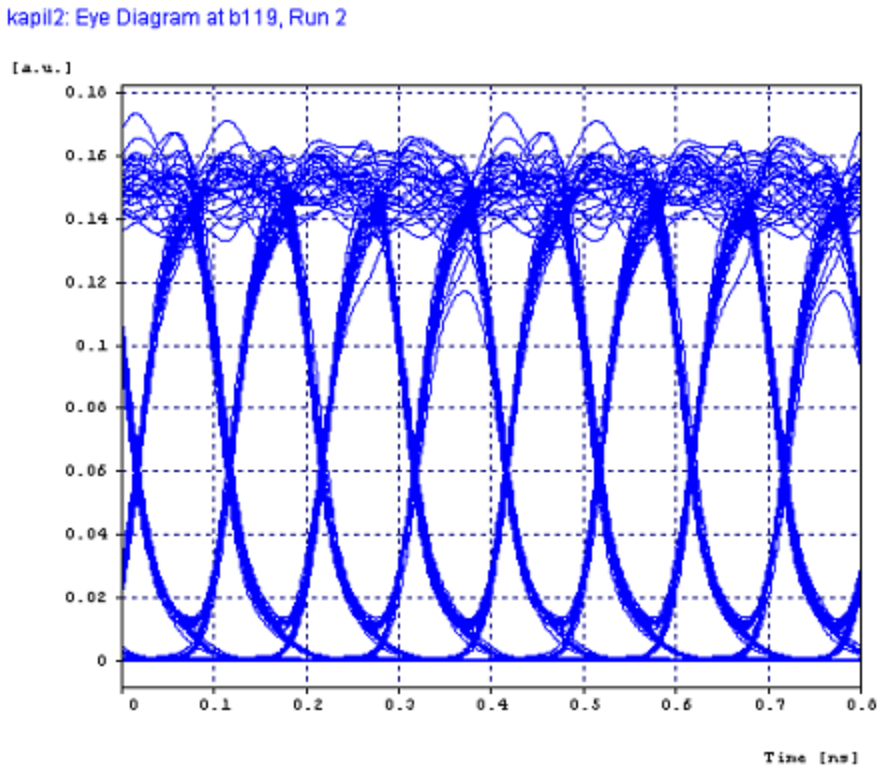


Figure 3.3: Eye Diagram at PMD= 60 ps/√km

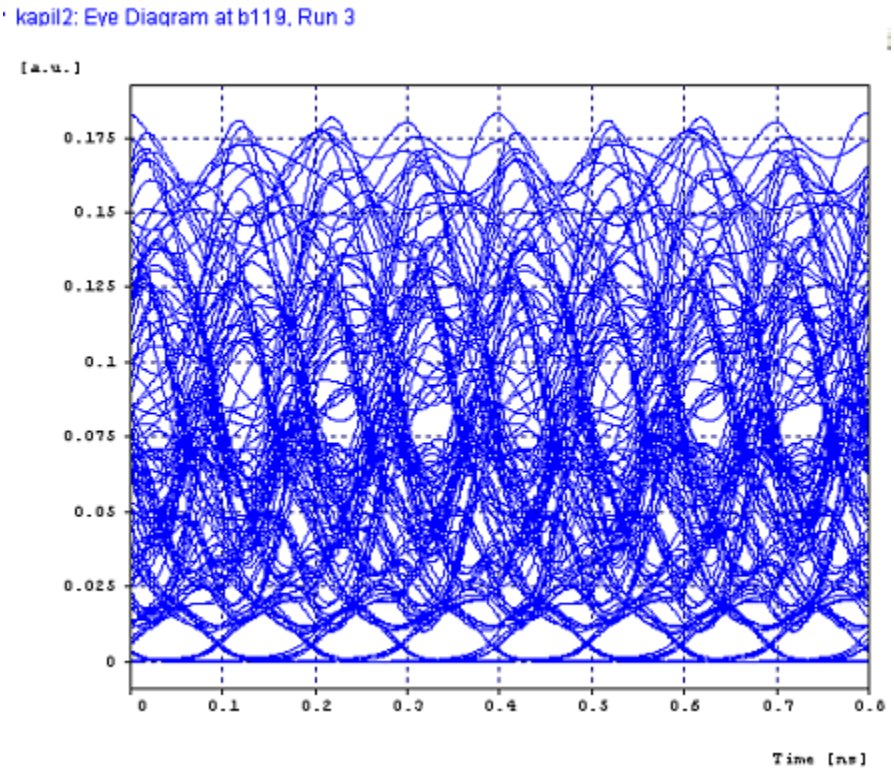


Figure 3.4: Eye Diagram at PMD= 120 ps/√km

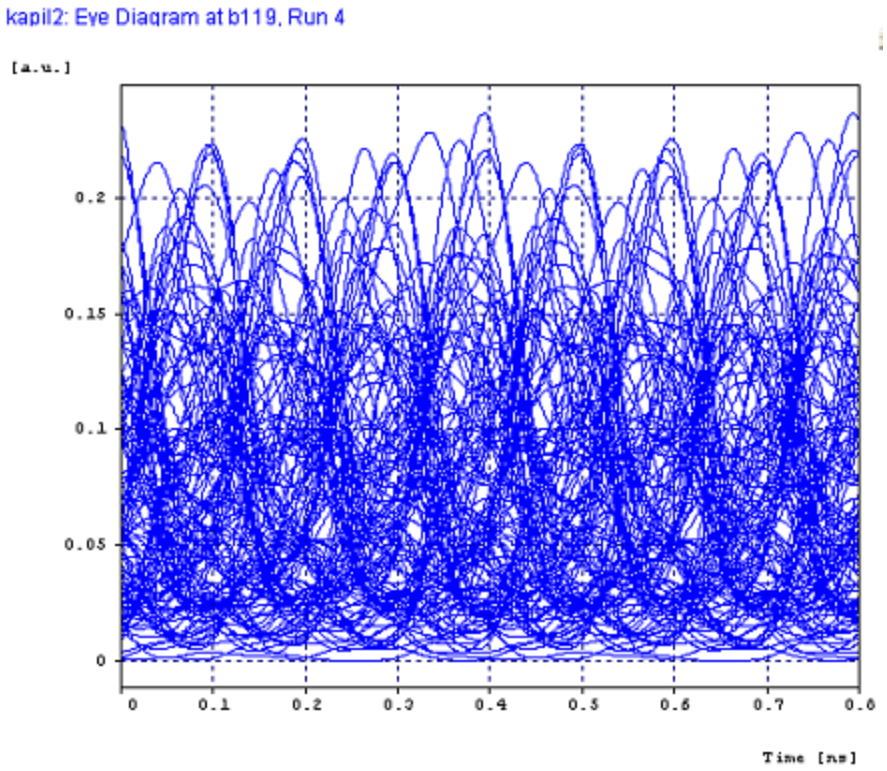


Figure 3.5: Eye Diagram at PMD= 180 ps/√km

This means that the performance of the system is getting weakened as the PMD increases. Further the figure 3.6 shows the Q value at the corresponding values of PMD. The figure 3.7 shows the value of eye opening at the corresponding values of PMD. The figure 3.8 shows the value of eye closure at the corresponding values of PMD. Fig 3.9 shows the value of electrical power at the corresponding values of PMD.

In further figures the values of the earlier described parameters i.e. eye opening, eye closing and power evaluation are plotted. The plots show that PMD effects do not follow a particular trend.

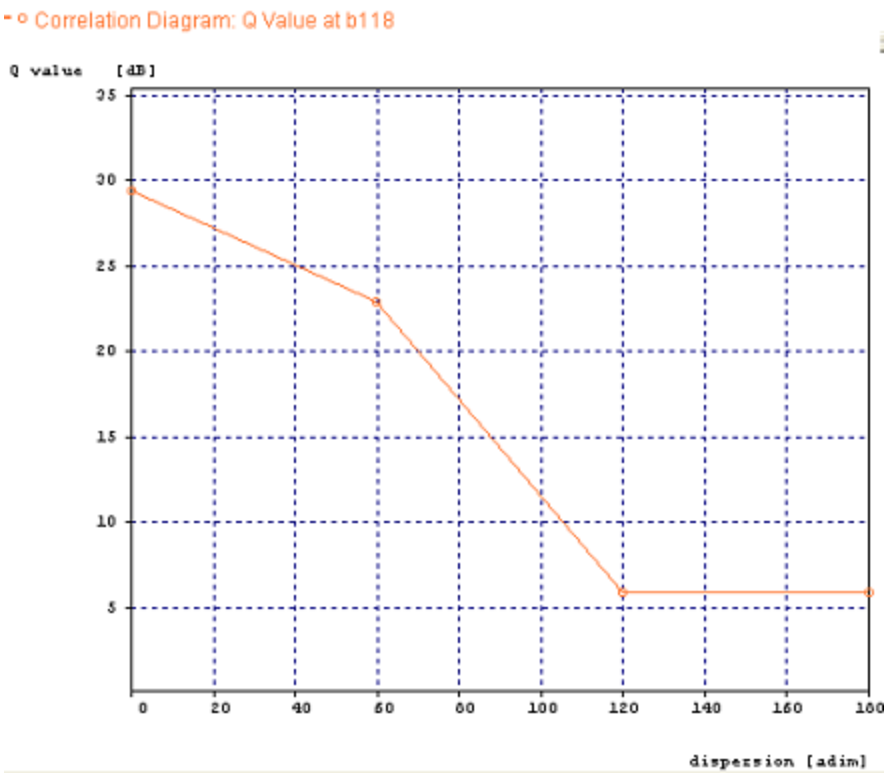


Figure 3.6: Q Value at Different values of PMD

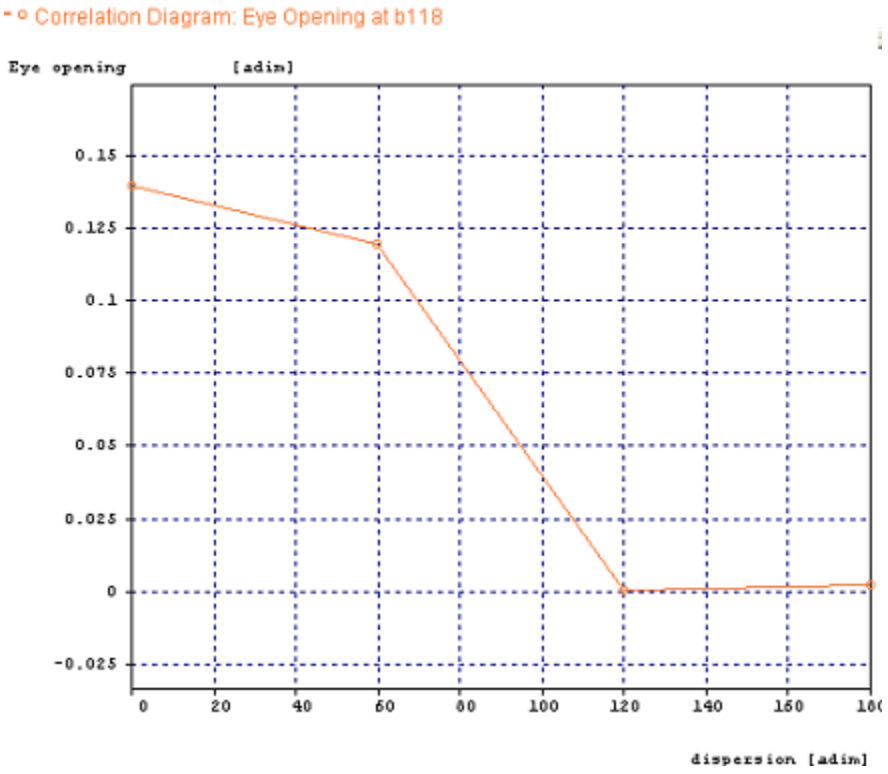


Figure 3.7: Eye Opening at Different values of PMD

Figure 3.8: Eye Closure at Different values of PMD

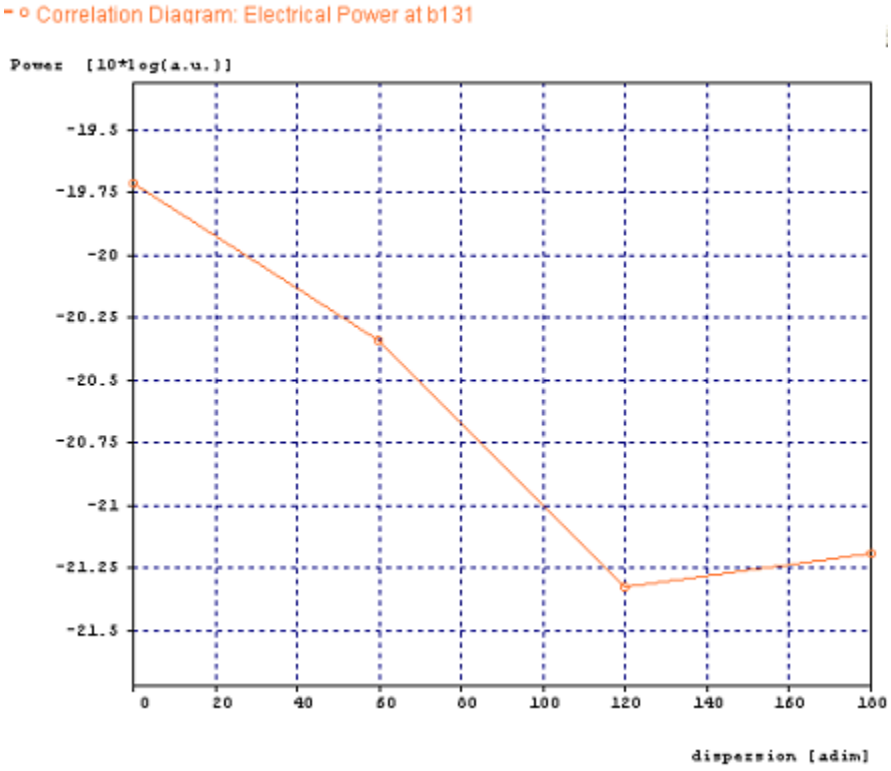


Figure 3.9: Electrical Power at Different values of PMD

The figures (3.6 to 3.9) describe the variation of the important parameters due to the variation in PMD. It is observed that eye opening decreases slowly as PMD increases from 0 to 60 ps/√km . After the PMD value of 60 ps/√km , the eye opening decreases up to minimum value at 120 ps/√km. After the PMD value of 120 ps/√km, the eye opening remains almost constant upto 180 ps/√km. The adverse impact of PMD variation over power is also observed in figure (3.9). At 0 PMD power is -19.6 dBm and it is reduced to -21.35 dBm at120 ps /√km . But a rise is seen as PMD goes to 180 ps /√km to the power - 21.20 dBm.

3.1.2 Conclusion

The effect of changing the value of PMD for four channel is reported in this objective. This effect is seen from the eye opening, eye closing and output power characteristics. The above discussed results show that the behaviour of PMD becomes unpredictable at higher values of PMD. It is reported that up to the PMD value of 120 ps/√km , the value of eye opening and output power decreased. It is studied that any further increase in value of PMD causes the great fluctuations in the characteristics of the measured parameters.

3.2 Simulation set-up for compensation of PMD

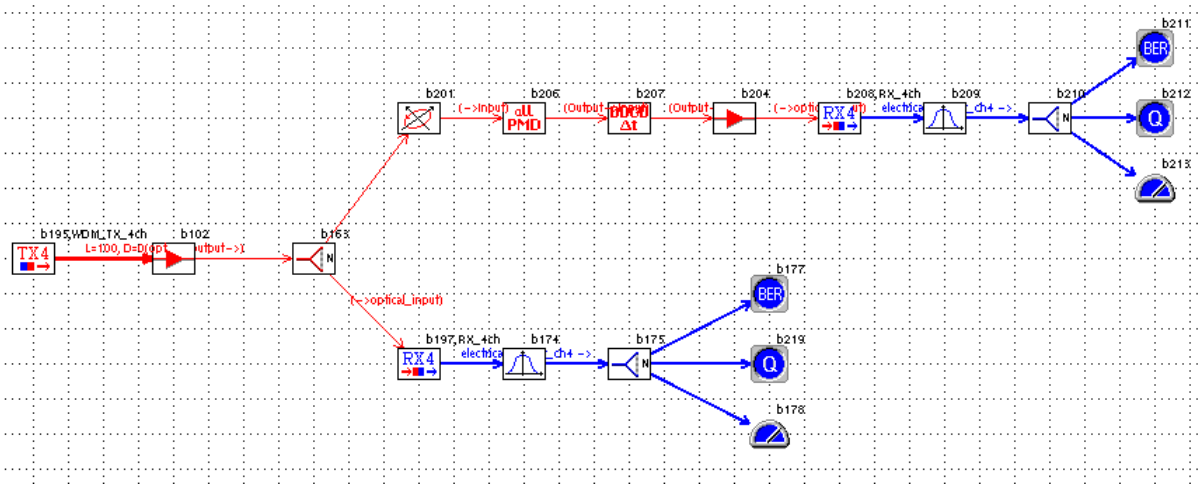


Figure 3.10: A NRZ simulation setup for PMD compensation using PMD emulator and VDGD: Variable Differential Group Delay with an average PMD of 10 ps. VDGD (Variable Differential Group Delay)

The above set-up can be obtained by choosing the desired components from the component library. The component can be taken by double clicking the component on the library and then place that component on the design area. Place the desired components in an order and the join them by the fibers

Choose the desired parameters of the different components by clicking right on the component. After making the set-up we have to check that weather there is any error in choosing the parameters or the system is ok. This can be checked by the VBS check and the SPT check. After checking the system data can be displayed through the data Display.

Various components which can be used are explained below:

Data Source

In this experimental set-up b195 shows the data source. This component simulates a pseudo-random or a deterministic logical signal generator. Baud rate, sequence length and logical signal level (number of bits per symbol) can be customized. When the logical signal level is greater than 1, the generated serial sequence is loaded into the output logical signal after a serial-to-parallel conversion. Here we use pseudo-random sequence. We can use bit rate from 2.5 Gbps to 10 Gbps and find that as the bit rate increases our PMD increases.

The period length of the corresponding pseudo-random sequence is 2*D*-1 bits, where *D* is the degree set by the Degree parameter. You can also specify an automatic evaluation of the polynomial degree by means of:

$$D=\frac{log_{10}(N_b+1)}{log_{10}2}$$

where *Nb* is:

$$N_b = int(T_{sim}.R_b)$$

T_{sim} is the total simulated time span (it is a global simulation parameter) and $R_b$is the actual bit-rate (the value displayed by the Corresponding Simulated Bit- Rate parameter)

Bit Edge with respect to simulation start time [bit fraction] [-]: when the deterministic option is selected, it is the shift of the bit edge with respect to the simulation start time. This shift is expressed as a fraction of the bit time (Edge/T). *Allowed values*: min 0; max 1; default 0 (if the Deterministic option is selected).

Starting Point: it sets how is selected the first bit of the simulation, between the pseudo-random sequence bits.

Random: the first bit of the simulation is randomly selected. This option is useful when several data sources are used in the same project, like in WDM systems, in order to ensure statistical independence of the used pseudo-random sequences. Deterministic: the first bit of the simulation is selected inside the chosen pseudorandom sequence giving the Starting point in the sequence parameter.

Laser Source

In this set-up b195 shows the Laser Source. This component simulates a laser. The output state of polarization is aligned with the geometrical *x*-axis, so as to be compatible with the other components such as the Polarization Rotator and the Polarization Modulator. Three models have been implemented:

· a simple model considering only the phase noise (CW Lorentzian Laser)

· a realistic model based on rate equation integration (Rate Equation Laser)

· an advanced model based on rate equation integration (VCSEL), taking into account the non-uniform distribution of the carriers in the VCSEL cavity and the temperature effects

·a realistic model based on rate equation integration for Separate Confinement Heterostructure Multi Quantum Well lasers (SCH-MQW) where physical parameters of the laser can be obtained with a fitting procedure over experimentally measured curves This model implements a simplified continuous wave (CW) laser. Laser phase noise is taken into account by generating a Lorentzian emission line shape whose FWHM (Full Width Half Maximum) is specified by the parameters. Two options are available for laser phase noise bandwidth: ideal (infinite bandwidth) or realistic (bandwidth-limited).

Laser Phase: sets the laser phase at the start of the simulation.

Random: the initial laser phase is randomly set. This option is useful when several lasers are used in the same simulation, like in WDM systems, in order to ensure a statistical randomization of the initial phases of the laser sources.

Deterministic: the initial laser phase is set by the Initial Laser Phase value. Initial Laser Phase [rad**]**: set the laser phase at the start of the simulation. *Allowed values*: min: 0; max: 2 ; default: 0 (if the Deterministic option is selected).

Laser Noise Bandwidth: sets the laser noise bandwidth.

. **Ideal**: infinite bandwidth phase noise.

. **Realistic**: bandwidth-limited phase noise. Phase noise is filtered using a two poles filter, therefore **Ralaxation Oscillation Peak Frequency** and **Ralaxation Oscillation Peak Overshoot** options are requested.

Driver

In this set-up b195 shows the driver. This component simulates an electrical driver. It converts logical input signal, a binary sequences of zeros and ones into an electrical signal. Several mapping laws are available, ranging from simple ones, such as NRZ and RZ rectangular shaped, to NRZ raised cosine, RZ raised cosine, RZ supergaussian and RZ soliton shaped pulses.

Signal Type and Shape: it opens the related dialog windows for the available models: NRZ Rectangular, NRZ Raised Cosine, RZ Rectangular, RZ Raised Cosine, RZ superGaussian and RZ Soliton.

Low Level [-]: it is the value of the output signal when a logical zero is transmitted. *Allowed values:* min -; max -; default 0.

High Level [-]: it is the value of the output signal when a logical one s transmitted. *Allowed values:* min -; max -; default +5.

This component simulates the NRZ raised cosine driver. As for the NRZ rectangular driver the output signal has two levels: one for ones and the other for zeros. Switching between the two levels is not instantaneous: it follows a raised cosine shape with a given roll-off.

The difference between this driver and the RZ raised cosine pulse driver lies in the fact that in the RZ modulation the signal is forced to return to the “0” level at the end of the each bit, also if there are two consecutive bits at the “1” level. The raised cosine waveform, when the driver is connected to a linear optical modulator, can shape either the optical amplitude or the optical power.

Polarizer

In this experimental set-up b201 shows the polarizer. This component simulates a polarizer, i.e. a component that allows to select a specific polarization of the input optical field,

blocking the orthogonal one. You can select the axis of the polarizer, i.e. the polarization that is allowed to pass through the polarizer, by specifying this polarization in the Stokes space representation. More specifically, you should specify the two angles 2α and2φ required to determine this polarization in the Stokes space using a spherical coordinate system (azimuthal and zenithal angles).

Azimuthal Angle of Polarizer Axis with Respect to Axis S_1 (2 alpha) [degrees]: the value of the azimuthal angle of polarizer axis over the Poincaré sphere. *Allowed values:* min -360; max +360; default 0.

Zenithal Angle of Polarizer Axis with Respect to the Equator (2 psi) [degrees]: the value of the zenithal angle of polarizer axis over the Poincarésphere. *Allowed values:* min -90; max +90; default 0.

Amplitude modulator

In this experimental set-up b195 shows the amplitude modulator. This module simulates a single input modulator. Two different models are available: linear and sin2 shaped Input-Output characteristics. The second transfer function is typical for the Mach-Zehnder external modulators based on the electro-optic effect in the LiNbO3 devices. For both models the chirping factor is included incorporating the parameter

This model implements a single arm Mach-Zehnder Amplitude Modulator with sin2 electrical shaped Input-Output P-V characteristic. This transfer function is typical for a Mach-Zehnder external modulator based on the electro-optic effects in the LiNbO3 devices. The input optical signal is multiplied by a factor dependent on:

. the input voltage *Vin* applied to the modulator arm

. the excess loss *ELdB* introduced by the modulator

. the extinction ratio *ERLIN*

. the chirp factor α

$$\alpha = 2P_{out}\frac{\frac{di}{dt}}{\frac{dP_{out}}{dt}}$$

Fiber

This component models the propagation of the optical signal along an optical fiber span. It is one of the fundamental and most complex components of the OptSim library. The non-linear Schrödinger equation governing the propagation of the optical field is integrated using "Time Domain Split-Step (TDSS)", an improved version of the well-known "Split-Step Numerical Method". Stochastic variations of all fiber characteristics and polarization related phenomena are taken into account.

Here we can use PMD fiber. We can turn ON the PMD of the fiber. We can also define the loss characteristics of the fiber. First and second order coefficients of the loss polynomial may be specified. It means that the function *dB(f)* is defined as follows:

$$\propto_{db}(f) = \propto_{0db} + \propto_{1db}(f - f_{0loss}) + \propto_{2db}(f - f_{0loss})^2$$

Where f_{0loss} is the reference frequency. You may specify the coefficient values or supply a description file. In the latter case the file must contain the profile of loss as a function of frequency or wavelength. This feature may be used, for example, to introduce data from measured results.

This component simulates an Erbium Doped Fiber Amplifier (EDFA). Several different models are available, ranging from simple ones, such as spectrally flat, fixed gain amplifier to the detailed physical model, fully resolved in the frequency/wavelength domain. Gain saturation (when taken into account) and the operating point of the EDFA is evaluated using an estimate of the input average power spectrum. Consequently, all models assume that gain saturation can be evaluated using a steady state approximation based on time-averaged values, neglecting the temporal properties of the amplifier. This assumption is valid whenever the signal at the input of the EDFA has a bandwidth of an order of magnitude greater than 5 kHz, which is the typical low-pass frequency of standard EDFA and is thus valid for virtually any optical communication system.

The amplifier models can be divided in two categories: "simplified" and "physical' models. There are three "simplified" models that are described through their gains and the commonly used noise figure parameters. Both the gain and the noise figure can be wavelength dependent. In this case, the gain and/or noise figure should be described through a file using the format described in detail in this Optical Amplifier Description Files. Two of the "simplified" models can take into account gain saturation, too, as described in Fixed

Output Power EDFA. A first model that automatically evaluates the gain so to satisfy the constraint on a given total output power, while another model takes into account *EDFA* gain saturation using a more sophisticated formula.

PMD emulator

In this experimental set-up b206 shows the PMD emulator. This component simulates the effect of Polarization Mode Dispersion (PMD) taking into account its frequency dependence. It reproduces the statistical PMD behavior of a fiber without any loss, dispersion or non-linearity. The PMD effect is simulated through the well-known waveplates model. The fiber is modeled by a set of concatenated equal length (*Lp*) fiber segments (waveplates). The Principal State of Polarization (PSP) orientation of each waveplate is a random variable. Instead, the differential group delay *p*, introduced by each waveplate, is the same for all the waveplates and it is proportional to the PMD coefficient (*PMD* in *ps* /$\sqrt{Km}$) of the simulated fiber and to the waveplate length *Lp* through the following formula :

$$\Delta\tau_p = \sqrt{\frac{3\pi}{8}}\,\delta_{PMD}\sqrt{L_P}$$

Moreover, the waveplates length *Lp* is related to the fiber beat length *LB* and the fiber correlation length *LC* by the following relation:

The average DGD is

$$(\Delta\tau) = \delta_{PMD}\sqrt{L_{fiber}}\ ,$$

and its variance is

$$\sigma\Delta_\sigma = \sqrt{\left(\frac{3\pi}{8} - 1\right)}.\ \delta_{PMD}\sqrt{L_{fiber}}$$

VDGD (Variable Differential Group Delay)

In this experimental set-up b207 shows the PMD emulator. This component simulates the effect of a variable differential group delay (DDGD). Specifying the Principal State of Polarization (PSP) it applies a deterministic delay between the optical signal components with respect to the PSPs. This figure below shows the component. The input optical signal is split into two branches and sent to the two polarizers POL1 and POL2. The two polarizers are complementary: you can set the POL1 polarization in the Stokes space representation,

POL2 is automatically set to the orthogonal polarization. See the polarizer description for more details. More specifically, for the polarizer POL1 you should specify the two angles 2 and 2 required to determine this polarization in the Stokes space (on the Poincarè sphere) using a spherical coordinate system (azimuth and zenith angles).

After the POL1 polarizer, an optical delayer is inserted, whose delay is set by the **rdelay** parameter. The signal exiting from POL2 is not delayed. Finally the two signals are added. As a result the two components experience a differential delay.

Through the parameter **rdelay**, you can set the optical relative group delay between the two branches. Notice that the optical delay actually applied in the simulation is an integer multiple of the simulation time sampling step, so the delay effectively used ' is related with the simulation bandwidth through the relationship:

σ'=Nearest-Integer$\left(\frac{\tau.BW_{VBS}}{0.8}\right)\frac{0.8}{BW_{VBS}}$

where BW_{VBS} is the VBS simulation bandwidth.

Optical receiver

In this experimental set-up b208 and b197 shows the receivers. b6 shows the receiver before emulation and b21 shows the receiver after emulation. This component simulates an optical receiver, including the photo detector. The purpose of the component is to provide an easy tool to estimate the receiver sensitivity, considering certain parameters from datasheets or by carrying out sensitivity measurements.

By "sensitivity" it is meant the value of the average optical signal power at receiver input needed to achieve a certain BER (Bit Error Rate) performance.

Moreover, this component includes an efficient semi-analytical technique that estimates the receiver BER versus the received optical power, as it is usually done in laboratory by placing a variable optical attenuator in front of the photodiode and by measuring the resulting BER. Please see the rest of the documentation for more information on this feature.

This component simulates an optical receiver by supplying a sensitivity value and the test conditions under which such sensitivity is measured.

BER estimator

In this experimental set-up b211 and b177 shows the BER before and after emulation respectively. This component estimates the Bit Error Rate (BER) of an electrical signal, for a binary modulation. This BER estimation does not work for multilevel modulation, such as PSK, QAM, etc.

The evaluation of the BER in optical system simulation is in general a nontrivial task. Error counting is usually impractical, since target BER values are typically of the order of 10-9 or less.

Numerical Results

The numerical results displayed by this component are:

. **BER at optimal decision threshold:** estimated BER at optimal threshold

. **Equivalent Q at optimal decision threshold:** Q related to estimated BER at optimal threshold, obtained inverting the formula:

$$\text{BER} = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right)$$

Electrical power meter

In this experimental set-up b213 and b178 shows the power meter before and after emulation respectively. This component simulates an electrical power meter: it evaluates the power, defined as the mean square value, of an electrical signal. The evaluation can be performed over the whole time domain simulation bandwidth or in a selected subrange of frequencies (Limited Bandwidth Electrical Power Meter).

If Whole is chosen as Measure Bandwidth parameter, the output data is the power, in mw and in dBm, of the input signal over the BWVBS bandwidth (time domain simulation bandwidth). If Limited is chosen as Measure Bandwidth parameter, the output data is the power, in mW and in dBm, of the input signal evaluated only over the selected bandwidth. This subrange of frequencies can be specified using the two fields Center frequency and Bandwidth.

The outputs are the power in squared amplitude units and in logarithmic unit [10*log10 (squared amplitude unit)] of the input signal averaged over the whole *Tsim*.

The current units of the result depend on the units of the electrical input signal and are not explicitly taken into account. For example, if the input is a voltage, the power is expressed in V^2 and in dB [V^2].

Filter

In this experimental set-up b209 and 174 shows the filter. This component simulates an electrical filter. Several different filter models are available, such as a single or double pole low-pass, Butterworth, Bessel, Chebychev, raised cosine, matched and user-defined. If needed, it is possible to compute and plot the transfer function of the simulated filters.

Type: opens the related dialog windows for the filter models, which can be chosen among Single Pole Lowpass, Two Pole Lowpass, Butterworth, Bessel, Chebychev, User Defined, Raised-Cosine and Matched Filter.

Here in this example we can use Bessel filter. In this model we can use PMD fiber and as the PMD of the fiber varies we can analyze various parameters.

3.2.1 Linking of these components in the set-up and its explanation

In this experimental setup we can transmit the source through the 4 channels at the transmitter section. Through channel 4 of data source we transmit input 10 Gbps and make the comparison at the output. Through Laser source we can transmit light after that we can modulate the input signal by passing through the amplitude modulator. Amplitude modular simulates the signal.

Than the signal can passing through the channel. The fiber can be used as a channel. As the signal can travel through the fiber various effects can cause the signal to disperse. The signal can be analyzed by the eye diagrams. It is the convenient way of studying the transmission of the bit sequence.

In the receiver section of the particular channel we have optical amplifiers, i.e. EDFAs, can be used to compensate for the losses in a transmission system. It can be used to amplify the signal. Now we can split the signal and study the effects of the PMD. We can study the signal before and after passing through the emulator. VDGD can be used before the receiver. Specifying the Principal State of Polarization (PSP) it applies a deterministic delay between the optical signal components with respect to the PSPs.

Then the signal can be filtered out by passing through the Bassel filter. Now we can analyze the output through the power meter, BER estimator and the electrical scope.

3.2.1.1 Objectives of the set-up:

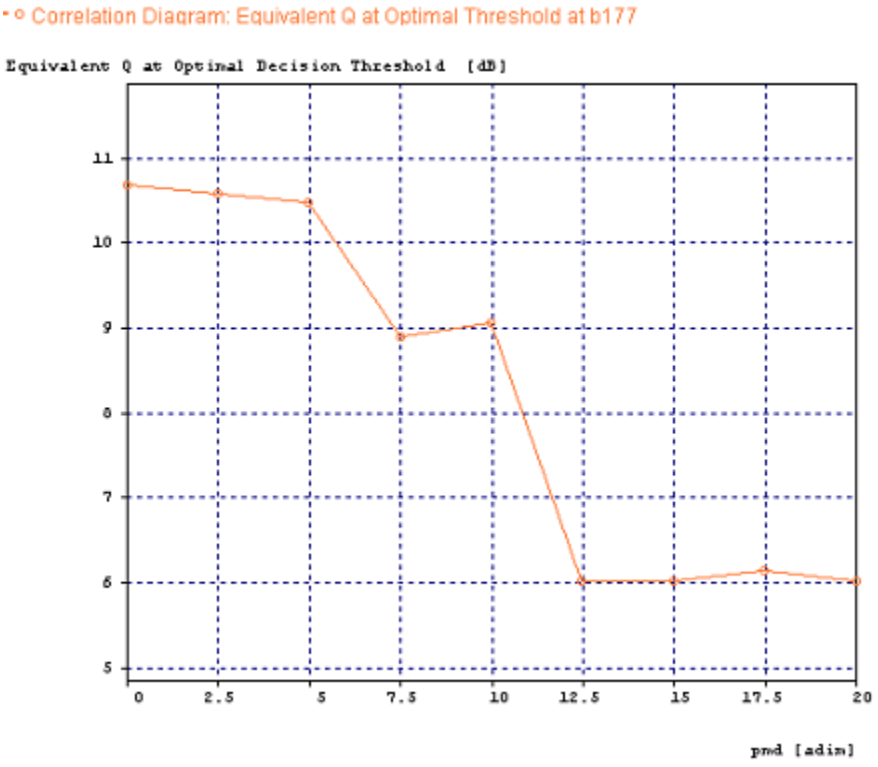
· This set-up can show that what happens when we transmit source whether it can be same at the output or it may be dispersed.

· This shows the effect of using PMD-emulator which can compensate the PMD occurs due to passing through the channel.

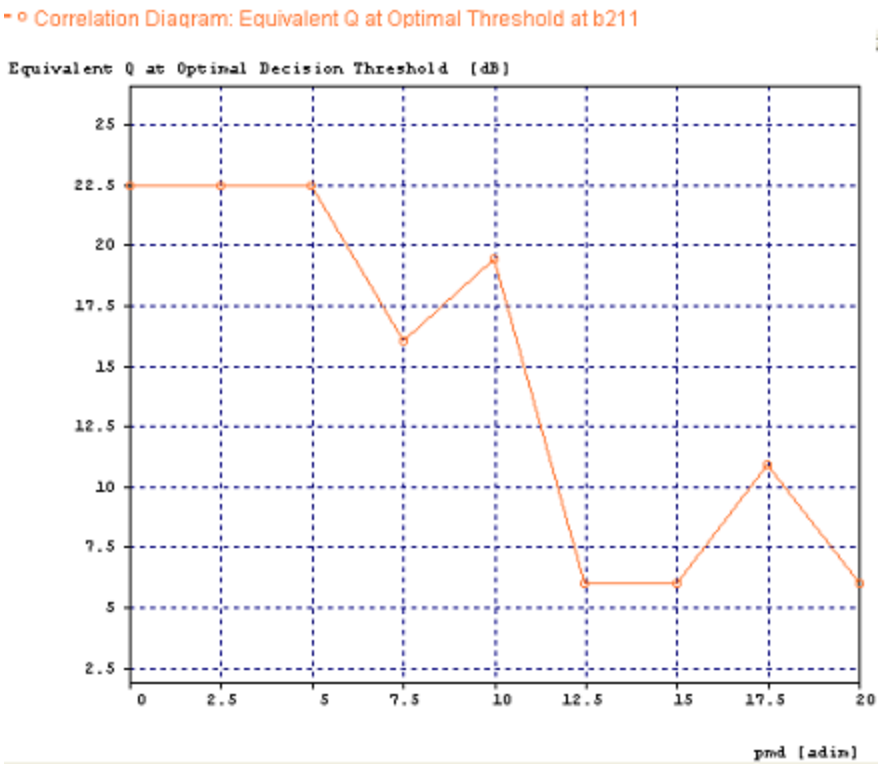
· This set-up shows the effect of using delay here we use variable differential group delay.

3.2.1.2 Results and discussions:

At the electric scope we get the Q variation and the BER equivalent with the PMD. It can be seen in the figure below:



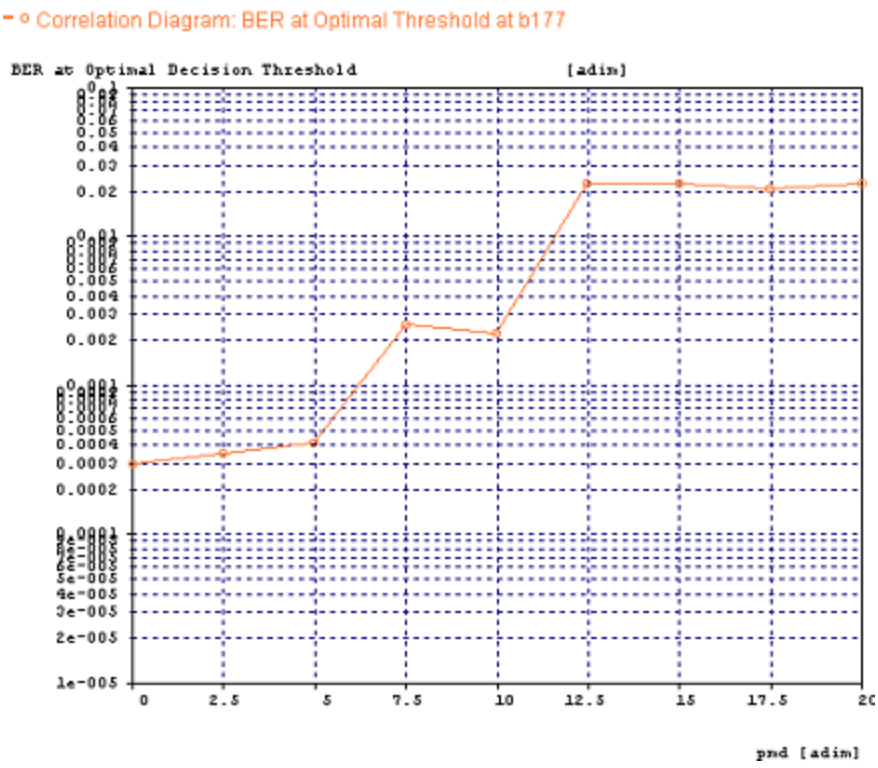
(a)



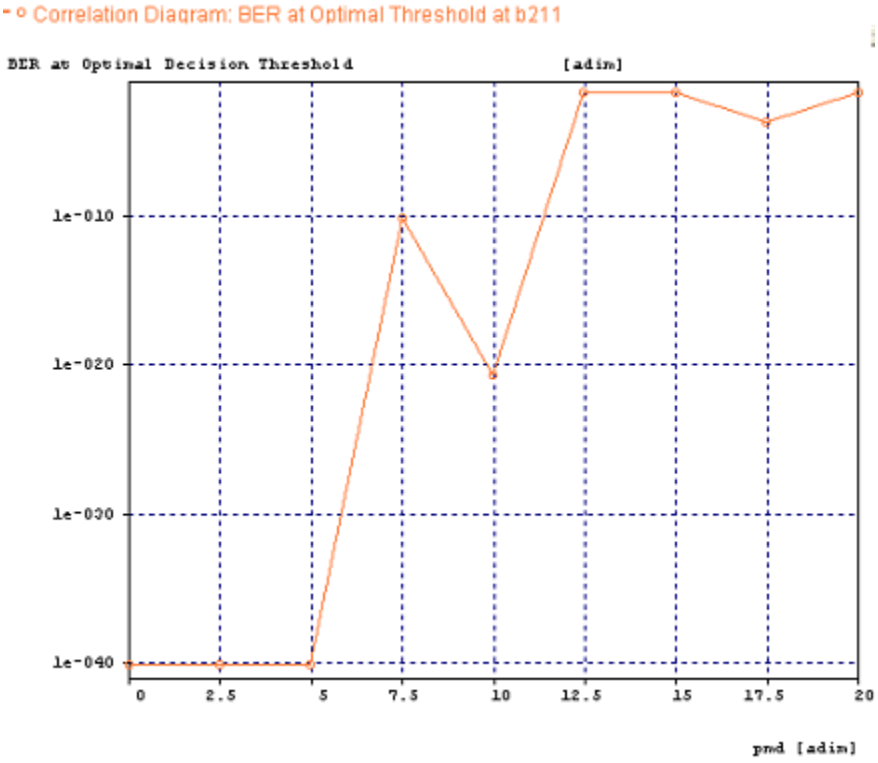
(b)

Figure 3.11: (a) the dispersion verses Equivalent Q before emulation (b) shows the dispersion verses Equivalent Q after emulation. These both figures are for NRZ raised cosine at channel 4.

The above figure shows that after applying emulator our equivalent Q can be increased.


Correlation Diagram: BER at Optimal Threshold at b177
BER at Optimal Decision Threshold
[adim]
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
9e-005
8e-005
7e-005
6e-005
5e-005
4e-005
3e-005
2e-005
1e-005
0
2.5
5
7.5
10
12.5
15
17.5
20
pmd [adim]

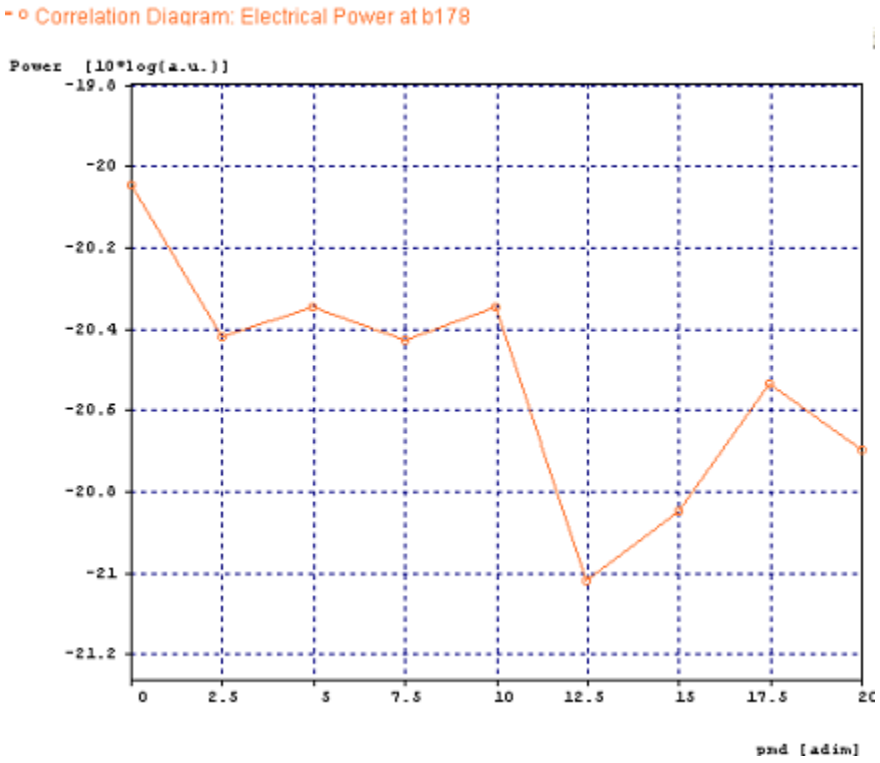
(a)


Correlation Diagram: BER at Optimal Threshold at b211
BER at Optimal Decision Threshold
[adim]
1e-010
1e-020
1e-030
1e-040
0
2.5
5
7.5
10
12.5
15
17.5
20
pmd [adim]

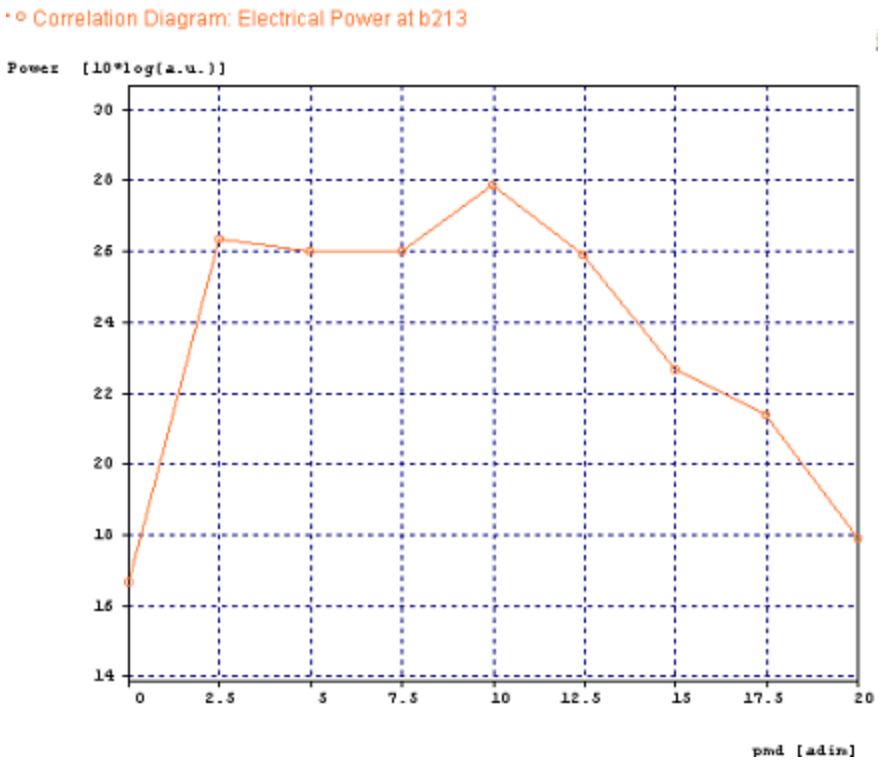
(b)

Figure 3.12: (a) the dispersion verses BER before emulation (b) the dispersion verses BER after emulation. These both figures are for NRZ raised cosine at channel 4.

This above figures shows that the BER decreases after emulation. At some value it increases and then decreases.



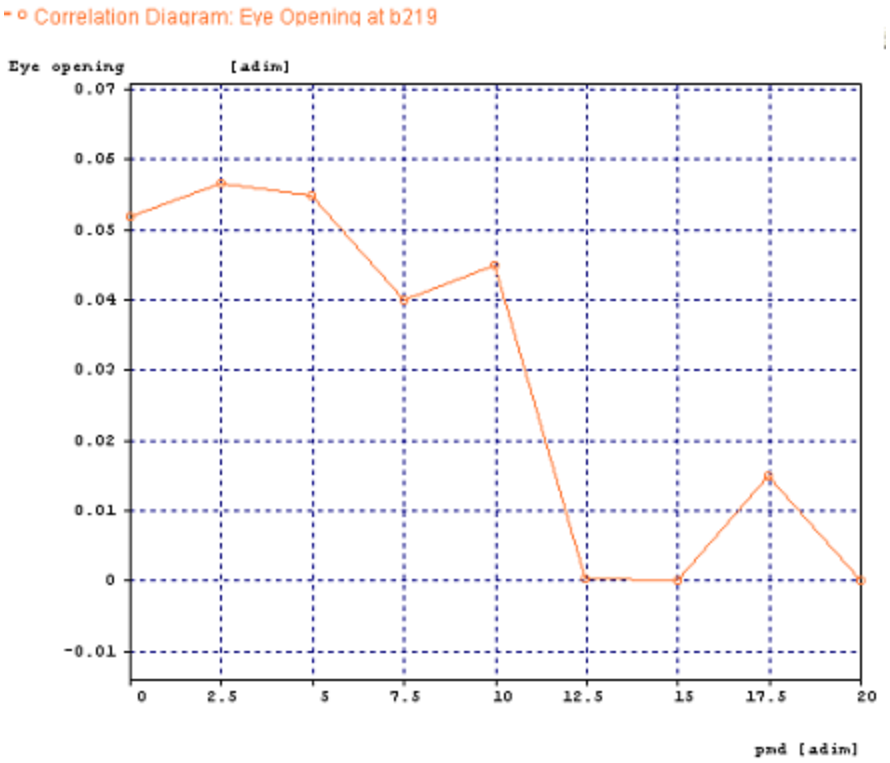
(a)



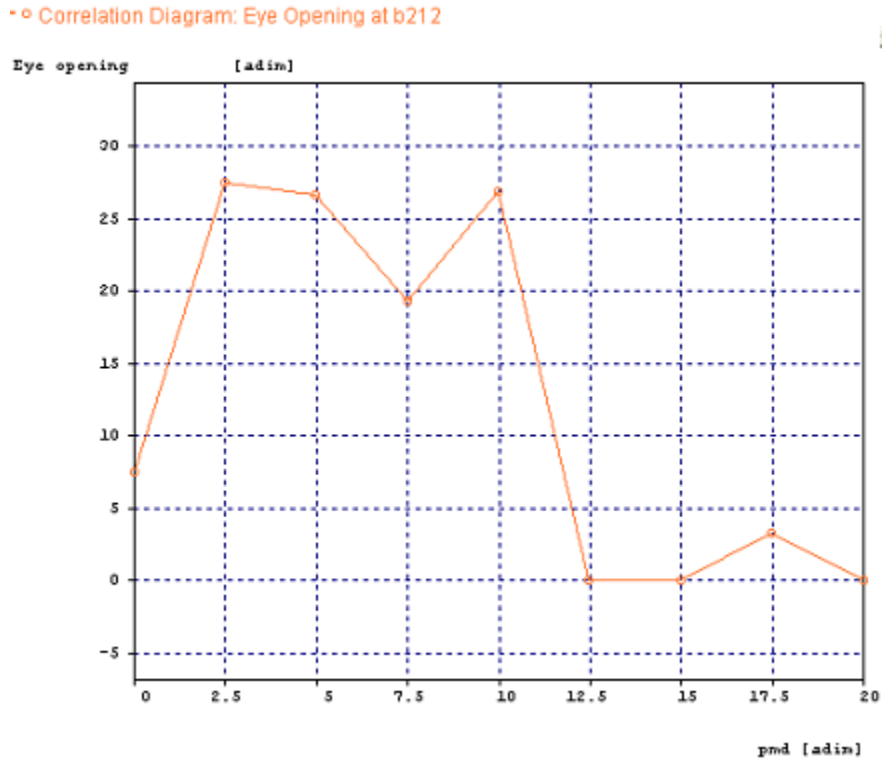
(b)

Figure 3.13: (a) the dispersion verses electrical power before emulation. (b) the dispersion verses electrical power after emulation. All values are for NRZ raised cosine at channel 4.

The above figure shows that after using emulator electric power increases by considerable amount.

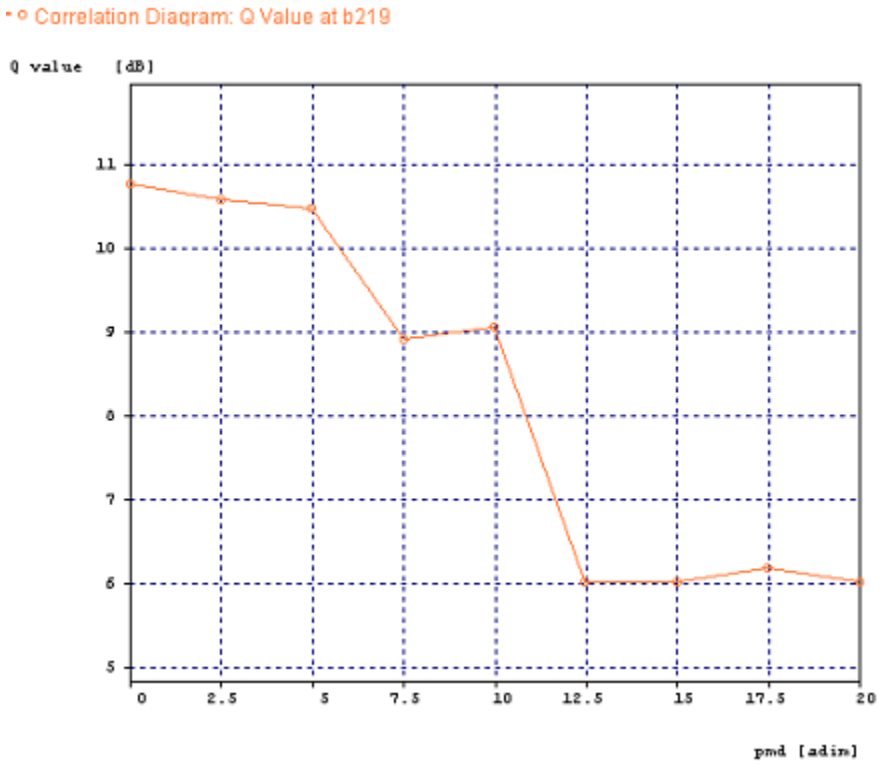

Correlation Diagram: Eye Opening at b219
Eye opening [adim]
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
2.5
5
7.5
10
12.5
15
17.5
20
pmd [adim]

(a)

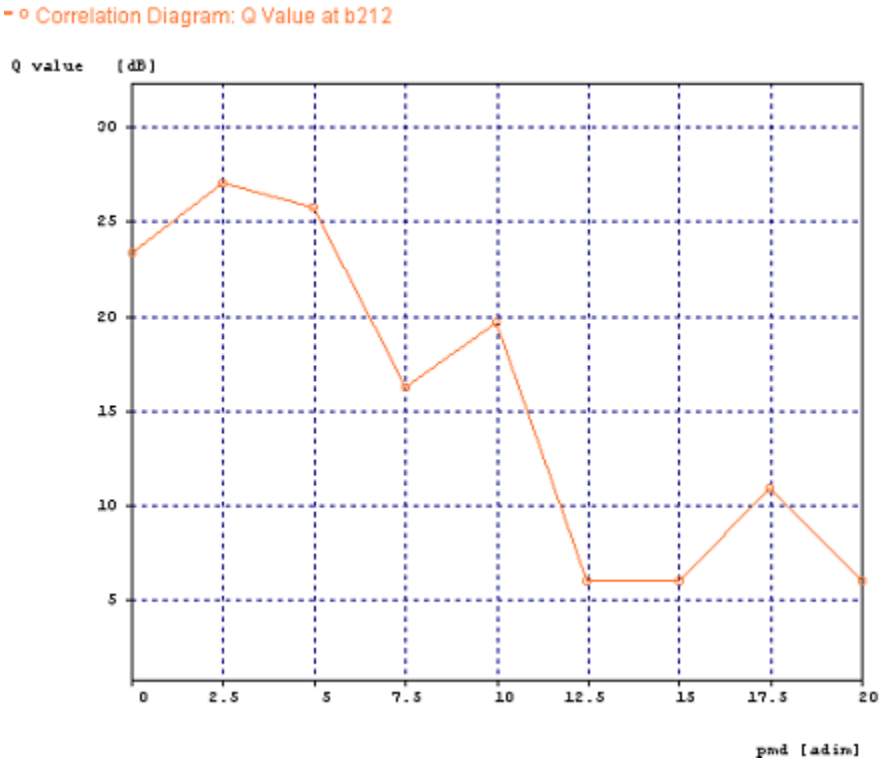

Correlation Diagram: Eye Opening at b212
Eye opening [adim]
30
25
20
15
10
5
0
-5
0
2.5
5
7.5
10
12.5
15
17.5
20
pmd [adim]

(b)

Figure 3.14: For channel 4 at 10 Gbps for NRZ raised cosine (a) Eye opening with PMD before emulation. (b) Eye opening with PMD after emulation

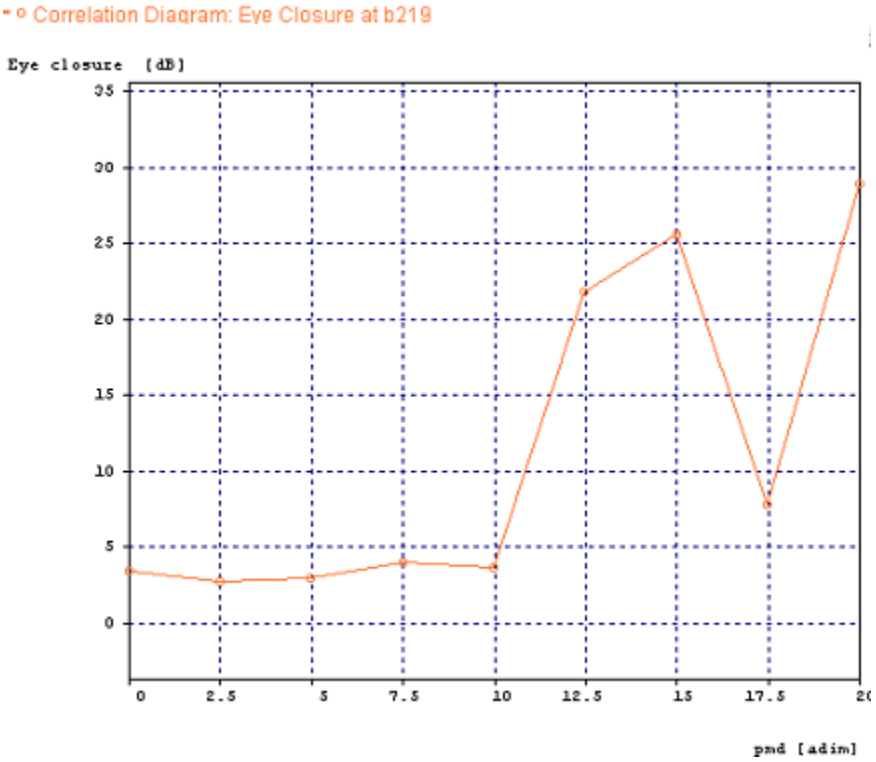


(a)

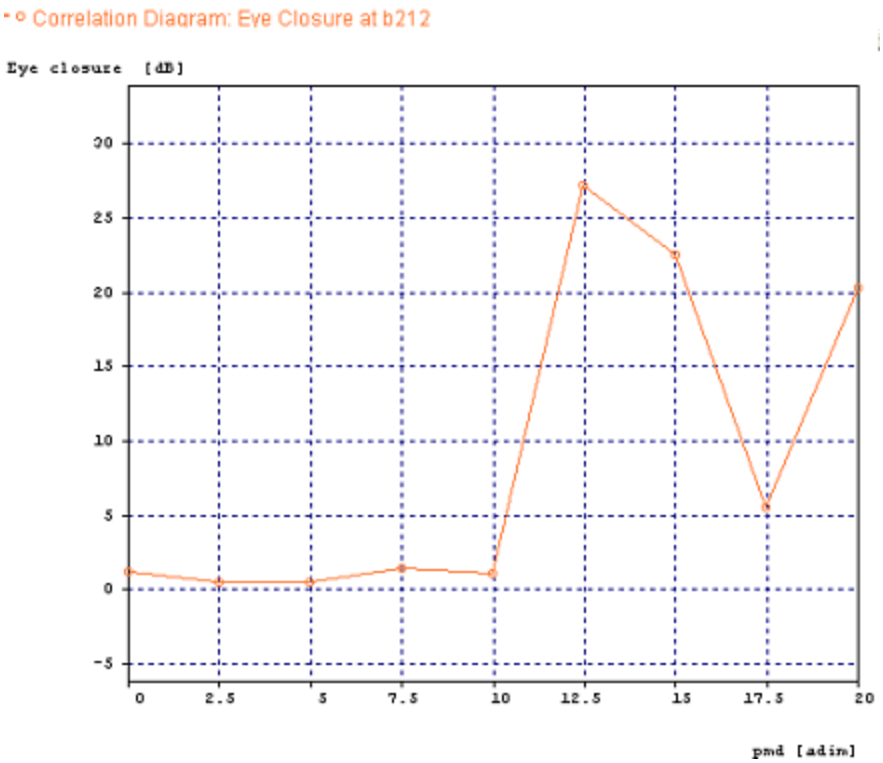


(b)

Figure 3.15: For channel 4 at 10 Gbps for NRZ raised cosine (a) Q value with PMD before emulation. (b) Q value with PMD after emulation.



(a)



(b)

Figure 3.16: For channel 4 at 10 Gbps for NRZ raised cosine (a) Eye closure with PMD before emulation. (b) Eye closure with PMD after emulation

CHAPTER 4

COMPENSATION TECHNIQUES OF PMD

The different compensation methods can be divided into different categories, depending on weather the compensation is performed electrically [46,49], opto-electronically [50] or optically or weather the compensation is done before or after compensation (pre or post compensation).

A straight forward method to reduce the PMD effects is to reduce the PMD effects optically is to launch the signal into PSP [47,48]. Figure 4.1 defines a first order compensation as it enables the compensation to first order only. Optical post compensation is currently an intense research field where both first order and higher order compensation have been suggested. The main problem must be focused upon how the PMD induced distortion should be compensated. Here in the below figures we show first order pre and post compensation. In the post compensation technique we can make it of any order.

The benefits of applying PMD compensation is also can also be treated analytically. The results and theory describe the expected pulse broadening for random and PSP oriented input polarizations, as well as the benefit of using an optical post compensation technique. The theory also includes an arbitrarily variable one stage compensator which can partially compensate for higher order PMD.

In the below set-ups we have four transmitters section, four channels and four receivers section. We transmits the signal from the channel one of the transmitter section. Here, we have Laser source and a data source and an amplitude modulator. The bit rate can be send through the data source and at the amplitude modulator the input signal can be modulated. Then the signal can be passed through the fiber channel. In figure 4.1 which is a pre-compensation technique we have an PMD emulator which act as a PMD compensator before the transmission through the fiber whereas in figure 4.2 which is a post- compensation technique we use PMD emulator after transmission through the fiber. In figures 4.1 and figure 4.2 we use first order compensation technique.

4.1 Compensation schemes

4.1.1 Optical pre compensation (PSP method)

It is simple technique to launch the light into the PSP to reduce the PMD effects. However, in practice the feedback signal can be connected back to the transmitter, which makes the compensation inherently slow. This method is obtained by the aligning the input SOP to one of the PSPs. This method can be applied in the installed links [7] as we know that PSPs are obtained in the stokes space whereas, in Jones space, which is more convenient in numerical simulations, the output PSPs are given by the eigen vectors. The block diagram for pre compensation is shown below that how the compensation is done before transmission.

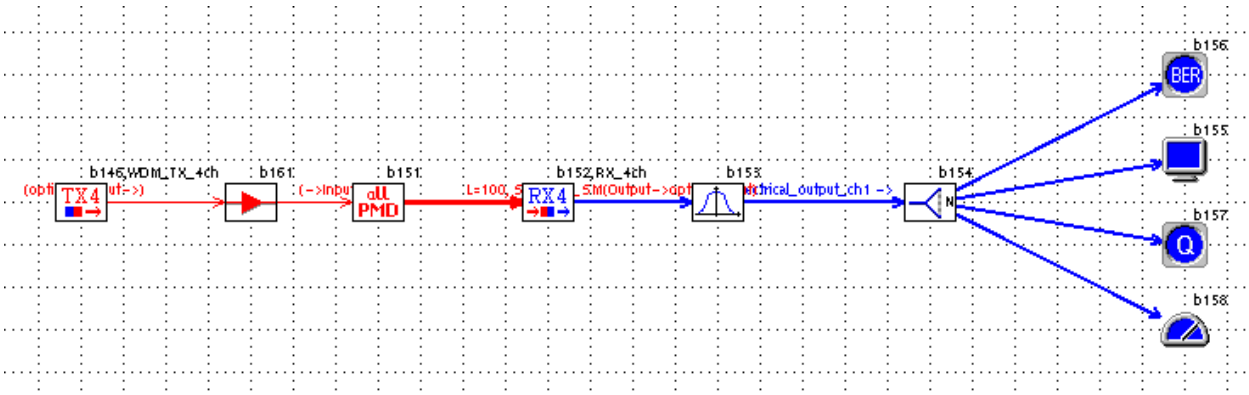


Figure 4.1: Simulation set-up for first order pre-compensation (PSP method)

4.1.2 Optical post compensation

The PMD induced distortion can be compensated for after transmission by introducing a birefringent element which cancels the DGD at the carrier frequency. This compensation element can consists of a number of sections which implies that the scheme has a certain number of control parameters are degree of freedom (DOF). The block diagram for optical post compensation after transmission is shown below:

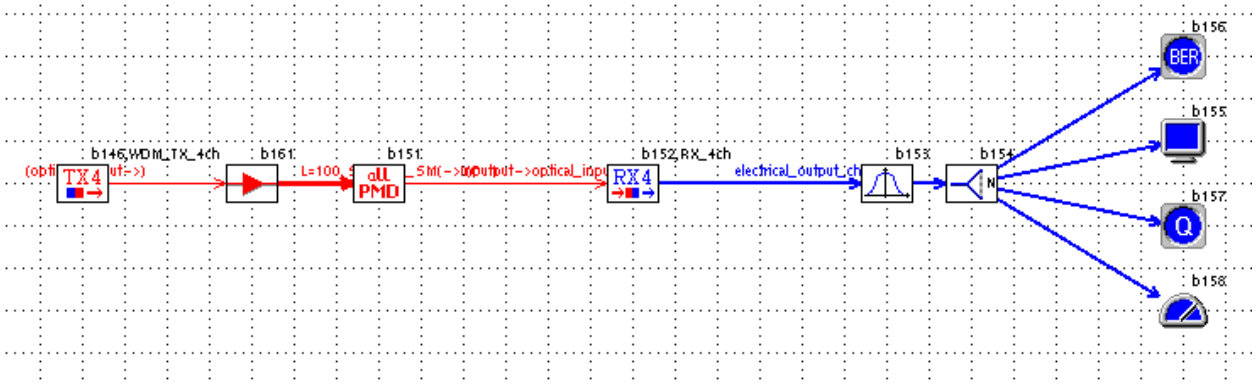


Figure 4.2: Simulation set-up for optical first order post- compensation

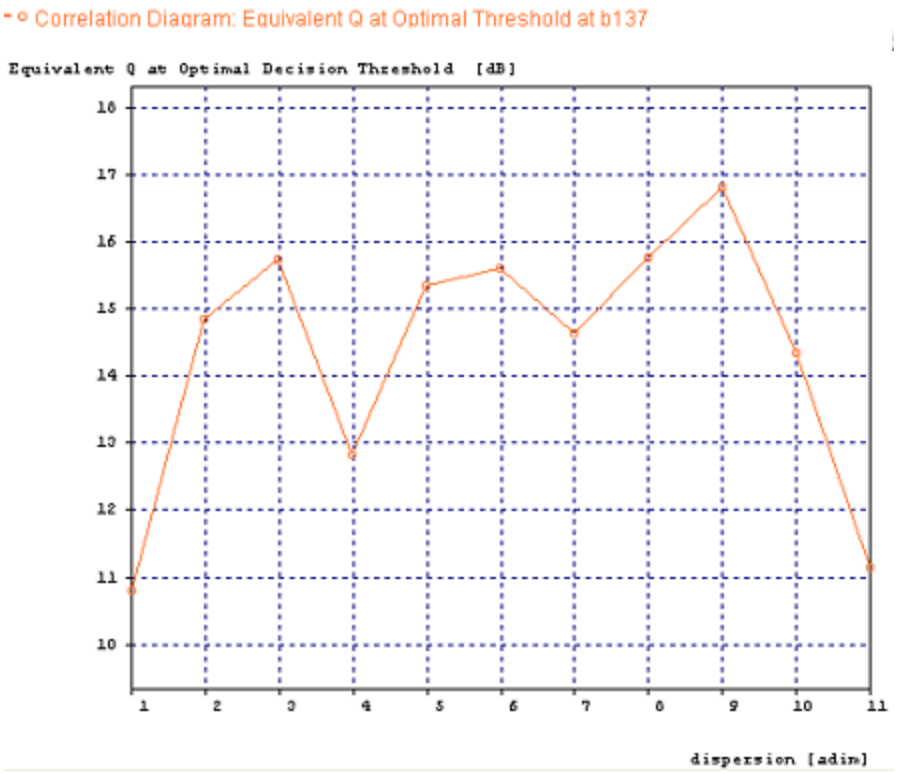
The higher the number of degree of freedom the more flexible the system becomes, enabling compensation for various DGD values and to some extent also for higher order PMD on the other hand , a more complicated control system is required this slows down the response and reduces the likelihood of maintaining the optimized state of the compensating system.

Here in this chapter we find that what effect on the system is when the bit rates changes and the PMD of the fiber increases.

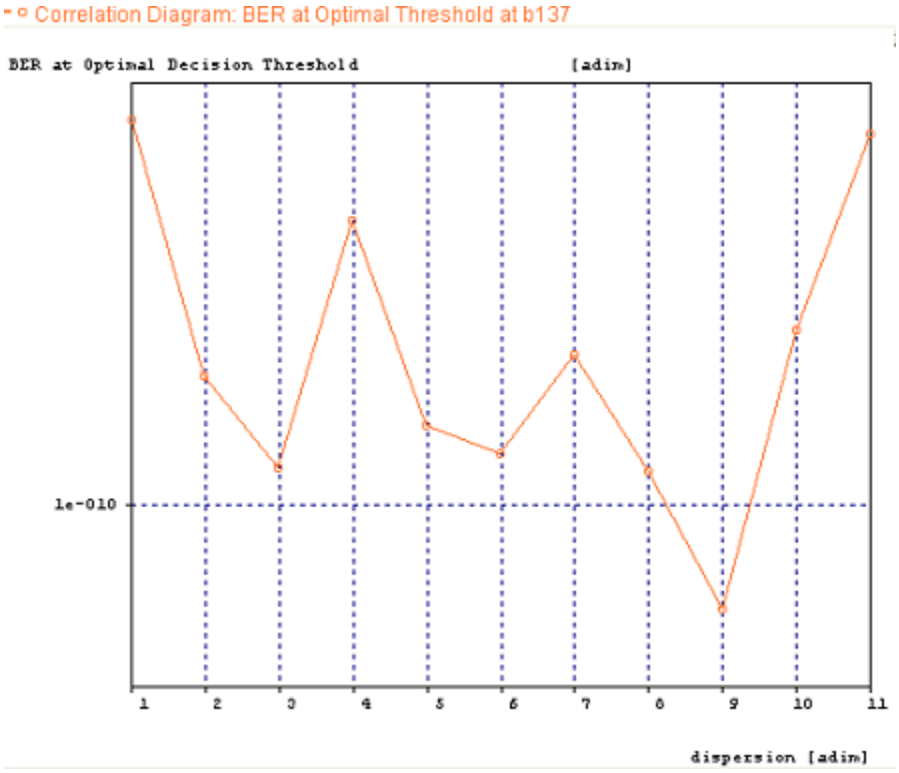
4.2 Results and Discussions

4.2.1 Results of pre-compensation

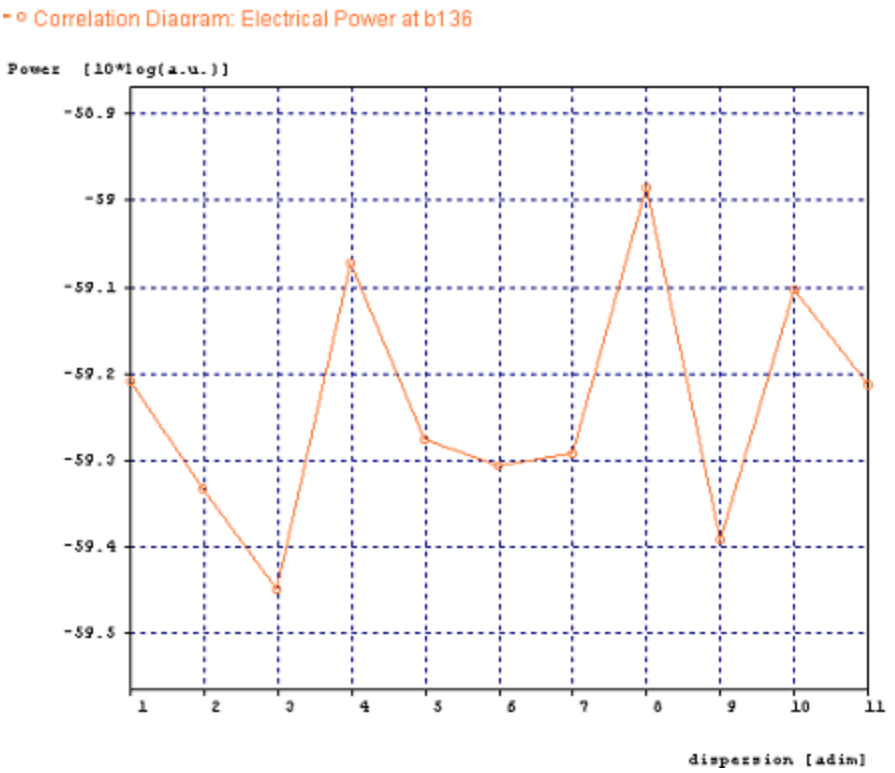
As we know that at 2.5 Gbps there is not much effect of PMD on the system. In the figure 4.3 shows the Q value, BER, electrical power, eye opening, eye closure and eye diagrams at the corresponding values of PMD. All these figures are for the channel one of the transmitter section at 2.5 Gbps.


Correlation Diagram: Equivalent Q at Optimal Threshold at b137
Equivalent Q at Optimal Decision Threshold [dB]
18
17
16
15
14
13
12
11
10
1
2
3
4
5
6
7
8
9
10
11
dispersion [adim]

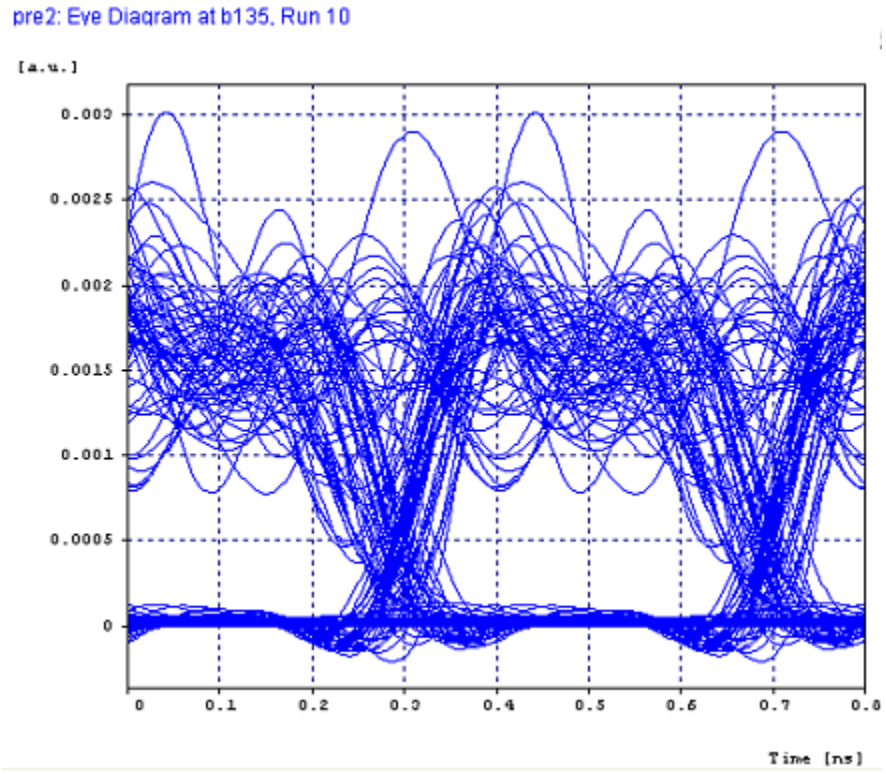
(a)


Correlation Diagram: BER at Optimal Threshold at b137
BER at Optimal Decision Threshold [adim]
1e-010
1
2
3
4
5
6
7
8
9
10
11
dispersion [adim]

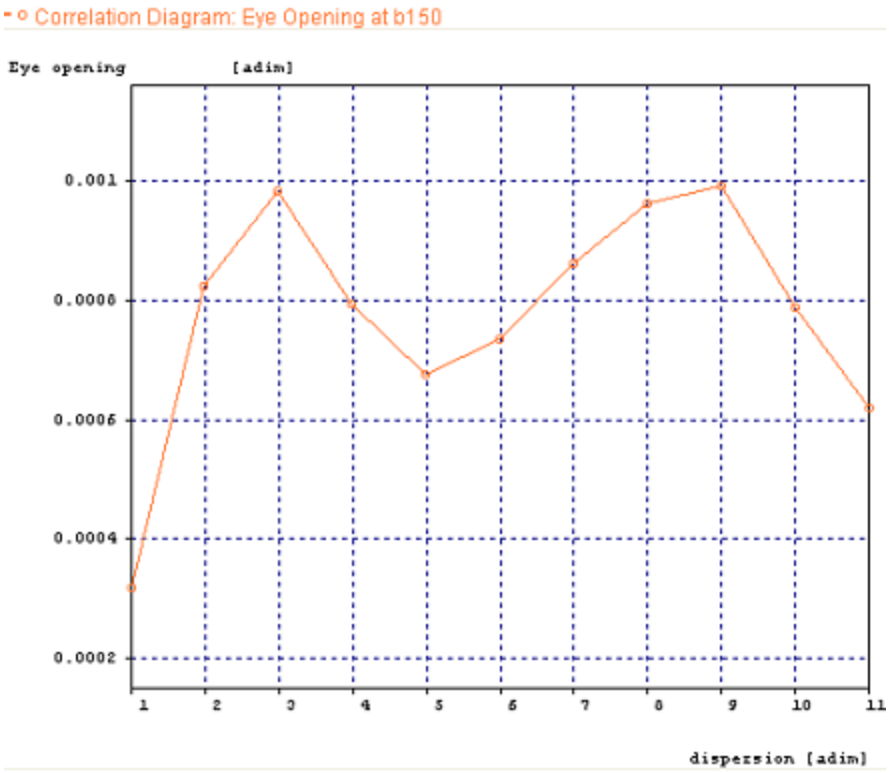
(b)


Correlation Diagram: Electrical Power at b136
Power [10*log(a.u.)]
-58.9
-59
-59.1
-59.2
-59.3
-59.4
-59.5
1
2
3
4
5
6
7
8
9
10
11
dispersion [adim]

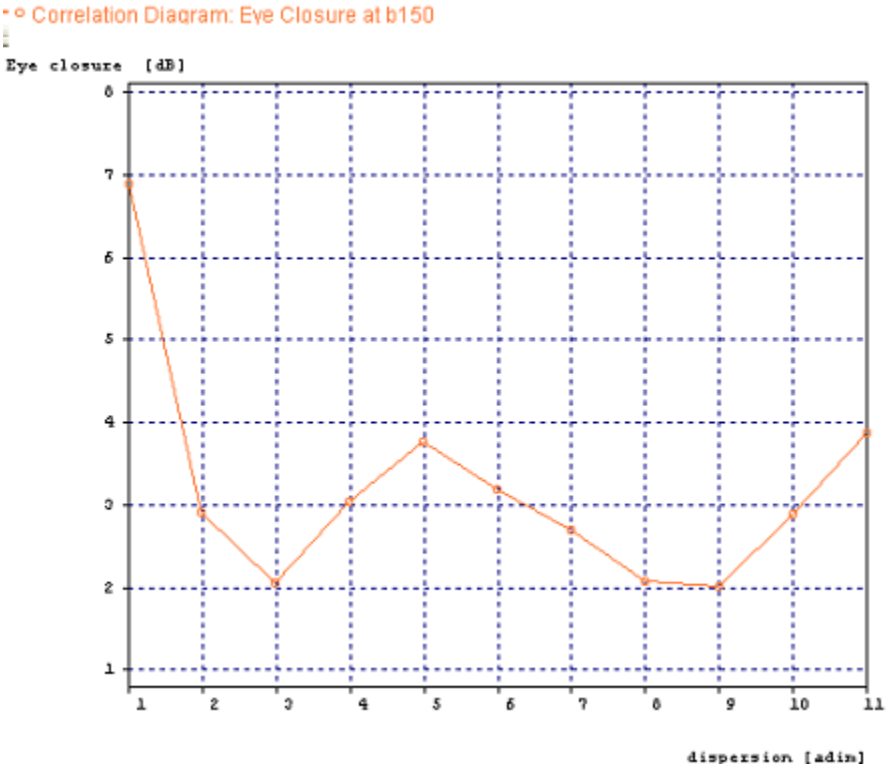
(c)


pre2: Eye Diagram at b135, Run 10
[a.u.]
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Time [ns]

(d)


Correlation Diagram: Eye Opening at b150
Eye opening [adim]
0.001
0.0008
0.0006
0.0004
0.0002
1
2
3
4
5
6
7
8
9
10
11
dispersion [adim]

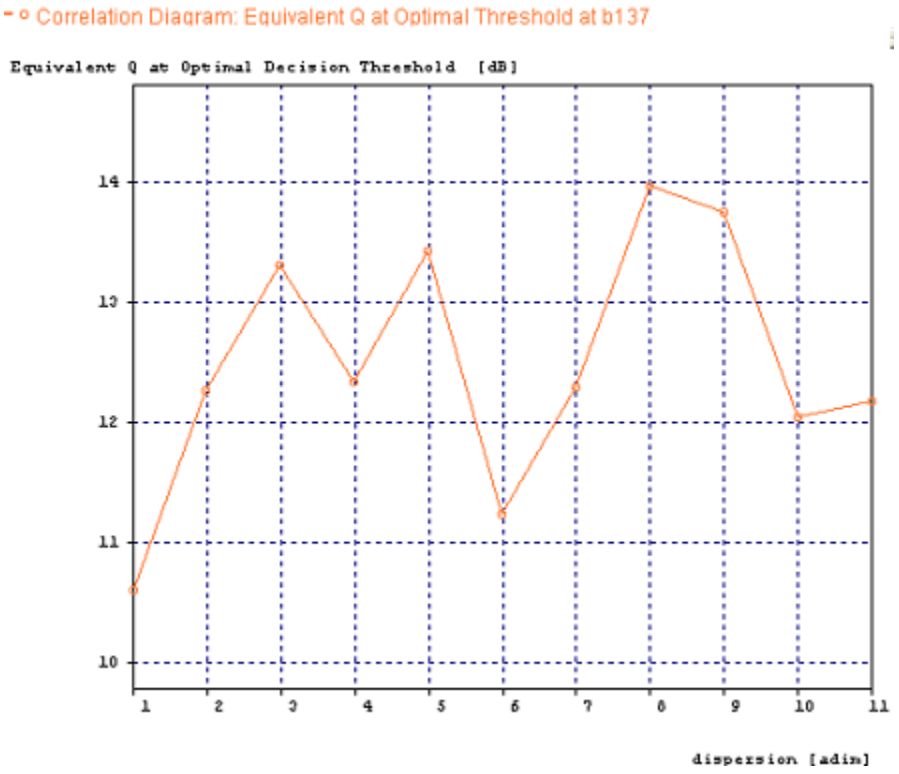
(e)


Correlation Diagram: Eye Closure at b150
Eye closure [dB]
8
7
6
5
4
3
2
1
1
2
3
4
5
6
7
8
9
10
11
dispersion [adim]

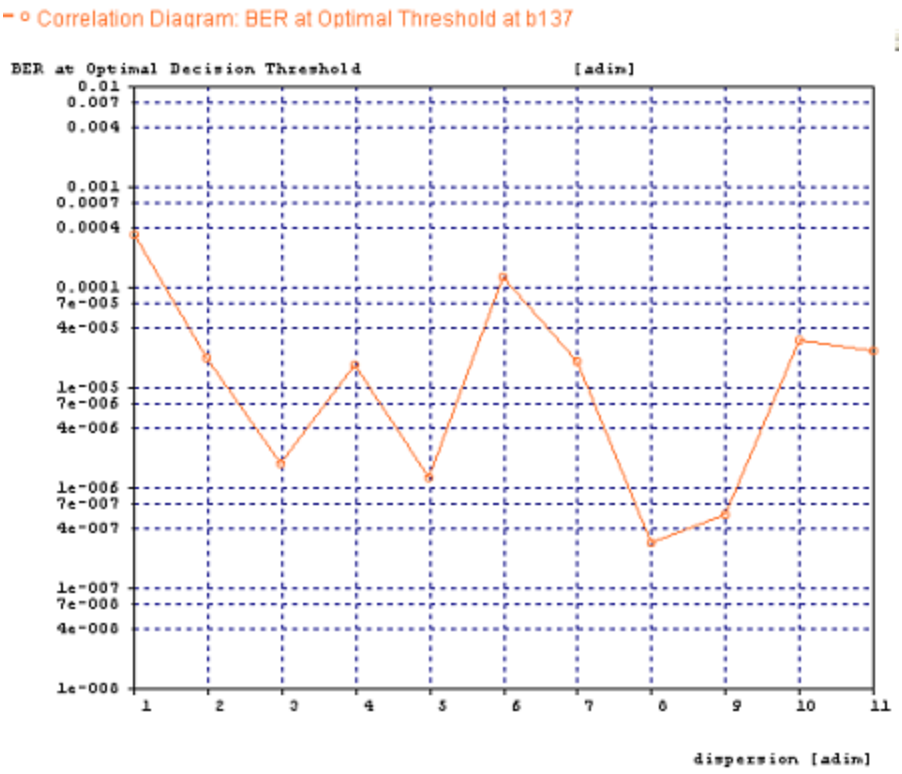
(f)

Figure 4.3: For channel 1 at 2.5 Gbps for NRZ raised cosine (a) PMD verses equivalent Q factor (b) PMD verses BER (c) the PMD verses electrical power (d) eye diagram at 10 *ps*/√ *km* (e) PMD verses eye opening (f) PMD verses eye closure.

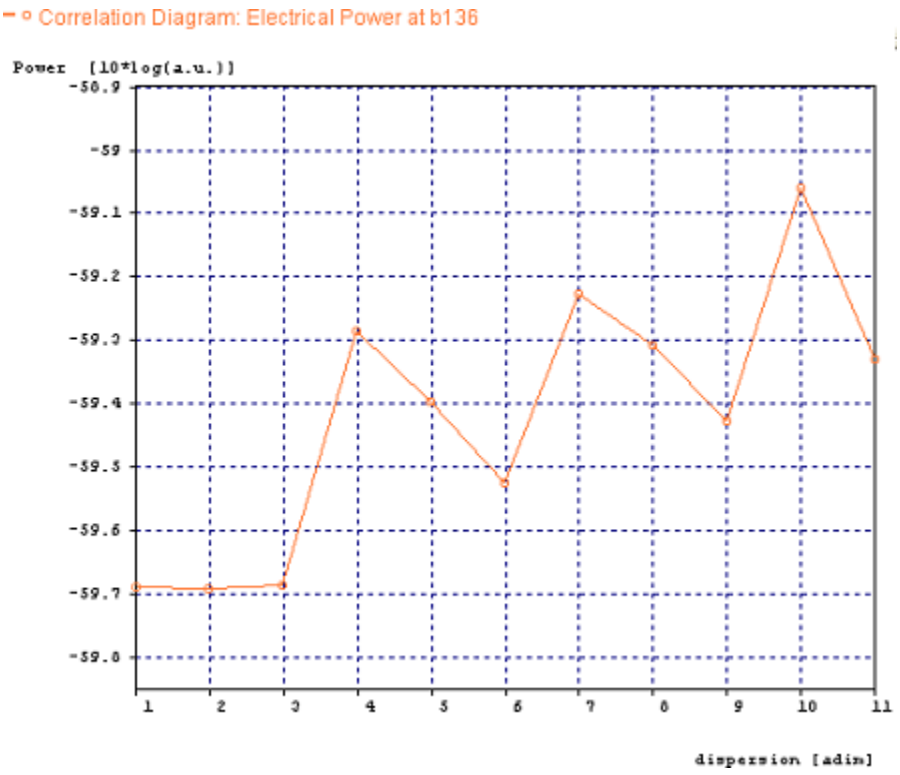
The figure 4.4 shows the Q value, BER, electrical power, eye opening, eye closure and eye diagrams at the corresponding values of PMD. All these figures are for the channel one of the transmitter section at 5 Gbps.



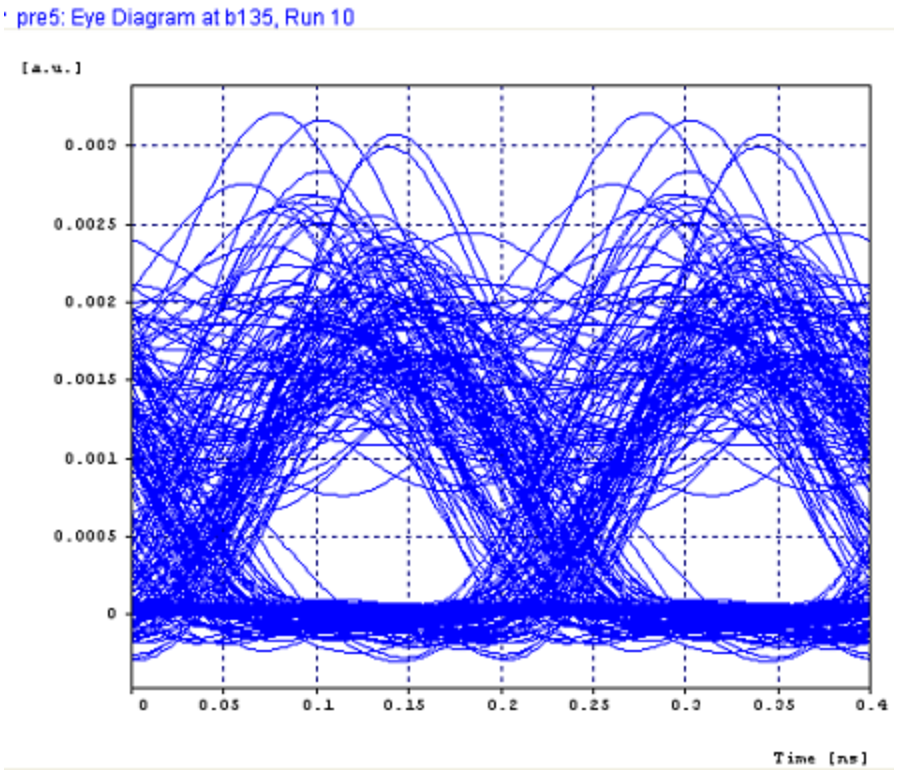
(a)


Correlation Diagram: BER at Optimal Threshold at b137
BER at Optimal Decision Threshold [adim]
0.01
0.007
0.004
0.001
0.0007
0.0004
0.0001
7e-005
4e-005
1e-005
7e-006
4e-006
1e-006
7e-007
4e-007
1e-007
7e-008
4e-008
1e-008
1 2 3 4 5 6 7 8 9 10 11
dispersion [adim]

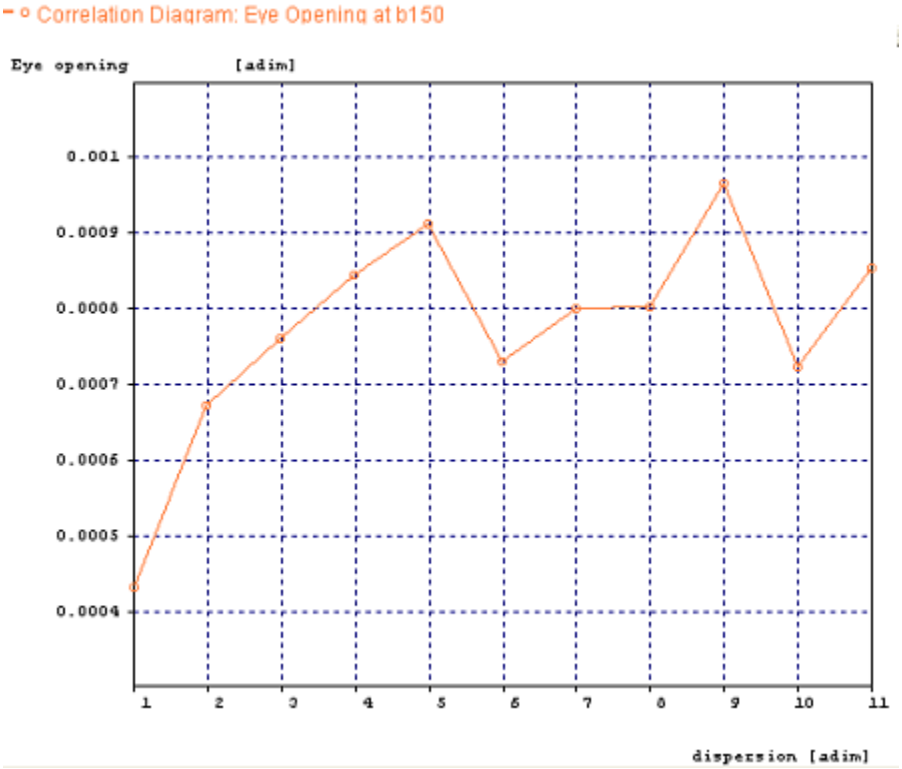
(b)


Correlation Diagram: Electrical Power at b136
Power [10*log(a.u.)]
-58.9
-59
-59.1
-59.2
-59.3
-59.4
-59.5
-59.6
-59.7
-59.8
1 2 3 4 5 6 7 8 9 10 11
dispersion [adim]

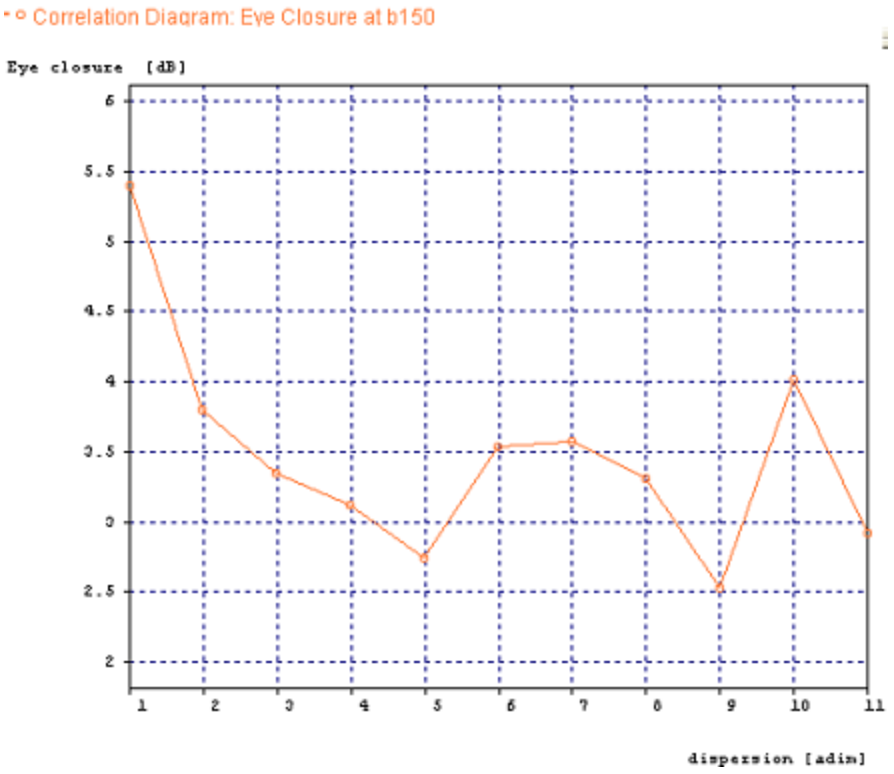
(c)


pre5: Eye Diagram at b135, Run 10
[a.u.]
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Time [ns]

(d)


Correlation Diagram: Eye Opening at b150
Eye opening
[adim]
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
1
2
3
4
5
6
7
8
9
10
11
dispersion [adim]

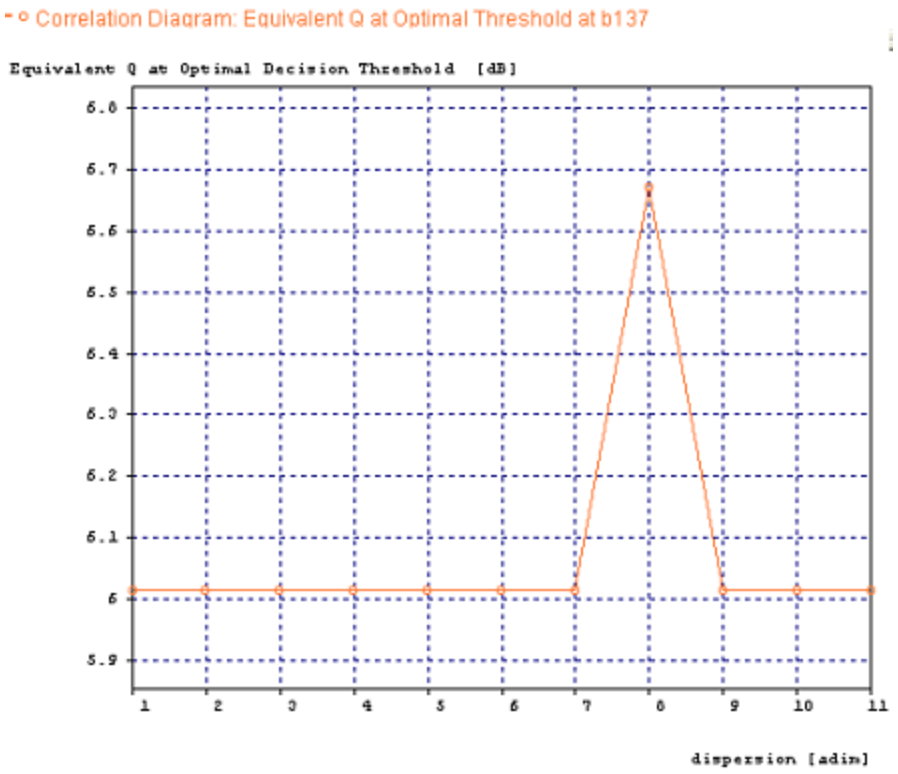
(e)



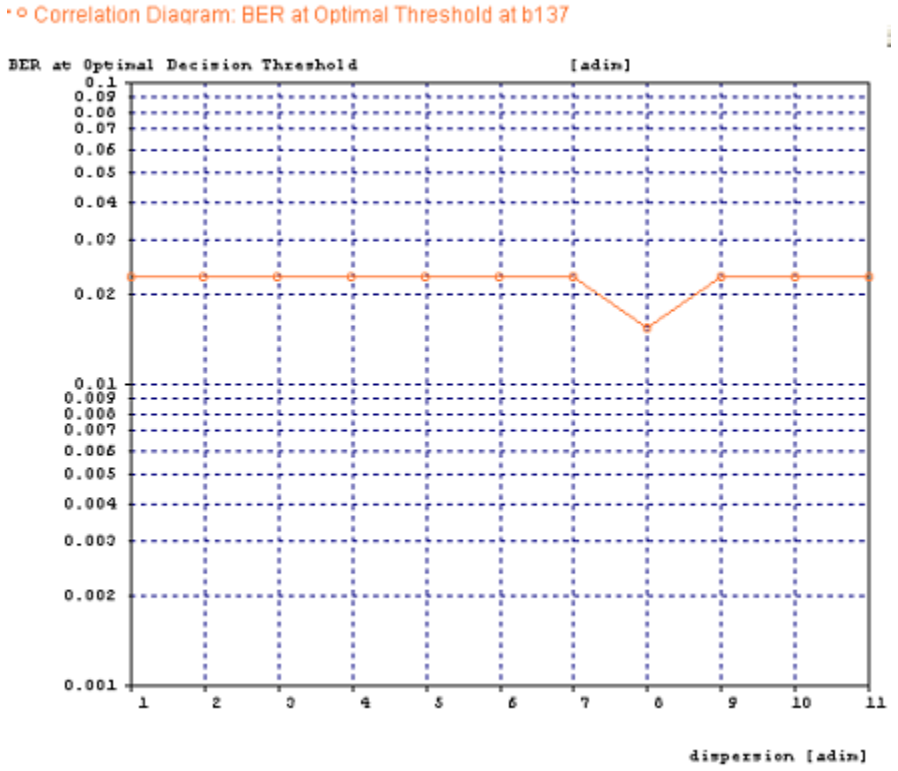
(f)

Figure 4.4: For channel 1 at 5 Gbps for NRZ raised cosine (a) PMD verses equivalent Q factor (b) PMD verses BER (c) the PMD verses electrical power (d) eye diagram at 10 *ps*/√ *km* (e) PMD verses eye opening (f) PMD verses eye closure.

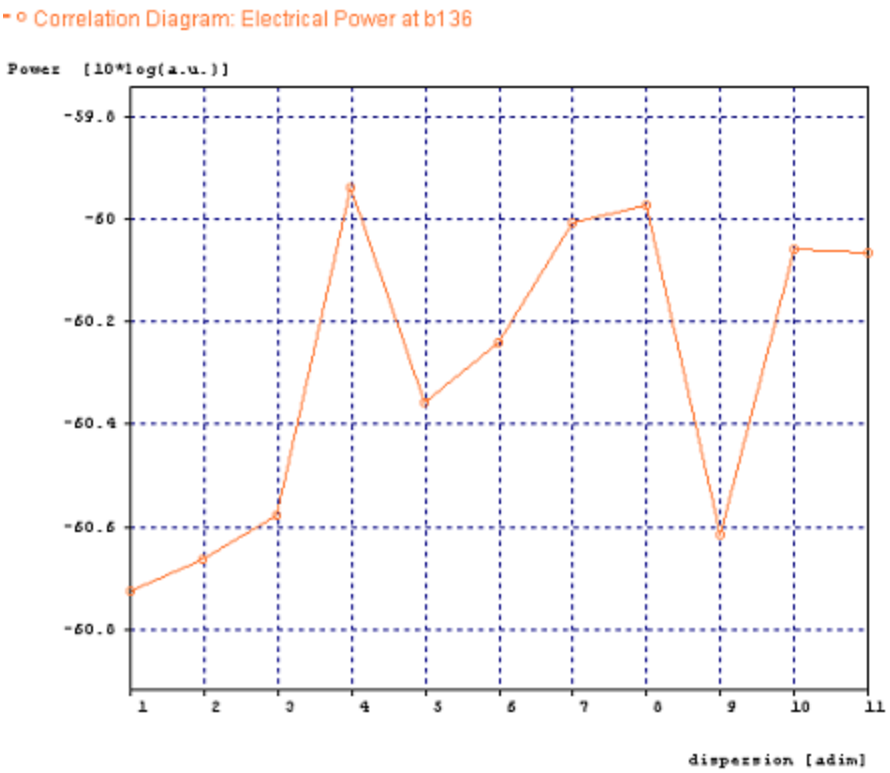
The figure 4.5 shows the Q value, BER, electrical power, eye opening, eye closure and eye diagrams at the corresponding values of PMD. All these figures are for the channel one of the transmitter section at 10 Gbps.


Correlation Diagram: Equivalent Q at Optimal Threshold at b137
Equivalent Q at Optimal Decision Threshold [dB]
6.8
6.7
6.6
6.5
6.4
6.3
6.2
6.1
6
5.9
1
2
3
4
5
6
7
8
9
10
11
dispersion [adim]

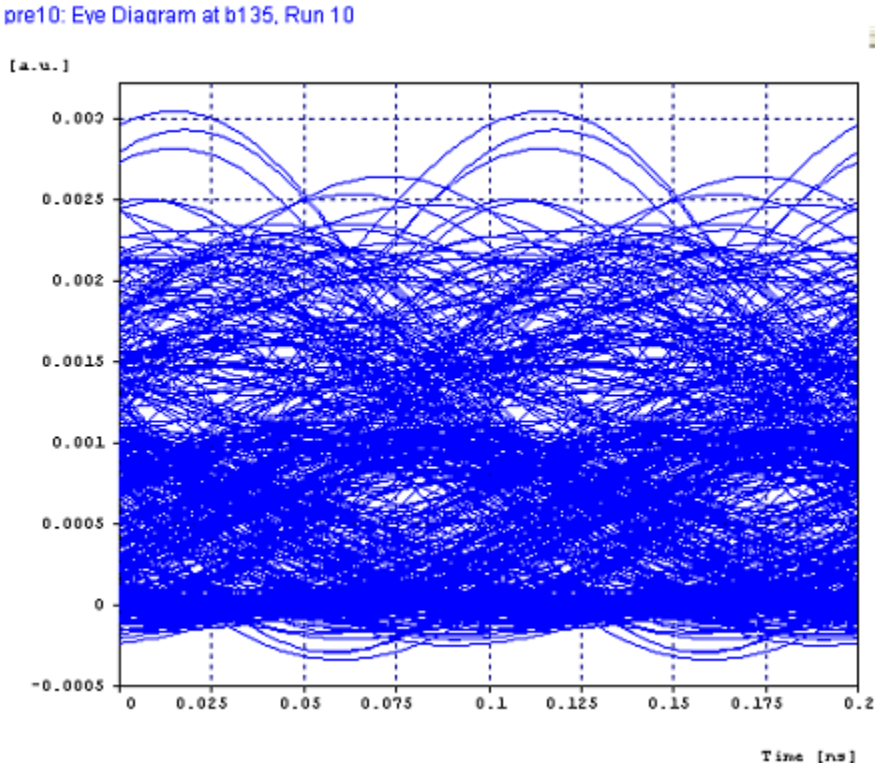
(a)


Correlation Diagram: BER at Optimal Threshold at b137
BER at Optimal Decision Threshold [adim]
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
1
2
3
4
5
6
7
8
9
10
11
dispersion [adim]

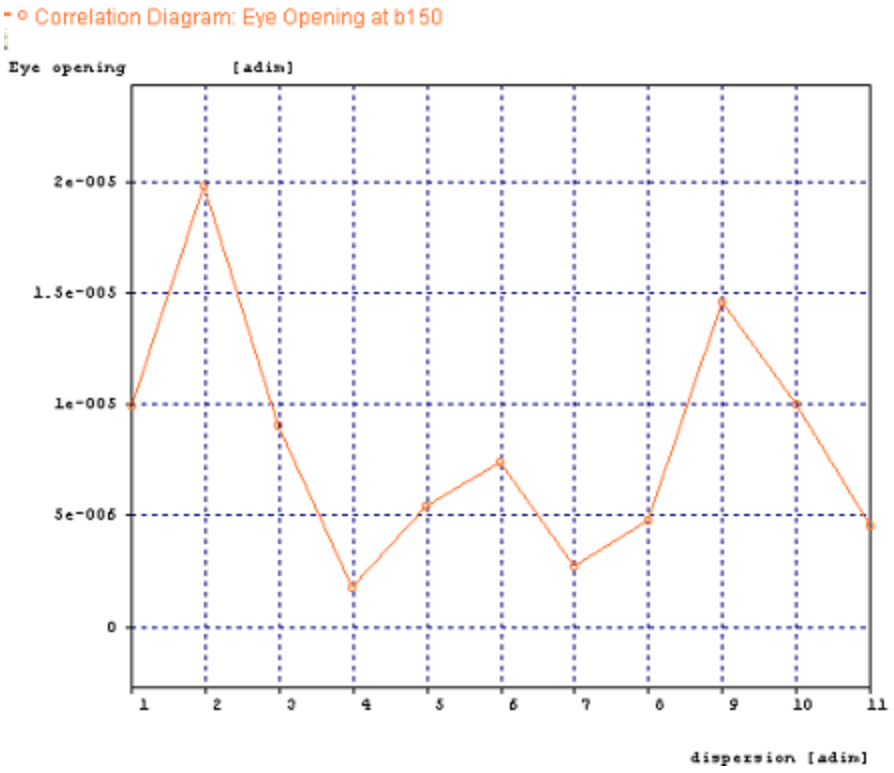
(b)


Correlation Diagram: Electrical Power at b136
Power [10*log(a.u.)]
-59.8
-60
-60.2
-60.4
-60.6
-60.8
1
2
3
4
5
6
7
8
9
10
11
dispersion [adim]

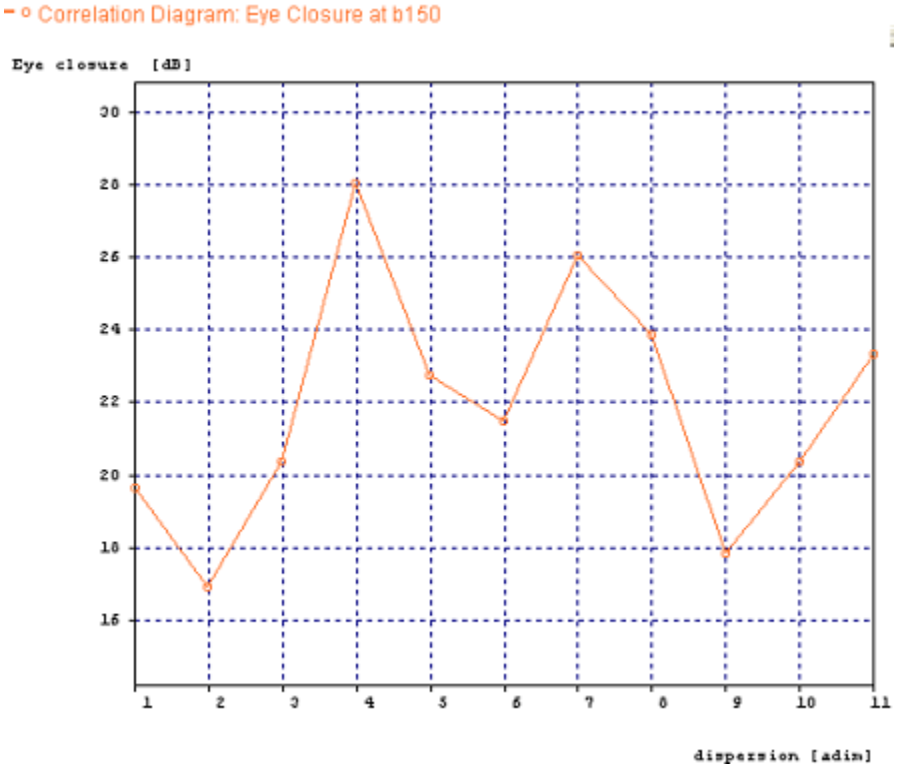
(c)


pre10: Eye Diagram at b135, Run 10
[a.u.]
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
-0.0005
0
0.025
0.05
0.075
0.1
0.125
0.15
0.175
0.2
Time [ns]

(d)


Correlation Diagram: Eye Opening at b150
Eye opening [adim]
2e-005
1.5e-005
1e-005
5e-006
0
1
2
3
4
5
6
7
8
9
10
11
dispersion [adim]

(e)


Correlation Diagram: Eye Closure at b150
Eye closure [dB]
30
28
26
24
22
20
18
16
1
2
3
4
5
6
7
8
9
10
11
dispersion [adim]

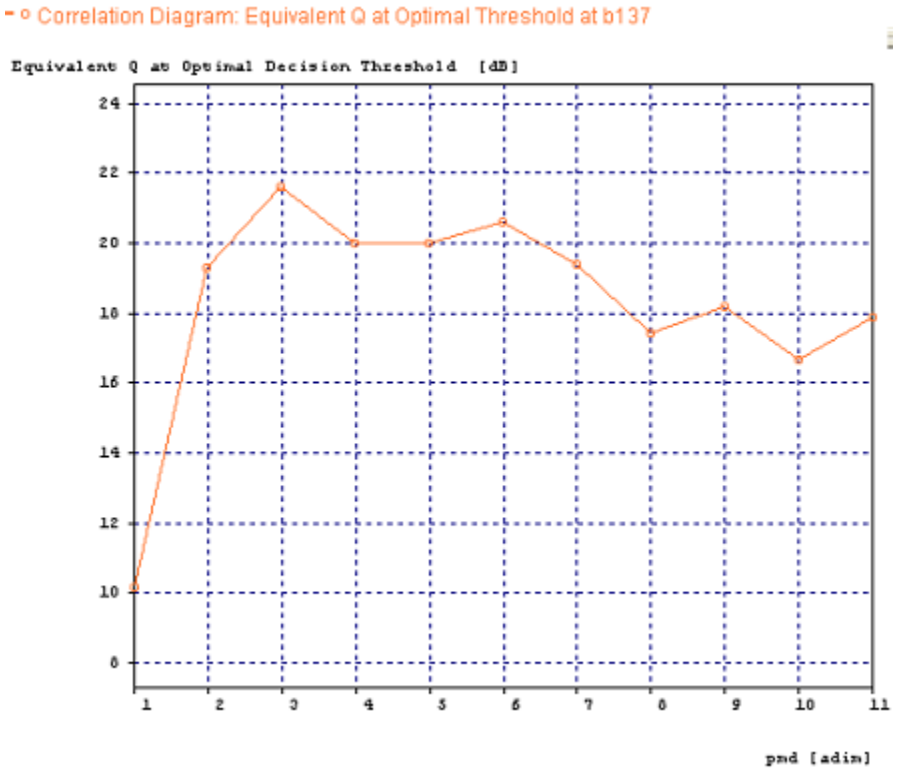
(f)

Figure 4.5: For channel 1 at 10 Gbps for NRZ raised cosine (a) PMD verses equivalent Q factor (b) PMD verses BER (c) the PMD verses electrical power (d) eye diagram at 10 *ps* /√ *km* (e) PMD verses eye opening (f) PMD verses eye closure.

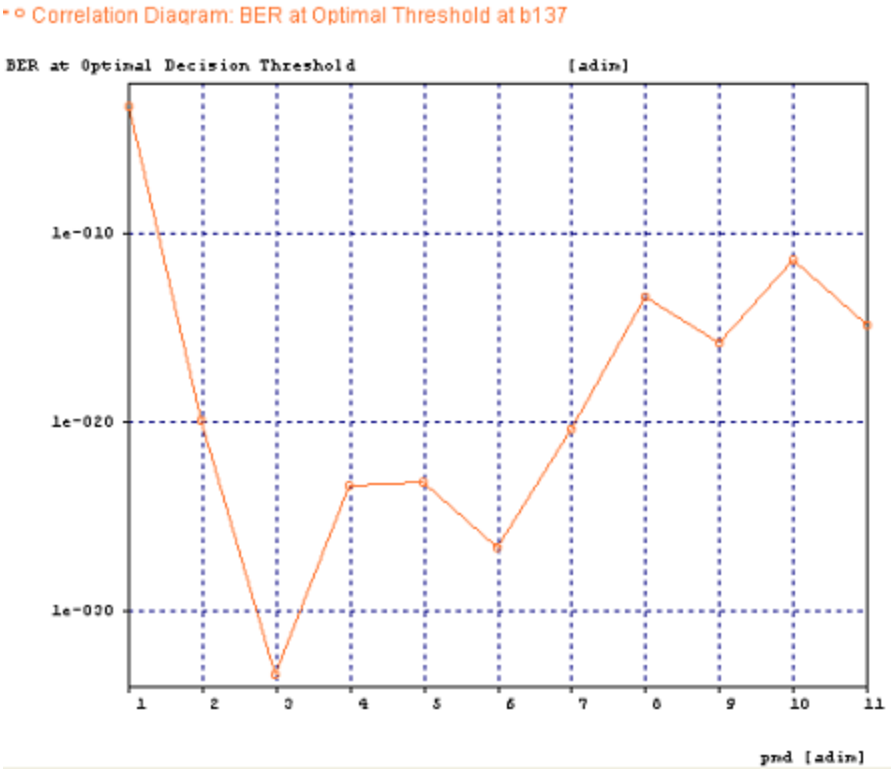
4.2.2 Results of post-compensation on first order PMD

Now we show the effect of the post compensation technique on the first order PMD. The effect of PMD at different bit rates is shown below :

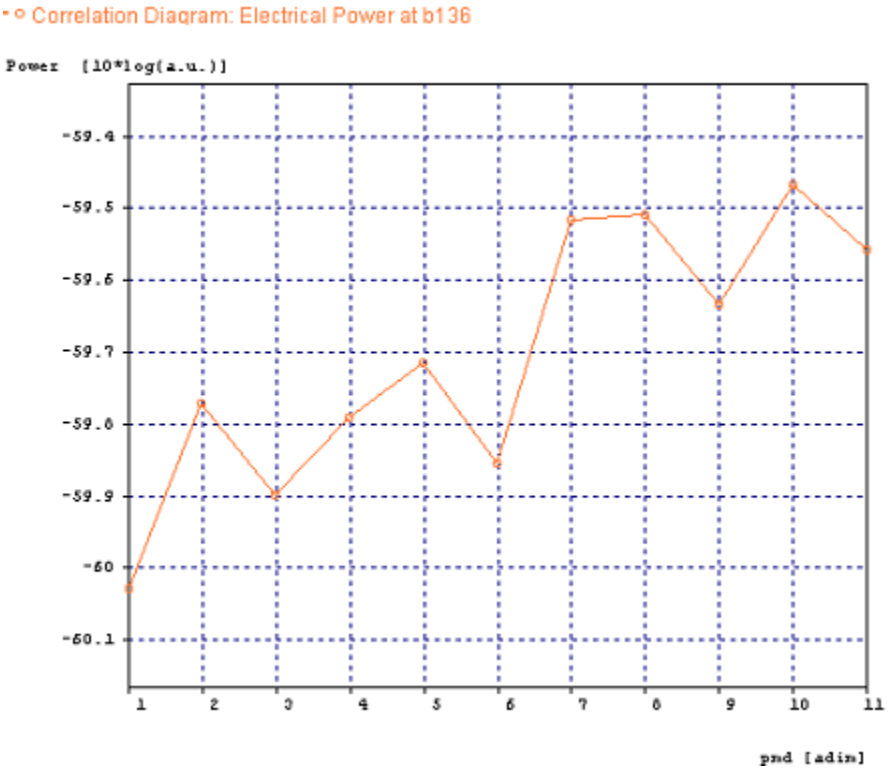
The figure 4.5 shows the Q value, BER, electrical power, eye opening, eye closure and eye diagrams at the corresponding values of PMD. All these figures are for the channel one of the transmitter section at 2.5 Gbps.



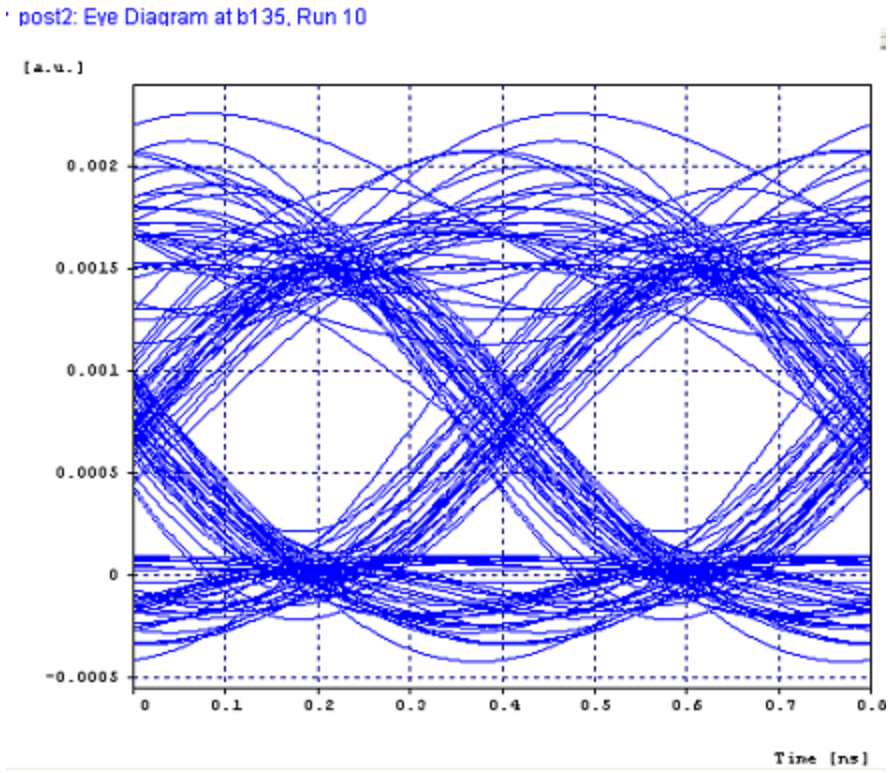
(a)


Correlation Diagram: BER at Optimal Threshold at b137
BER at Optimal Decision Threshold [adim]
1e-010
1e-020
1e-030
1
2
3
4
5
6
7
8
9
10
11
pnd [adim]

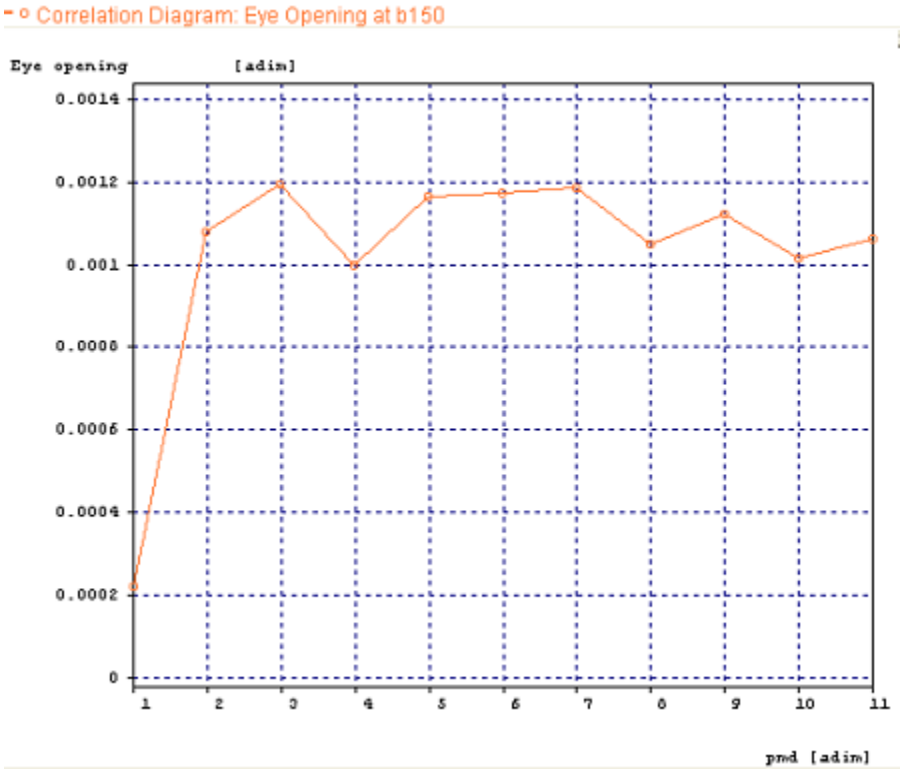
(b)


Correlation Diagram: Electrical Power at b136
Power [10*log(a.u.)]
-59.4
-59.5
-59.6
-59.7
-59.8
-59.9
-60
-60.1
1
2
3
4
5
6
7
8
9
10
11
pnd [adim]

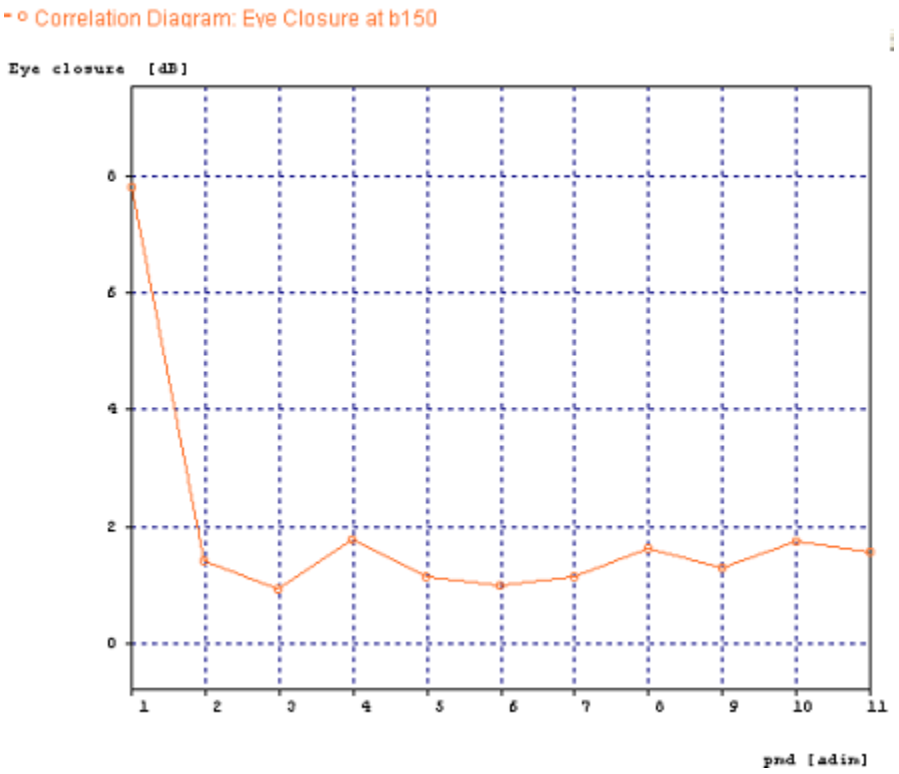
(c)


post2: Eye Diagram at b135, Run 10
[a.u.]
0.002
0.0015
0.001
0.0005
0
-0.0005
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Time [ns]

(d)


Correlation Diagram: Eye Opening at b150
Eye opening
[adim]
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
1
2
3
4
5
6
7
8
9
10
11
pmd [adim]

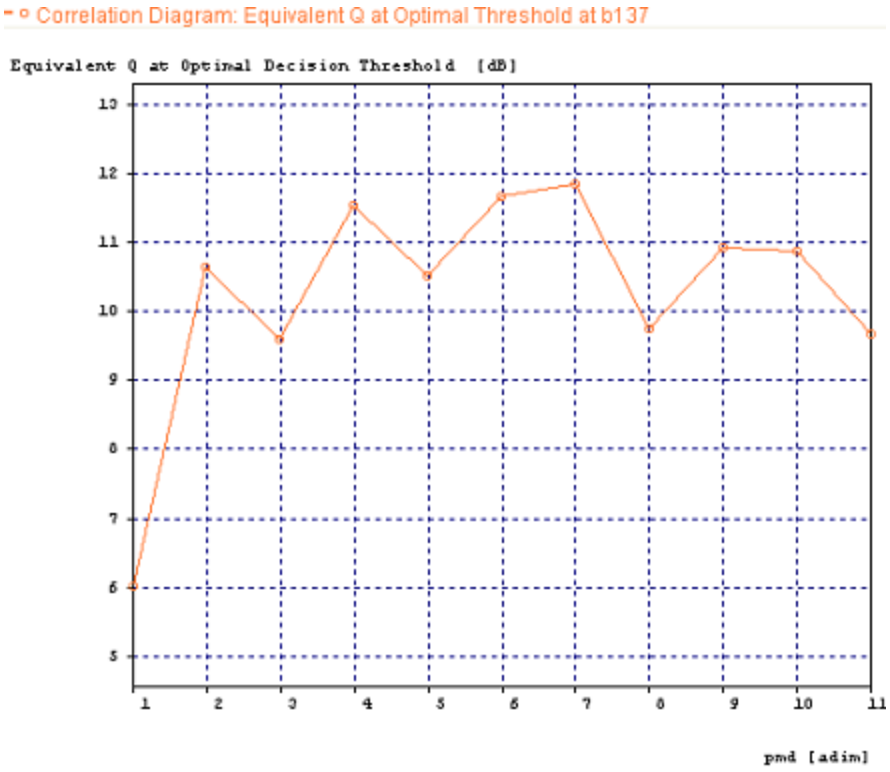
(e)



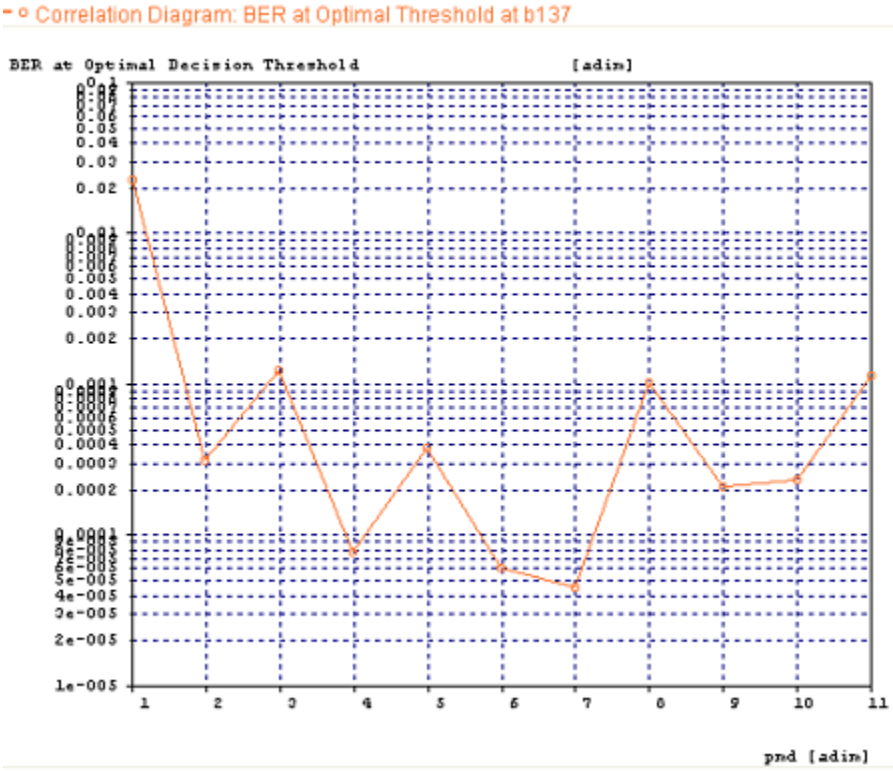
(f)

Figure 4.6: For channel 1 at 2.5 Gbps for NRZ raised cosine (a) PMD verses equivalent Q factor (b) PMD verses BER (c) the PMD verses electrical power (d) eye diagram at 10 *ps*/√ *km* (e) PMD verses eye opening (f) PMD verses eye closure.

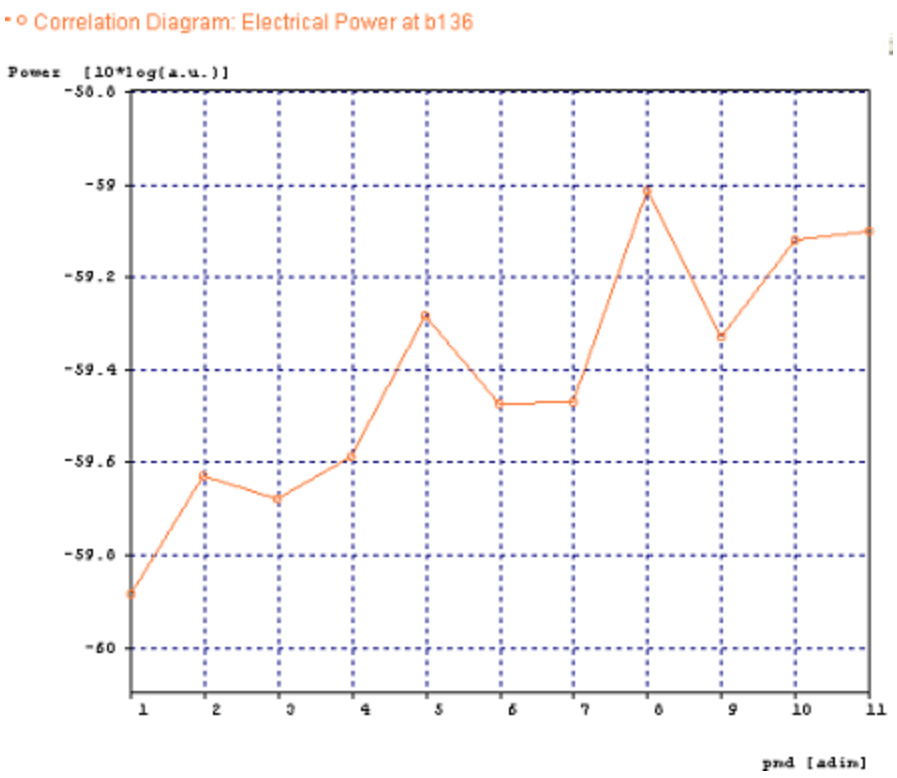
The figure 4.7 shows the Q value, BER, electrical power, eye opening, eye closure and eye diagrams at the corresponding values of PMD. All these figures are for the channel one of the transmitter section at 5 Gbps.


Correlation Diagram: Equivalent Q at Optimal Threshold at b137
Equivalent Q at Optimal Decision Threshold [dB]
13
12
11
10
9
8
7
6
5
1
2
3
4
5
6
7
8
9
10
11
pmd [adim]

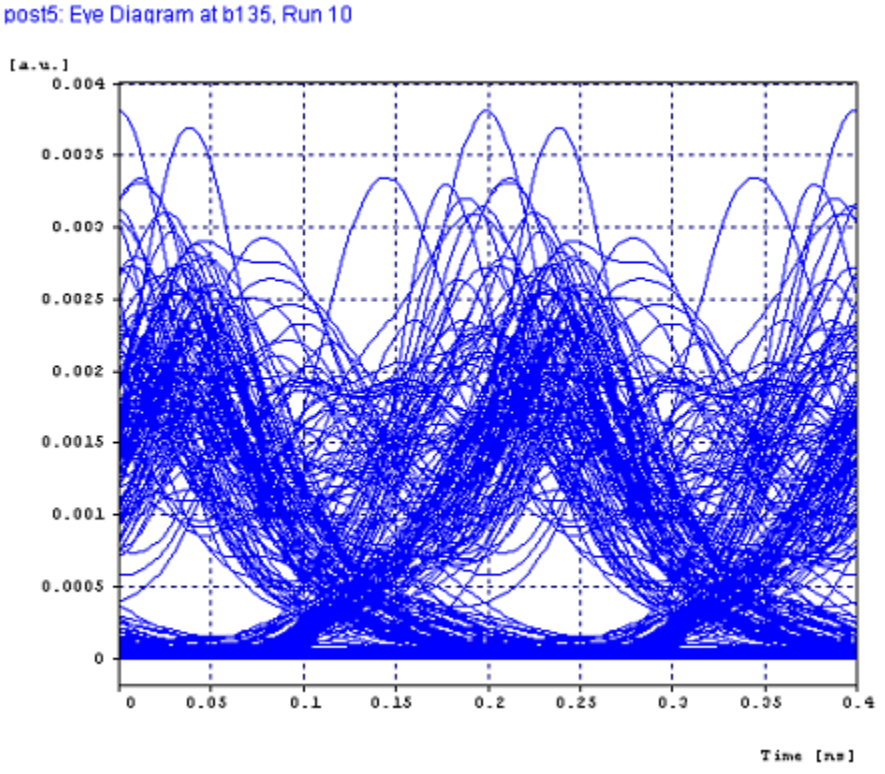
(a)


Correlation Diagram: BER at Optimal Threshold at b137
BER at Optimal Decision Threshold [adim]
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
9e-005
8e-005
7e-005
6e-005
5e-005
4e-005
3e-005
2e-005
1e-005
1
2
3
4
5
6
7
8
9
10
11
pmd [adim]

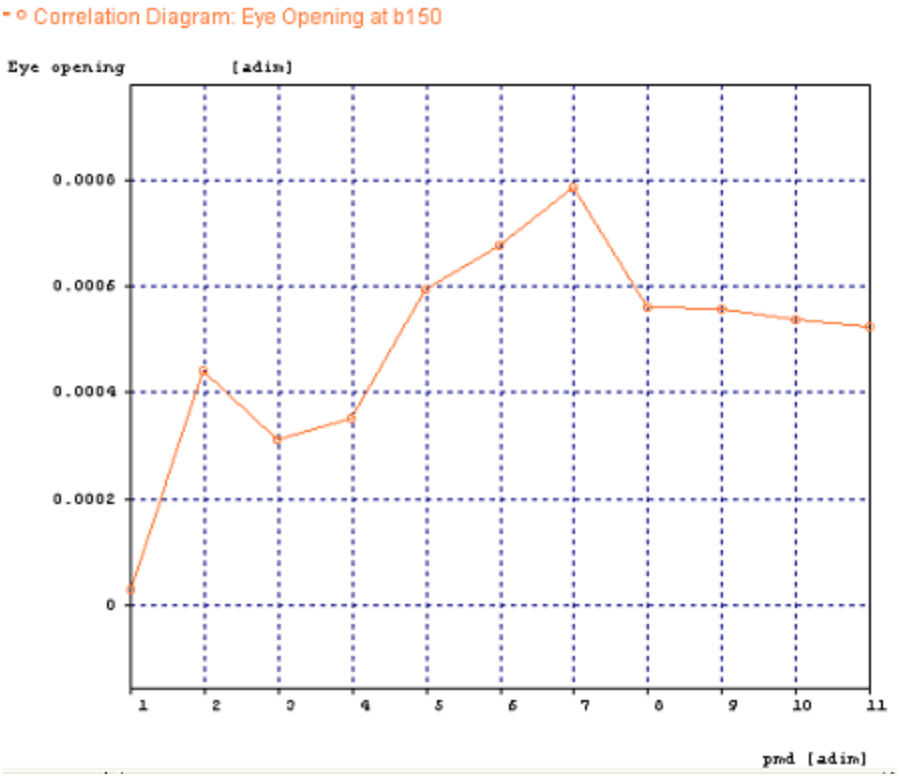
(b)


Correlation Diagram: Electrical Power at b136
Power [10*log(a.u.)]
-58.8
-59
-59.2
-59.4
-59.6
-59.8
-60
1
2
3
4
5
6
7
8
9
10
11
pwd [adim]

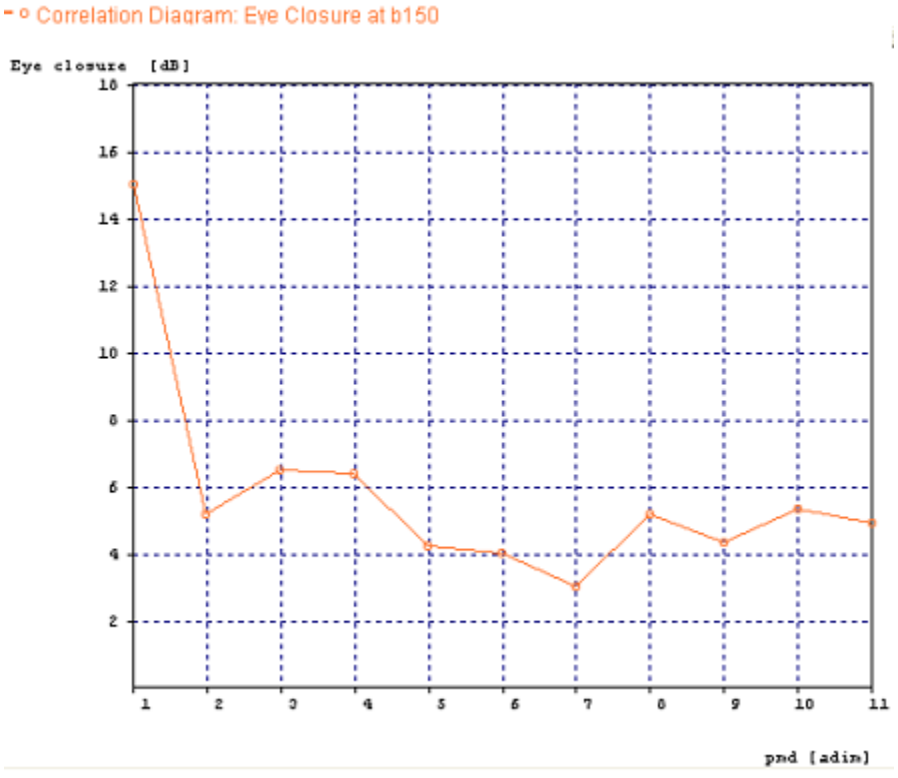
(c)


post5: Eye Diagram at b135, Run 10
[a.u.]
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Time [ns]

(d)


Correlation Diagram: Eye Opening at b150
Eye opening [adim]
0.0008
0.0006
0.0004
0.0002
0
1
2
3
4
5
6
7
8
9
10
11
pmd [adim]

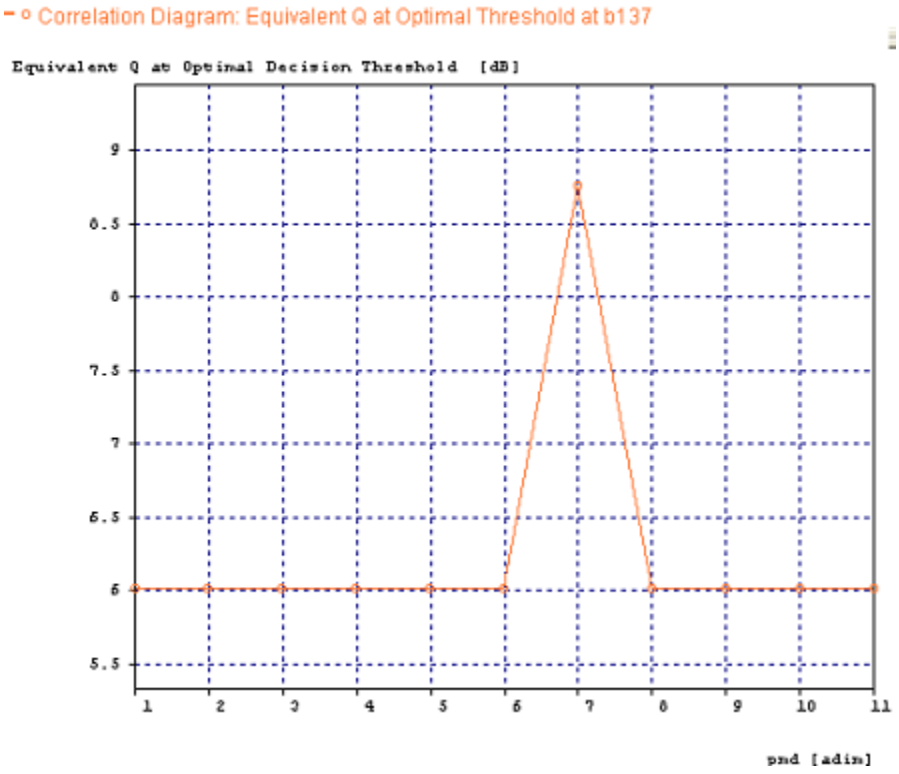
(e)


Correlation Diagram: Eye Closure at b150
Eye closure [dB]
16
14
12
10
8
6
4
2
1
2
3
4
5
6
7
8
9
10
11
pmd [adim]

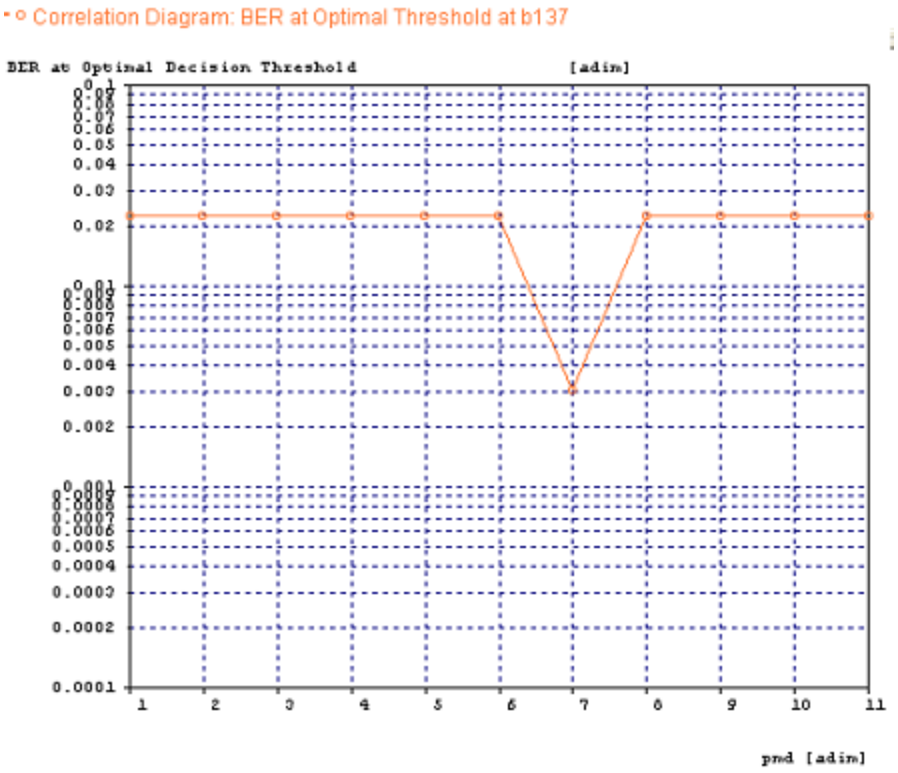
(f)

Figure 4.7: For channel 1 at 5 Gbps for NRZ raised cosine (a) PMD verses equivalent Q factor (b) PMD verses BER (c) the PMD verses electrical power (d) eye diagram at 10 *ps*/√ *km* (e) PMD verses eye opening (f) PMD verses eye closure.

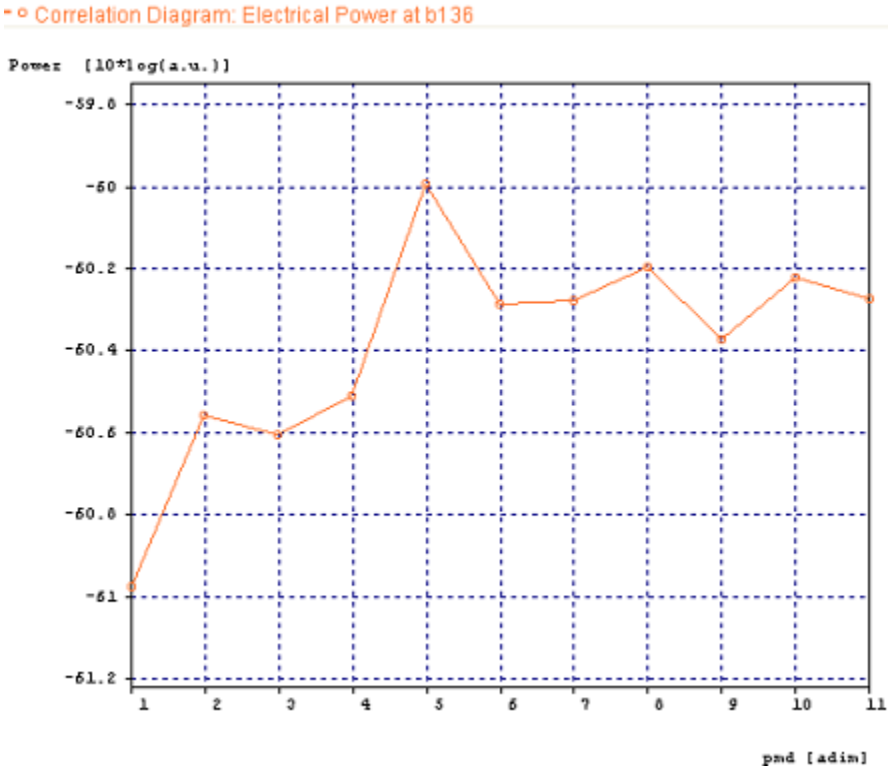
The figure 4.8 shows the Q value, BER, electrical power, eye opening, eye closure and eye diagrams at the corresponding values of PMD. All these figures are for the channel one of the transmitter section at 10 Gbps.



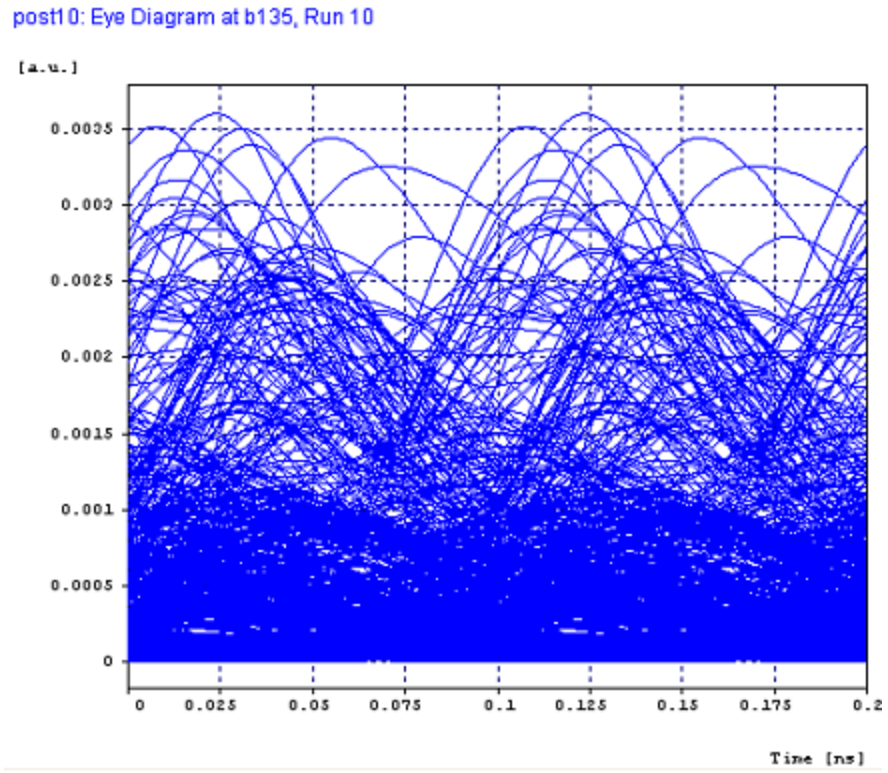
(a)


Correlation Diagram: BER at Optimal Threshold at b137
BER at Optimal Decision Threshold [adim]
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
1 2 3 4 5 6 7 8 9 10 11
pmd [adim]

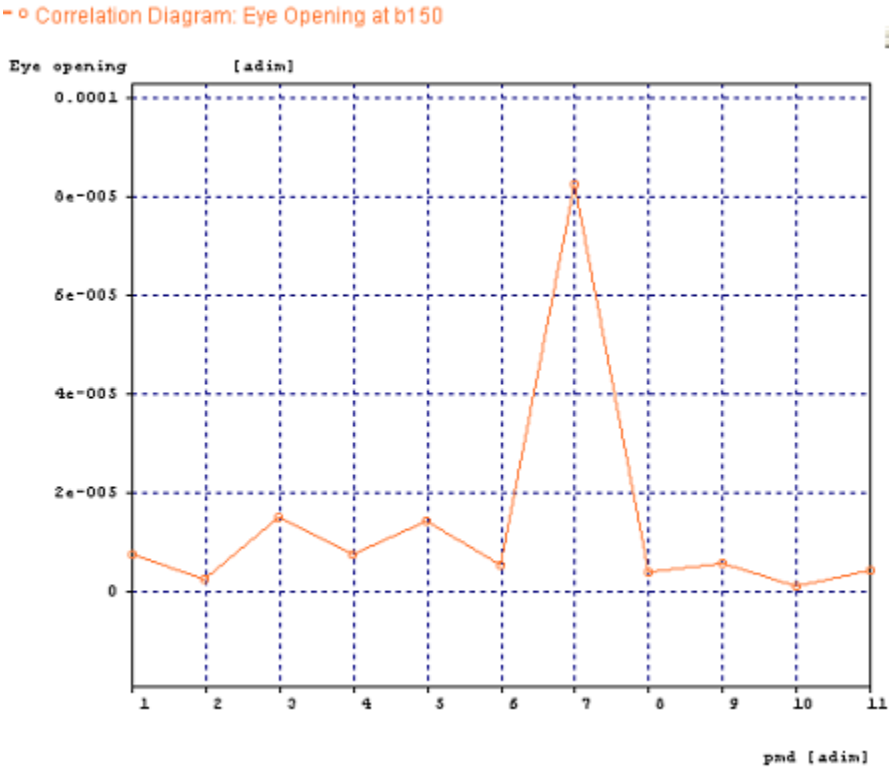
(b)


Correlation Diagram: Electrical Power at b136
Power [10*log(a.u.)]
-59.8
-60
-60.2
-60.4
-60.6
-60.8
-61
-61.2
1 2 3 4 5 6 7 8 9 10 11
pmd [adim]

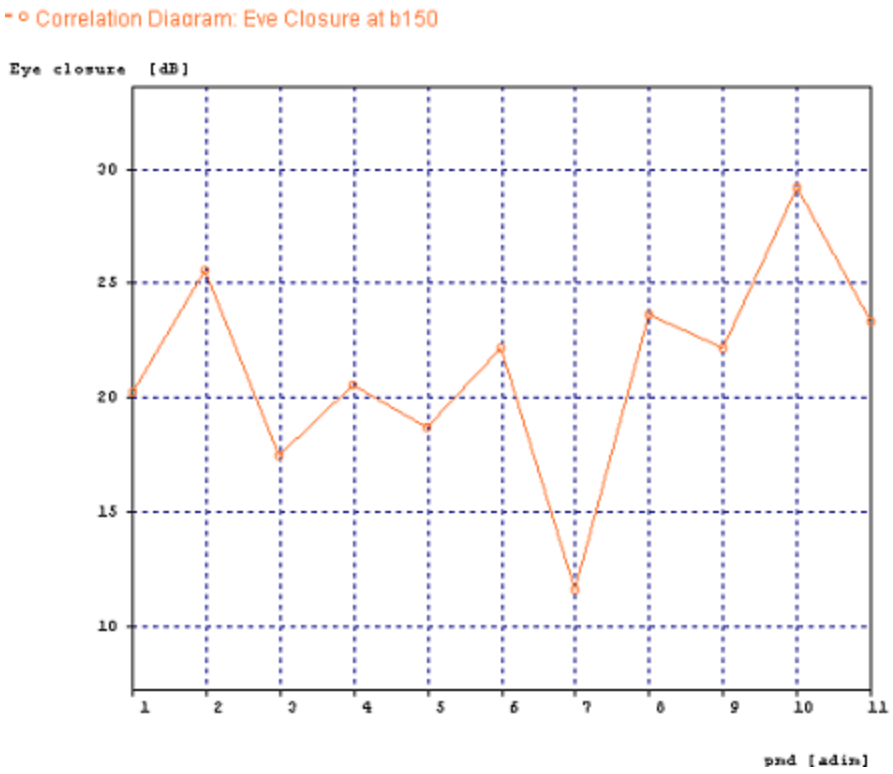
(c)


post10: Eye Diagram at b135, Run 10
[a.u.]
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
0
0.025
0.05
0.075
0.1
0.125
0.15
0.175
0.2
Time [ns]

(d)


Correlation Diagram: Eye Opening at b150
Eye opening
[adim]
0.0001
8e-005
6e-005
4e-005
2e-005
0
1
2
3
4
5
6
7
8
9
10
11
pmd [adim]

(e)



(f)

Figure 4.8: For channel 1 at 10 Gbps for NRZ raised cosine (a) PMD verses equivalent Q factor (b) PMD verses BER (c) the PMD verses electrical power (d) eye diagram at 10 *ps*/√ *km* (e) PMD verses eye opening (f) PMD verses eye closure.

4.3 Conclusion

Form the above results we have shown the variation of BER, Equivalent Q, Electrical power, eye opening, eye closure and eye diagrams at 10 *ps* /√*km*. We have shown all these parameters at different bit rates from 2.5 Gbps to 10 Gbps. Here, we find the effects of PMD on the output power and the eye diagrams. We find that as the PMD of the fiber channel increases the eye becomes closed. At 0 PMD the eye is more open as compared to the 10 *ps* /√*km* .

We know that as the PMD increases the BER increases and the output electrical power decreases but as we see in the above figures sometimes the BER decreases and the electrical power increases, this is due to the effect of the dispersion on the PMD. A linear effect of the dispersion compensates the nonlinear effects of the PMD of the fiber. We analyze the effect of the PMD on the system. As the PMD increases the BER of the system

increases because the input SOP does not match the PSP at the output of the system. We have also analyzed the effect of PMD on the Q factor of the system. As the PMD of the fiber increases the Q factor starts decaying.

Chapter 5

CONCLUSIONS AND FURTHER SCOPE OF WORK

The work presented here is emphasized on the effects of Polarization Mode Dispersion (PMD) over the optical transmission system and its simulation at different bit rates.

5.1 Conclusions

We analyzed the effect of changing the value of PMD in the 3rd chapter. This effect is seen from the eye opening, eye closing and output power characteristics which shows that the behaviour of PMD becomes unpredictable at higher bit rates of PMD. It is reported that the increase in the value of PMD causes the great fluctuations in the characteristics of the measured parameters. Also in this chapter we have shown that when we transmit the source the output gets dispersed. With the help of PMD emulator we can compensate the PMD, also we have shown the effect of using the delay.

In the 4th chapter we have shown the variation of BER, equivalent Q, electrical power, eye opening, eye closure and eye diagrams at different bit rates from 2.5 Gbps to 10 Gbps. We find that as the PMD of the fiber channel increases the eye becomes closed. As the PMD increases the BER of the system increases because the input SOP does not match the PSP at the output of the system. We have also analyzed the effect of PMD on the Q factor of the system. As the PMD of the fiber increases the Q factor starts decaying.

5.2 Scope for future work

The basic principle of how PMD exists in fiber optical communication systems is now well understood. There exists transmission systems using old fiber that are entirely limited to PMD even at data rate of 2.5 Gbps and there is still lot to do in order to combat PMD in practice. All actions to reduce the effect of PMD must be weighed against the cost of installing new, low PMD fiber. The PMD distribution along the link is also important for nonlinear solitons transmission systems.

The PMD monitoring mechanism based on DOP is here to stay. Following that will be the need to test the PMD compensation system's performance at 40 Gbps data rate. The bit-rate independence of the PMD compensation system will make the transition to the realm

of 40 Gbps a rather simple one. Next will be the issue of higher-order PMD. As we go towards upgrading the channel bit rate to 40 Gbps and beyond, also new fibers with low PMD will have their limitations. At 40 Gbps, the higher-order PMD (especially second-order PMD) effects will not be negligible. The performance of the PMD compensator can be evaluated in the higher-order PMD environment also. Finally, the PMD compensation system's performance can be evaluated for other modulation formats such as RZ (return to-zero) and NRZ (non-return to zero).

The research on PMD compensation is currently an intense but there are yet no commercial compensators available. Much research should be performed on how the error signal to the compensator is generated and on different algorithms to control the compensation.

Finally, all these aspects must be taken into account simultaneously in order to realize future ultra-high bit rate transmission systems, and further experimental studies must be performed on the signal transmission properties.

REFERENCES

[1] F.P. Kapron , D. B. Keck and R. D. Maurer, " Radiation losses in glass optical waveguides ," *Appl. Phys. Lett*., vol. 17, pp. 423-425, 1970.

[2]I. Hayashi, M. B. Panish, P. W. Foy and S. Sumski, "Junction lasers which operate continuously at room temperature," *Appl. Phys. Lett*. , vol. 17, pp. 109 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," *J. Lightwave Technol.*, vol.4, pp. 870-876, 1986.

[4] Rashleigh, S. C. & Ulrich, M. *Opt. Lett.* vol**.** 3**,** pp. 60–62 1978

[5] Poole, C. D. & Wagner, R. E. *Elect. Lett vol.* 22, pp. 1029–1030. 1986

[6] Poole, C. D. & Nagel, J. A. in *Optical Fiber Telecommunications*, eds. Kaminow, I. P. & Koch, T. L. (Academic, San Diego), vol. 3A, pp. 114– 161. 1997

[7] J. P. Gordon and H. Kogelnik, "PMD fundamentals: Polarization mode dispersion in optical fibers", vol. 97, pp. 4541-4550, 2000

[8] C. D. Poole, R. W. Tkach, A. R. Chraplyvy, and D. A. Fishman, Fading in Lightwave Systems Due to Polarization-Mode Dispersion, *IEEE Photonics Technol. Lett*. vol. 3 (1) pp 68-70 1991

[9] C. De Anglis, A. Galtarossa, G. Gianello, F. Matera, and M. Schiano, "Time evolution of polarization mode dispersion in long terrestrial links", *J. Lightwave Techno*l. vol. 10 (5) pp 552-555, 1992

[10] T. Takahashi, T. Imai, and M. Aiki, "Automatic compensation technique for timewise fluctuating polarization mode dispersion in in-line amplifier systems", *Electron. Lett*. vol. 30, pp. 348-349, 1994

[11] R. Noé, D. Sandel, M. Yoshida-Dierolf, S. Hinz, V. Mirvoda, A. Schöpflin, C. Glingener, E. Gottwald, C. Scheerer, G. Fischer, T. Weyrauch, and W. Haase, "Polarization Mode Dispersion Compensation at 10, 20, and 40 Gbps with Various Optical Equalizers", *J. Lightwave Technol*. vol. 17 (9) pp.1602-1616, 1999.

[12] J. H. Winters, and R. D. Gitlin, "Electrical signal processing techniques in long-haul fiber-optic systems", *IEEE Transactions on Communications*, vol. 38 (9)) pp.1439-1453, 1990

[13] J. H. Winters, and M. A. Santoro, "Experimental Equalization of Polarization Dispersion", *IEEE Photonics Technol. Lett*., vol. 2 (8) pp. 591-593, 1990

[14] H. Bülow, R. Ballentin, W. Baumert, G. Maisonneuve, G. Thielecke, and T. Wehren, "Adaptive PMD Mitigation at 10 Gbit/s Using an Electronic SiGe Equalizer IC, Proc. ECOC'99 II(WeC3.4) pp. 138-139. (Nice, France, 1999).

[15] G.J. Foschini and C. D. Poole, " Statistical theory in polarization dispersion in single mode fibers", Journal Of Lightwave Technology, vol. 9, pp. 1439- 1457, November 1991.

[16] T. Merker, N. Hahnenkamp, P. Meissner," Comparison of PMDCompensation Techniques at 10 Gbit/s Using an Optical First-Order Compensator and Electrical Transversal Filter", pp. 105-110.

[17] Ling-wei Guo, Ying-wu Zhou, Zu-jie Fang, " Pulse broadening in optical fiber with polarization mode dispersion and polarization dependent loss", Optics Communication pp. 83-87, 2003.

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

[19] Md. Zaini Jamaludin, Ahmad Fauzi Abas, Ahmad Shukri Muhammad Noor and Mohamad Khazani Abdullah, Issues On Polarization Mode Dispersion (PMD) For High Speed Fiber Optics Transmission, Suranaree J. Sci. Technol. 12(2):98-106, May 2005.

[20] J. P. Gordon and H. Kogelnik, "PMD fundamentals: Polarization mode dispersion in optical fibers", Bell Laboratories, Lucent Technologies, February 2, 2000.

[21] G. P. Agrawal, "Fiber Optic Comm. Systems", John Wiley and Sons, New York, 1997.

[22] R.K. Boncek, A. McCurdy, and A. Sorby, "Polarization Mode Dispersion, Frequently Asked Questions", ITU-T G.652 Characteristics of a single-mode optical fibre and cable, March 2003.

[23] Gerd keiser, "Optical fiber communication", third edition, Mc- Graw-Hill Series in Electrical Engineering.

[24] John M. Senior, "Optical fiber communication", second edition, Principles and practice, 1999.

[25] R. Khosravani, I. T. Lima, E. Ibragimov, A. E. Willner and C. R. Menyuk, " Time and Frequency Domain Characteristics of Polarization-Mode Dispersion Emulators", *IEEE Photonics Technology Letters*, vol. 13, pp.127-129, NO. 2, February 2001.

[26] Kogelnik, H., R.M. Jopson and L.E.Nelson, “Polarization-Mode Dispersion," Chapter 15, *Optical Fiber Telecommunications*, volume IV B, edited by I.P.Kaminow and T.Li, Academic Press, San Diego, CA, 2002.

[27] Poole, C. D. and R. E. Wagner, “Phenomenological approach to polarization mode dispersion in long single-mode fibers,” *Electronics Letters*, vol. 22(19), pp.1029- 1030, 1986.

[28] Poole, C. D. & Nagel, J. A. in Optical Fiber Telecommunications, eds. Kaminow, I. P. & 29 Koch, T. L. (Academic, San Diego), vol. 3A, pp. 114–161. 1997.

[29] N. S. Bergano and C. R. Davidson, “Wavelength division multiplexing in longhaul transmission systems,” J. Lightwave Technol., vol. 14, pp. 1229–1308, June 1996.

[30] I. P. Kaminov and T. L. Koch, Optical Fiber Telecommunications IIIA. San Diego, CA: Academic, 1997, ch. 8 and 9.

[31] T. Naito, T. Terahara, T. Chikama, and M. Suyama, “Four 5-Gbps WDM transmission over 4760-km straight-line using pre- and post-dispersion compensation and FWM cross talk reduction,” in Conf. Optical Fiber Communications ’96. Washington, DC: Opt. Soc. Amer., 1996, paper WM3.

[32] A. Sano, Y. Miyamoto, S. Kuwahara, and H. Tobo, “A 40 Gbps WDM Transmission with SPM/XPM Suppression Through Prechirping and Dispersion Management”, Journal of Lightwave Technology, 18(11):1519–1527, Nov. 2000.

[33] G.J. Foschini and C. D. Poole, “Statistical theory in polarization dispersion in single mode fibers”, Journal of Lightwave Technology, vol. 9, pp. 1439- 1457, November 1991.

[34] Daniel Mahgerefteh, Curtis R. Menyuk, “ Effect of first order PMD compensation on pulse broadening in a fiber with randomly varying Birefringence”, IETE Photonics Technology Letters. vol. 11, pp. 340-342, March 1999.

[35] M. Wegmuller, S. Demma, C. Vinegoni, and N. GIsin, “Emulator of first and second order polarization mode dispersion”, IETE Photonics Technology Letters. Vol. 14, pp. 630-632, May 2002.

[36] Ling Wei Guo, Ying-Wu Zhou, Zu Jie Fang, “Pulse broadening in optical fiber with PMD”, Optics communication, pp. 83-87, 2003.

[37] Andrew J. Stark, Yu-Ting Hsueh, Steven Searcy, Thomas F. Detwiler,, Cheng Liu and Mark M. Filer, “Scaling 112 Gb/s optical networks with the nonlinear threshold metric”, *J. Lightwave Technol.*, vol. 30, no.9, May 1, 2012

[38] Md Zaini Jamaludin, Ahmad Fauzi Abas, Ahmad Shukri Muhammad Noor and Mohamad Khazani Abdullah, "Issues on polarization mode dispersion (pmd) for high speed fiber optics transmission", Suranaree J. Sci. Technol. 12(2):98-106, May 27, 2005.

[39] S. Zentner Pilinsky, Z. Sipus, L. Sumichrast, "The Influence of Polarization Mode Dispersion on High Bit-Rate Optical Transmission Systems", IEEE photonic technology letters, 2004.

[40] G. P. Aggarwal, "Nonlinear fiber optics", Academic, New York, 2001.

[41] Fan Zhang, Christian-A. Bunge, Klaus Petermann and Andre Richter, "Optimum dispersion mapping of single-channel 40 Gbps return-to-zero differential phase shift keying transmission systems", Optics Express 6613, Vol. 14, No. 15, 24 July 2006.

[42] Ruben S. Luís, Daniel Fonseca, António Luís Jesus Teixeira, and Paulo Monteiro, "Dispersion Management of Electrically Pre-compensated RZ Single-Sideband Signals at 10 Gbps Without Inline Dispersion Compensation", IEEE Photonics Technology Letters, Vol. 19, No. 14, July 15, 2007.

[43] L.S. Yan, Q. Yu., A.E. Willner, X. Steve Yao, " Compensation of higher order polarization mode dispersion using polarization controller", IEEE Photonics Technology Letters, vol. 14, pp. 858-860, 2002

[44] T. Merker, N. Hahnenkamp, P. Meissner, "Comparison of PMD Compensation Techniques at 10 Gbit/s Using an Optical First-Order Compensator and Electrical Transversal Filter", *Institute for Hochfrequenztechnik*, pp 105-110.

[45] R.Gowri Manohari, T.Sabapathi, "Analysis and reduction of polarization mode dispersion in an optical fiber", 2011 International Conference on Recent Advancements in Electrical, Electronics and Control Engineering, pp. 438-441.

[46] J.H. Winters and M.A. Santoro, " Experimental equalization of polarization dispersion," *IEEE Photon. Technol. Lett.* , vol. 2, pp. 591-593, 1990.

[47] T. Ono, S. Yamazaki, H. Shimizu and H. Emura, "Polarization control method for suppressing polarization mode dispersion in optical transmission systems," *J. Lightwave Technol.*, vol. 12, pp. 891-898, 1994.

[48] T. Takahashi, T.Imai and M. Aiki, "Automatic compensation technique for timewise fluctuation PMD in inline amplifier systems", *Electron. Lett.* , vol. 30, pp. 348-349, 1994

[49] B. Bakshi, J. Hansryd , P. A. Anderekson, J Brentel, E. Koltveit, B. E. Olsson and M. Karlsson, " Experimental observation of soliton robustness to polarization mode dispersion pulse broadening", *Electron. Lett*., vol. 2, pp. 591-592, 1999.

[50] B. W. Hakki, "Polarization mode dispersion compensation using phase diversity detection", *IEEE Photon. Technol. Lett.*, vol. 9, pp. 121-123, 1997.