Compensation of Polarization Mode Dispersion

A Thesis

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Abstract

The topic of thesis is "Compensation of Polarization Mode Dispersion (PMD)" in Fiber optics communication and its impact on high speed data transmission. 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. The effect of using solitons has also been quantified in both conventional and dispersion managed, PMD distorted systems and. The new set-up uses the degree of polarization (DOP) of the received optical signal for monitoring the fiber-link's PMD.

By simulation we analyze the affec 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 of 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.

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LIST OF ABBREVIATIONS

DM	Dispersion Management
DOF	Degree of Freedom
DOP	Degree of Polarization
PDG	Polarization Dependent Gain
PDL	Polarization Dependent Loss
PMD	Polarization Mode Dispersion
PMF	Polarization Maintaining Fiber
SMF	Single Mode Fiber
TDM	Time Domain Multiplexing
XPM	Cross Phase Modulation

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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. The mid 1980s saw telecommunication carriers like Sprint establish extensive fiber optic backbone networks. And 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.

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.

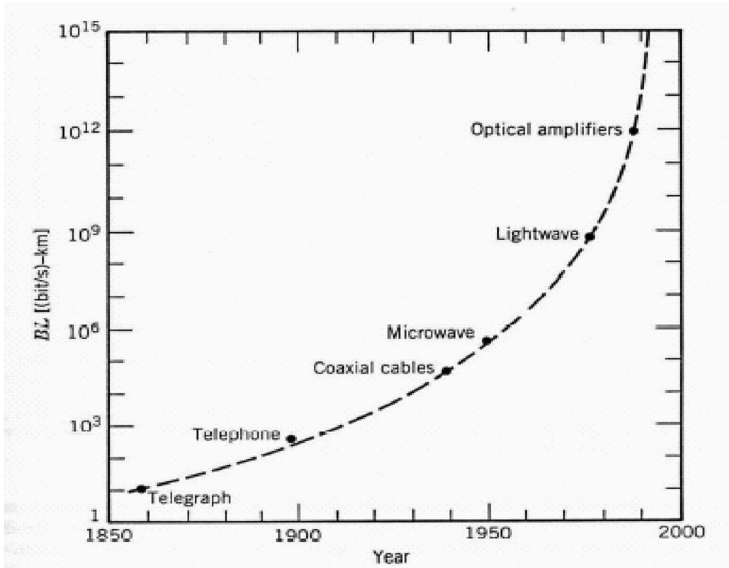


Figure 1.1: Increase in the bit rate –distance (B-L) product since 1850 [1]

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.

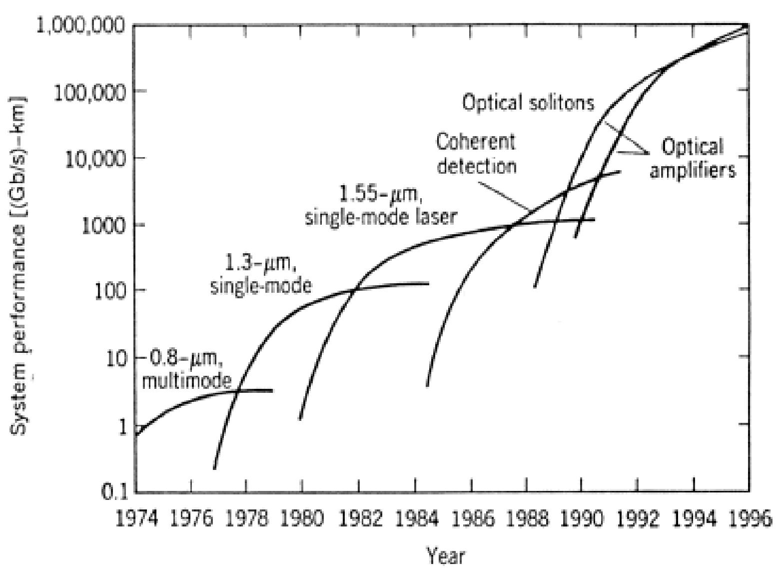


Figure 1.2: Progress in optical fiber communication since 1974

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 ($< 0.1 ps/\sqrt{km}$). 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.

Objectives of the thesis:

The various objectives are discussed below:

- 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 compensate ordering of PMD such as first order and second order PMD. To analyze the effect of using single polarization controller in first order and two polarization controller in second order of compensation.
- 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 20 $ps/\sqrt{km}$
- To analyze the effect of the PMD on the electrical power at the output of the system.
- Linear effects of the dispersion decays the effects of the non-linear effects of the PMD

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

Thesis Organization

In chapter 2, we discussed 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 this chapter we have talked about the various measurement techniques such as Jones matrix, Poincare Sphere etc. we also discuss the various compensation techniques and its types and the basics models of compensation of first-order, second order and higher order of PMD. Then we have presented the literature survey. In this topic we have talked about the research papers, which we analyze during our research period and what we have done after that. We have approximately discussed 15 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 and by using delay at different bit rates. There we have analyzed the results by using delay or after applying PMD emulator. This chapter also makes a system modeling of the solitons.

In chapter 4, we studied the different compensation techniques and how we apply them on the ordering of the PMD i.e. first order compensation or second order compensation. 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.

Chapter 2

POLARIZATION MODE DISPERSION

Polarization Mode Dispersion is a physical phenomenon in optical fiber that causes light pulses to spread in time. If the amount of spread (dispersion) is excessive, adjacent light pulses will overlap and interfere with each other. This interference will manifest itself as an increased Bit Error Rate as the receiver may be unable to discern adjacent bits from each other. As the bit spacing decreases, as in high data-rate transmissions such as 10 Gbps or 40 Gbps [18], excessive PMD will severely impact network operation.

2.1 Overview of PMD

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. While this is important for today's 2.5 and 10 Gbps networks [18], it will become critical as we progress towards Ultra Long-Haul 10 Gbps and 40 Gbps networks. Before PMD can be eliminated it must first be understood. As its name implies Polarization Mode Dispersion is based on the polarization of light. In essence, different polarizations of light travel at different velocities. You might ask yourself, "Shouldn't light travel at the speed of light regardless of its polarization state, it is still light after all?" While this is technically true, there is one more factor that must be considered, the medium in which the light is traveling. All things being equal, light will propagate at the same velocity regardless of its polarization state, however, in a silica-based optical fiber, all things are not equal.

As a result of a property of optical fibers called 'birefringence', different polarizations of light are propagated at different velocities through the fiber. As laser light is generally highly polarized, the digital bits that they emit contain light that is also highly polarized. 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 [19]. 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.

As bit rate increase to 10 Gbps and 40 Gbps, polarization mode dispersion becomes one of the leading causes of the signal degradation in data transmission [20, 21]. A physical phenomenon in optical fiber that is statistical in nature, PMD causes dispersion or spreading of pulses in time and distance, causes adjacent signal pulses to overlap and produce bit errors. As the bit spacing decreases, such as in high data transmission rates, PMD adversely impacts the performance of optical networks.

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), inter-modal dispersion is nonexistent.

Polarization mode dispersion (PMD) is caused by asymmetries and stress distribution in the fiber core, which locally leads to birefringence [22], i.e. a polarization dependent refractive index. Globally, the birefringence is combined with random polarization mode coupling to understand how PMD arises in optical fibers, it is best to start by considering a short section with uniform birefringence within a long span. Any single mode fiber can than be modeled as a concatenation of many such arbitrarily oriented birefringent elements.

2.1.1 Refractive Index

Light within a medium travels at a slower speed than in a 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 traveling 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 [23].

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) traveling at different speeds through the fiber. The result is a Differential Group Delay, measured in $ps/\sqrt{km}$, 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.

2.1.2 Birefringence

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

$$\Delta\beta = \beta_s - \beta_f = \frac{\omega n_s}{c} - \frac{\omega n_f}{c} = \frac{\omega \Delta n}{c} = \frac{2\pi}{\lambda}\Delta n \qquad 2.1$$

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 the 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 2.1. 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.

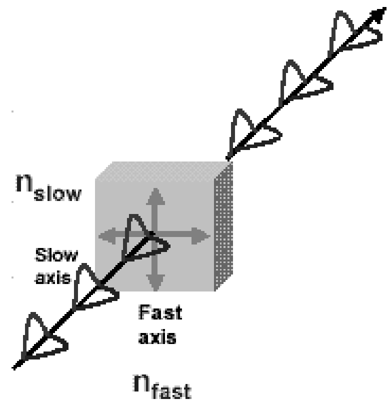


Figure 2.1: The local birefringence in an optical fiber changes the polarization state of the light from linear to elliptic, circular etc.

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,** $L_B = \lambda / \Delta n$ **.** 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 eq. 2.1 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), $\Delta \tau$, which is obtained by taking derivative with respect to frequency of the propagation constants of eq. 2.2, i.e.

$$\Delta \tau = \frac{L}{\Delta v_g} = \frac{d\Delta\beta}{d\omega} L = \left(\frac{\Delta n}{c} + \frac{\omega}{c} \frac{d\Delta n}{d\omega} \right) L \qquad 2.2$$

where Δv_g is the group velocity difference between the orthogonal modes. The quantity $\Delta \tau / L$ is usually expressed in units of picoseconds per kilometer of length for a uniformly birefringent element such as a short fiber length. Figure 2.1 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)[25,26].

2.2 Pulse-broadening due to PMD

It is relatively easy to determine the pulse broadening/ splitting that occurs as an effect of pure first order PMD. Some investigations have been made on pulse broadening due to lower- order PMD (first and second) [27, 29]. However, an explicit formula for the RMS broadening of pulses affected by (all-order) PMD was recently derived [28]. The output pulse width (in the absence of chromatic dispersion) is given by

$$\tau^2 = \tau_o^2 + \frac{1}{4}\left(\langle\Omega^2\rangle - \left[s.\langle\Omega\rangle\right]^2\right) \qquad 2.3$$

where τ is RMS intensity pulse width, τ_0 is the initial RMS pulse width, s is the input polarization state of the signal in stokes space, f(t) is the initial pulse amplitude and $f(\omega)$ and its Fourier transform is defined as f(ω)= $\int_{-\infty}^{\infty} f(t)\exp(-i\omega t)d\omega$. Finally, the bracket notation indicates integration over the normalized pulse spectrum, so that $\langle a\rangle \equiv \frac{1}{2\pi}\int_{-\infty}^{\infty} a\left|f(\omega)\right|^2 d\omega = a$, if a is constant. To apply this formula, the measured DGD (and PSPs), is integrated over the pulse spectrum. In the special case of pure first-order PMD, the PMD-vector is constant, $\Omega = \Delta\tau\Omega$ and the pulse broadening is given by

$$\tau^2 = \tau_0^2 + \frac{\Delta\tau^2}{4}\left(1 - (s.\Omega)^2\right) \qquad 2.4$$

The maximum broadening is obtained if the pulse is launched between the PSPs so that $s.\Omega = 0$, while no broadening occurs when $s..\Omega = \pm 1$, which corresponds to launching the pulse into the PSP. The expected pulse broadening in the presence of an average PMD can also be determined by calculating the expected value.

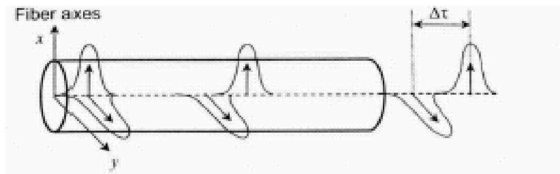


Figure 2.2: A pulse launched with equal power on the two birefringent axes x and y of a short fiber segment gets separated by the DGD (□□) at the output [22]

As mentioned earlier, since all telecommunication grade fibers fall in the “long” fiber category, it is necessary to bring out their differences from the “short” fibers. The relation between PMD induced delay and fiber length is no longer linear in the case of long fibers. This is because of the phenomenon called mode coupling that is taking place in all fibers longer than a certain statistical length called correlation length or coupling length. Fibers that are shorter than the correlation length are considered to belong to the “short” fiber category and all the other fibers are considered to belong to the “long” fiber category. As a lightwave propagates down a fiber, there is a constant sharing of energies between the two propagating modes. This random exchange of energies is due to the varying stresses or perturbations that are experienced by the fiber along its length.

In order to define the correlation length, let us assume that a lightwave signal is input into a fiber, aligned to a certain polarization mode. The correlation length is a statistical quantity defined as the length at which the average power in the orthogonal polarization mode (the mode perpendicular to the input mode) is within $\frac{1}{e^2}$ of the power in the input mode [2]. The correlation length can vary between a few meters to more than a kilometer depending on whether it is a spooled fiber or a cabled fiber. The effect of mode coupling is that the DGD has a square root of length dependence rather than a linear length dependence.

However, in either case, PMD causes dispersion or broadening of the lightwave signal. Whereas this broadening is predictable in the case of short length fibers, it is probabilistic for long length fibers. In digital fiber-optic systems, estimating the power penalty incurred can assess the PMD effects. The expression for the PMD induced power penalty is [2]:

$$\varepsilon \equiv A\frac{\Delta\tau^2\gamma(1-\gamma)}{T^2} \qquad 2.5$$

where, γ is the power penalty in dB, $\Delta\tau$ is the DGD, □is the power splitting ratio between the two component modes (0,1), *T* is the full-width at half maximum of the lightwave pulse. The factor *A* is a dimensionless parameter determined by the pulse shape and receiver characteristics. Another relation that gives an estimate of the PMD induced limitation on the bit rate and the span of a digital fiber-optic system is [2]:

$$B^2L = \frac{0.02}{(PMD)^2} \qquad 2.6$$

where, B and L are the bit-rate (Gbps) and link length (km), respectively, and PMD has the units of ps/$\sqrt{\ }$km. This relation was arrived at by considering the case that the PMD induced delay must be less than 14% of the bit period in order to avoid incurring PMD-induced power penalty of 1 dB or greater for a period of 30 min per year [2]. Figure 1.5 shows the bit error fluctuations due to the variable nature of PMD and the influence of temperature on its variability.

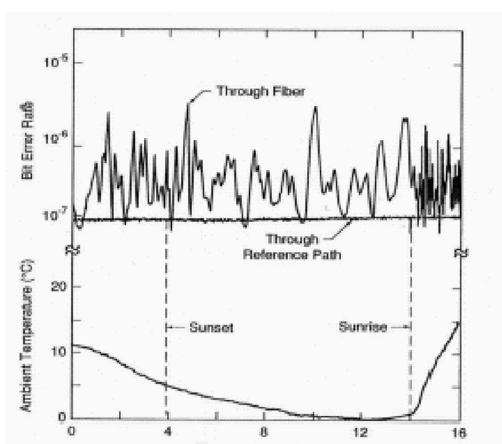


Figure 2.3: Measured bit error rate fluctuations due to PMD in a digital fiber optic system. The rate of ambient temperature change appears to change the rate of the fluctuations.

2.3 Causes of PMD

The major cause of the PMD is the asymmetry of the fiber optic strand. Asymmetry is simply that the fiber core is slightly out of round, or oval. Fiber asymmetry may be inherent in the fiber from the manufacturing process, or it may be a result of mechanical stress on the deployed fiber. The inherent asymmetries of the fiber are fairly constant over time. The mechanical stress on the optical fiber can originate from a variety of sources. One that very difficult to control is diurnal (day and night) and seasonal heating and cooling of the optical fiber. Another source of mechanical stress can originate from nearby sources of vibration. For example, much fiber is deployed alongside railroad tracks because of the ease of right-of-way and construction. However, vibrations from passing trains can contribute to stress on the optical fiber. Although much fiber is deployed in the ground and often within conduits, it is still subject to temperature variations and corresponding mechanical stress. PMD can vary in different section of fiber and so can the number of sections that exhibit these differing PMD values. Longer fiber and higher PMD coefficient equate to more asymmetry, lower quality, and higher PMD [22,30].

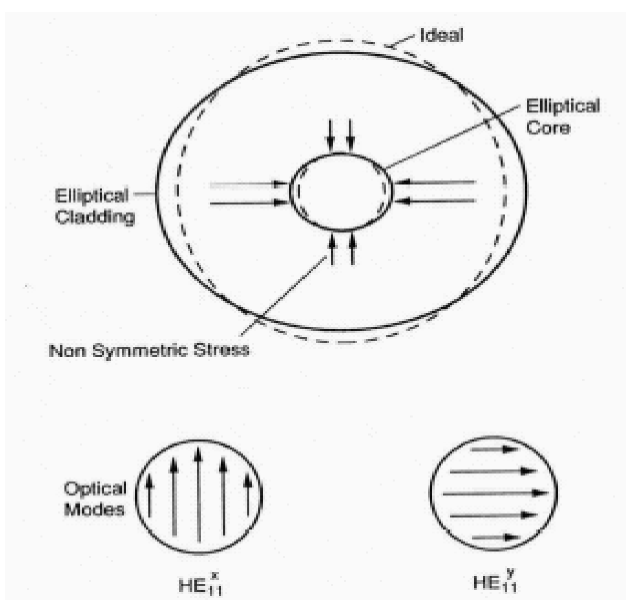


Figure 2.4: Stresses and modes in a single mode fiber [2]

In reality, however, there are two modes of propagation of light even through a single-mode fiber. In spite of the measures taken to provide a symmetrical core cross-section, there is some asymmetry. (Figure 2.4 illustrates how stress can induce asymmetry in the fiber core). The consequence of this asymmetry of core cross-section is the existence of birefringence. As a result, when a light pulse is input into a fiber core, it is decomposed into two orthogonally polarized components that propagate with different propagation characteristics [22,30]. The pulses arrive at the output differentially delayed. This difference between the delays is termed as the differential group delay (DGD). It is this DGD that causes an input pulse to appear broadened at the output. And this effect on the pulse is commonly called PMD.

2.4 Effects of PMD

The effects of PMD are signal degradation and data loss. Relevant parameters here are a power penalty or BER and an outage probability. Power penalty is measured in decibels, i.e., the amount of signal power the fiber can attenuate before there is an unacceptable the bit error rate. If, for example the in addition to the time variance, PMD also varies over wavelengths. PMD is the single biggest challenge facing system vendors and carriers as they attempt to deploy 40 Gbps optical networks. However, PMD is not just a problem at 40 Gbps; it is also evident in 10 Gbps optical networks as well. PMD, and specifically DGD, can disperse the transmitted optical bit and cause bit errors at the receiver. If there is relatively few bit errors at the receiver, than usually other mechanisms of the transmission system can satisfactorily recover the lost transmitted information. The DGD component of PMD was measured in time separation of the polarized pulses of the optical bit[22,30]. The average separation can be calculated from the PMD coefficient of the fiber.

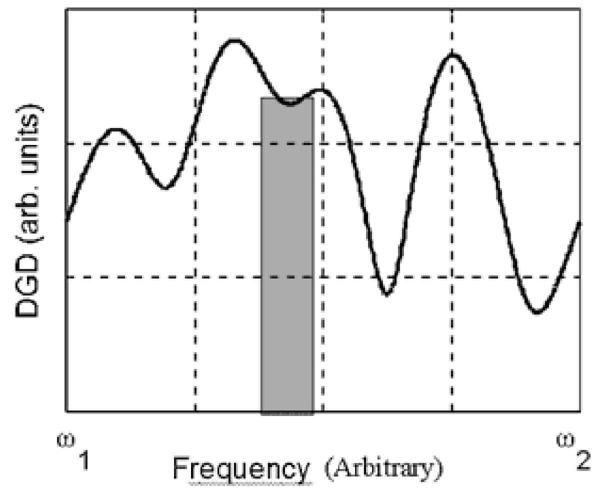


Figure 2.5: This shows how DGD varies with frequency

2.5 Characterization of PMD

PMD in telecommunication fibers is a stochastic or random process. Therefore the penalties due to PMD are also random. In order to develop effective compensation techniques it is necessary to understand the nature and characteristics of PMD.

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. 3 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.

PSP and DGD themselves exhibit dependence on optical frequency. Higher order PMD become important when the bandwidth of the optical signal is large compared with the PMD frequency dependence. 10Gbps and 40Gbps signals typically suffer from higher order PMD due to their wide channel bandwidths. HOPMD is difficult because the PSP shift, changing the direction of the PMD vector over the channel bandwidth.

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 [32]:

$$\vec{\tau} = \Delta\tau\widehat{P} \qquad 2.7$$

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 ($\widehat{P}$) is along the axis that joins the two output PSP points in Stokes space [31,32]. Any input state of polarization (SOP) can be expressed as the vector sum of two components, each component being aligned with one of the PSPs. For a narrow band source (i.e., considering only first-order PMD) the output electric field vector from a fiber can be given as [33]:

$$\overline{E_{out}}(t) = c_+ p_+ .\overline{E_{in}}(t+\tau_+) + c_- \ p_- .\overline{E_{in}}(t+\tau_-) \qquad 2.8$$

where

$$\overline{E_{out}}(t) and \overline{E_{in}}(t)$$

are output and input electric field vectors respectively. c_- and c_+ are complex coefficients required to indicate the field amplitude launched along the slow PSP and fast PSP respectively. The magnitudes, | c| and | c|, correspond to the power splitting ratio , seen in (1.3). $p_+ and p_-$ are unit vectors specifying the output polarization states (referred to as output PSPs) of the two components. The difference is $\Delta\tau$, the DGD. This relation shows that the amount of broadening of the output pulse due to PMD is dependent upon the values of the quantities, c_- and c_+.

2.6 Measurement methods of PMD

A number of different techniques have been demonstrated for measuring the PMD in a fiber. Techniques that make use of a polarimeter, which can measure the output polarization state, are necessary for a full theoretical interpretation and convenient for measurement for both the DGD and PSPs as a function of wavelength. Two examples of this category are **Poincare sphere** method and **Jones matrix method.** A simpler technique that is not dependent on a full polarimeter is the **Fixed analyzer technique,** which in principle is only able to determine one component of the polarization Stokes vector. The backscattering techniques for measurement of distributed PMD, which will be discussed later [34,35,21].

It is impractical to try to measure dispersion in real time due to the high frequency involved .We shall discuss various PMD measurement techniques in brief

Techniques of measuring PMD

- Wavelength scanning /fixed analyzer (frequency domain)
- Interferometeric method (time domain)
- Jones matrix eigen analysis (frequency domain)
- Poincare sphere

2.6.1 Wavelength scanning/ fixed analyzer method

In both wavelength scanning method – Fourier's transform method and extreme counting data, is performed with either one of the two steps as shown in fig. The source polarizer (p) and the analyzer input polarizer (p) are fixed at same value .For the constant launch polarization state the transmission power verses wavelength is performed .In the absence of birefringence in the DUT , the polarized light from the source would always reach the analyzer polarization at the same angle and the constant power would be measured as shown in fig. However, where birefringence is involved, polarization state turns in a cyclic fashion proportional to the birefringence. The polarization output power also reflects the cycles. The number of extreme can be counted and PMD can be obtained

2.6.2 Interferometeric method

This method typically uses the set up shown in fig. The interferometer may be of Michelson type with an open beam splitter, a prismatic beam splitter or a fiber coupler. The moving mirror introduces a variable delay between the two interferrometric forms and each polarization state is recombined according to this delay scanning the delay makes sure autocorrelation possible. The integration is performed by the detector and the delay is swept by the mirror. The closer the frequencies, the longer the two signals can be sufficiently synchronized to be combined through constructive interferences In the absence of PMD, the autocorrelation measurement yields the coherence time autocorrelation of the source. PMD thus can be obtained, since, it increases the effective coherence time of the source and its autocorrelation width.

2.6.3 Jones matrix

Polarization dependence is also characterized by Jones matrix very suitably. In the former case, we use real four element vectors, real 4*4 Mueller matrices. In that case, two waves are added incoherently (addition of optical powers), and then the Strokes vector of resulting wave is the sum of the individual vectors. Now in this case when two waves are added coherently (addition of optical fields), Jones vector of the resulting wave is the sum of the individual Jones vectors and complex 2*2 matrices. In cases, when polarization states are not known at each point individually. The evolution of optical fields in the fiber can be described by the complex

Jones matrix T

$$\begin{bmatrix} E_{ox} \\ E_{oy} \end{bmatrix} = T \begin{bmatrix} E_{ix} \\ E_{iy} \end{bmatrix} \qquad 2.9$$

Where E_i and E_o are the Jones vectors describing the input output optical field, respectively. The fiber attenuation (α) and average propagation constant (β) can be taken out of the Jones Matrix .

$$T = \exp\{-(\alpha/2 + j\beta)z\}U \qquad 2.10$$

When there is no polarization dependent loss, the normalized Jones matrix U is unitary . The matrix U can then be written as ,

$$U = \begin{bmatrix} U_1 & U_2 \\ -U_2^* & U_1^* \end{bmatrix} \qquad with \qquad |\mathrm{u}_1|^2 + |u_2|^2 = 1 \qquad 2.11$$

where u_1 and u_2 are complex numbers, that usually are function of wavelength

$$\varpi_1 = |u_1|^2, \quad \omega_2 = |u_2|^2, \quad \varphi_1 = \arg(u_1),$$

so, $u_1 and u_2$ are written as

$$u_1 = \sqrt{\omega_1} e^{j\varphi_1}$$

$$u_2 = \sqrt{\omega_2 e^{j\varphi_2}}$$

$Both \omega_1 and \omega_2$ are in the interval $[0,1]$, since $\omega_1 + \omega_2 = 1, \omega_1 \geq 0, \omega_2 \geq 0$.

The phase $\varphi_1 and \varphi_2$ are in the interval $[0,2\pi]$: So, all phases are modulo 2π

2.6.4 Poincare sphere method

This technique provides perhaps the simplest correspondence to theory and the definition of PMD. By measuring the output SOP versus frequency (wavelength) for at least two input SOPs, the PMD-vector, Ω, and its modulus, the DGD, $\Delta\tau$, can be obtained as a function of frequency (wavelength). PMD vector can be calculated by the following equation

$$\Omega(\omega) = \frac{\frac{ds_i}{d\omega} * \frac{ds_j}{d\omega}}{\frac{ds_i}{d\omega} . s_j} \qquad 2.12$$

where $s_i and \;\; s_j$ represents two output SOPs. A large error in the calculations can occur when one of the output states is near one of the PSPs, so that the cross product in equation above is small. Therefore, three input SOPs can be used to minimize the error, where pairs of measurements must satisfy certain criteria. This removes inaccurate measurements, where the SOPs are close to the principle states. The PMD vector can be calculated as the average of the vectors that satisfy the criteria. This technique utilizing gated Rayleigh scattered light to measure the DGD accumulation along the installed fibers.

Three polarization effects that leads to impairments in the long haul optical fiber transmission system are:

- PMD
- Polarization dependent loss (PDL)
- Polarization dependent gain (PDG)

2.7 PMD compensation

Number of methods has been suggested to compensate or reduce the influence of PMD in fiber optic systems. The main problem is the temporal drift of the PMD characteristics, which requires any compensation technique to dramatically adapt to changes while the system is in service. Simulating PMD for continual testing of compensators and equipment tolerances has proven to be a very difficult, costly, and time consuming process due to its dynamic nature. The emulation of PMD allows the recreation of rare events and behaviors of an optical field fiber in the laboratory more often and accurately than one can observe in the field. To properly emulate PMD in real world situations the emulator must have the ability to change the SOP at a very fast rate, emulate first and higher order PMD simultaneously, and be capable of simulating actual existing situations in the real world due in part to the dynamic fluctuations of PMD [36]. Many of the research and development groups that have demonstrated PMD emulators tend to rely on randomly varying the polarization state of light launched into PM (Polarization Maintaining) fiber sections or expensive birefringence crystals. Sunrise Telecom, collaborating with the University of Ottawa, has created the new Dynamic Polarization Mode Dispersion Emulator (DPMDE) [37] DPMDE raises the existing technology to a higher level by randomly varying the birefringence of each squeezer in a biased manner to track the dynamics of PMD in time. This allows for specific environmental characteristics or fiber types to be emulated.

The different compensation methods have been divided into different categories, depending upon whether the compensation is performed electrically, opto electronically or optically or whether the compensation is performed before or after transmission (pre- or post- compensation). A straight forward method to reduce the PMD effects optically is to launch the signal into a PSP.

It is defined as a first order compensation as it enables compensation of PMD to first order only. Optical post compensation is currently intense research fields where both first and higher order compensators have been suggested two main problems have been focused upon; how an error signal should be extracted and how the PMD induced distortion should be compensated [36-51].

2.7.1 Techniques of compensation of polarization mode dispersion

There are four techniques that are able to cope with polarization fluctuations:

a. Polarization control.

This technique tries to keep the state of polarization (SOP) of the received signal under control by means of endless control schemes such as using polarization maintaining fiber transducer or integrated optic lithium niobate (LiNbO3) device.

b. Polarization-maintaining fibers.

These special types of fabricated fibers can maintain the State of Polarization (SOP) once the light is launched from the fiber. This is the easiest method; however the disadvantage of polarization-maintaining fibers is that they are very expensive to fabricate.

c. Polarization scrambling.

This technique works on a principle that spreads the signal power over different States of Polarization (SOP) during transmission of every bit, so that the system performance is unaffected by the changes in the received field.

d. Polarization diversity.

This technique aims at modifying the receiving strategy so that the system performance is unaffected by the changes of the received field.

All the PMD compensation must employ a feedback or a feed-forward system. Polarization mode dispersion has long been regarded as a severe, ultimate limitation in high bit rate optical fiber communication systems. Consequently, there is a large interest in techniques of PMD compensation. Several models have been framed and put into practice. Due to the statistical nature of PMD, PMD compensators have to be adaptable. Most current PMD compensators employ feedback control algorithms, which continuously adjust multiple control parameters to optimize the signal quality. The compensators functions and complexities are both determined by the number of control parameters. High order PMD compensator requires a large number of control parameters, which make it difficult to realize real time compensation.

2.7.1.1 Feed-forward PMD Compensation

There is a large interest in techniques of PMD compensation. Due to statistical nature of PMD, PMD compensators have to be adaptable. Most current PMD compensators employ feedback compensators, which continuously adjust multiple control parameters to optimize the signal quality. The compensators functions and complexities are both determined by the number of control parameters [40]. High order PMD compensator requires a large number of control parameters, which makes it difficult to realize real time compensation. Recently, a feed-forward PMD compensation technique was demonstrated and a theoretical modal of complete compensation of both the first and second order of PMD was proposed. A feed-forward technique, using a fixed delay element, has also been demonstrated recently [19]. The adjustments to the polarization controller are made based on real time PSP characterization using measurements from a Polarimeter. Figure 2.6 is a block diagram representation of this technique[45]

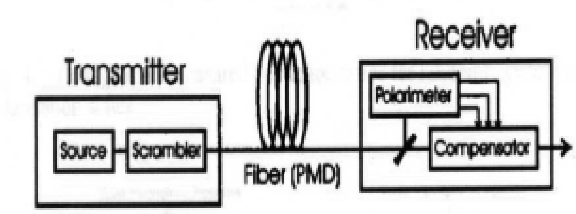


Figure 2.6: Block diagram of the proposed feed-forward PMD compensator

The three main considerations of feed forward PMD compensator are given below:

1. The perturbations in the delays of the fixed DGD segments
2. The errors in the delays of the variable DGD segments
3. The errors in the rotation angles of the PCs

2.7.1.2 Feedback PMD Compensation

There are several technologies that can be utilized to compensate for the effects of PMD. As the transmission channel bit rate increases beyond 10 Gbps, the polarization-mode dispersion (PMD) becomes one of the most serious limiting factors. The PMD effect comes from the randomly varying environmental conditions such as temperature, stress, fiber bending or twist, etc. To cope with this randomness, all the PMD compensation techniques must employ a feedback or a feed-forward system. For the effective implementation of PMD compensator (PMDC), various approaches have been suggested not only for the feedback/ feed forward systems, but also for the PMD monitoring technique and the means of time delay generations[22.46].These technologies have included the following:

- Mechanical devices that actually squeeze a portion of the fiber in order to realign the polarization pulses of the optical bit. In other words, a mechanical PMDC “counter-stresses” the fiber. The primary drawback of this method is that mechanical devices are more prone to failure over long durations; e.g., the original mechanical “step” switches of early voice networks, a technology of the early 20th century, demanded frequent maintenance and were prone to problems.
- Electronic devices that work after the receiver decoder, manipulating electrons in order to reduce bit errors. The primary drawback to this method is the difficulty in correcting an optical problem at the electronic layer.

The optimal placement of a PMDC in a network is directly prior to the receiver function of a transmission system. In long haul and ultra long-haul multichannel optical systems, the receiver is usually located within the DWDM optical transmission equipment at the central office or point-of-presence (POP) site.

There are two general types of DWDM transmission systems. Systems where the receiver function is within the DWDM network element are known as “open” DWDM systems. The most reliable and efficient PMDC technology is the use of adaptive optics to realign and correct the pulses of dispersed optical bits. The high-level concept of adaptive optic technology is shown in Figure 2.7.

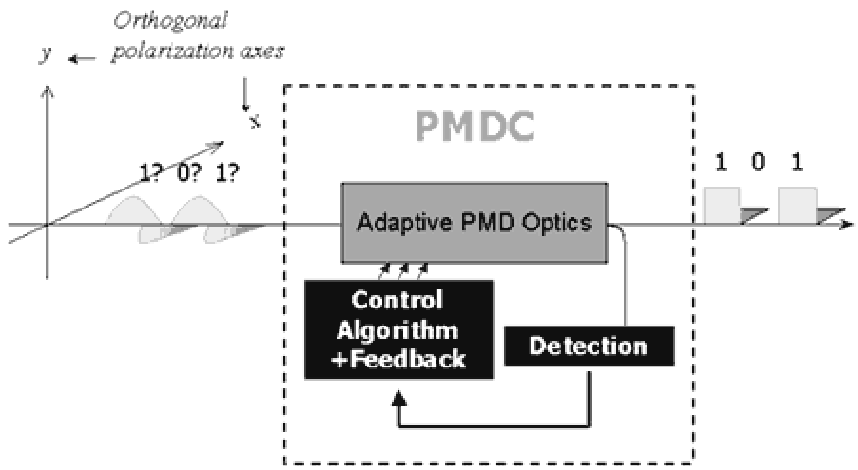


Figure 2.7: This shows the feedback compensator

Polarization-mode dispersion (PMD) remains the dominant bit rate limiting effect in long single mode (SM) fibers. PMD compensation is based on splitting the signal after transmission into two parts, which are aligned with either of the two principal states of polarization (PSP) of the fiber. Each part on its own does not suffer from PMD in first order approximation, but has undergone different group delays. The differential group delay (DGD) may be equalized by launching the fast signal part into the slow eigenstate of a polarization maintaining (PM) high birefringent fiber and vice versa.

This approach works well as long as the PSP of the compensator (i.e. the combination of polarization controller (PC) and PM fiber) matches to the PSP of the SM fiber, but residual DGD appears due to misalignment, if the PSP's vary with the signal wavelength. Considering now transcontinental cable lengths, wavelength multiplexing, and future multigigabit rates, PMD compensation will require close approximation of the PSP's of SM fiber and compensator PSP over a larger bandwidth, i.e. the 1st-order approach of treating the compensator PSP as constant must be extended to PSP's, which are linear or higher order function of frequency. Here, we theoretically and experimentally describe a compensator, which provides linear PSP variation.

2.7.2 Comparison of feed-forward and feed-back techniques for PMD compensation

So far, several examples of the feed-back method for adaptive PMD compensation were described. However, there also exists the feed-forward method of PMD compensation. Figure 2.8 shows the feed-forward and feedback techniques.

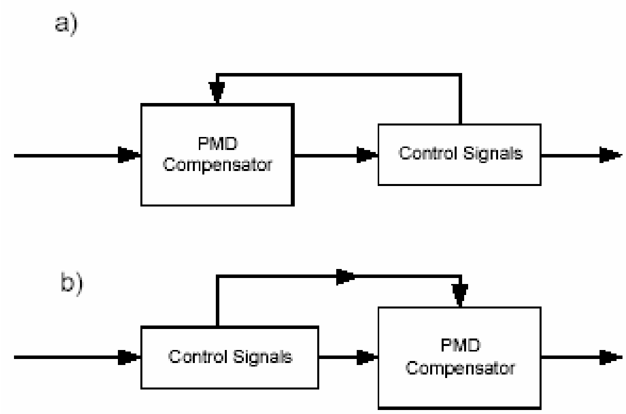


Figure 2.8: (a) Feed-back method (b) Feed-forward method

2.7.3 PMD compensation strategies

The more widely researched PMD compensation techniques are summarized in section 4.6.1, followed by a summary of other techniques.

2.7.3.1 Optical PMD compensation techniques

Optical PMD compensators typically comprise of a polarization controlling device, an optical delay element (fixed or variable) and allied electronics which provide control signals to the optical components based on feed-back information about the link's PMD. Either electronic circuitry can be used to reduce signal distortions after detection or optical devices in front of the receiver can be used to compensate for the actual fiber characteristics. Since the signal processing demands for electronic mitigation increase with higher transmission rates, thus ultimately limiting the mitigation capabilities, we concentrate on optical solutions.

An optical PMD compensator consists of a PMD equalizer, a polarization controller and a feedback loop, using a suitable monitor signal. Several stages made of equalizer and polarization controller may be concatenated to compensate for higher order PMD. The PMD equalizer is a birefringent element of either fixed or variable DGD, while the polarization controller is used to match the axes of the equalizer with the principal axes of the fiber. A suitable monitor signal, basically independent of bit rate and modulation format, is the degree of polarization (DOP), which is measured using a polarimeter. The power ratio of polarized light to total incident light decreases with increasing DGD of the fiber.

2.7.4 Classification based on order of compensation

Depending on the versatility and compensation capability, PMD compensators can be classified as half-order, first-order and second-order compensators. A half-order compensator comprises of a polarization controller and a fixed optical delay element. In addition, there is a feed-back control mechanism to provide appropriate control signals to the polarization controller. The principle of operation is that the polarization controller is adjusted so as to minimize the combined DGD of the link and the compensator. The delay element is fixed. Since this compensator can only compensate for a fixed amount of DGD, rather than varying delays, it is sometimes referred to as a half-order compensator. A half-order compensator configuration, consisting of a polarization controller and a segment of high birefringence fiber (fixed delay element). The polarization controller adjustment was made based on a feed-back signal which was the power level of the tone corresponding to half the data rate in the received base-band spectrum. Figure 2.9 is a reproduction of the PMD compensator

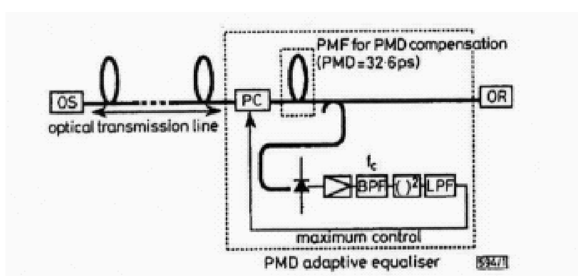


Figure 2.9: Half-order PMD compensator. (OS-optical source, PC-polarization controller, LPF and BPF-low-pass and band-pass filters, () 2 – square-law detector, OR-optical receiver)

A first-order PMD compensator is slightly more complex than a half-order compensator since it has a variable delay element instead of a fixed delay element. A feedback mechanism provides control signals for adjusting both the polarization controller and the delay element. The first-order compensator can be employed to counter different amounts of DGD values. The first-order configuration described in [42] uses a polarization controller and a variable delay element. Based on the feedback signal, polarization and delay adjustments are executed so as to minimize the PMD effects.

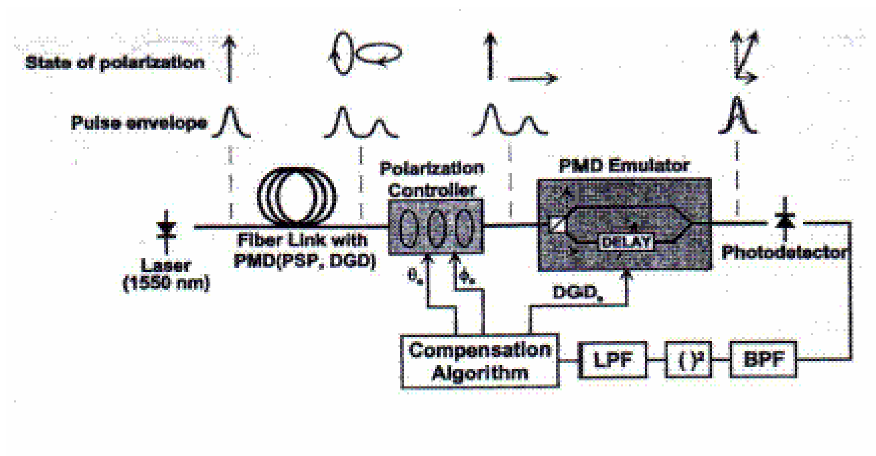


Figure 2.10: First-order adaptive PMD compensator functional block diagram. (LPF and BPF low-pass and band-pass Filters, ( ) 2 - square-law Detector) [3]

In order to increase the accuracy of the PMD compensation, the SOP of the optical signal may be scrambled before the signal is launched into the fiber link. Figure 2.10 is a block diagram of the PMD compensation system.

The polarization controller is a lithium-niobate based device. The control signals for the variable delay and the polarization controller are based on the power level of the received base-band spectrum. A first-order compensator, using the DOP of the received signal as the feedback parameter, has been shown to compensate for PMD at data rates of 40 Gbps and 80 Gbps [41]. An advantage of using the DOP as the feedback parameter is that compensation can be made bit-rate independent.

Figure 2.11-b is a block diagram of a DOP feed-back based, first-order PMD compensator [21] (also referred to as a post-compensation method owing to the compensator's location on the receiver side). Another approach for first-order PMD compensation is called the PSP transmission method. The PSP

transmission method is a pre-compensation method in which a polarization controller is used to align the SOP of the optical signal with a PSP of the fiber link. Figure 2.11-a shows the block diagram of a first-order PMD compensator based on the PSP transmission method [47].

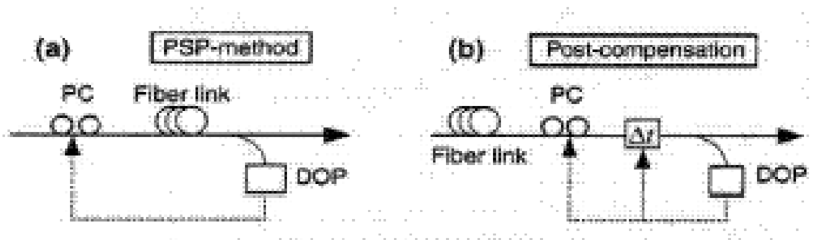


Figure 2.11: First-order PMD compensation: a) PSP method b) post-compensation method (PC-polarization controller, t-variable delay element) [14]

Given the increasing data-rates and the expanding bandwidth, importance has been attached to second-order PMD compensation also. One proposed configuration uses two polarization controllers and two pieces of high birefringence fiber. The compensator's PSPs are made to vary linearly with frequency so as to compensate for PMD over a larger bandwidth. The principle of changing the PSPs of the compensator as a linear function of frequency is made use of in the configuration. However, the set-up includes three polarization controllers and two variable delay lines (or one variable delay line and one Faraday rotator). Figure 2.12 is a block diagram of the compensator [43,44].

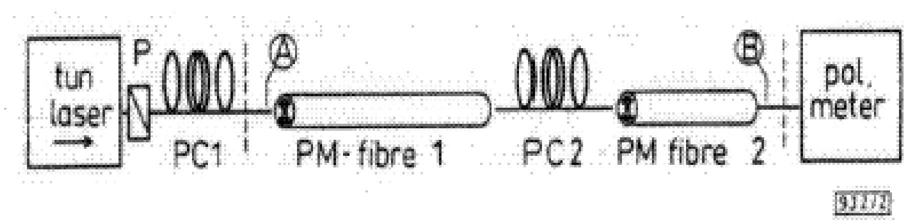


Figure 2.12: Second-order PMD compensator block diagram. (PC1 and PC2-Polarization Controllers)

2.8 Polarization maintaining fibers

Another solution for polarization impairment is polarization maintaining fibers. Jeunhomme has proposed a single mode fiber cable design which allows the stable transmission of a circular polarization state with good extinction ratio without orienting the fiber at joints for circular polarization maintaining single mode fiber cable, low birefringence serves the purposes. Noda has proposed various kinds of polarization maintaining fibers and their applications with those concerned with high birefringence.

The characteristics of polarization maintaining fibers could describe by modal birefringence or beat length, mode coupling parameter, and crosstalk and transmission loss. Modal birefringence is the difference of the effective refractive index between the orthogonal linear polarization modes and is related to beat length

L_P and polarization dispersion τ_P as following

$$L_P = \lambda / B = 2\pi / \delta\beta$$

$$\tau_P = B/c$$

where $\delta\beta$ is the difference of propagation constant between the two orthogonal modes of polarization.

It maintains the polarization of the light that originally entered the fiber by isolating the two orthogonal polarizations from each other even while they travel down the same single mode fibers.

Light in two polarization modes experiences about the same attenuation. However, the fiber manufacturing process deliberately introduces strain, which maintains refractive index differ for the two polarizations, a condition called birefringence. This means that the two polarizations travel through the fiber at different speeds. If linearly polarized light enters a polarization maintaining fibers with polarization parallel to one of its polarizing axis, the polarization will remain unchanged along the length of the fiber.

Basically, polarization maintaining fiber is available in Lo-Bi and Hi- Bi values. In Hi-Bi fibers, B>10 ^(-5). These fibers are again of two kinds : Two polarization fibers and single polarization fibers. Two polarization fibers are conventionally called polarization maintaining fibers. Utilizing large difference of the bending losses between the orthogonal modes, a long single polarization fiber shows a different behavior in length dependent crosstalk than does a two polarization fiber.

2.9 Soliton transmission and PMD

For the past decade great efforts have been made to understand the effects of PMD on optical system performance and to find methods to overcome them. Fortunately, it has been proven that optical solitons have inherent robustness to PMD due to nonlinear effect even in dispersion shifted fiber (DSF).

The origin of group velocity dispersion (GVD) in optical fibers is the frequency dependence of the refractive index. The different spectral components of the optical pulse will therefore have different group velocities, thus leading to pulse broadening. The refractive index is also weakly power dependent which is the origin of the various non linear effects. A pulse will modulate the refractive index by its own intensity modulation which leads to a phase modulation of the pulse, referred to as a **self phase modulation** (SPM). By choosing an appropriate power and shape, the effects of chromatic dispersion and SPM can be balanced. Such a pulse is called an **optical solitons.**

Solitons systems were first introduced to compensate for chromatic dispersion by taking advantage of non linear effects [52]. If the solitons systems are to work properly in practice, the dispersion needs to be rather low. In the early 90’s DSF together with EDFAs corresponds to low loss region of the fibers. A high power is used in solitons systems, the SNR can be sustained over longer transmission distances, compared to linear systems. Still, the optical power and the amplifier distance etc. must be suited to the dispersion, which is not always convenient in the installed links. There are also other problems to take into consideration in solitons systems: various sources of timing jitter [53-54]’ solitons interaction and collisions etc.[55].

As new kinds of dispersion compensating fibers (DCF) were produced to cancel the dispersion in SMFs, soliton systems were given less attention. This line of action is called dispersion management (DM). In recent years, it has been found that solitons can also be used in DM systems [56,57] and the term dispersion managed (DM) solitons has become wide spread. DM solitons have some major advantages compared to conventional solitons. For example they have reduced timing jitter and less four- wave mixing (FWM) induced crosstalk between different WDM channels, and also, as higher power can be tolerated , an even higher SNR can be sustained. Dm systems are characterized by a periodically alternating dispersion parameters.

Optical solitons are not only robust to chromatic dispersion but also to other kinds of perturbations, such as PMD. The two orthogonal polarization states that are differently delayed as an effect of PMD , used in nonlinear cross phase modulation (XPM) that mutually shifts one another's frequencies in opposite direction. Through the chromatic dispersion, the two polarization states have different speeds that fortunately counteract the PMD. This phenomenon is sometimes called soliton trapping and works optimally in PM fibers [58].

2.10 Literature Survey

G.J. Foschini and C. D. Poole [15] 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 intersymbol 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.

R. Khosravani, I. T. Lima, P. Ebrahimi, E. Ibragimove, A.E. Willner and C. R. Menyuk, [25] characterized the PMD emulators on time and frequency domain. In this paper a new technique to realistically emulate PMD is investigated both experimentally and theoretically. This paper demonstrate a PMD emulator using Rota table connectors between sections of polarization maintaining fibers that generates an ensemble of high PMD fiber realizations by randomly rotating the connectors. This paper had been shown that: 1. the DGD of this emulator is Maxwellian Distributed over an ensemble of fiber realizations at any fixed optical frequency; and 2. the frequency autocorrelation function of the PMD emulator resembles that in a real fiber when averaged over an ensemble of fiber realizations. A realistic autocorrelation function is required for proper emulation of higher order PMD and indicates the feasibility of using this emulator for wavelength division multiplexing (WDM) system.

A.O. Lima, I. T. Lima, Jr., C. R. Menyuk*, Fellow, IEEE*, G. Biondini, B. S. Marks, and W. L. Kath [29] gave their ideas on the statistical analysis of the performance of PMD compensators using multiple importance sampling. This paper evaluate the performance of fixed and variable differential group delay (DGD) polarization-mode dispersion (PMD) compensators as the first- and second-order PMD varies using multiple importance sampling. They show that importance sampling yields estimates of the average penalty with low variance over the entire region of interest of first- and second-order PMD. We also show that there is little advantage in using a compensator with a variable-DGD element and that the performance of a compensator that minimizes the residual DGD at the central frequency of the channel is considerably worse than a compensator that maximizes the eye opening.

H. Sunnerud, M. Karlsson and P.A. Anderkson [33] gave their ideas towards the analytical theory for PMD compensation. This paper derived exact analytical expressions for the expected pulse broadening in fiber optic transmission systems suffering from both first- and higher- order PMD. Further more we quantify the benefit of using two simple PMD compensation techniques. The first method is to launch the signal into the PSP, which is first order pre-compensation technique. The second approach is to add a birefringent element after the system to compensate the PMD to first order at one specific wavelength.

A.Djupsjöbacka [34] had provided his ideas on Differential Group-Delay Statistics for Polarization Mode Dispersion Emulators. This paper dealt with the theoretical study on differential group delay (DGD) statistics for common models of polarization-mode dispersion (PMD) emulators. His study would show, for the first time to our knowledge, which the statistics for the length of the PMD vector will not necessarily behave as a system with three degrees of freedom when the number of actions in the PMD emulator is low. However, when the number of sections is large, i.e., 10 sections or more, the length of the PMD vector is well described with a system with three degrees of freedom.

The purpose of this paper was twofold. First, he investigated two common types of PMD emulators and compared them with ideal systems with two and three degrees of freedom. The reason for the inclusion of the system with two degrees of freedom had been explained. He investigated how well different polarization controllers will scramble polarization, and show that the choice of polarization controller might matter when a PMD emulator with only a few sections shall be built.

Eckhardt, H. Rosenfeldt and R. Ulrich [36] analyzed the broadband compensation of Polarization-Mode Dispersion. In this paper the author described that the Polarization-Mode Dispersion (PMD) in long SM-fibers is today the performance limiting factor in a large variety of optical systems, e.g. high-speed telecommunication links or polarization-sensitive interferometric setups. They demonstrated the compensation of the PMD of a 7km long SM-fiber by means of 18cm piece of highly birefringent PM-fiber. We achieved reduction of the amount of the PMD by a factor of 8 within 10nm bandwidth. They also investigated the possibility of increasing this bandwidth by employing higher orders of compensation. Experimental results agree well with numerical simulations.

Ding Wang, Michael R. Mathews, and James F. Bernnan as in [37] dealt their ideas towards the performance of dispersion compensation gratings at 10 Gbps NRZ data via an external $LiNbO_3$ modulator. This paper had also show that the group delay ripple of chirped fiber gratings causes the DGD to vary rapidly with wavelength and make PMD measurement difficult to interpret. Both direction and magnitude of the PMD vector of dispersion compensation grating must be considered when estimating its system penalty. They proposed high bandwidth measurements to first order PMD. Optical fiber birefringence causes polarization-dependent variations in the system performance of the dispersion compensation gratings fluctuations also occur because different regions of the grating phase ripple with corresponding changes in the system performance.

Ivan T. Lima, OSA Reza Khosravani, Paniz Ebrahimi, Edem Ibragimov*,* Curtis R. Menyuk*, Fellow* and Alan Eli Willner [38] dealt with the comparison of Polarization Mode Dispersion Emulators. In this paper they analyzed that the polarization mode dispersion (PMD) emulators comprised of a small number of sections of polarization maintaining fibers with polarization scattering at the beginning of each section. Unlike previously studied devices, these emulators allow the emulation of a whole ensemble of fibers. They derived the analytical expressions and determined the two main criteria that characterize the quality of PMD emulation. The experimental results were in good agreement with the theoretical predictions.

H. Rosenfeldt, Ch. Knothe, R. Ulrich, and E. brinkmeyer [41] had showed their ideas for automatic PMD compensation at 40 Gbps using 3- dimensional DOP evaluation for feedback. In this paper the authors demonstrate that polarization scrambling combined with degree of polarization (DOP) evaluation enables PMD compensation without feedback fading due to varying input polarization. PMD of an installed fiber as well as PMD of an emulator was successfully compensated. This paper showed the combination of polarization scrambling and continuous DOP measurement offers the opportunity for the bit rate insensitive compensation of PMD. The 3- dimensional DOP evaluation of the received data signal is capable of different data formats and evaluation of PMD as well as first- and second- orders PMD of the link

Daniel Mahgerefteh, Curtis R. Menyuk [42] dealt with the effect of First-order PMD compensation on pulse broadening in the fiber with randomly varying birefringence. They had show 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 [43] analyzed the impact of first and second order polarization mode dispersion, they also found hat 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.

Jorn Patscher and Ralf Eckhardt [44] gave their ideas towards the component for second order compensation of PMD. They characterize the compensator containing high birefringent fibers and polarization controllers, which is adapted to these variation and promises enlarged bandwidth. The compensation of polarization mode dispersion in long fibers by using principle states of polarization in limited in bandwidths when these states vary with frequency. The differential group delay may be equalized by launching the fast signal part into the slow eigenstate of a polarization maintaining higher birefringent fiber and vice versa.

Houxun Miao, Changxi Yang, Shiguang Li, and Yingbai Yan [45] discussed their ideas for the feed-forward polarization mode dispersion compensation with a step control algorithm. They had showed the feed-forward PMD compensation with three segments which is capable of compensating for the first and second order PMD in a transmission fiber. A step control algorithm is proposed. The compensator shows good robustness to possible perturbations. The advantages of the Feed Forward PMD compensation model over PMD compensators are described. They had proposed a feed- forward PMD compensator with three segments, which is capable of compensating the first- and second- order PMD in the transmission fiber. the performance robustness of the three compensators has been simulated by considering perturbations in: (1) the delays of fixed DGD segments (2) the delays of the variable DGD segments (3) the rotation angles of the PCs.

XU Wen-Cheng, Chen Wei- Cheng, LUO Ai- Ping and LIU Song- Hao [47] provided with the idea for suppression and compensation of the third order dispersion effect on polarization modes in birefringent fibers. They had showed the affects of the third order dispersion (TOD) PMD on the fiber of the system. It destroys the orthogonal polarization modes in optical birefringent fibers. A new method is proposed to compensate for the PMD by means of cascading the fibers with the positive and negative TOD. It is practicable in long transmission.

They tell the limitation of the PMD in the fiber optic communication system. They showed the effects of the third order dispersion on the PMD in a soliton system and that TOD destroys the polarization modes in DSFs and results in soliton instability in optical fibers.

According to the paper given in [48], 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.

G. X. Ning S. Aditya , P Shum, C. Q. Wu, Y. D. Gong and H. Dong [49] provided their ideas toward higher- order polarization mode dispersion: new expressions induced pulse broadening and its compensation. In this paper hey derived new expressions for the PMD vector including the second- and third-order effects. These new expressions were used to obtain explicit expressions for PMD induced pulse broadening. The pulse broadening expressions reveal that an increase in the first- and second- order derivatives of DGD with respect to frequency always increases pulse broadening. A change of direction of the first order PMD vector also increases pulse broadening. In most cases, the second- and third- order PMD cannot be compensated completely. This paper gives the expressions for minimum pulse broadening in the presence of second- and third-order PMD. This paper derived the relation between them and the new relation lead to new expression for second and third order PMD induced pulse broadening. They showed that the change of direction of the second- order PMD vector makes the pulse broadening less.

T. Merker, N. Hahnenkamp, P. Meissner [50] 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.

L.S. Yan, Q. Yu., A.E. Willner, X. Steve Yao [51] 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.

Chapter 3

SYSTEM MODELING FOR COMPENSATION 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 set-up for compensation of PMD

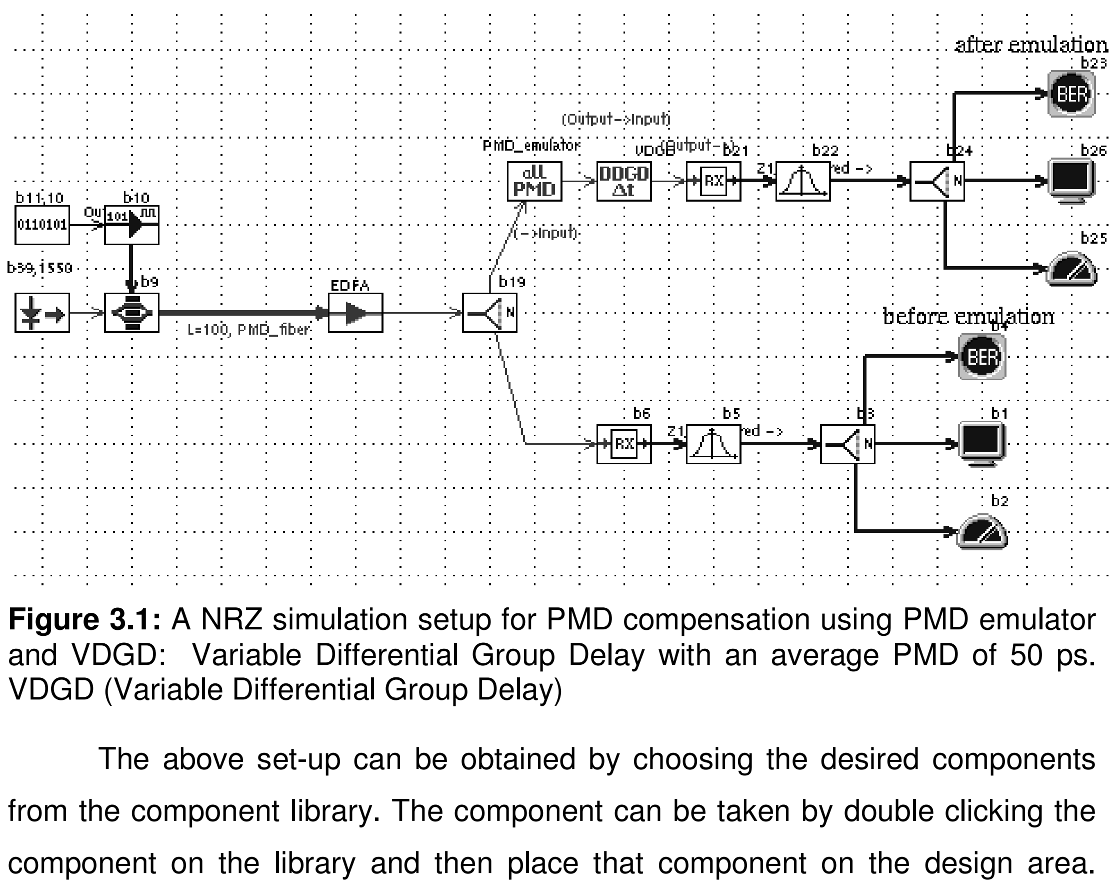


Figure 3.1: A NRZ simulation setup for PMD compensation using PMD emulator and VDGD: Variable Differential Group Delay with an average PMD of 50 ps. VDGD (Variable Differential Group Delay)

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 b11 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:

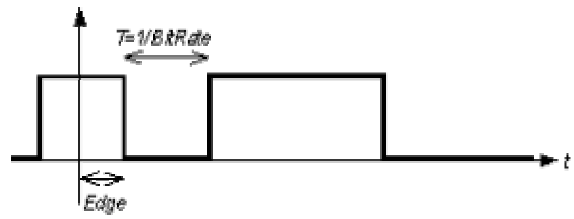
$$D = \frac{\log_{10}(N_b + 1)}{\log_{10} 2}$$

where N_b is:

$$N_b = \text{int}\left(T_{sim} \cdot R_b\right)$$

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, see Figure below). *Allowed values*: min 0; max 1; default 0 (if the **Deterministic** option is selected).



(a)

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 pseudo-random sequence giving the Starting point in the sequence parameter.

Laser Source

In this set-up b39 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: 2π; 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 b10 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.

Amplitude modulator

In this experimental set-up b9 shows the amplitude modulator. This module simulates a single input modulator. Two different models are available: linear and $\sin^2$ shaped Input-Output characteristics. The second transfer function is typical for the Mach-Zehnder external modulators based on the electro-optic effect in the $LiNbO_3$ devices. For both models the chirping factor is included incorporating the αparameter

This model implements a single arm Mach-Zehnder Amplitude Modulator with $\sin^2$ 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 $LiNbO_3$ devices.

The input optical signal is multiplied by a factor dependent on:

- the input voltage V_{in} applied to the modulator arm
- the excess loss EL_{dB} introduced by the modulator
- the extinction ratio ER_{LIN}
- the chirp factor α

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

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 $\alpha_{dB}(f)$ is defined as follows:

$$\alpha_{dB}(f) = \alpha_{0dB} + \alpha_{1dB}(f - f_{0,loss}) + \alpha_{2dB}(f - f_{0,loss})^2$$

Where $f_{0,loss}$ 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

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 (L_p) fiber segments (waveplates). The Principal State of Polarization (PSP) orientation of each waveplate is a random variable. Instead, the differential group delay $\Delta\tau_p$, introduced by each waveplate, is the same for all the waveplates and it is proportional to the PMD coefficient (δ_{PMD} in $ps/\sqrt{Km}$) of the simulated fiber and to the waveplate length L_p through the following formula :

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

Moreover, the waveplates length L_p is related to the fiber beat length L_B and the fiber correlation length L_C by the following relation:

The average DGD is

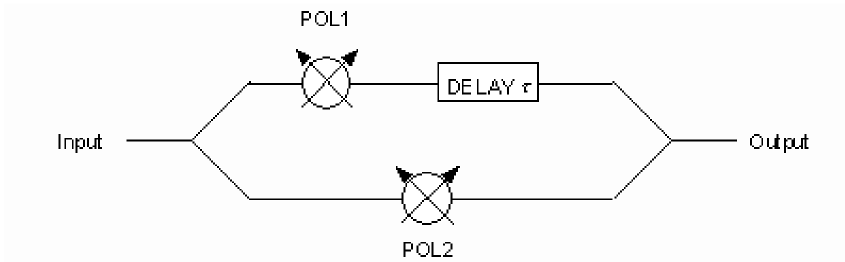
$$\langle\Delta\tau\rangle = \delta_{PMD}\sqrt{L_{fiber}},$$

and its variance is

$$\sigma_{\Delta\tau} = \sqrt{\left(\frac{3\pi}{8}-1\right)}\cdot\delta_{PMD}\sqrt{L_{fiber}}.$$

VDGD (Variable Differential Group Delay)

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



(b)

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 2α and 2ϕ 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 τ 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 τ 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 τ' is related with the simulation bandwidth through the relationship:

$$\tau' = Nearest\_Integer\left(\frac{\tau \cdot BW_{VBS}}{0.8}\right)\frac{0.8}{BW_{VBS}}$$

where BW_{VBS} is the VBS simulation bandwidth.

Optical receiver

In this experimental set-up b6 and b21 shows the receivers. b6 shows the receiver before emulation and b21 shows the receiver after emulation. This component simulates an optical receiver, including the photodetector. 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 b4 and b23 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:

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

Electrical scope

In this experimental set-up b1 and b26 shows the electrical scope before and after emulation respectively. This component simulates an oscilloscope for electrical signals. It collects data that will be available for the following diagrams:

- amplitude of the electrical signal
- eye diagram
- power spectrum of the electrical signal.

Electrical power meter

In this experimental set-up b2 and b25 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 BW_{VBS} 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*$\log_{10}$ (squared amplitude unit)] of the input signal averaged over the whole T_{sim}.

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

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

In this experimental setup we can transmit the source through the transmitter section.

In the transmitter section we have data source through which we can transmit input from 2.5 Gbps to 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 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.

Objective 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.

3.3 Results and discussions:

At the PMD emulator we get the following graph which shows the DGD at the PMD emulator. This shows that as the PMD increases how the DGD varies.

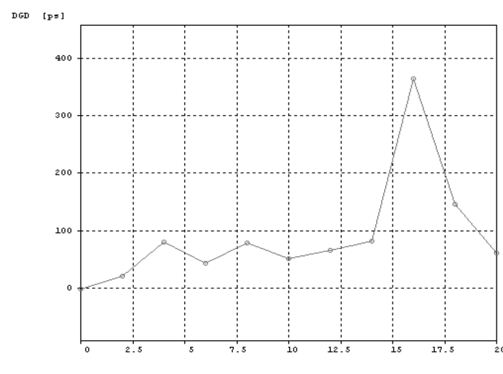
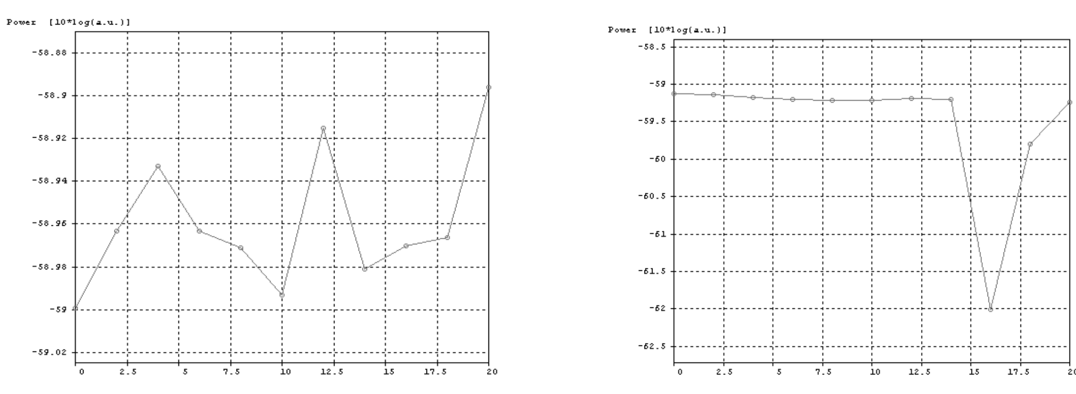


Figure 3.2: DGD at PMD emulator

At the electrical power meter we get the following results before and after emulation.

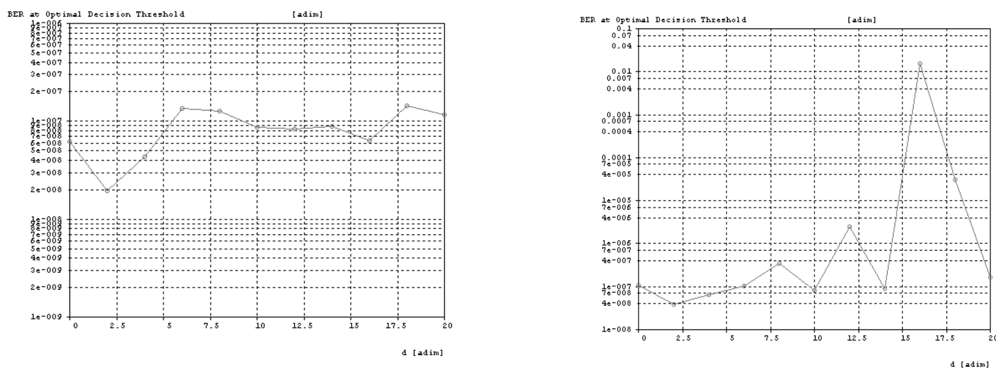


(a) (b)

Figure 3.3: (a) the dispersion verses electrical power before emulation. (b) the dispersion verses electrical power after emulation. All values are for NRZ raised cosine

The above figure shows that after using emulator electric power increases and upto some extent it is constant.

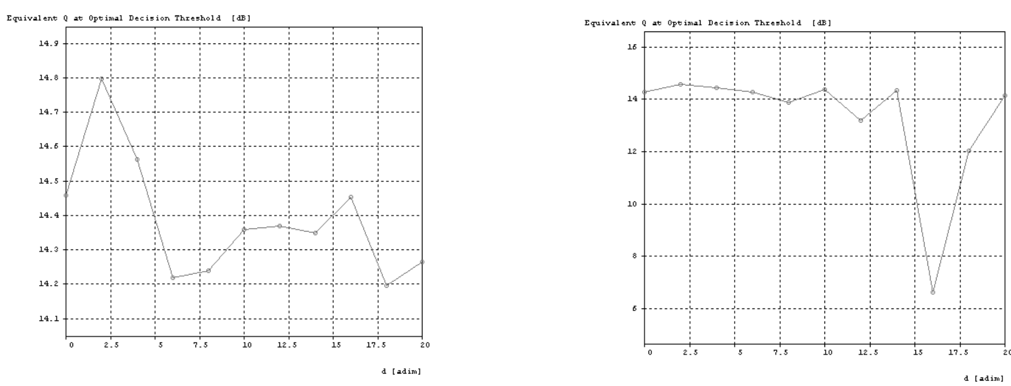
At the electric scope we get the BER and the equivalent Q variation with the PMD. It can be seen in the figure below:



(a) (b)

Figure 3.4: (a) the dispersion verses BER before emulation (b) the dispersion verses BER after emulation. These both figures are for NRZ raised cosine.

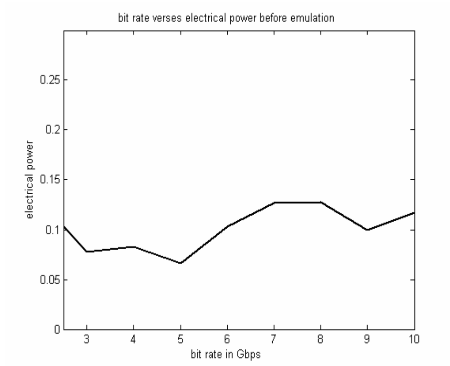
This figure shows that the BER decreases after emulation. At some value it increases and then decreases.



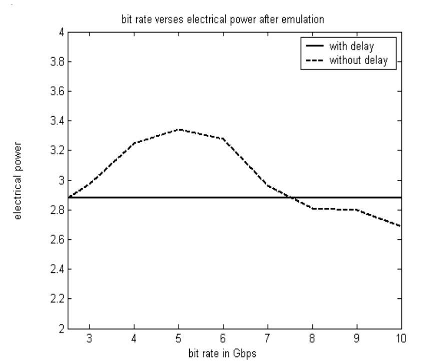
(a) (b)

Figure 3.5: (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.

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

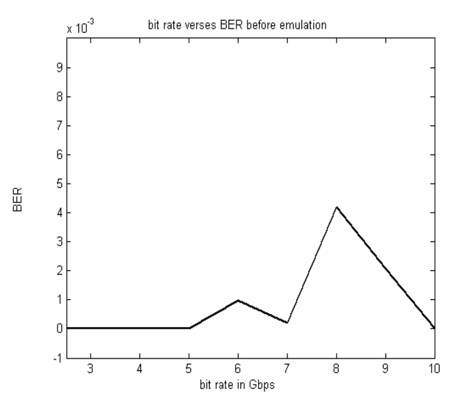


(a)

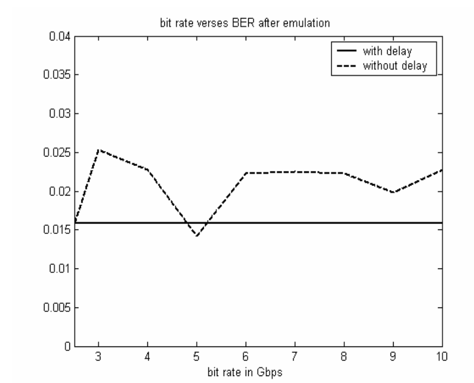


(b)

Figure 3.6: (a) Electrical power varies with bit rate before emulation (b) BER varies with bit rate with and without delay after emulation. Both values are for NRZ raised cosine.

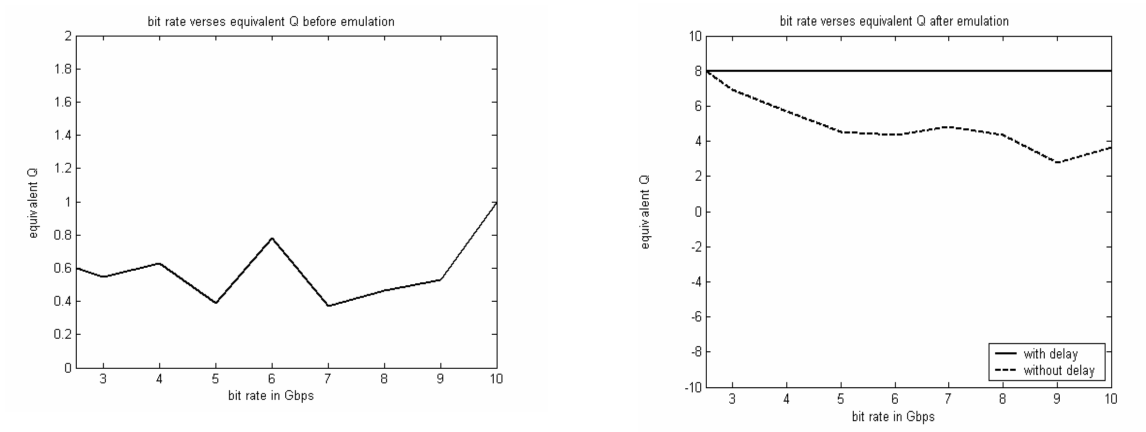


(a)



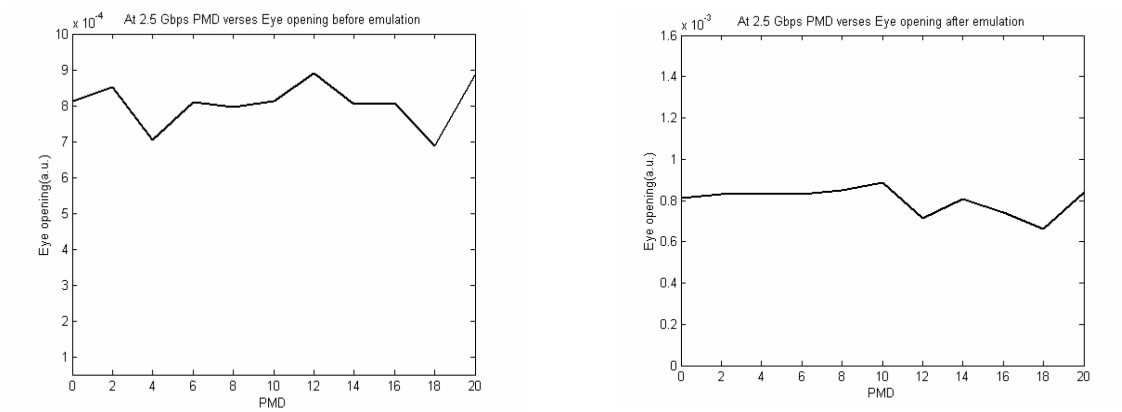
(b)

Figure 3.7: (a) BER varies with bit rate before emulation (b) BER varies with bit rate with and without delay after emulation. Both values are for NRZ raised cosine.



(a) (b)

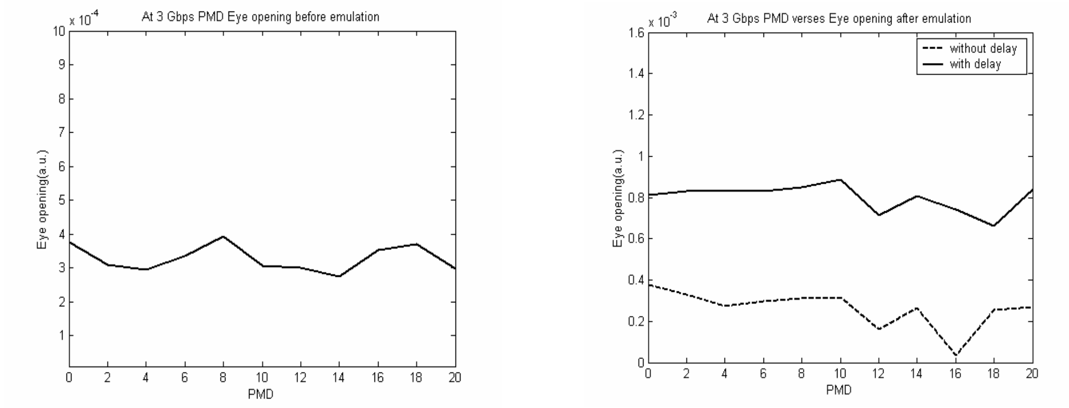
Figure 3.8: (a) Equivalent Q factor varies with bit rate before emulation (b) BER varies with bit rate with and without delay after emulation. Both values are for NRZ raised cosine



(a) (b)

Figure 3.9: At 2.5 Gbps for NRZ raised cosine (a) Eye opening with PMD before emulation. (b) Eye opening with PMD after emulation

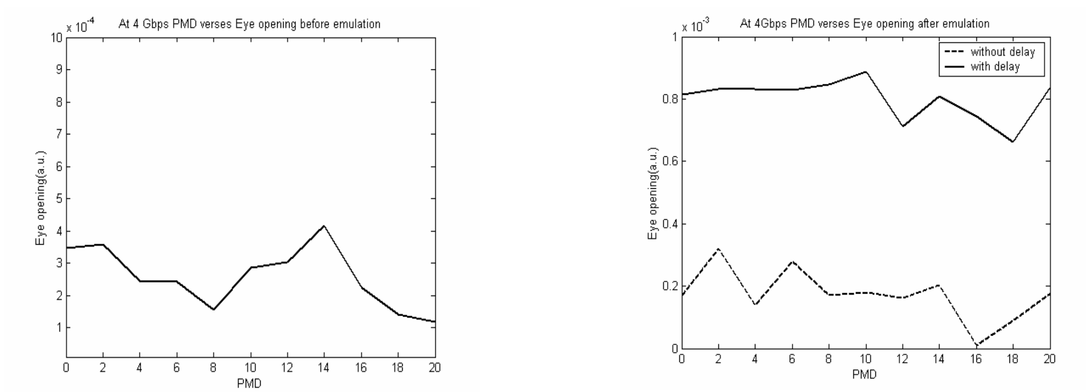
This figure shows that after emulation by using delay the eye opening becomes almost constant. We analyze from this figure that there is not much variation by applying emulator and delay. At 2.5 Gbps after emulation there is no effect of using delay because at this bit rate the PMD is not that much to affect the system and so there is no need to compensate it by using VDGD.



(a) (b)

Figure 3.10: At 3 Gbps for NRZ raised cosine (a) Eye opening with PMD before emulation. (b) Eye opening with PMD after emulation

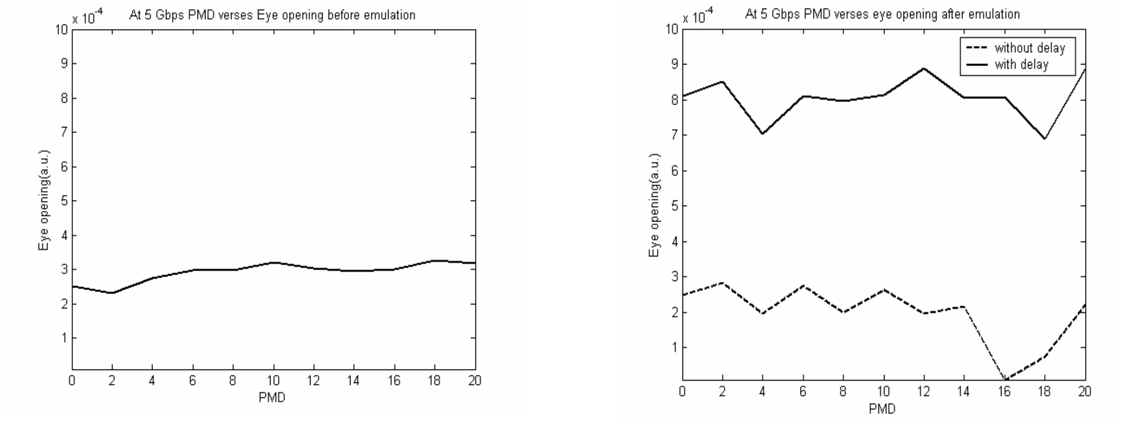
This figure shows that after emulation by using delay the eye opening becomes almost constant. We analyze from this figure that after using the delay the eye becomes more open. As the eye is open the closure is that much less.



(a) (b)

Figure 3.11: At 4 Gbps for NRZ raised cosine (a) Eye opening with PMD before emulation. (b) Eye opening with PMD after emulation

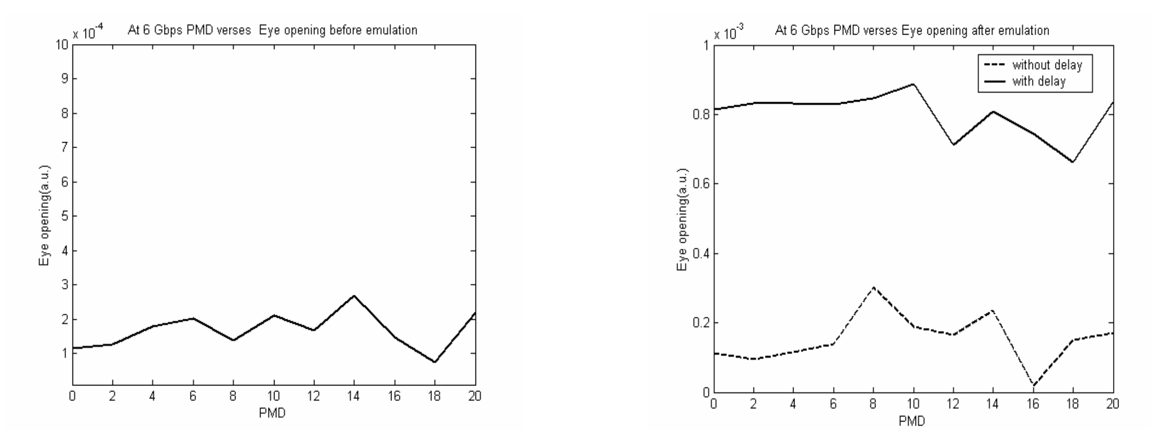
This figure shows that after emulation by using delay the eye opening becomes almost constant. We analyze from this figure that after using the delay the eye becomes more open. As the eye is open the closure is that much less.



(a) (b)

Figure 3.12: At 5 Gbps for NRZ raised cosine (a) Eye opening with PMD before emulation. (b) Eye opening with PMD after emulation

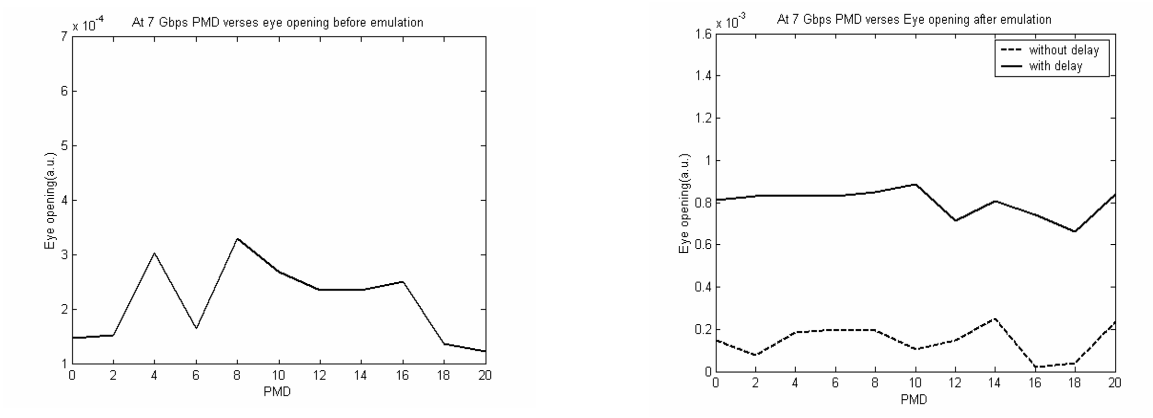
This figure shows that after emulation by using delay the eye opening becomes almost constant. We analyze from this figure that after using the delay the eye becomes more open. As the eye is open the closure is that much less.



(a) (b)

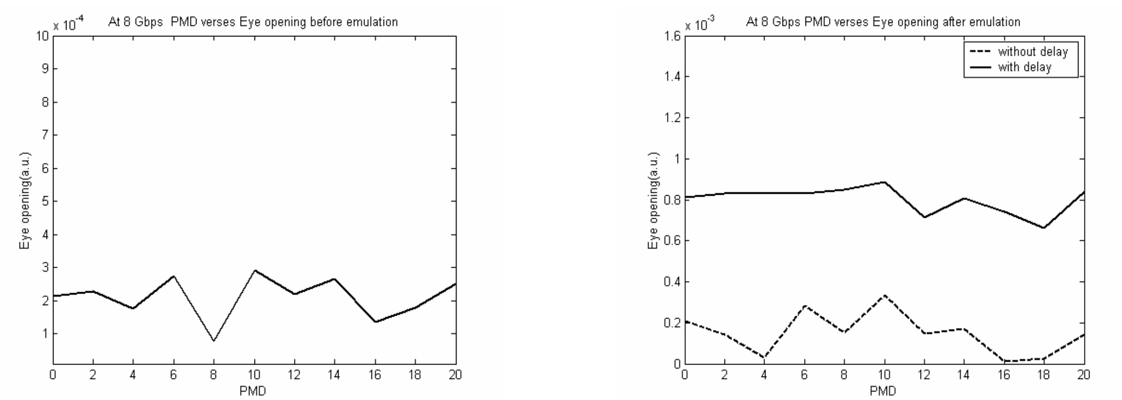
Figure 3.13: At 6 Gbps for NRZ raised cosine (a) Eye opening with PMD before emulation. (b) Eye opening with PMD after emulation

This figure shows that after emulation by using delay the eye opening becomes almost constant. We analyze from this figure that after using the delay the eye becomes more open. As the eye is open the closure is that much less.



(a) (b)

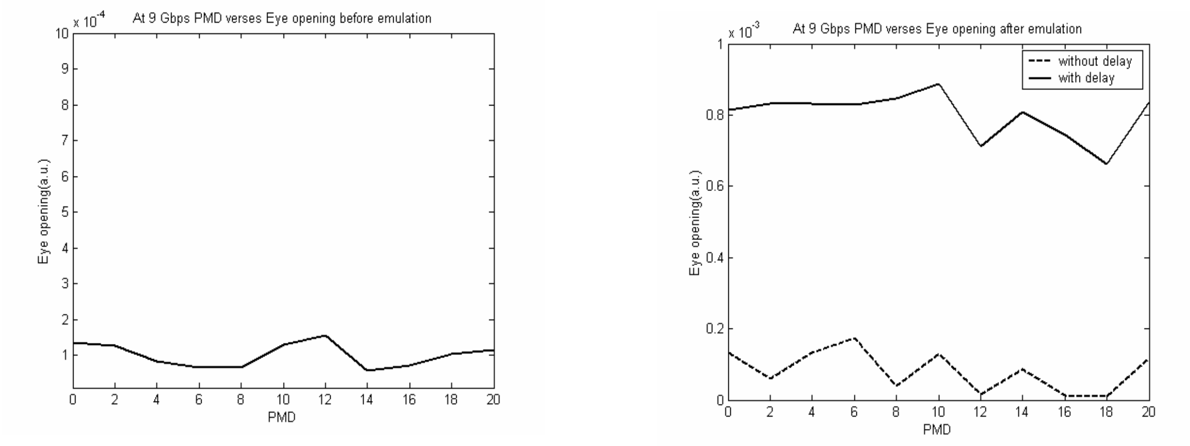
Figure 3.14: At 7 Gbps for NRZ raised cosine (a) Eye opening with PMD before emulation. (b) Eye opening with PMD after emulation



(a) (b)

Figure 3.15: At 8 Gbps for NRZ raised cosine (a) Eye opening with PMD before emulation. (b) Eye opening with PMD after emulation

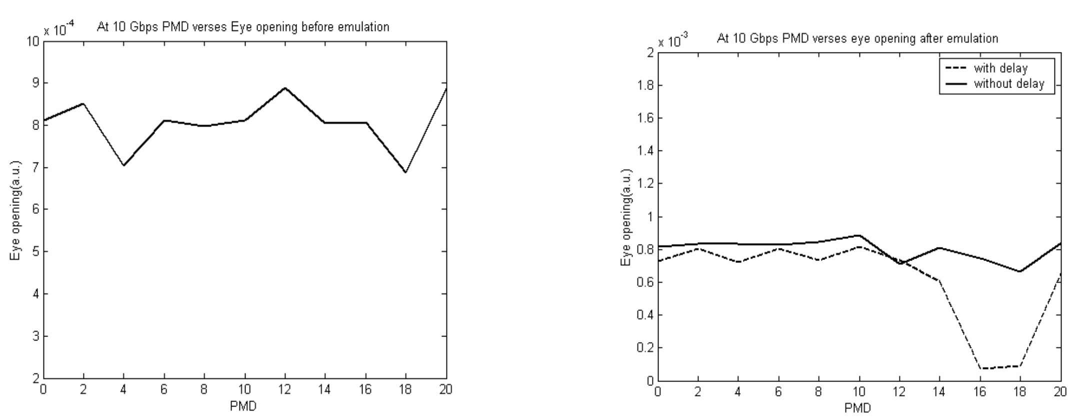
This figure shows that after emulation by using delay the eye opening becomes almost constant. We analyze from this figure that after using the delay the eye becomes more open. As the eye is open the closure is that much less.



(a) (b)

Figure 3.16: At 9 Gbps for NRZ raised cosine (a) Eye opening with PMD before emulation. (b) Eye opening with PMD after emulation

This figure shows that after emulation by using delay the eye opening becomes almost constant. We analyze from this figure that after using the delay the eye becomes more open. As the eye is open the closure is that much less.



(a) (b)

Figure 3.17: At 10 Gbps for NRZ raised cosine (a) Eye opening with PMD before emulation. (b) Eye opening with PMD after emulation

3.4 Solitons used as compensator

It has been proven that optical solitons have inherent robustness to PMD due to nonlinear effect even in dispersion shifted fiber (DSF).

The origin of group velocity dispersion (GVD) in optical fibers is the frequency dependence of the refractive index. The different spectral components of the optical pulse will therefore have different group velocities, thus leading to pulse broadening. The refractive index is also weakly power dependent which is the origin of the various non linear effects. A pulse will modulate the refractive index. By choosing an appropriate power and shape, the effects of chromatic dispersion and SPM can be balanced. Such a pulse is called an **optical solitons** as described in chapter 3.

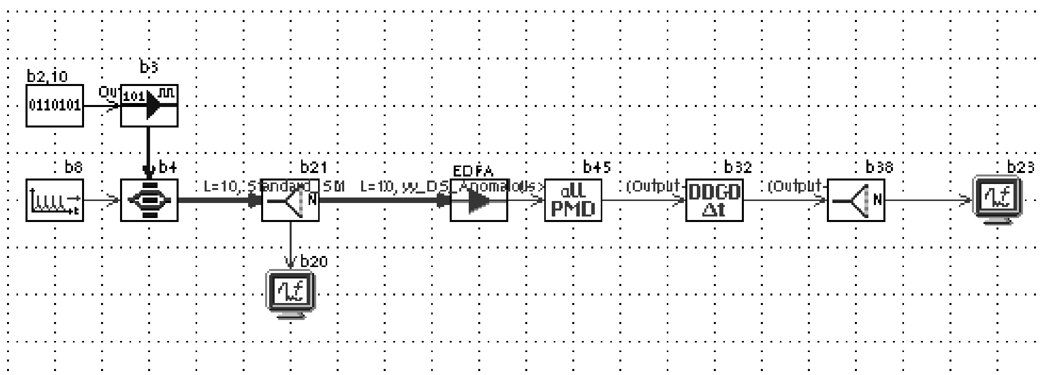
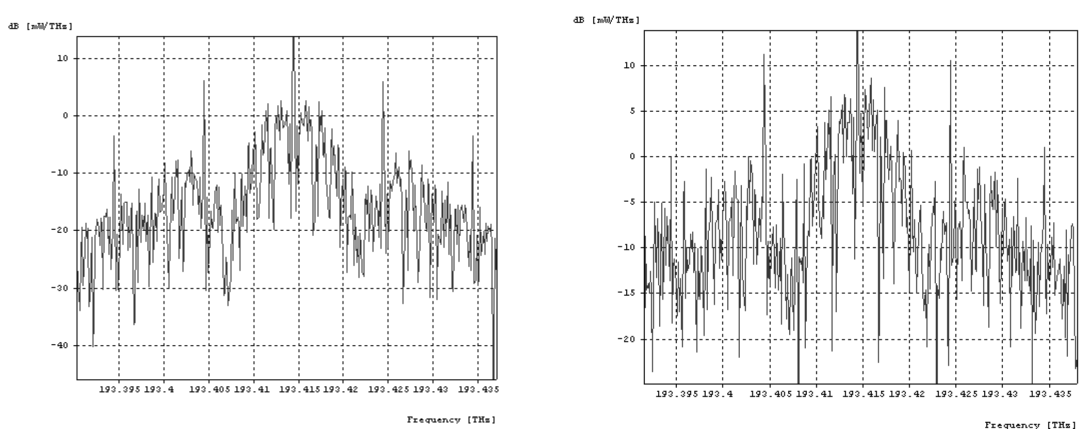


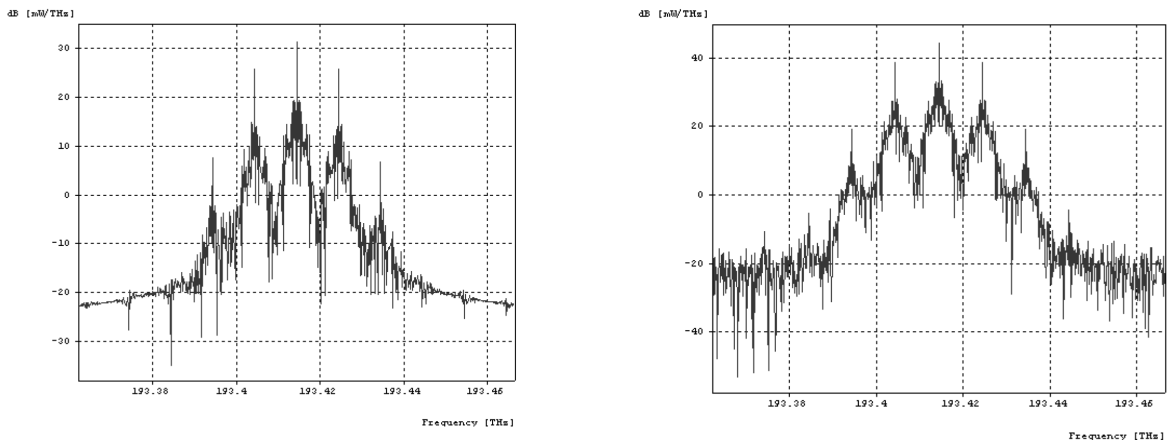
Figure 3.18: Experimental set-up which can act as soliton



(a) (b)

Figure 3.19: The pulse spectrum at 10 Gbps NRZ raised cosine when the PMD of the fiber is zero (a) at the input before transmitted through the DSF (b) at the output after passing through the DSF. Input spectrum compared to the output distorted with PMD, but compensated by the solitons.

From both the spectrums we observed that at the output the spectrum is approximately same, there is not much change in the spectrum i.e. power at the output. This shows that it can act as a soliton. Here, at the input the highest peak frequency is 193.414 THz and the highest peak power is 17.100822 dB (mw/THz) and at the output the highest peak frequency is same and the peak power is 22.407818 dB (mw/THz).



(a) (b)

Figure 3.20: The pulse spectrum at 10 Gbps NRZ raised cosine when the PMD of the fiber is 20 $ps/\sqrt{km}$ (a) at the input before transmitted through the DSF (b) at the output after passing through the DSF. Input spectrum compared to the output distorted with PMD, but compensated by the solitons.

From both the spectrums we observed that at the output the spectrum is approximately same, there is not much change in the spectrum i.e. power at the output. This shows that it can act as a soliton. At the input the peak frequency is same and if the PMD 20 $ps/\sqrt{km}$ but the peak power is 31.354343 dB (mw/THz) and at the output the highest peak power is 44.607910 dB (mw/THz).

If the solitons systems are to work properly in practice, the dispersion needs to be rather low. In the early 90's DSF together with EDFAs corresponds to low loss region of the fibers. A high power is used in solitons systems, the SNR can be sustained over longer transmission distances, compared to linear systems.

Chapter 4

COMPENSATION TECHNIQUES OF PMD

The different compensation methods can be divided into different categories, depending on weather the compensation is performed electrically [59,62], opto-electronically [63] 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 [60, 61]. Figure 4.1 defined 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 above 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 above set-ups we have a transmitter section, a channel and a receiver section. We can transmit the signal from 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. In figure 4.3 we use second order post 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.

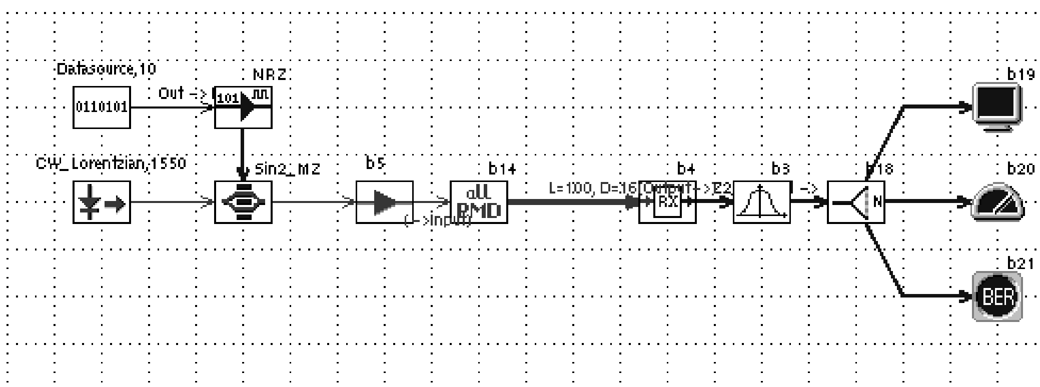


Figure 4.1: Simulation set-up for first order pre-compensation (PSP method)

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 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. The block diagram for optical post compensation after transmission is shown below:

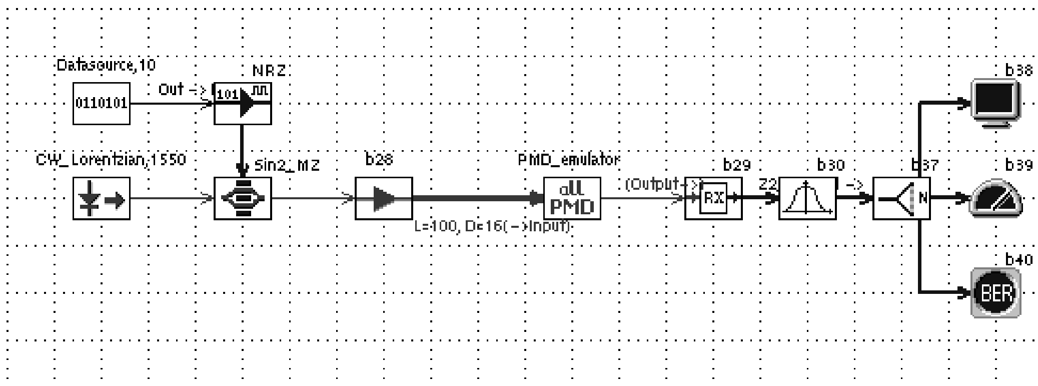


Figure 4.2: Simulation set-up for optical first order post- compensation

The compensator will not be able to fully cancel the DGD if a single section of fixed length of used. A simple control system with only two DOF is sufficient as in the case of PSP method. Second order post compensation can be shown in the figure below:

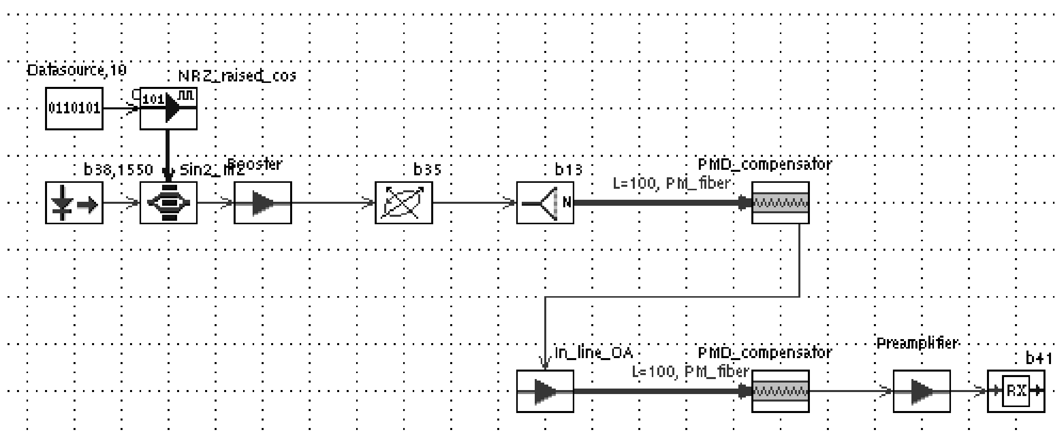


Figure 4.3: Simulation set-up for optical second order post compensation

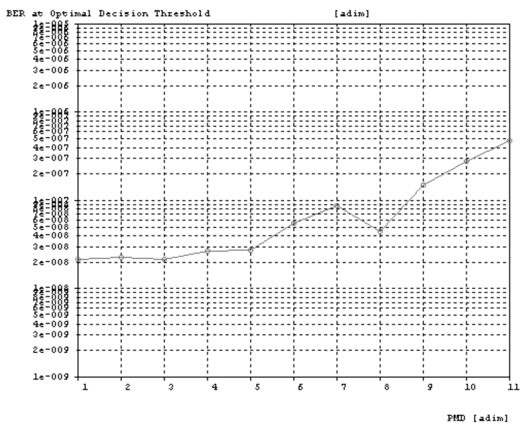
In the above shown experimental set ups we have transmit power from the Laser source. The bit rate can be changed from data source. This can be modulated through the amplitude modulator and then can be transmitted through the fiber channel. After transmission we can compensate the dispersion through the PMD emulator and then it can be received at the receiver. After receiving the compensated signal we can filter it out. Then we get the BER, electrical power and the eye diagrams.

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

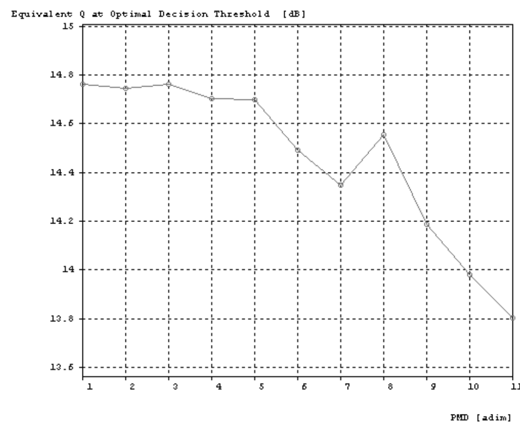
4.2 Results and Discussions

4.2.1 Results of pre-compensation

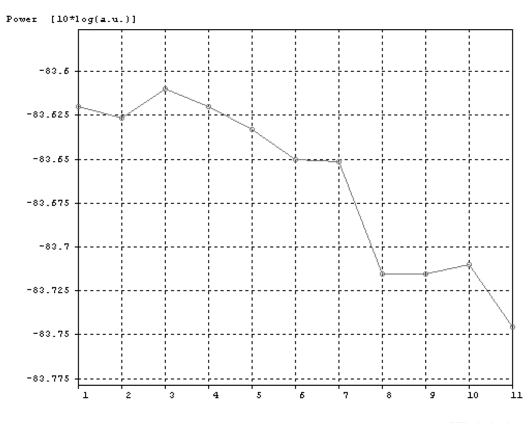
As we know that 2.5 Gbps there is not much effect of PMD on the system. We have seen that as the PMD increases BER increases.



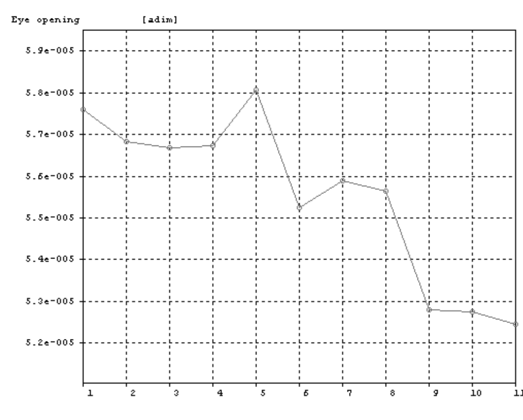
(a)



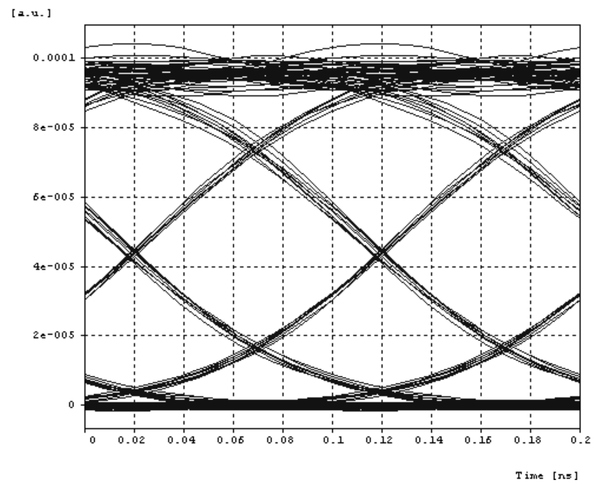
(b)



(c)

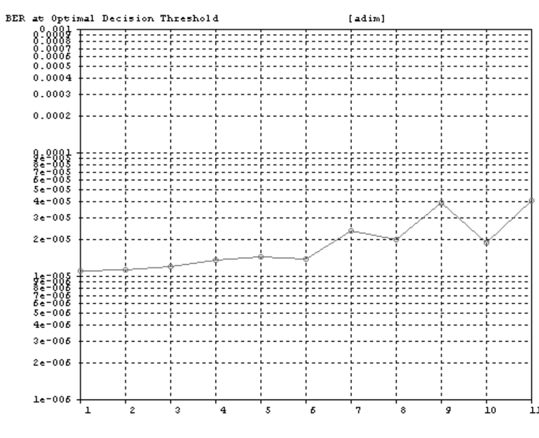


(d)

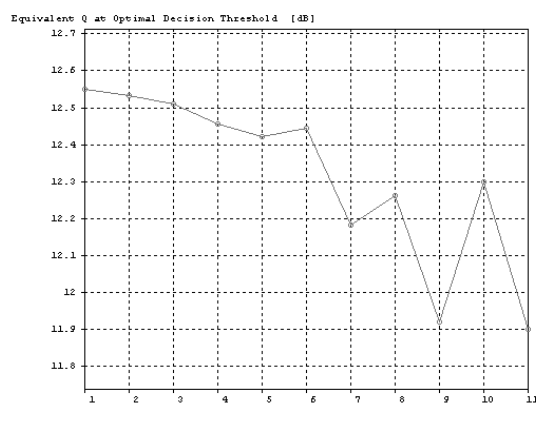


(e)

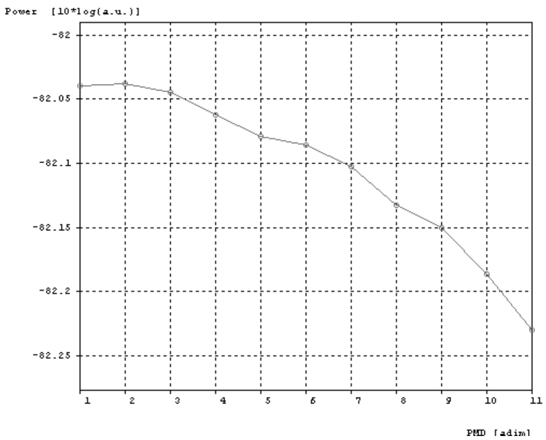
Figure 4.4: At 2.5 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) eye diagram at 20 $ps/\sqrt{km}$.



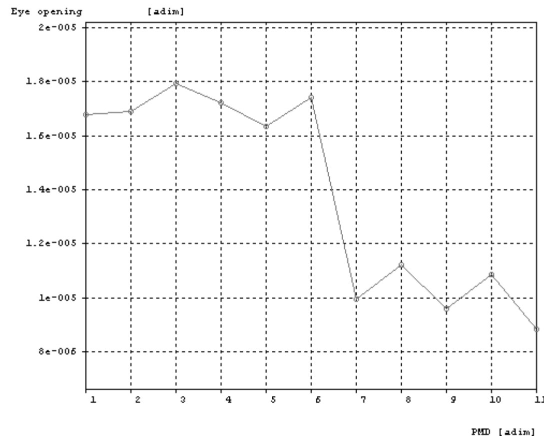
(a)



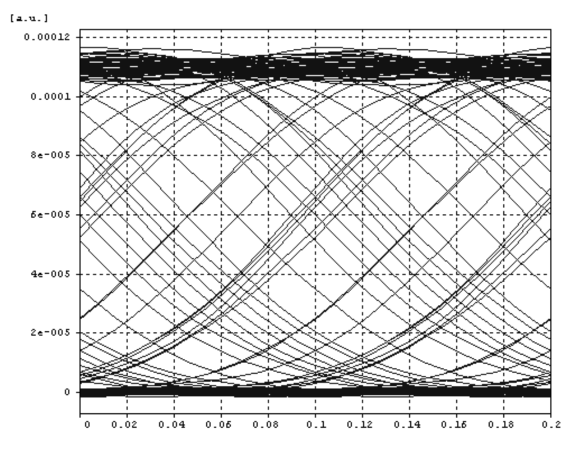
(b)



(c)

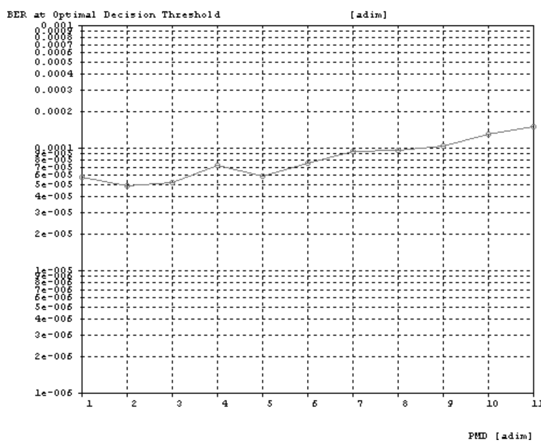


(d)

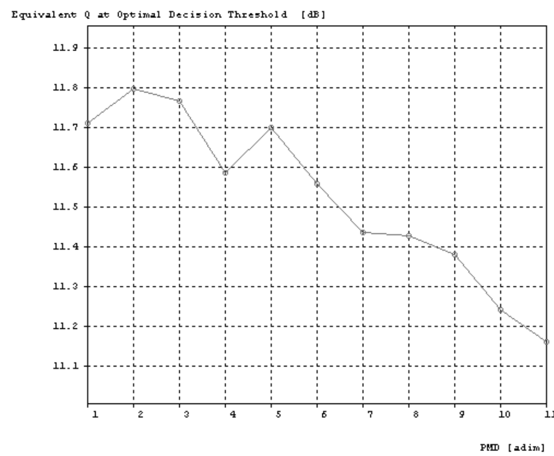


(e)

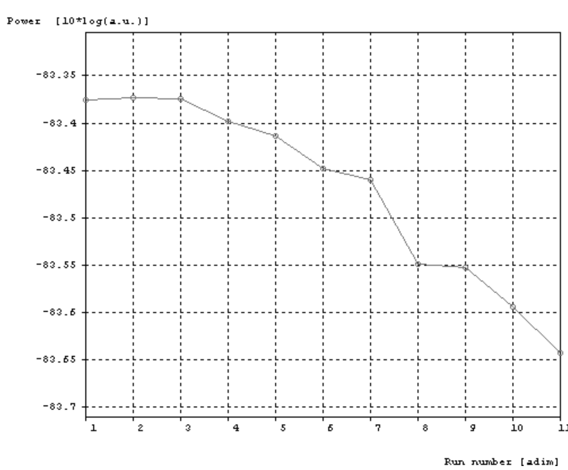
Figure 4.5: At 3 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$.


BER at Optimal Decision Threshold [adim]
PMD [adim]

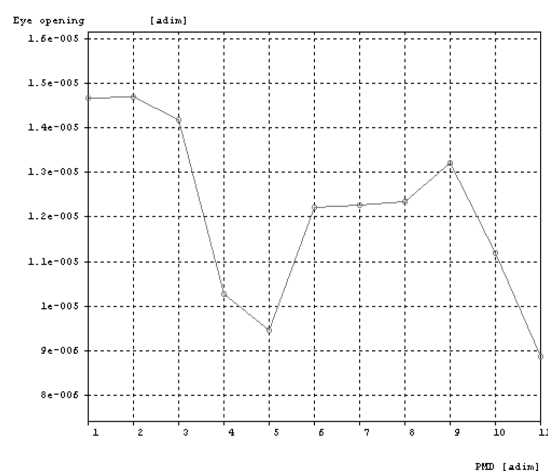
(a)


Equivalent Q at Optimal Decision Threshold [dB]
PMD [adim]

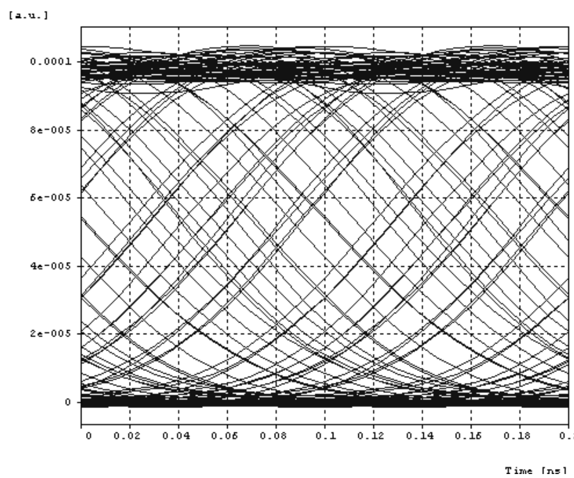
(b)


Power [10*log(a.u.)]
Run number [adim]

(c)

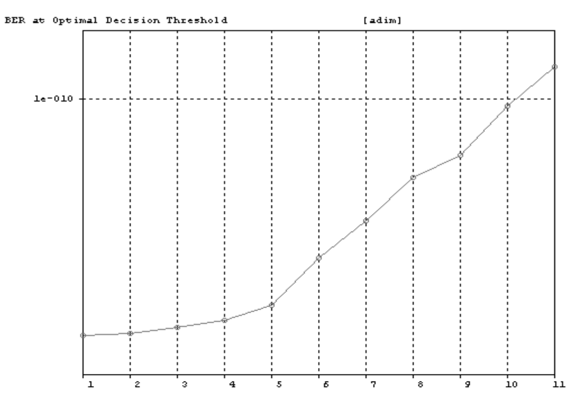

Eye opening [adim]
PMD [adim]

(d)

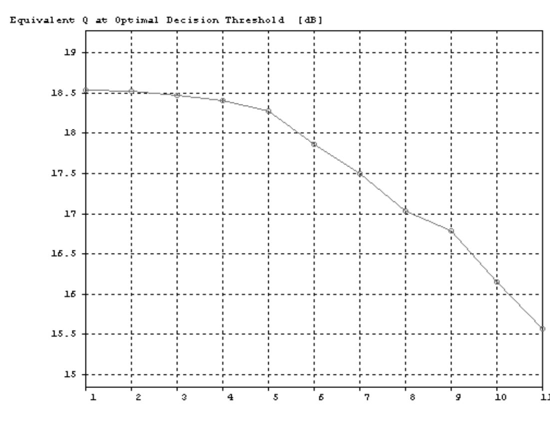


(e)

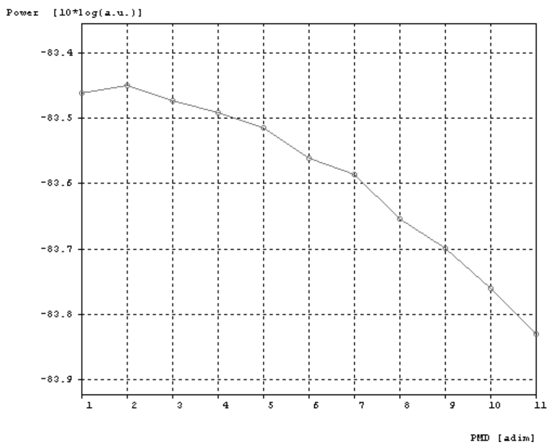
Figure 4.6: At 4 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$.



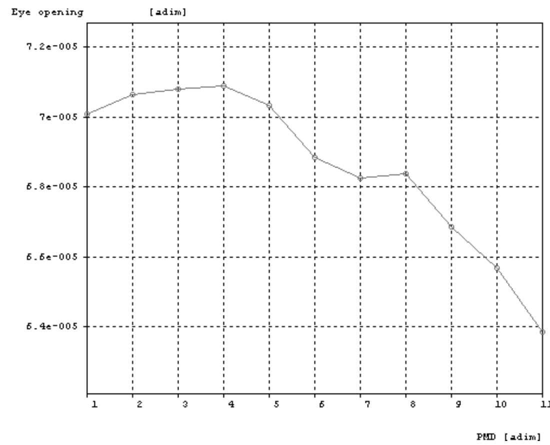
(a)



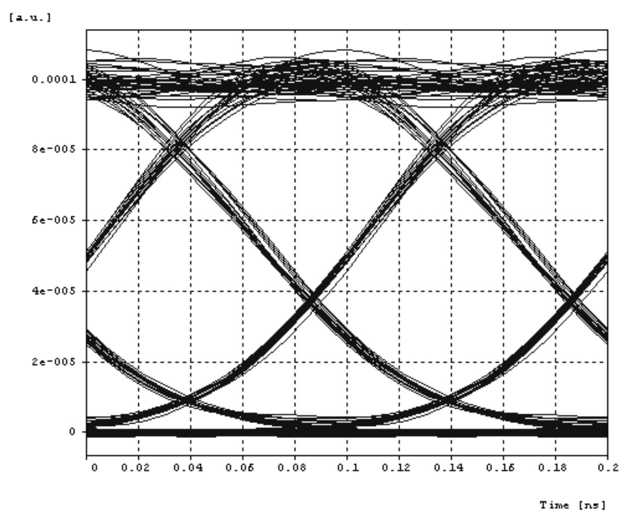
(b)



(c)

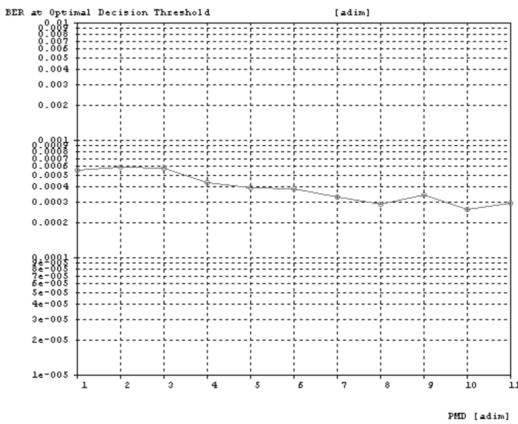


(d)



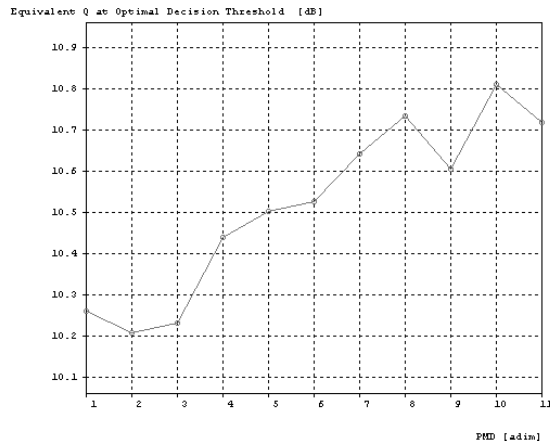
(e)

Figure 4.7: At 5 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$.



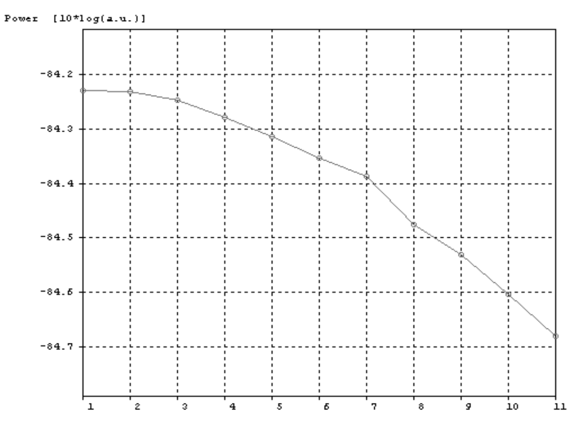
BER at Optimal Decision Threshold [adim]
0.01
0.005
0.004
0.003
0.002
0.001
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
5e-005
4e-005
3e-005
2e-005
1e-005
1 2 3 4 5 6 7 8 9 10 11
PMD [adim]

(a)



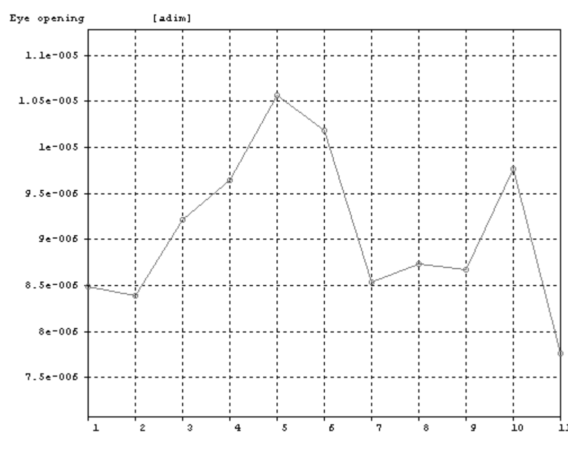
Equivalent Q at Optimal Decision Threshold [dB]
10.9
10.8
10.7
10.6
10.5
10.4
10.3
10.2
10.1
1 2 3 4 5 6 7 8 9 10 11
PMD [adim]

(b)



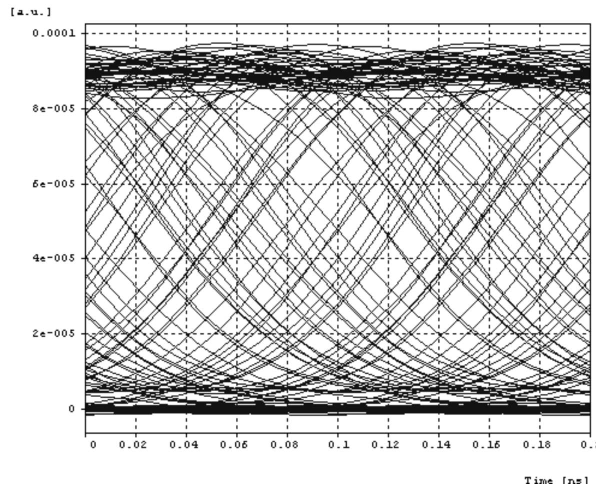
Power [10*log(a.u.)]
-84.2
-84.3
-84.4
-84.5
-84.6
-84.7
1 2 3 4 5 6 7 8 9 10 11
PMD [adim]

(c)



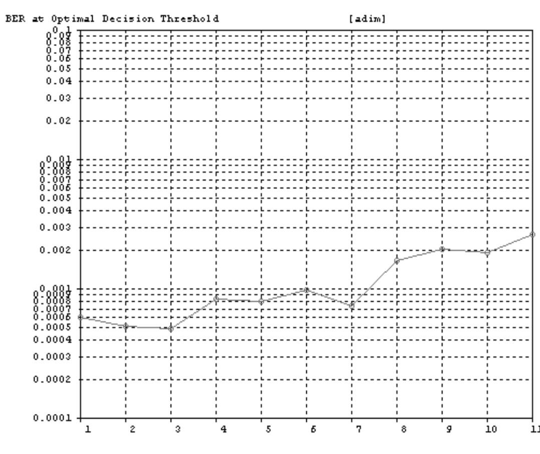
Eye opening [adim]
1.1e-005
1.05e-005
1e-005
9.5e-006
9e-006
8.5e-006
8e-006
7.5e-006
1 2 3 4 5 6 7 8 9 10 11
PMD [adim]

(d)

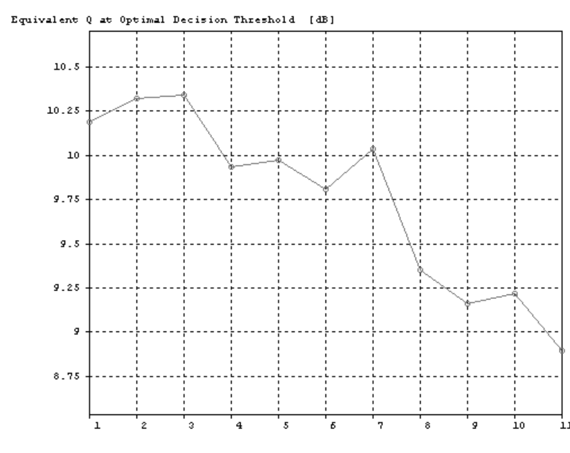


(e)

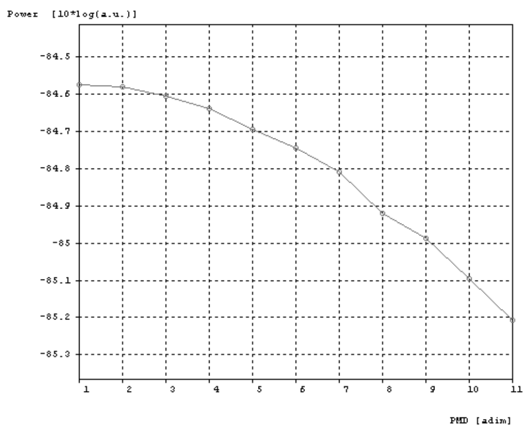
Figure 4.8: At 6 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$.



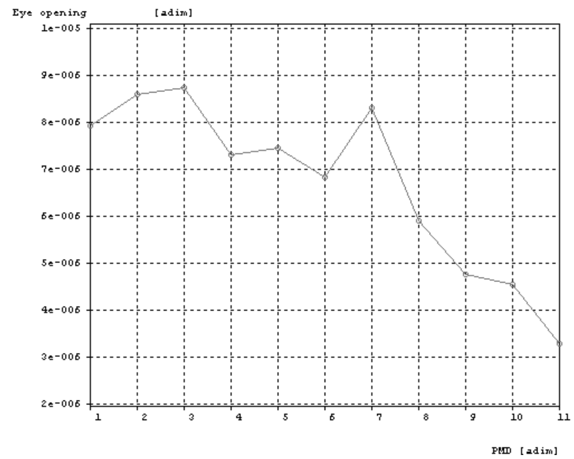
(a)



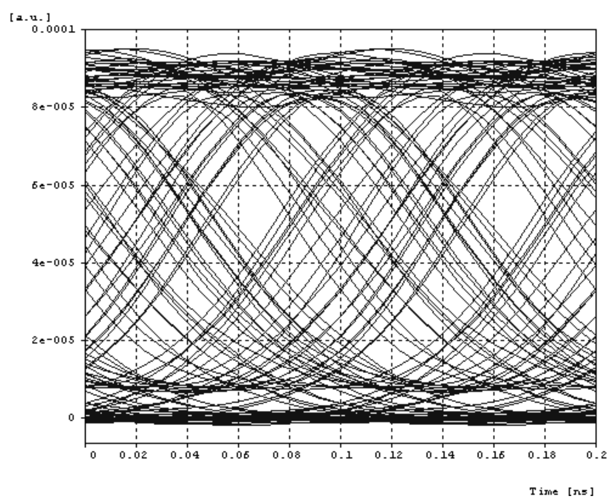
(b)



(c)

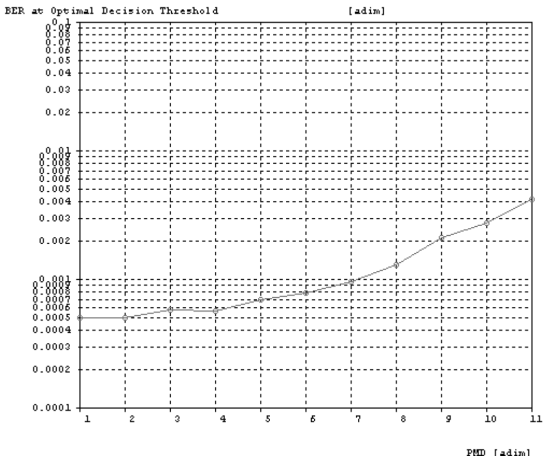


(d)

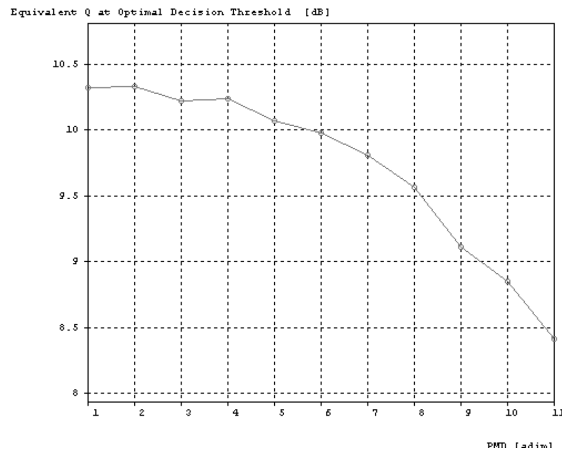


(e)

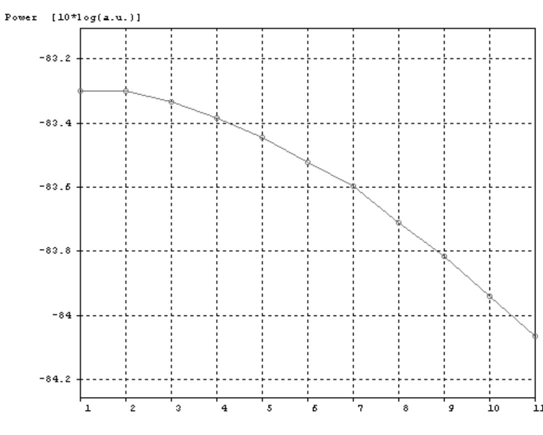
Figure 4.9: At 7 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$.


BER at Optimal Decision Threshold
[adim]
PMD [adim]

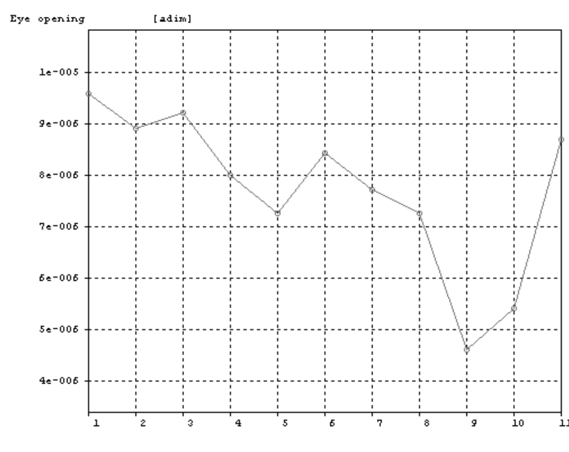
(a)


Equivalent Q at Optimal Decision Threshold [dB]

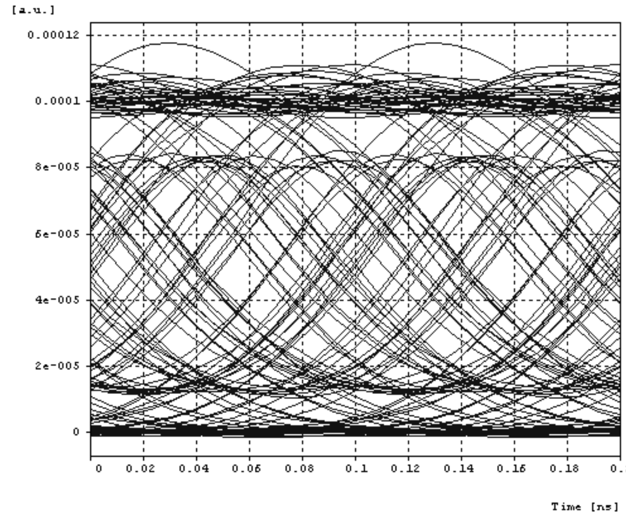
(b)


Power [10*log(a.u.)]
PMD [adim]

(c)

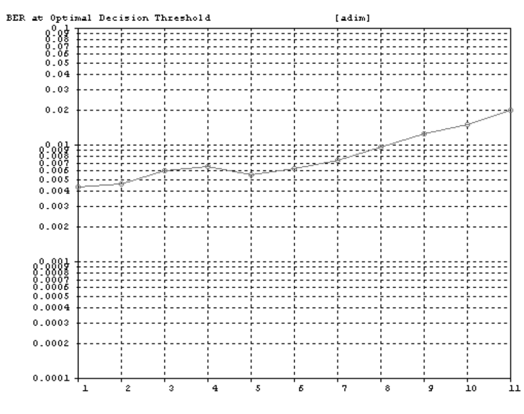

Eye opening
[adim]
PMD [adim]

(d)

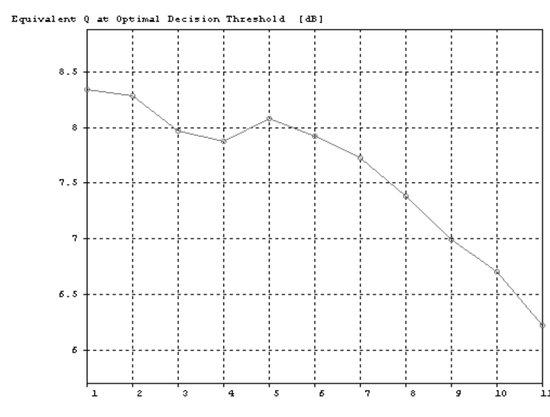


(e)

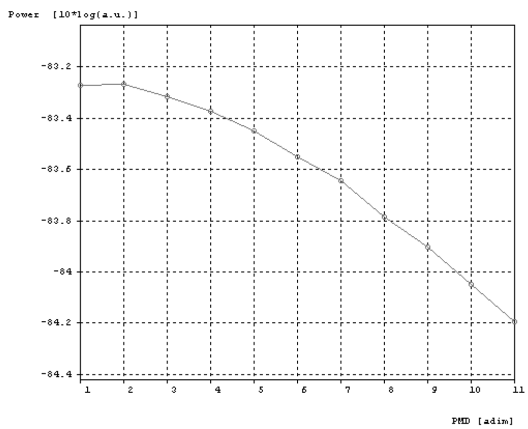
Figure 4.10: At 8 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$.



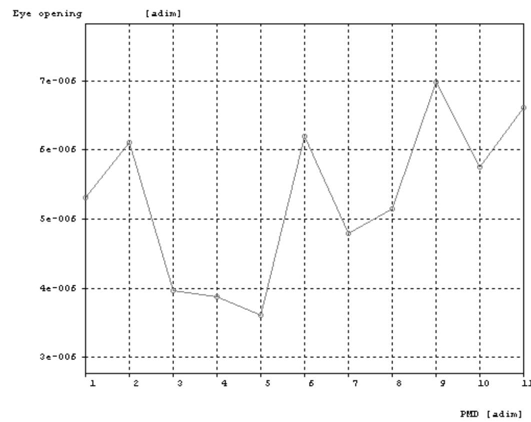
(a)



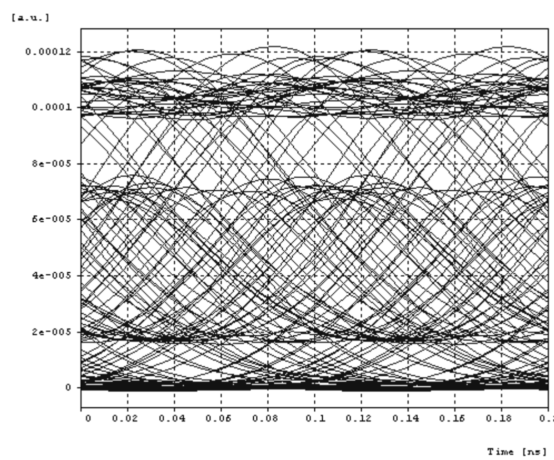
(b)



(c)

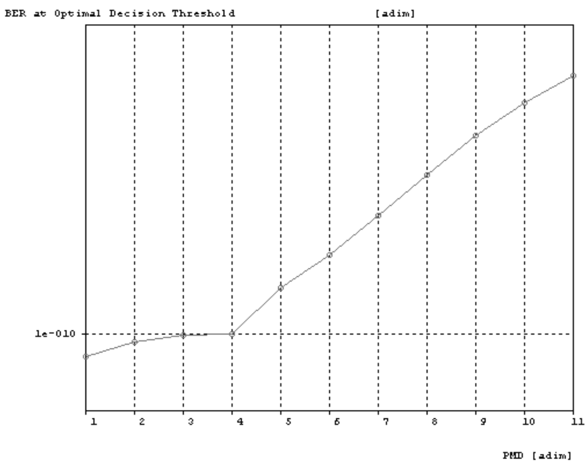


(d)

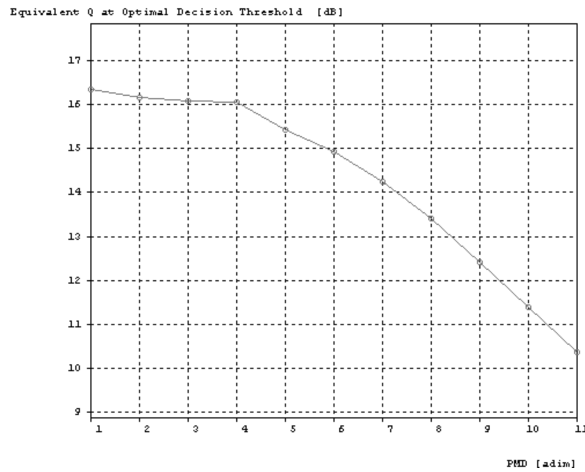


(e)

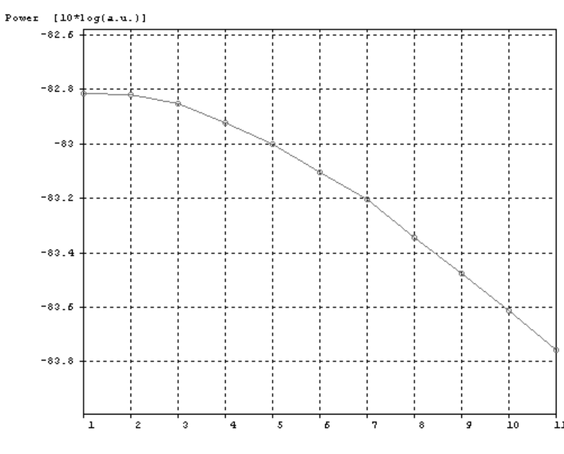
Figure 4.11: At 9 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$.


BER at Optimal Decision Threshold
[adim]
1e-010
1 2 3 4 5 6 7 8 9 10 11
PMD [adim]

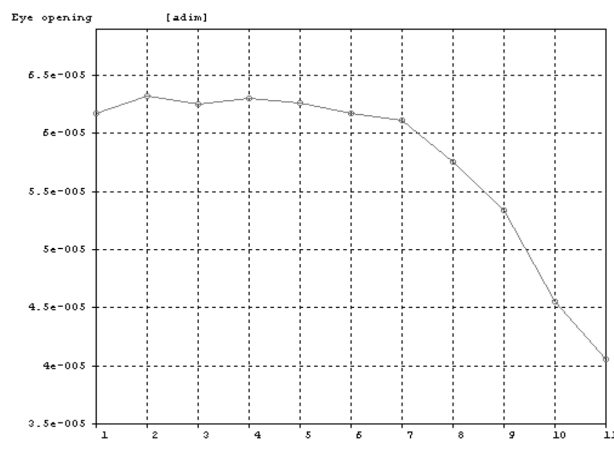
(a)


Equivalent Q at Optimal Decision Threshold [dB]
17 16 15 14 13 12 11 10 9
1 2 3 4 5 6 7 8 9 10 11
PMD [adim]

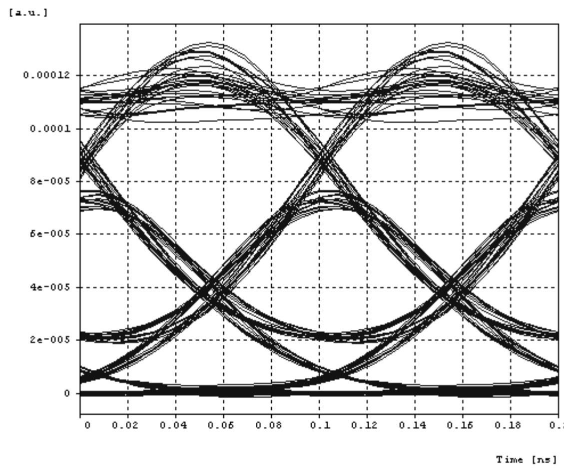
(b)


Power [10*log(a.u.)]
-82.6 -82.8 -83 -83.2 -83.4 -83.6 -83.8
1 2 3 4 5 6 7 8 9 10 11
PMD [adim]

(c)


Eye opening [adim]
6.5e-005 6e-005 5.5e-005 5e-005 4.5e-005 4e-005 3.5e-005
1 2 3 4 5 6 7 8 9 10 11
PMD [adim]

(d)

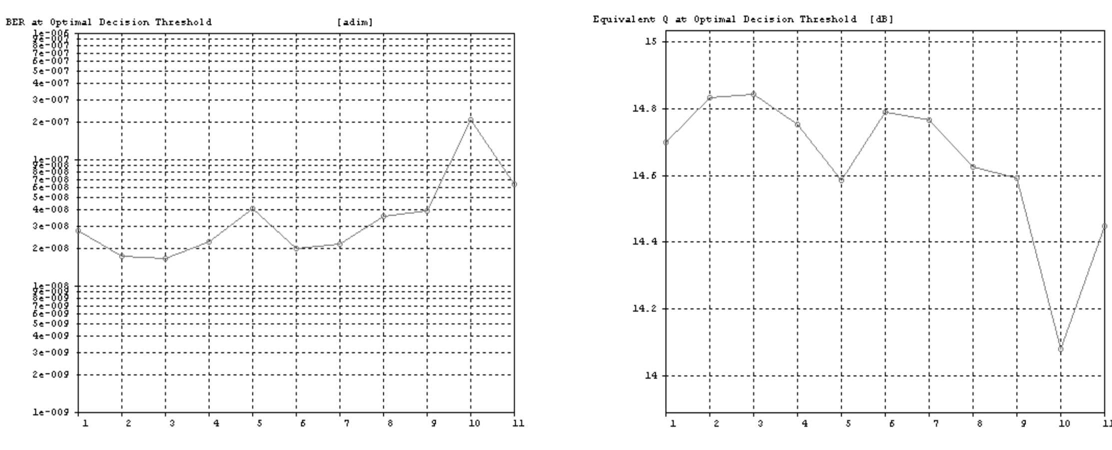


(e)

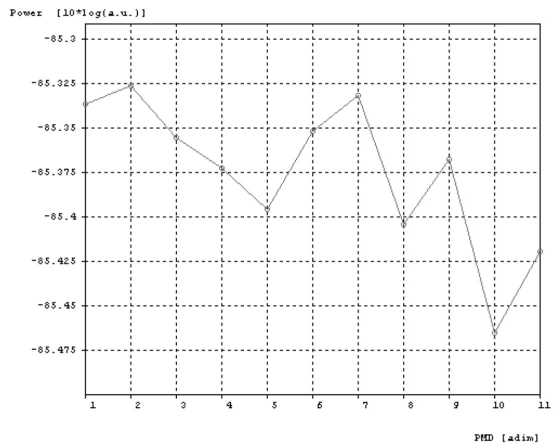
Figure 4.12: At 10 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$.

4.2.2 Results of post-compensation on first order PMD

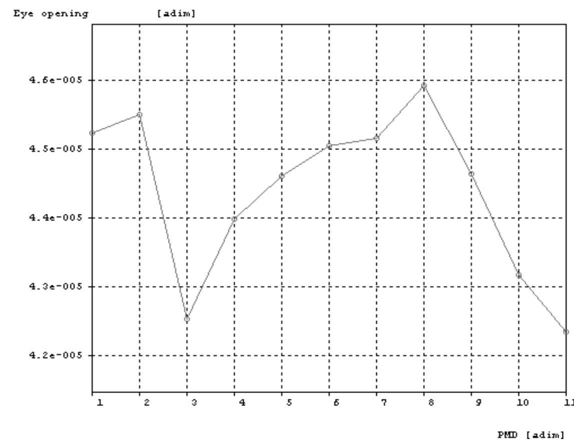
Now we show the effect of the post compensation technique on the first order PMD. The effect of PMD at different bit rates is shown below :



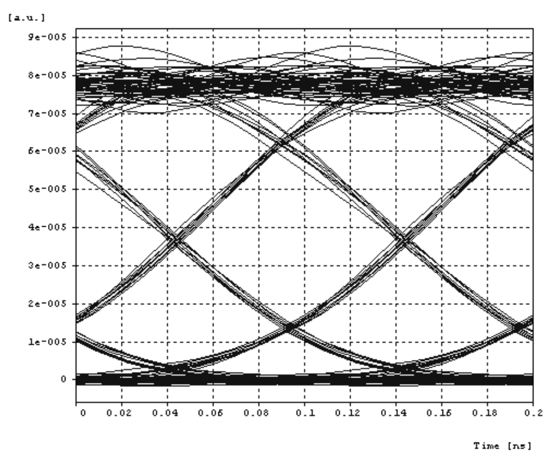
(a) (b)



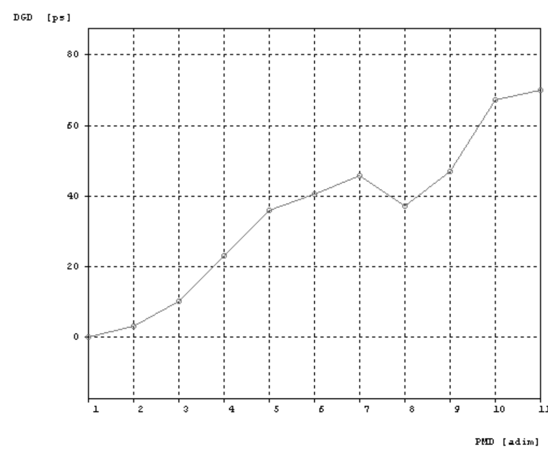
(c)



(d)

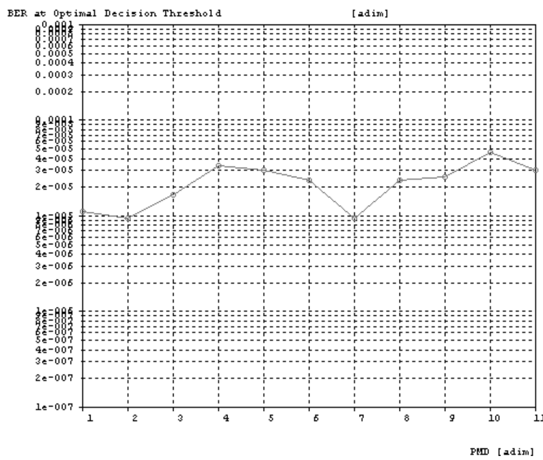


(e)

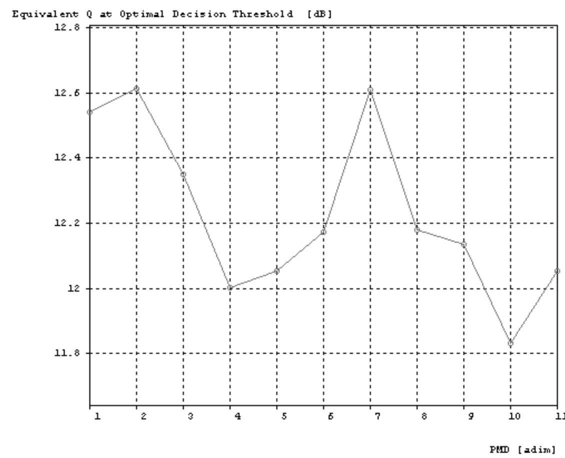


(f)

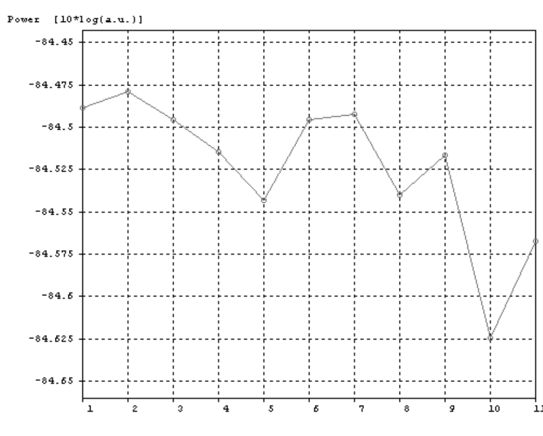
Figure 4.13: At 2.5 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$ (f) DGD at the PMD emulator


BER at Optimal Decision Threshold
[adim]
0.0003
0.0002
2e-005
3e-005
4e-005
2e-006
3e-006
4e-006
2e-007
3e-007
4e-007
1e-007
1
2
3
4
5
6
7
8
9
10
11
PMD [adim]

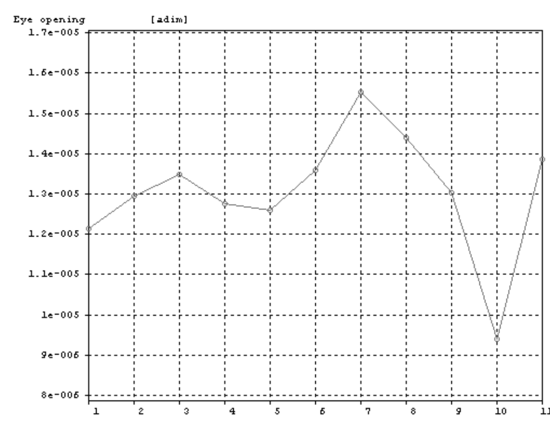
(a)


Equivalent Q at Optimal Decision Threshold [dB]
12.8
12.6
12.4
12.2
12
11.8
1
2
3
4
5
6
7
8
9
10
11
PMD [adim]

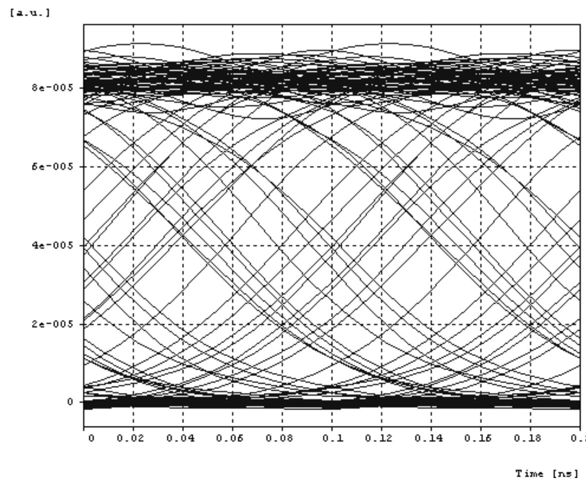
(b)


Power [10*log(a.u.)]
-84.45
-84.475
-84.5
-84.525
-84.55
-84.575
-84.6
-84.625
-84.65
1
2
3
4
5
6
7
8
9
10
11

(c)

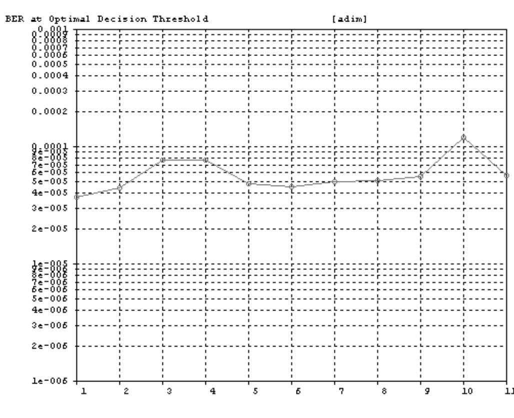

Eye opening
[adim]
1.7e-005
1.6e-005
1.5e-005
1.4e-005
1.3e-005
1.2e-005
1.1e-005
1e-005
9e-006
8e-006
1
2
3
4
5
6
7
8
9
10
11
PMD [adim]

(d)

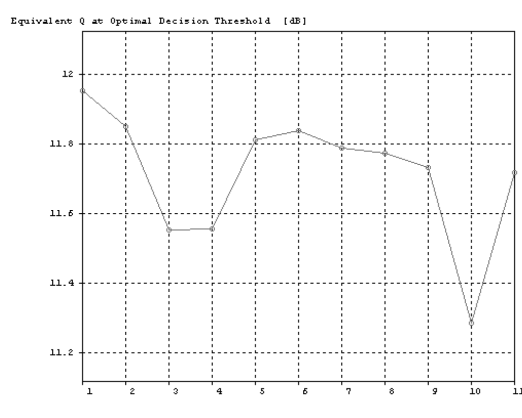


(e)

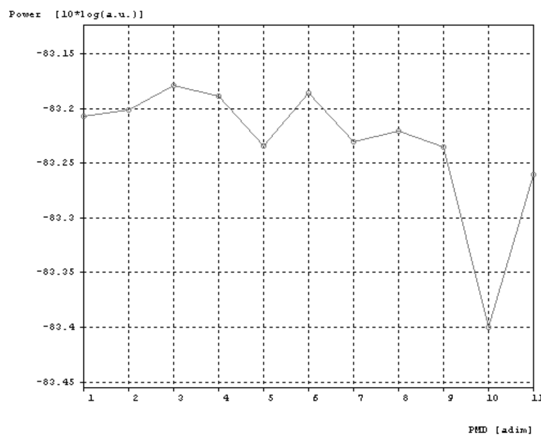
Figure 4.14: At 3 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$



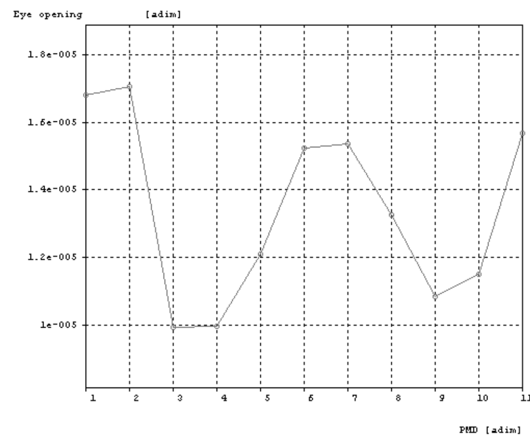
(a)



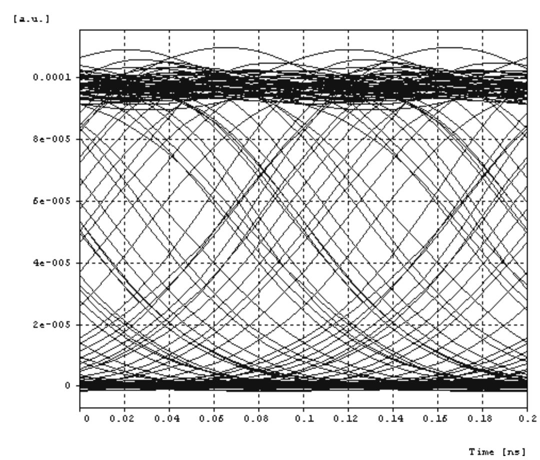
(b)



(c)

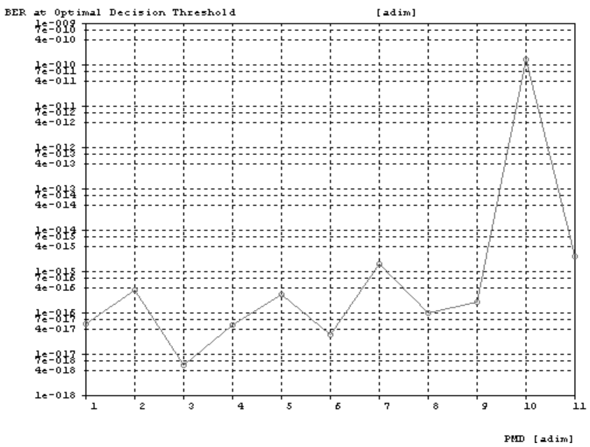


(d)

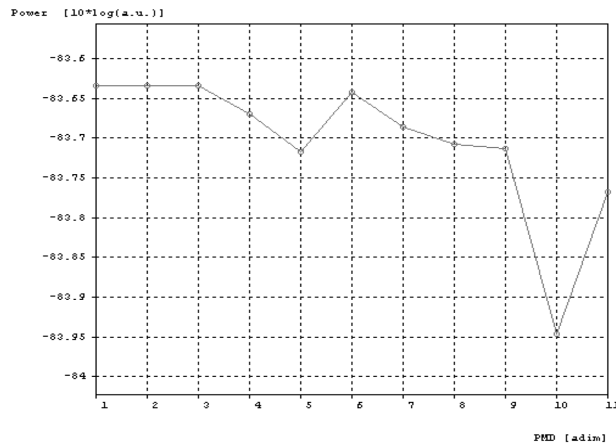


(e)

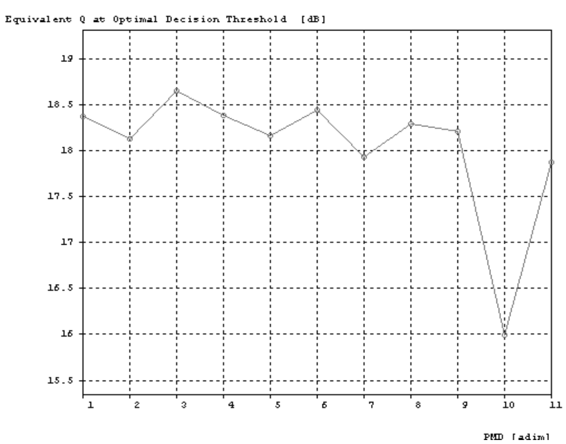
Figure 4.15: At 4 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$


BER at Optimal Decision Threshold [adim]
4e-010
4e-011
4e-012
4e-013
4e-014
4e-015
4e-016
4e-017
4e-018
1e-018
1 2 3 4 5 6 7 8 9 10 11
PMD [adim]

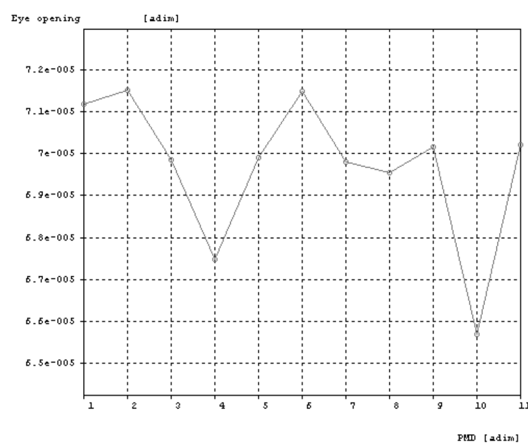
(a)


Power [10*log(a.u.)]
-83.6
-83.65
-83.7
-83.75
-83.8
-83.85
-83.9
-83.95
-84
1 2 3 4 5 6 7 8 9 10 11
PMD [adim]

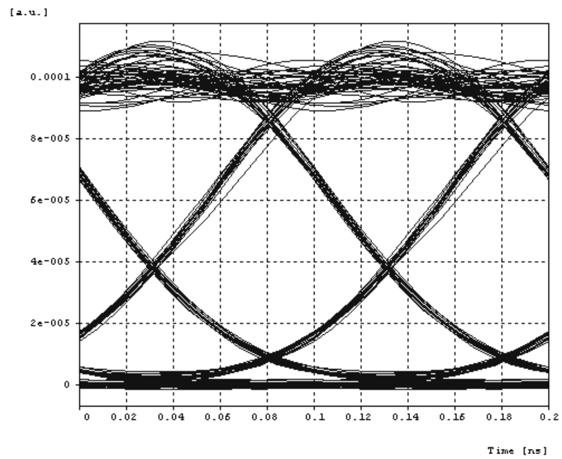
(b)


Equivalent Q at Optimal Decision Threshold [dB]
19
18.5
18
17.5
17
16.5
16
15.5
1 2 3 4 5 6 7 8 9 10 11
PMD [adim]

(c)

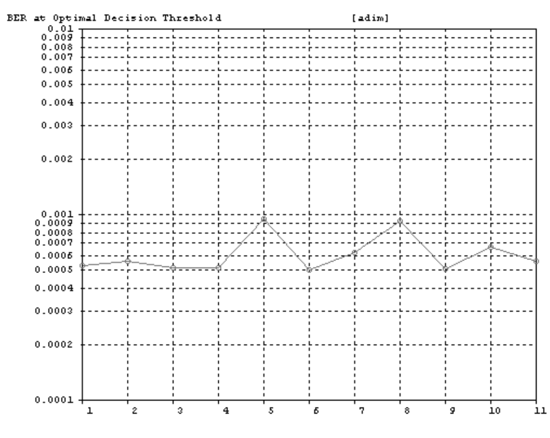

Eye opening [adim]
7.2e-005
7.1e-005
7e-005
6.9e-005
6.8e-005
6.7e-005
6.6e-005
6.5e-005
1 2 3 4 5 6 7 8 9 10 11
PMD [adim]

(d)

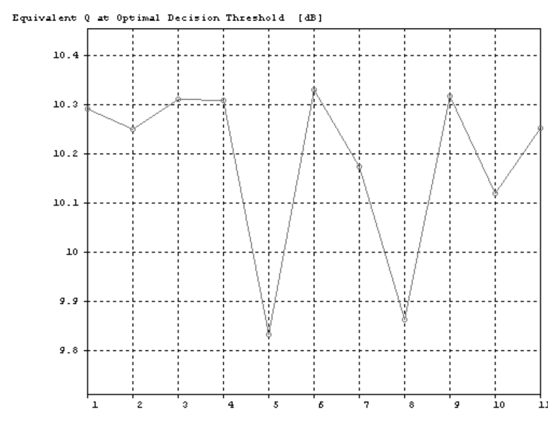


(e)

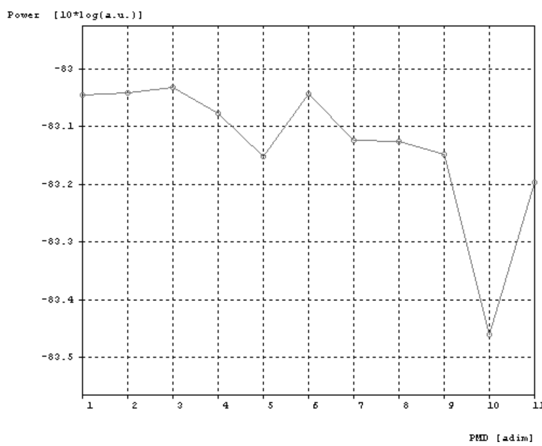
Figure 4.16: At 5 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$



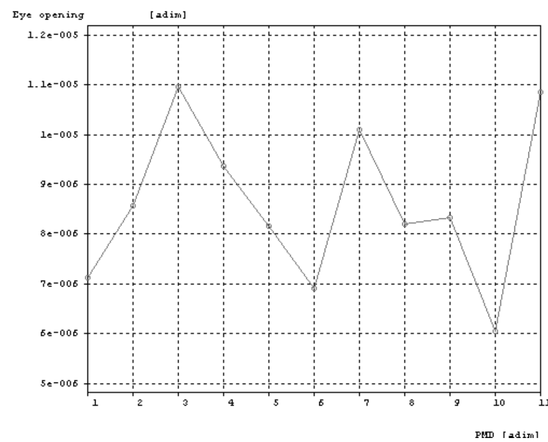
(a)



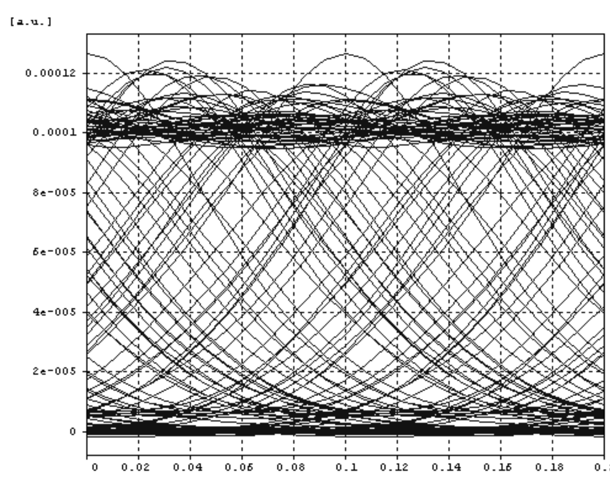
(b)



(c)

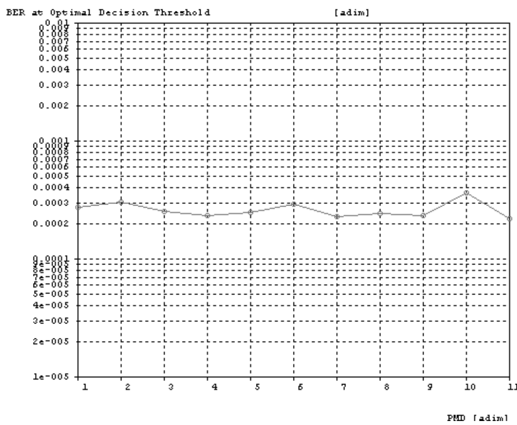


(d)

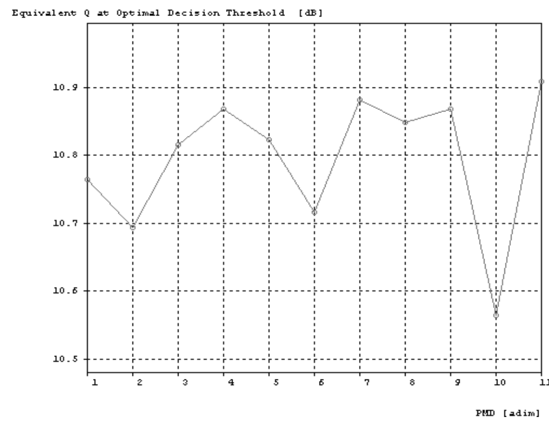


(e)

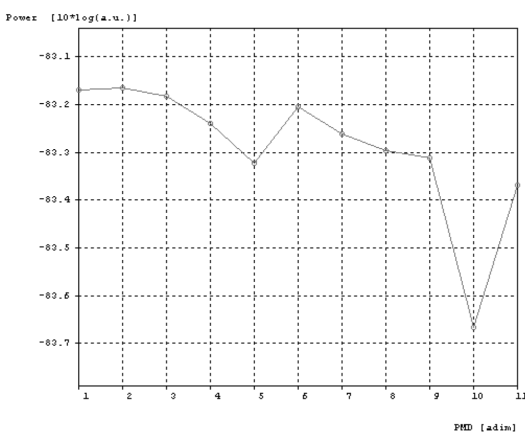
Figure 4.17: At 6 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$


BER at Optimal Decision Threshold [adim]
PMD [adim]

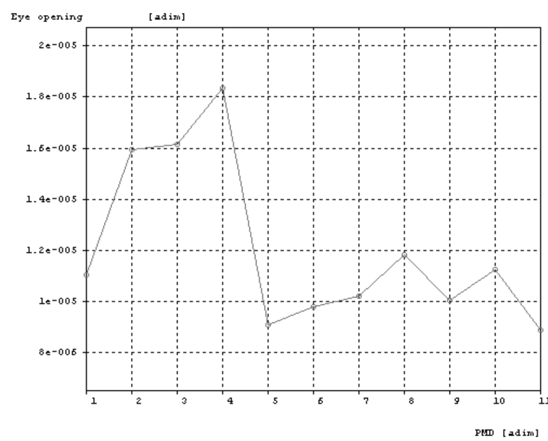
(a)


Equivalent Q at Optimal Decision Threshold [dB]
PMD [adim]

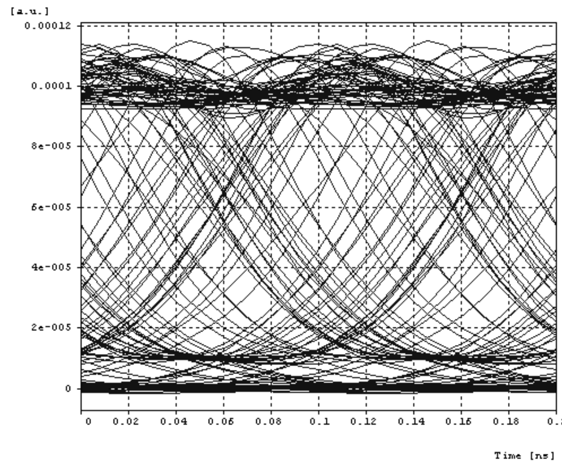
(b)


Power [10*log(a.u.)]
PMD [adim]

(c)

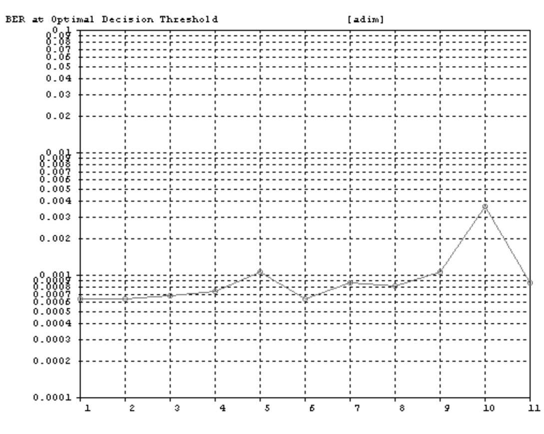

Eye opening [adim]
PMD [adim]

(d)

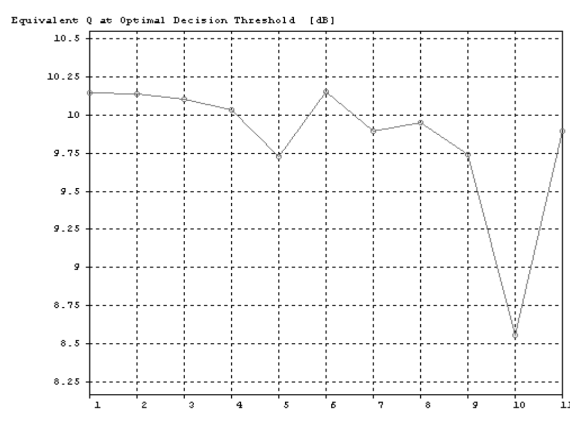


(e)

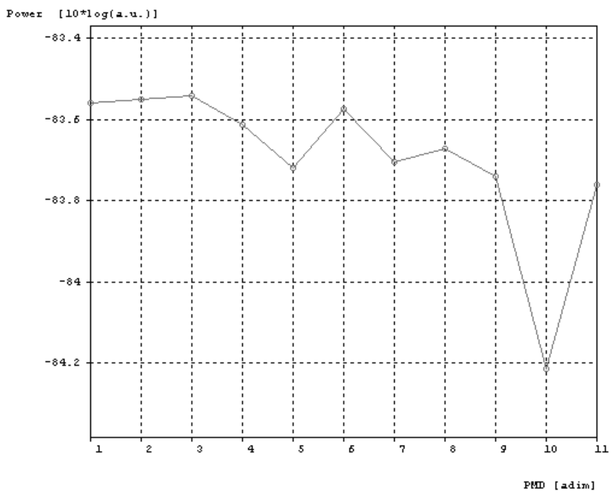
Figure 4.18: At 7 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$



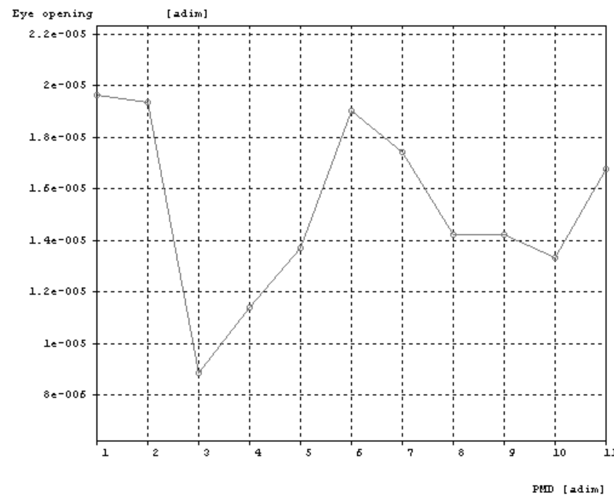
(a)



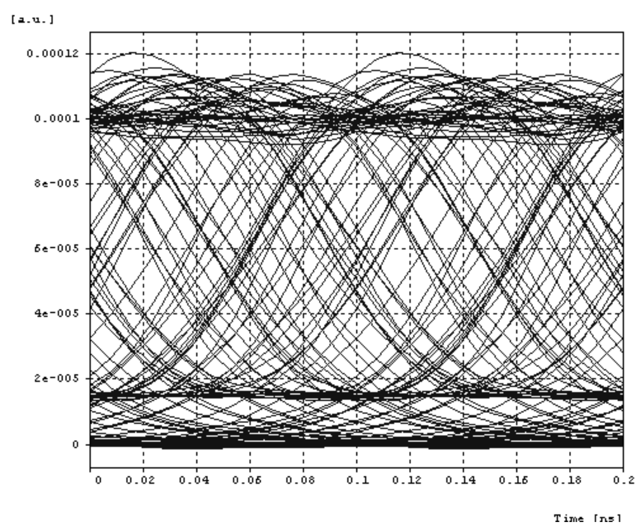
(b)



(c)

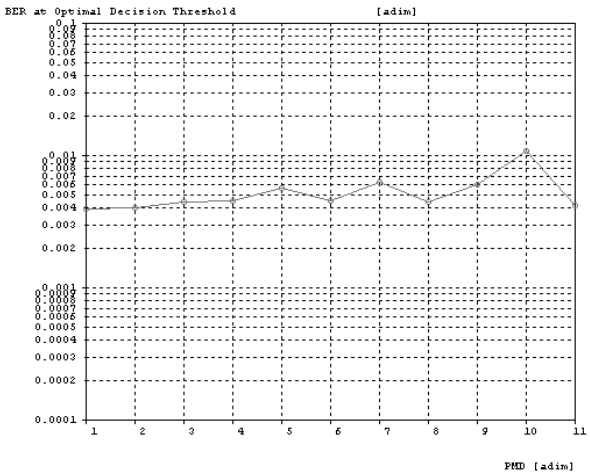


(d)

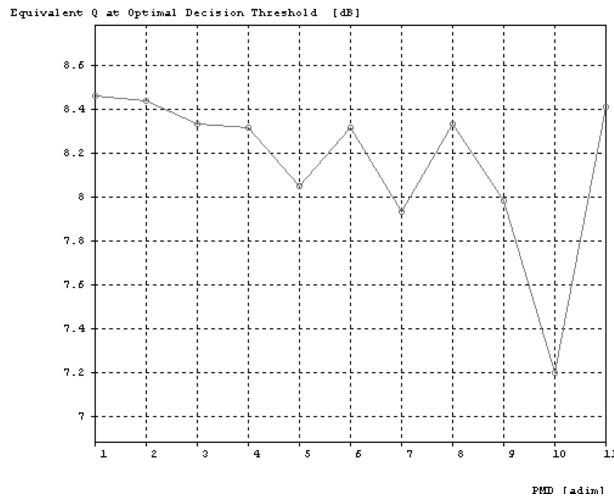


(e)

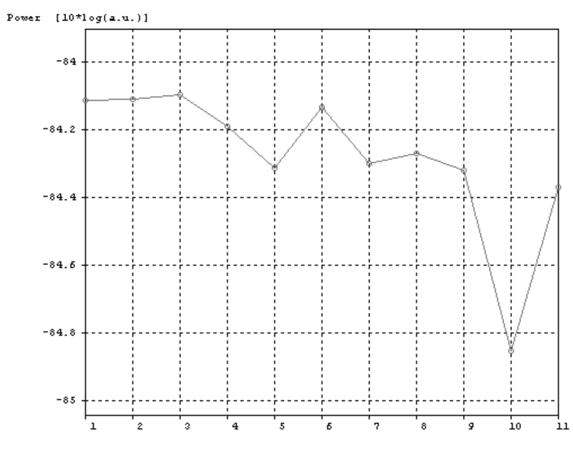
Figure 4.19: At 8 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$


BER at Optimal Decision Threshold [adim]
0.1
0.04
0.03
0.02
0.01
0.004
0.003
0.002
0.001
0.0004
0.0003
0.0002
0.0001
1 2 3 4 5 6 7 8 9 10 11
PMD [adim]

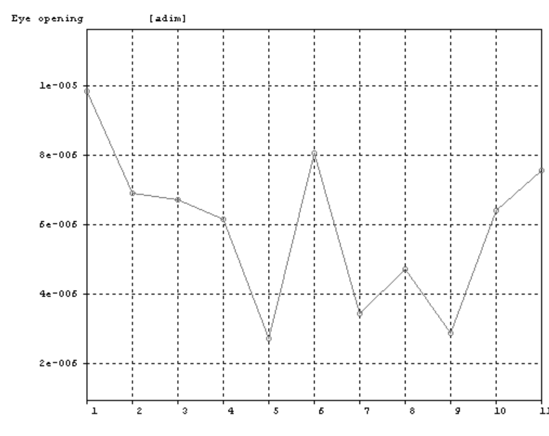
(a)


Equivalent Q at Optimal Decision Threshold [dB]
8.6
8.4
8.2
8
7.8
7.6
7.4
7.2
7
1 2 3 4 5 6 7 8 9 10 11

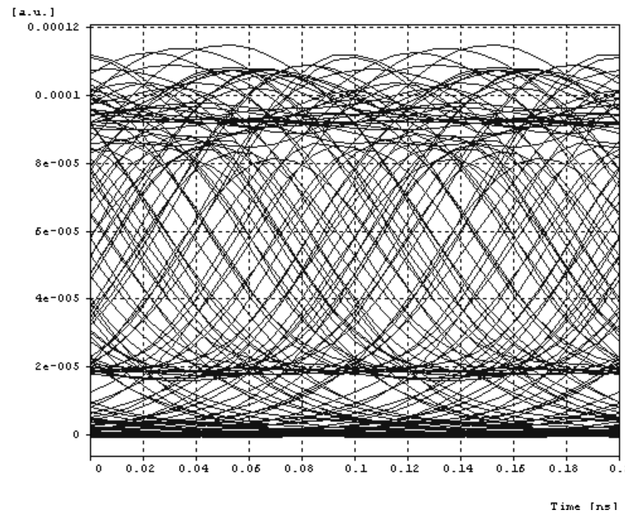
(b)


Power [10*log(a.u.)]
-84
-84.2
-84.4
-84.6
-84.8
-85
1 2 3 4 5 6 7 8 9 10 11
PMD [adim]

(c)

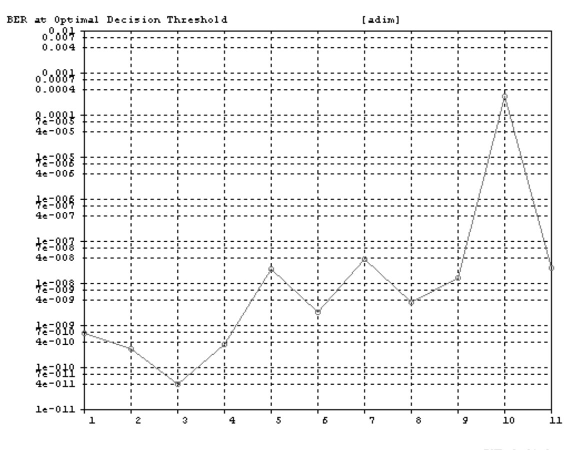

Eye opening [adim]
1e-005
8e-006
6e-006
4e-006
2e-006
1 2 3 4 5 6 7 8 9 10 11

(d)

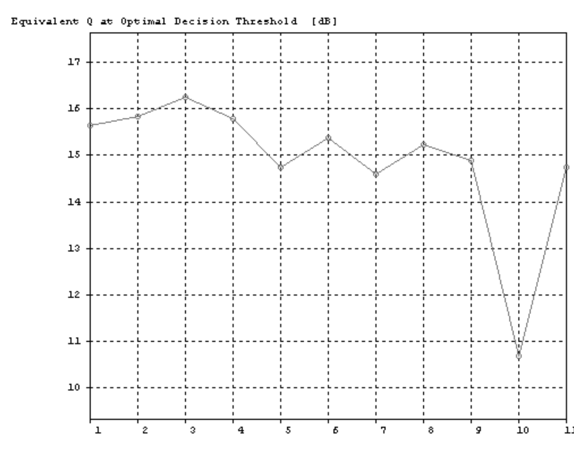


(e)

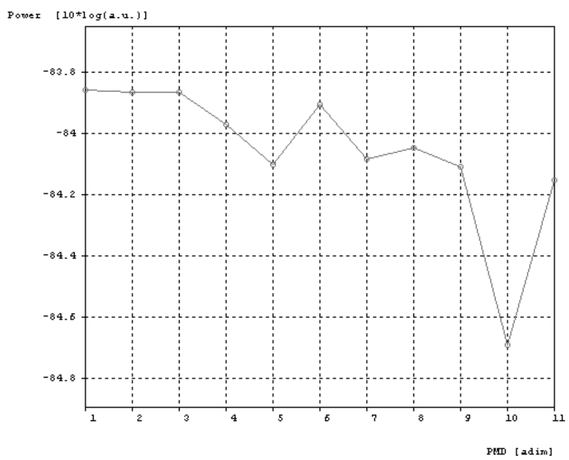
Figure 4.20: At 9 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$



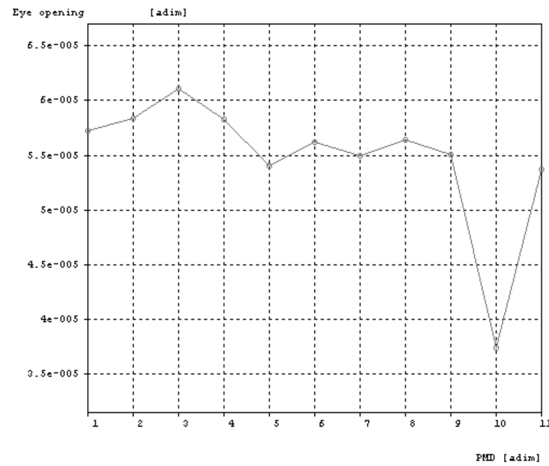
(a)



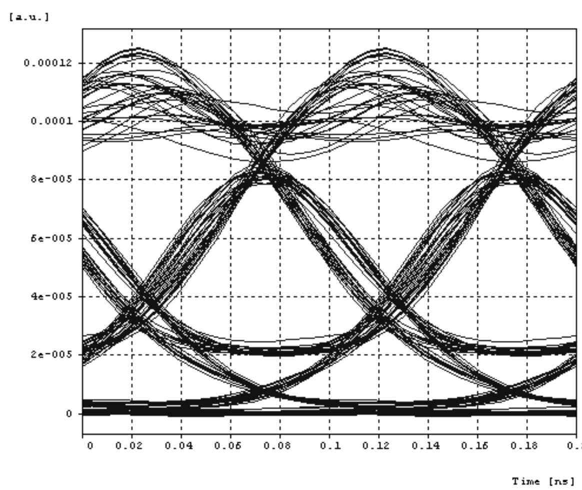
(b)



(c)



(d)

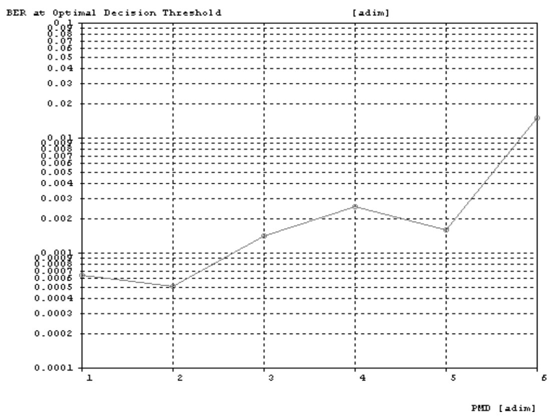


(e)

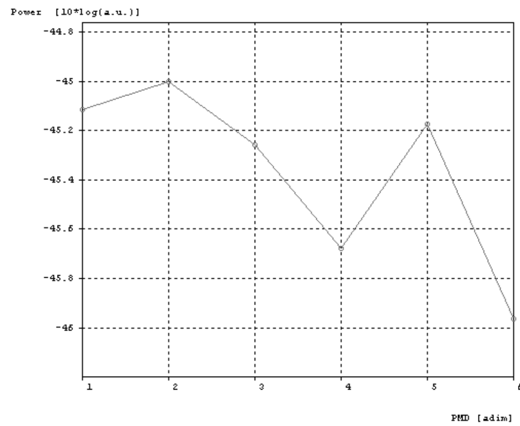
Figure 4.21: At 10 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram at 20 $ps/\sqrt{km}$

4.2.3 Results of post-compensation on second order PMD

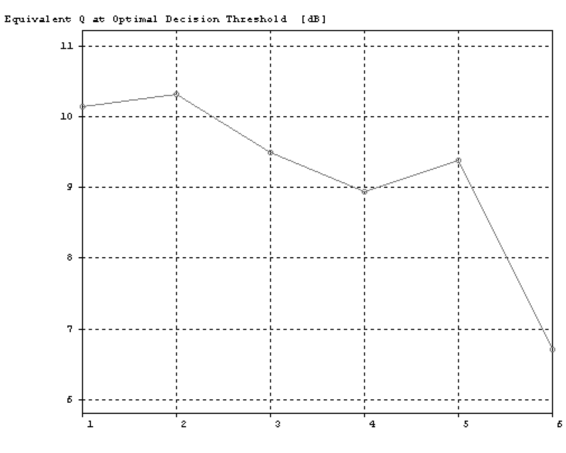
Now we analyze the results of the second order post compensation technique at different bit rates. The effect of increasing the PMD on the output is shown below:



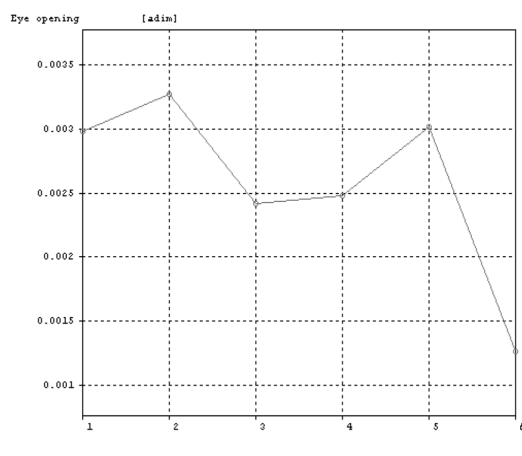
(a)



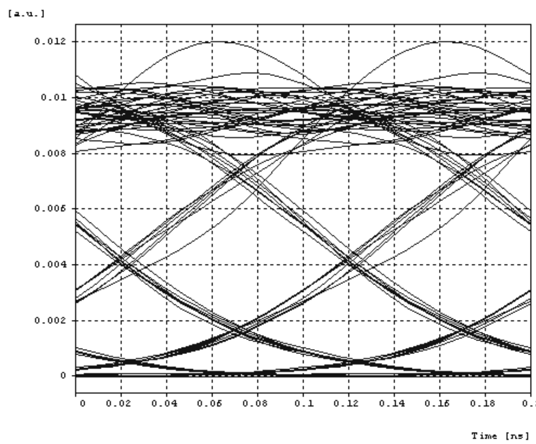
(b)



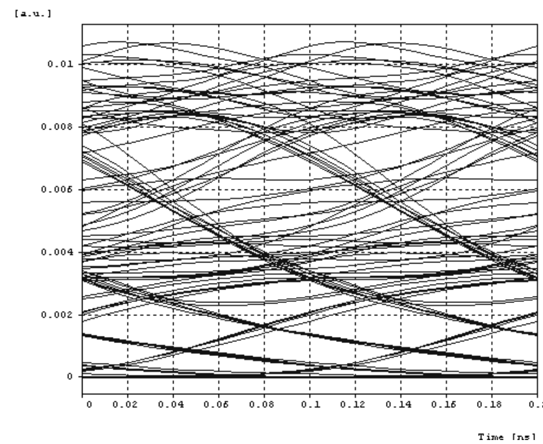
(c)



(d)

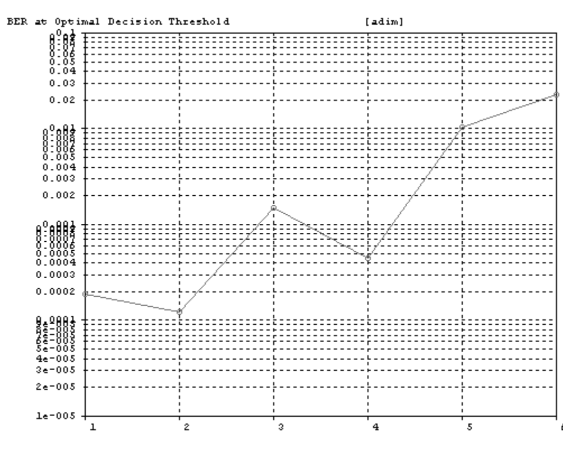


(e)

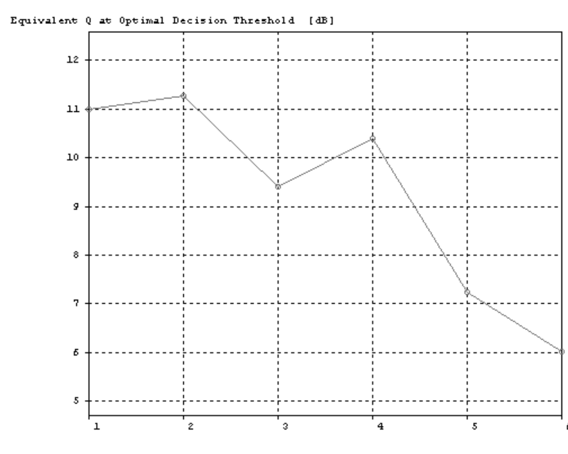


(f)

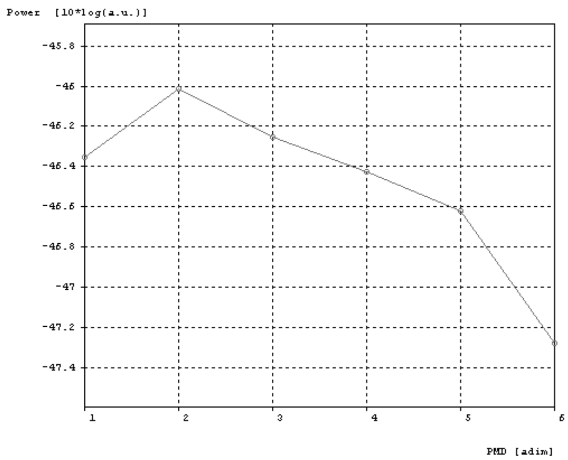
Figure 4.22: At 2.5 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram when PMD is 0 (f) Eye diagram at 20 $ps/\sqrt{km}$



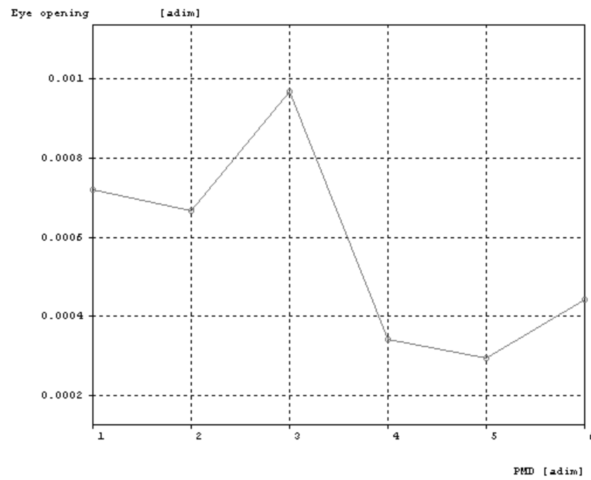
(a)



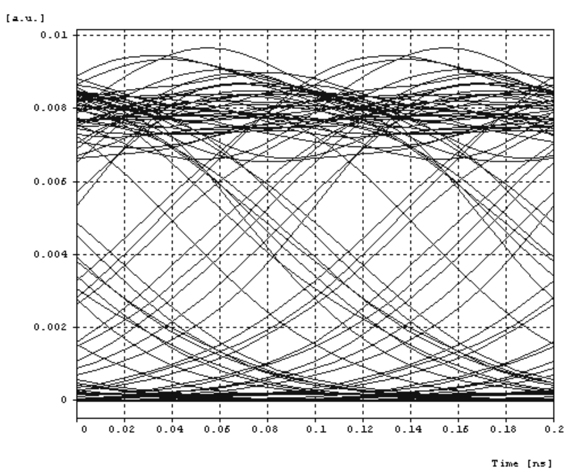
(b)



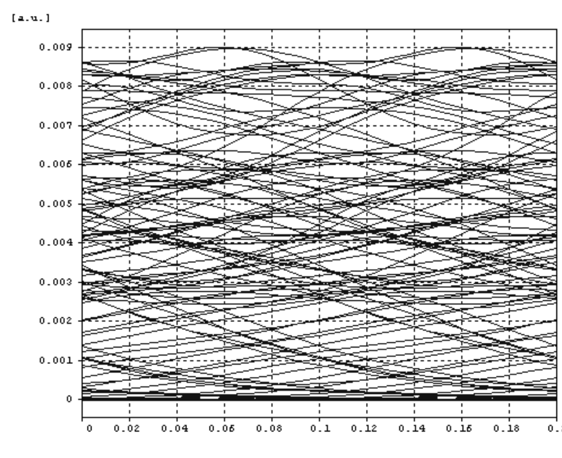
(c)



(d)

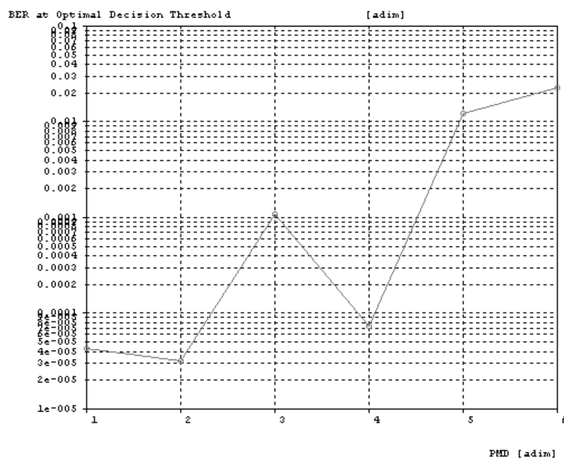


(e)

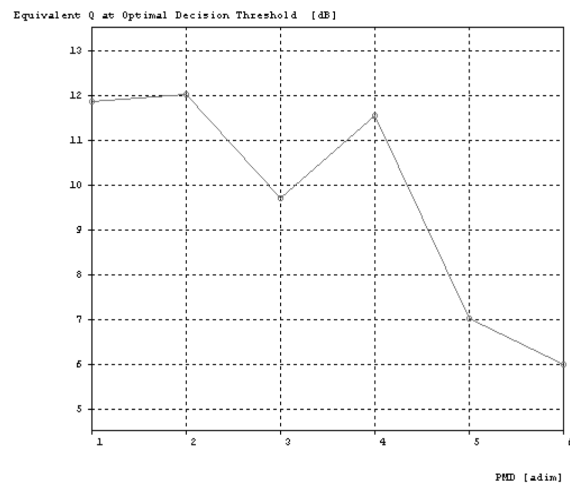


(f)

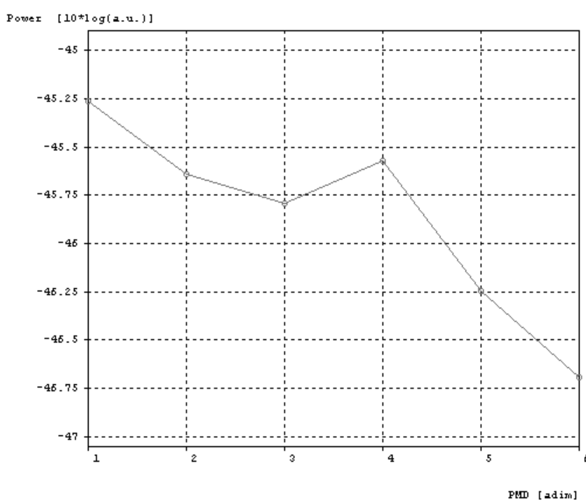
Figure 4.23: At 3 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram when PMD is 0 (f) Eye diagram at 20 $ps/\sqrt{km}$


BER at Optimal Decision Threshold
[adim]
PMD [adim]

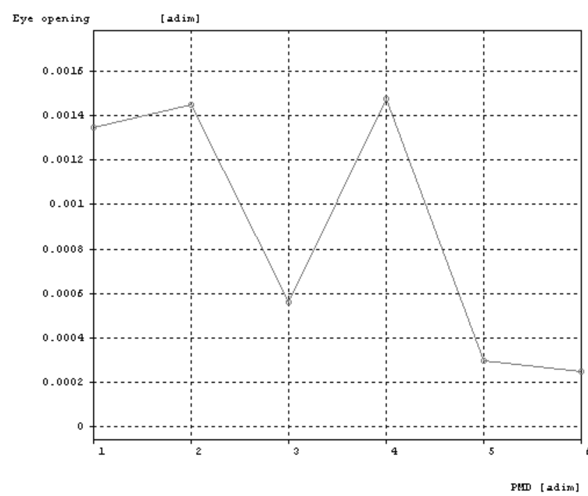
(a)


Equivalent Q at Optimal Decision Threshold [dB]
PMD [adim]

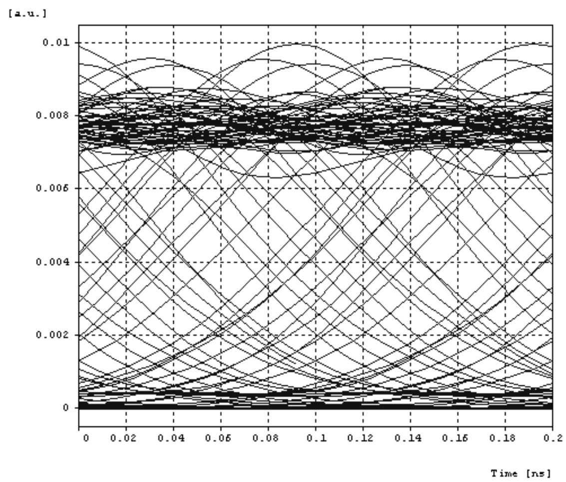
(b)


Power [10*log(a.u.)]
PMD [adim]

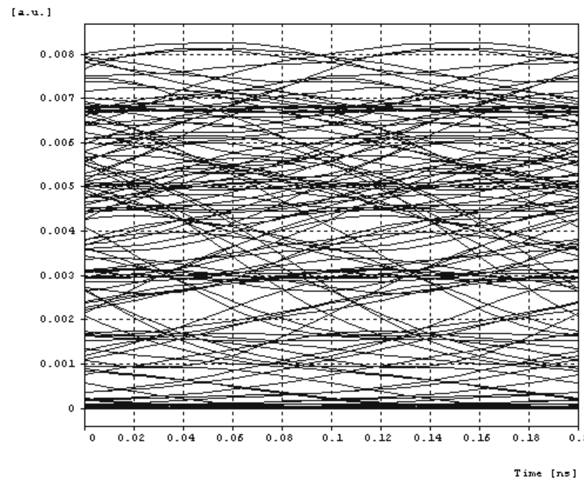
(c)


Eye opening
[adim]
PMD [adim]

(d)

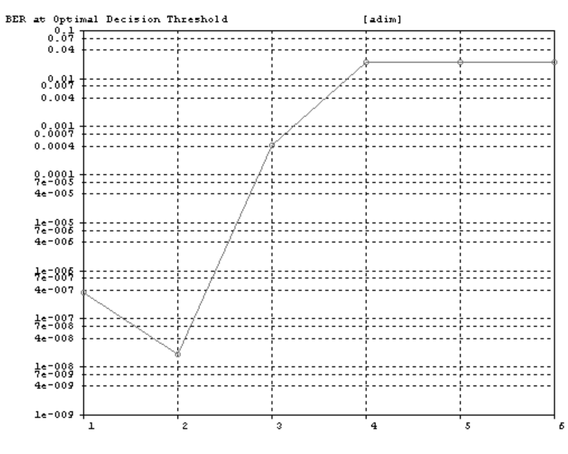


(e)

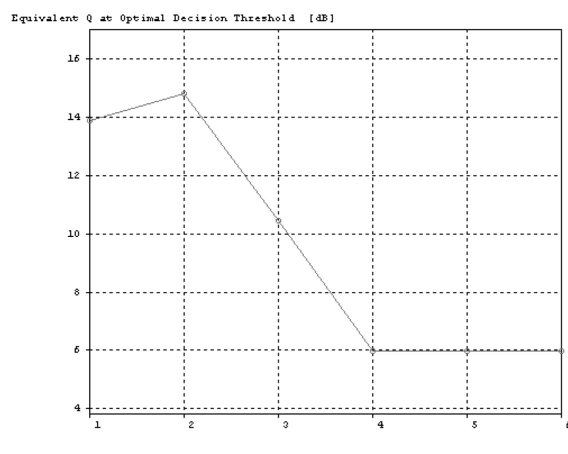


(f)

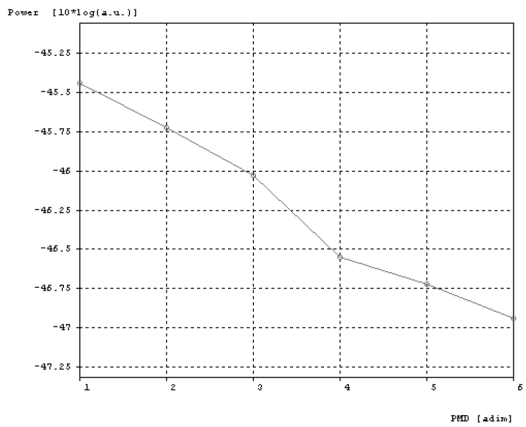
Figure 4.24: At 4 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram when PMD is 0 (f) Eye diagram at 20 $ps/\sqrt{km}$



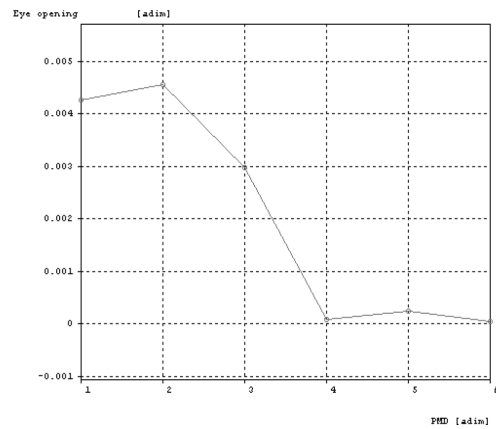
(a)



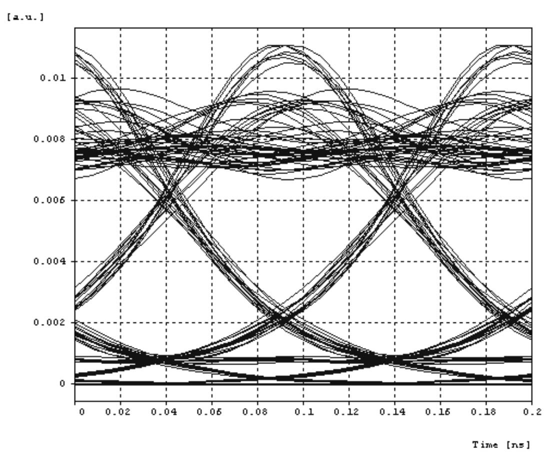
(b)



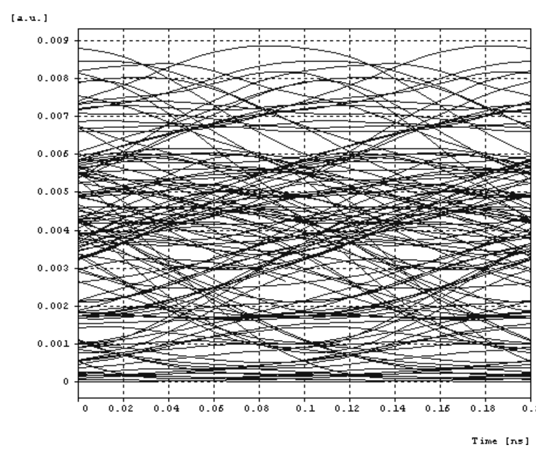
(c)



(d)

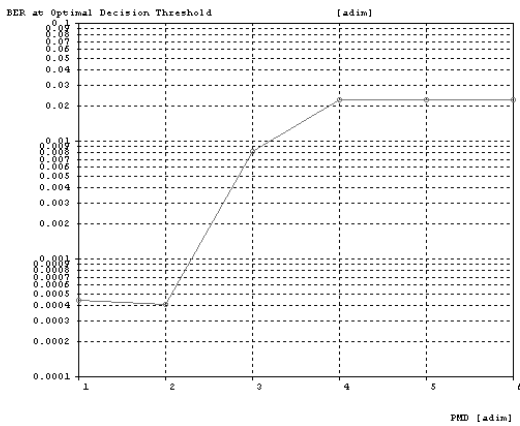


(e)

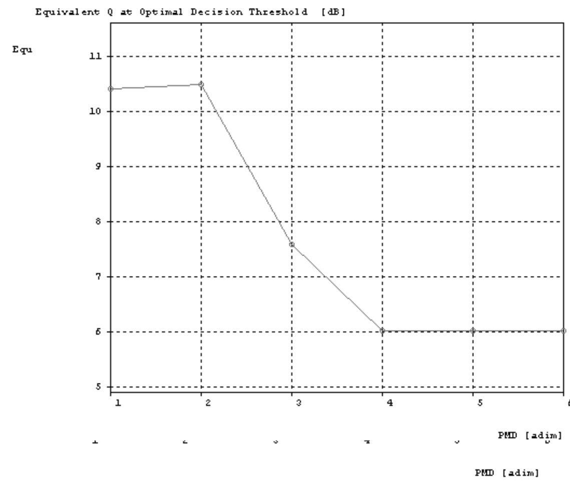


(f)

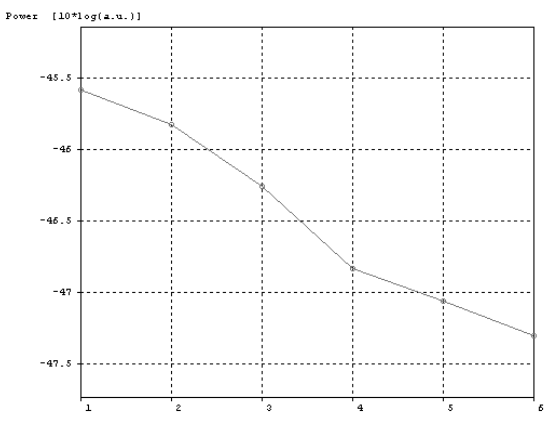
Figure 4.25: At 5 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram when PMD is 0 (f) Eye diagram at 20 $ps/\sqrt{km}$


BER at Optimal Decision Threshold [adim]
0.1
0.05
0.04
0.03
0.02
0.005
0.004
0.003
0.002
0.001
0.0005
0.0004
0.0003
0.0002
0.0001
1
2
3
4
5
6
PMD [adim]

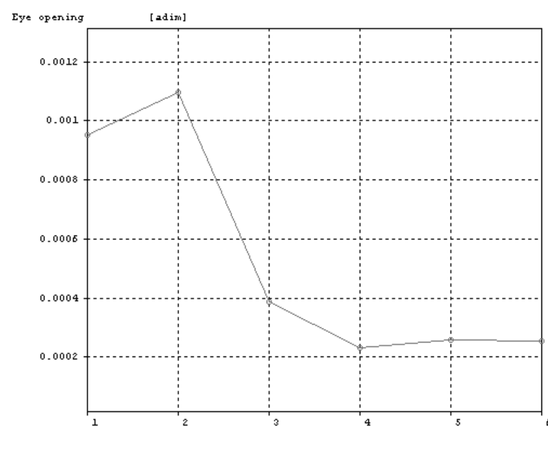
(a)


Equivalent Q at Optimal Decision Threshold [dB]
Equ
11
10
9
8
7
6
5
1
2
3
4
5
6
PMD [adim]
PMD [adim]

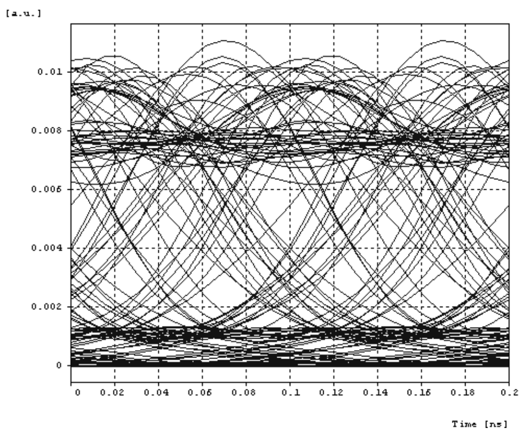
(b)


Power [10*log(a.u.)]
-45.5
-46
-46.5
-47
-47.5
1
2
3
4
5
6
PMD [adim]

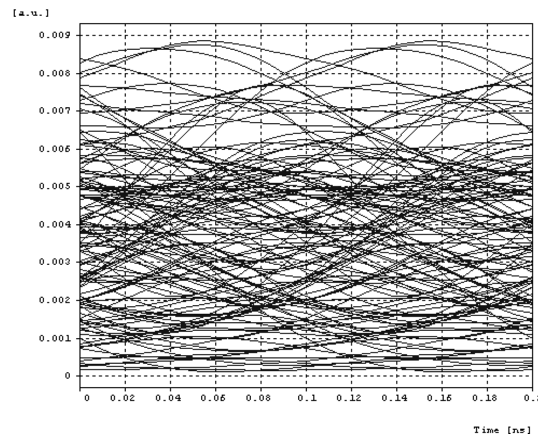
(c)


Eye opening [adim]
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
1
2
3
4
5
6
PMD [adim]

(d)

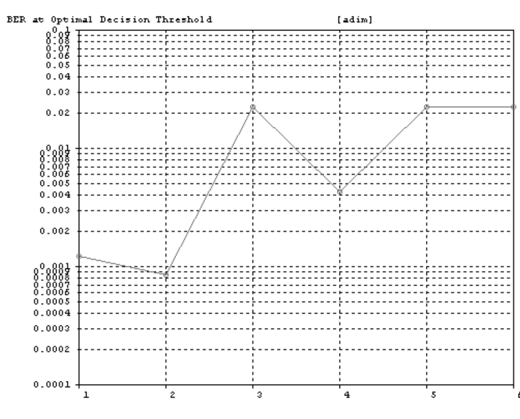


(e)

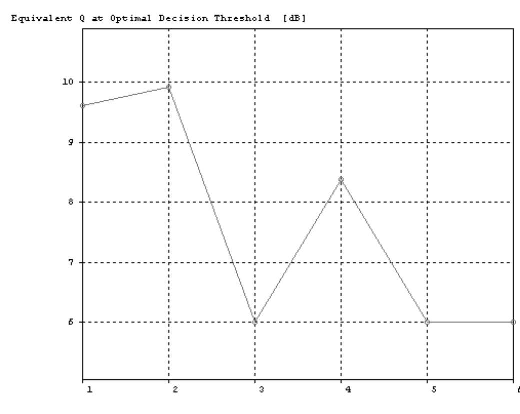


(f)

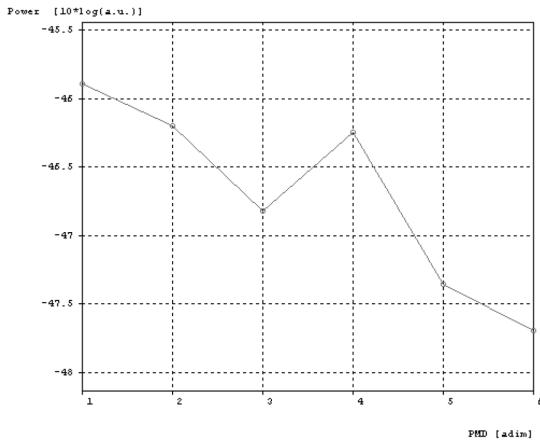
Figure 4.26: At 6 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram when PMD is 0 (f) Eye diagram at 20 $ps/\sqrt{km}$



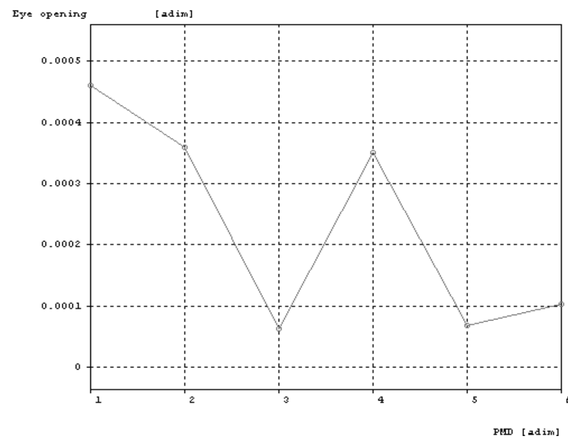
(a)



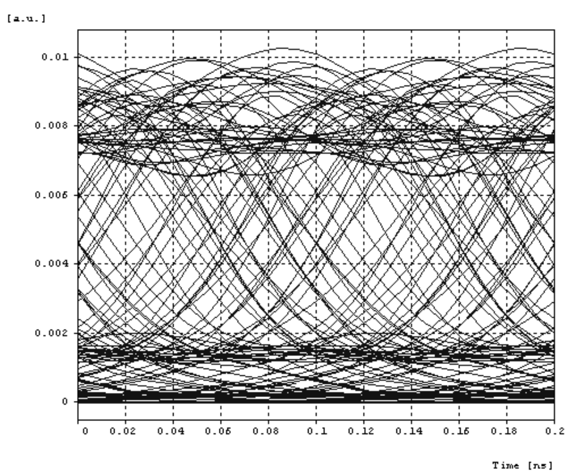
(b)



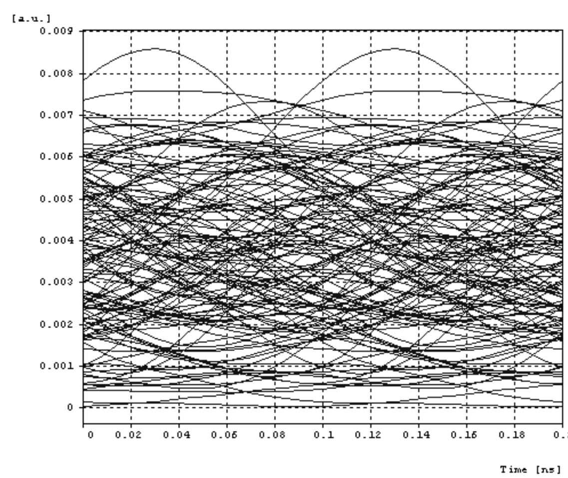
(c)



(d)

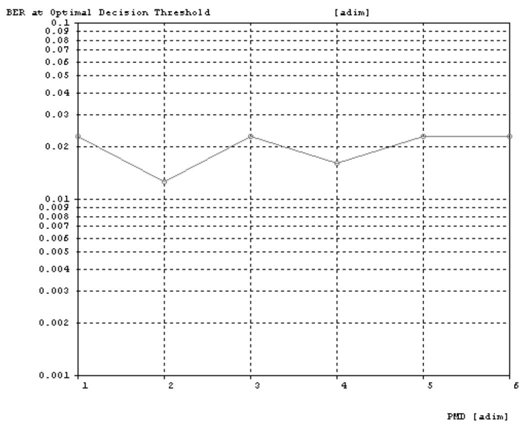


(e)

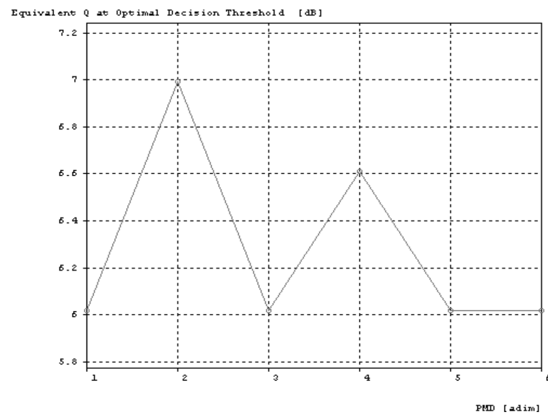


(f)

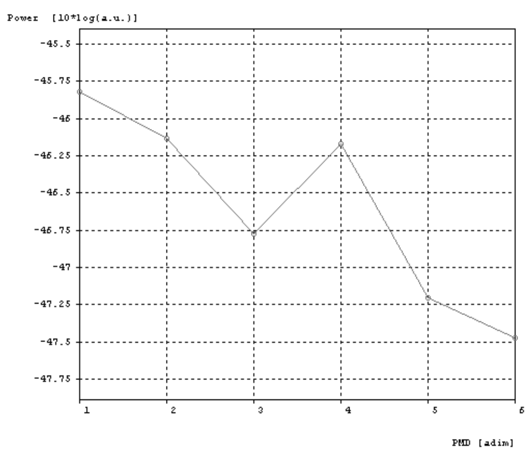
Figure 4.27: At 7 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram when PMD is 0 (f) Eye diagram at 20 $ps/\sqrt{km}$


BER at Optimal Decision Threshold [adim]
PMD [adim]

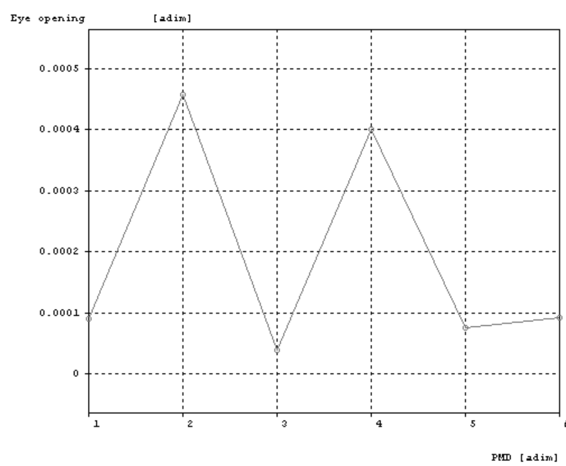
(a)


Equivalent Q at Optimal Decision Threshold [dB]
PMD [adim]

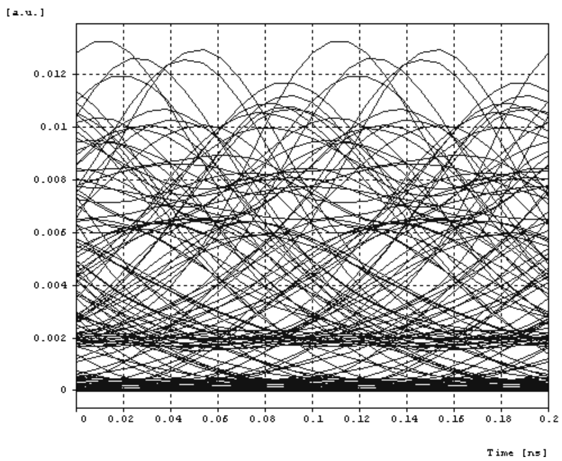
(b)


Power [10*log(a.u.)]
PMD [adim]

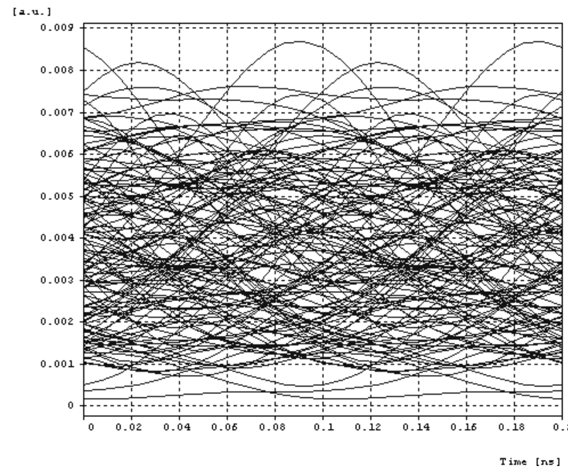
(c)


Eye opening [adim]
PMD [adim]

(d)

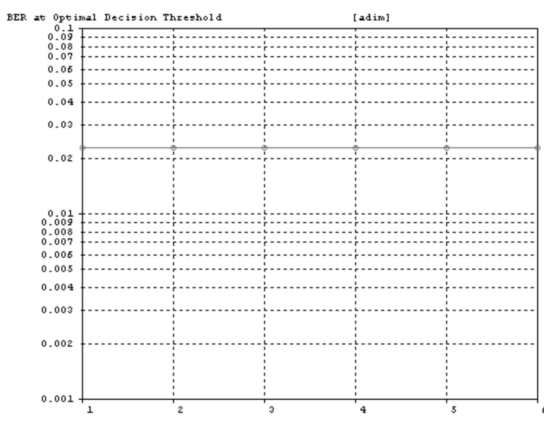


(e)

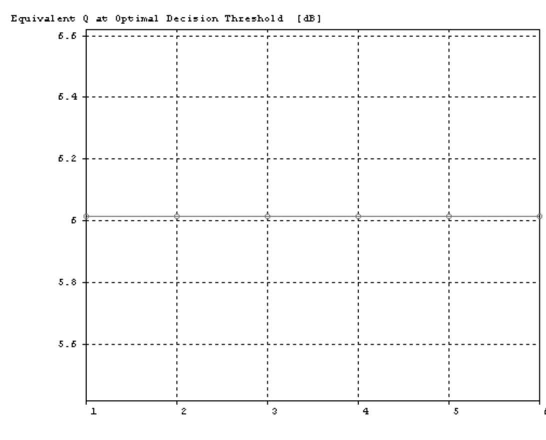


(f)

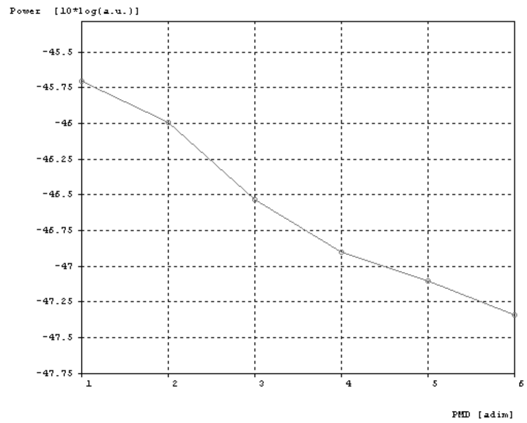
Figure 4.28: At 8 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram when PMD is 0 (f) Eye diagram at 20 $ps/\sqrt{km}$



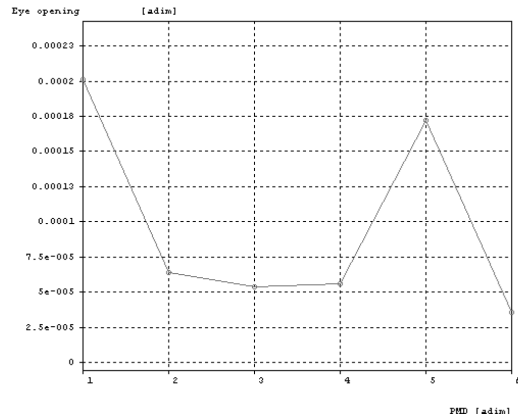
(a)



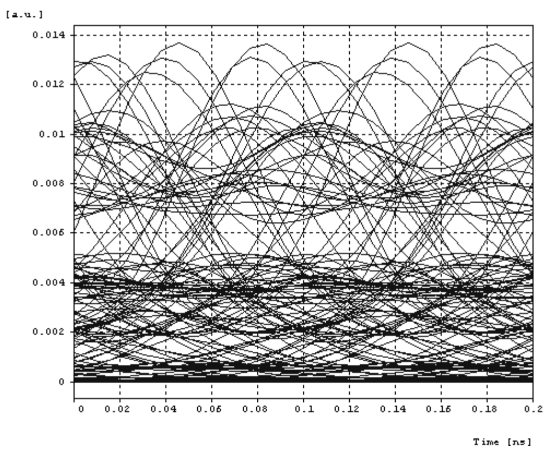
(b)



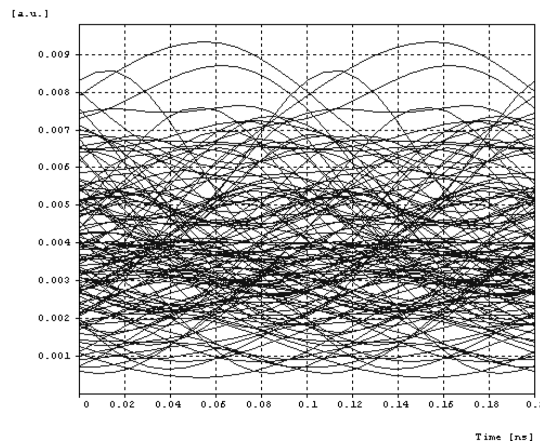
(c)



(d)

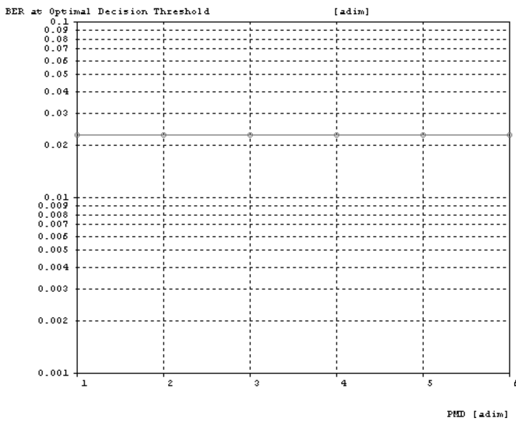


(e)

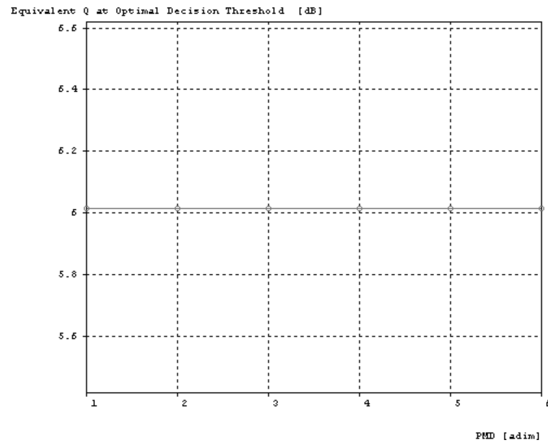


(f)

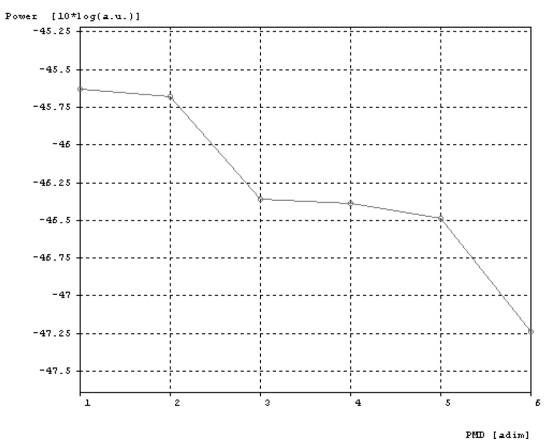
Figure 4.29: At 9 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram when PMD is 0 (f) Eye diagram at 20 $ps/\sqrt{km}$


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
PMD [adim]

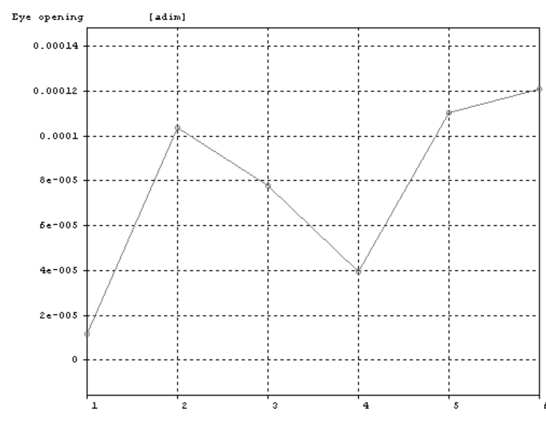
(a)


Equivalent Q at Optimal Decision Threshold [dB]
6.6
6.4
6.2
6
5.8
5.6
1 2 3 4 5 6
PMD [adim]

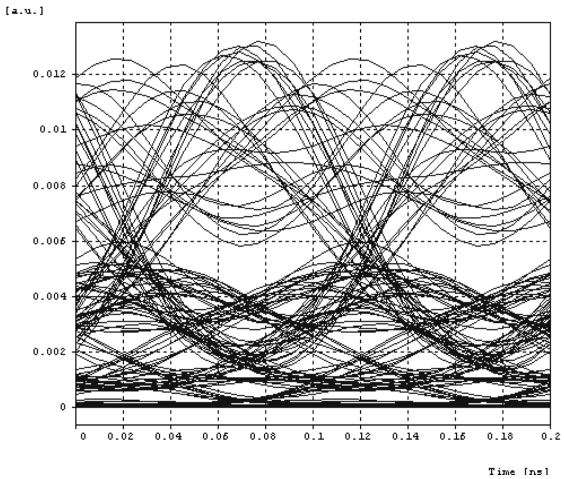
(b)


Power [10*log(a.u.)]
-45.25
-45.5
-45.75
-46
-46.25
-46.5
-46.75
-47
-47.25
-47.5
1 2 3 4 5 6
PMD [adim]

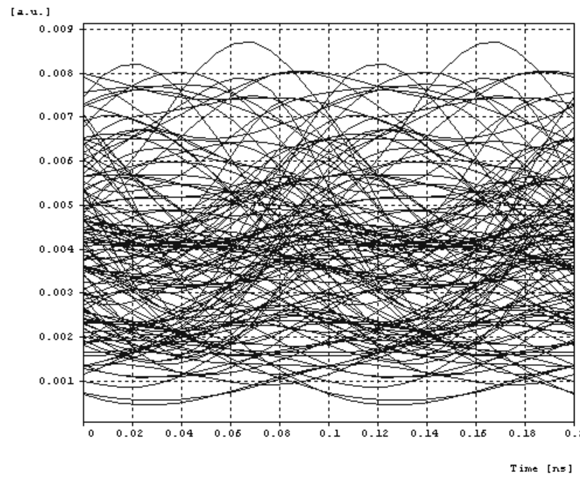
(c)


Eye opening [adim]
0.00014
0.00012
0.0001
8e-005
6e-005
4e-005
2e-005
0
1 2 3 4 5 6
PMD [adim]

(d)



(e)



(f)

Figure 4.30: At 10 Gbps for NRZ raised cosine (a) PMD verses BER (b) PMD verses equivalent Q factor (c) the PMD verses electrical power (d) PMD verses eye opening (e) Eye diagram when PMD is 0 (f) Eye diagram at 20 $ps/\sqrt{km}$.

Chapter 5

CONCLUSIONS AND FURTHER SCOPE OF WORK

5.1 Conclusions

Form the above results we have shown the variation of BER, Equivalent Q, Electrical power eye diagrams at 20 $ps/\sqrt{km}$. We have shown all theses 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. In the second order PMD compensation we find the difference at different PMD at 0 $ps/\sqrt{km}$ and 20 $ps/\sqrt{km}$ through 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 20 $ps/\sqrt{km}$.

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. To compensate the PMD of the system we have to align the light along the PSP and canceling the PMD- vector at the carrier frequency. (b) shows the PMD verses equivalent Q. here we analyze the effect of PMD on the Q factor of the system. As the PMD of the fiber increases the Q factor starts decaying.

In the setup for SOPMD compensation optical fiber birefringence causes polarization-dependent variations in the system performance for dispersion compensation gratings (DCGs). Here, we use gratings as the compensators.

Although tunable fiber Bragg gratings are a flexible and promising solution for dispersion compensation [5,12], but we still have the problem of variable optical communication path characteristics, environmental fluctuations, and the indifference of applications that are themselves in a constant state of change and requires re-design and re-fabrication of an appropriate fiber Bragg grating for each case. Therefore an alternative novel technique of dispersion compensation based on adaptive fiber Bragg gratings scheme would overcome these problems.

5.2 Scope for future work

The basic principle of how we PMD manifests in fiber optic 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.

Non linear transmission systems in the presence of PMD must be investigated in more detail. Both conventional and dispersion managed solitons transmission system possess inherent PMD robustness, but experimental studies aimed at quantifying this property in transmission systems with digitally encoded data should be performed.

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.

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