B.Sc. in Computer Science and Engineering Thesis

PMD Tolerance of Various Modulation Formats in 40 Gb/s DWDM Systems in Presence of Nonlinearities

Submitted by

Mohammod Faisol
201014006

Sofia Zerin Tamanna Rahman
201014014

Md. Mahbub-e-Zaman
201014021

Supervised by

Lieutenant Colonel Kazi Abu Taher, psc, te
Instructor Class-'A'
Department of Computer Science and Engineering
Military Institute of Science and Technology

Department of Computer Science and Engineering
Military Institute of Science and Technology

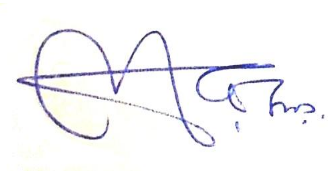
CERTIFICATION

This thesis paper titled **"PMD Tolerance of Various Modulation Formats in 40 Gb/s DWDM Systems in Presence of Nonlinearities"**, submitted by the group as mentioned below has been accepted as satisfactory in partial fulfillment of the requirements for the degree B.Sc. in Computer Science and Engineering on December 2013.

Group Members:

Mohammod Faisol
Sofia Zerin Tamanna Rahman
Md. Mahbub-e-Zaman

Supervisor:



Lieutenant Colonel Kazi Abu Taher, psc, te
Instructor Class-'A'
Department of Computer Science and Engineering
Military Institute of Science and Technology
Dhaka, Bangladesh.

CANDIDATES' DECLARATION

This is to certify that the work presented in this thesis paper is the outcome of the investigation and research carried out by the following students under the supervision of Lieutenant Colonel Kazi Abu Taher, Instructor Class-'A', Department of Computer Science and Engineering, Military Institute of Science and Technology, Dhaka, Bangladesh.

It is also declared that neither this thesis paper nor any part there of has been submitted anywhere else for the award of any degree, diploma or other qualifications.

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Mohammod Faisol
201014006

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Sofia Zerin Tamanna Rahman
201014014

————————————-

Md. Mahbub-e-Zaman
201014021

ACKNOWLEDGEMENT

We are thankful to Almighty Allah for his blessings for the successful completion of our thesis. Our heartiest gratitude, profound indebtedness and deep respect go to our supervisor Lieutenant Colonel Kazi Abu Taher, Instructor Class-'A', Department of Computer Science and Engineering, Military Institute of Science and Technology, Dhaka, Bangladesh, for his constant supervision, affectionate guidance and great encouragement and motivation. His keen interest on the topic and valuable advices throughout the study was of great help in completing thesis.

We are especially grateful to the Department of Computer Science and Engineering (CSE) of Military Institute of Science and Technology (MIST) for providing their all out support during the thesis work.

Finally, we would like to thank our families and our course mates for their appreciable assistance, patience and suggestions during the course of our thesis.

Dhaka
December 2013

Mohammod Faisol
Sofia Zerin Tamanna Rahman
Md. Mahbub-e-Zaman

ABSTRACT

Different modulation formats are being used to mitigate either the PMD or the nonlinear effects. CSRZ-DPSK and CSRZ-DQPSK systems show high suitability for ultra- high spectral efficient DWDM systems and high resilience to dispersion compensation tolerances and fiber nonlinearities but a correct picture of their performance is absent. As the symbol rate is reduced, the spectral width is also significantly reduced. A DQPSK signal at bit rate B has the same spectral width as an OOK signal at bit rate B/2, for RZ waveforms. We have made an effort to quantify the effectiveness of CSRZ-DPSK and CSRZ-DQPSK in compensating PMD and also to find out their correlation. DQPSK has shown better PMD tolerance since it has the ability to double the spectral efficiency and relaxed dispersion management. We simulated single channel as well as multichannel optical fiber communication systems with varying parameters. The performances of the systems are evaluated with high as well as low PMD coefficients in the presence or absence of nonlinear effects. The performance of the systems will be evaluated mainly in terms of graphical representations.

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LIST OF ABBREVIATION

AWGN : Additive White Gaussian Noise
CD : Chromatic Dispersion
CSRZ : Carrier-Suppressed Return-To-Zero
DCF : Dispersion Compensating Fiber
DGD : Differential Group Delay
DPSK : Differential Phase Shift Keying
DQPSK : Differential Quadrature Phase Shift Keying
DSF : Dispersion Shifted Fiber
FDM : Frequency Division Multiplexing
FLAG : Fiber Loop Around the Globe
FWM : Four-Wave Mixing
EDFA : Erbium-Doped Single Mode Fiber Amplifier
LED : Light Emitting Diode
MZM : Mach-Zehnder Modulator
NSE : Nonlinear Schrodinger Equation
NRZ : Non Return-to-Zero
OOK : On/Off Keying
OADM : Optical Add-Drop Multiplexer
PSP : Principal States Of Polarization
PMD : Polarization Mode Dispersion
RZ : Return to Zero
SBS : Stimulated Brillouin Scattering
SOP : State of Polarization
SPM : Self-Phase Modulation
SRS : Stimulated Raman Scattering
WDM : Wavelength Division Multiplexing
XPolM : Cross Polarization Modulation
XPM : Cross-Phase Modulation

CHAPTER 1

INTRODUCTION

1.1 Overview of The Chapter

Due to the tremendous growth of Internet and World Wide Web (WWW), the data rate of current optical fiber communication systems has been pushed from lower bit rates to 10 Gbit/s-40 Gbit/s and beyond. Transmissions in optical fiber communication systems are impaired and ultimately limited by the four 'horsemen' of optical fiber communication systems: chromatic dispersion, amplified spontaneous emission noise from amplifiers, polarization effects and fiber nonlinearities [1]. In this chapter, at first we give an historical perspective of optical communication, then provide some key concepts of polarization mode dispersion (PMD) and nonlinearity, brief discussion about different modulation techniques, literature review, motivation of the research work and its objectives, and finally an overview of the thesis work.

1.2 Historical Perspective of Fiber Optic Communication Systems

Even though an optical communication system had been convinced in the late 18th century by a French Engineer Claude Chappe who constructed an optical telegraph, electrical communication systems became the first dominant modern communication method since the advent of telegraphy in the 1830s. Until the early 1980s, most of fixed (non-radio) signal transmission was carried by metallic cable (twisted wire pairs and coaxial cable) systems. However, large attenuation and limited bandwidth of coaxial cable limited its capacity upgrade.

The bit rate of most advanced coaxial systems was put into service in the United States in 1975 was 274 Mbit/s. At around the same time, there was a need of conversion from analog to digital transmission to improve transmission quality, which requires further increase of transmission bandwidth. Many efforts were made to overcome drawbacks of coaxial cable during 1960s and 1970s. In 1966, Kao and Hockham proposed the use of optical fiber as a guiding medium for optical signal. Four years later, a major breakthrough occurred when the fiber loss was reduced to about 20 dB/km from previous values of more than 1000 dB/km. Since that time, optical communication technology has developed rapidly to achieve larger transmission capacity and longer transmission distance. The capacity of transmission has been increased about 100 fold in every 10 years.

The first generation of optical communication was designed with multi-mode fibers and direct bandgap GaAs light emitting diodes (LEDs), which operate in 800 nm - 900 nm wavelength range. Large modal dispersion of multi-mode fibers and high fiber loss at 850 nm ($>$ 5 dB/km) limited both the transmission distance and bit rate. In the second generation, multi-mode fiber were replaced by single-mode fibers, and the center wavelength of light source was shifted to 1300 nm, where optical fibers have minimum dispersion and lower loss of about 0.5 dB/km. However, there was still a strong demand to increase repeater spacing further, which could be achieved by operating at 1500 nm where optical fibers have an intrinsic minimum loss around 0.2 dB/km. Larger dispersion in 1550 nm window delayed moving to a new generation until dispersion shifted fiber (DSF) became available. Dispersion shifted fibers reduce the large amount of dispersion in the 1550 nm window by modifying the index profile of the fiber while keeping the benefit of low loss at the 1500 nm window.

An important advancement was that an erbium-doped single mode fiber amplifier (EDFA) at 1550 nm was found to be ideally suited as an amplifying medium for modern fiber optic communication systems. Invention of EDFA had a profound impact especially on the design of long-haul under-sea system. The EDFA band, or the range of wavelengths over which the EFDA can operate, proved to be an important factor in fixing the wavelength of operation of present day fiber optic systems. The EDFA band is wide enough to support many wavelengths simultaneously. This led to the development of wavelength division multiplexing (WDM) systems or the simultaneous propagation of several wavelengths of light through a fiber, where each wavelength can carry a different data stream.

In the late 1990s, the demand for bandwidth, especially with the huge growth of the internet, fueled a rapid increase in the data rates. As the number of channels and data rates rose, certain phenomenon such as chromatic dispersion (CD) and nonlinearities began to show up as obstacles. CD being deterministic in nature could be effectively compensated for by using special fibers called dispersion compensating fibers (DCF) and other novel devices. At high bit rate ($>$10 Gb/s) PMD constitutes the ultimate impairment for the transmission of optical signals. Digital signals propagating through an optical fiber with PMD may be broadened during transmission and as a consequence spread beyond their allocated bit slot and interfere with neighboring bits. Researchers in late 1980s and early 1990s realized that PMD in presence of nonlinearity would have to be addressed because of its significant impact on the performance of multi-gigabit per second optical communication systems operating over the embedded optical fiber network.

1.3 Evolution of PMD and Nonlinearities in Optical Fiber

With the ever increasing bit rates in fiber transmission, PMD remains a significant transmission obstacle. Even though a large amount of PMD mitigation methods have been suggested and evaluated, they usually need to be implemented on a channel-by-channel basis in WDM systems, and in fact, there exist fundamental reasons for why such per-channel compensation must be adopted. The central issue is that, if a broadband compensation is attempted, the compensation at one wavelength might lead to worse performance at another channel. In fact, when adding birefringence to a system (as is done in active optical PMD compensation), the average PMD at wavelengths not specifically compensated will increase.

In WDM systems, the fiber nonlinearities that dominate are the crosstalk from four-wave mixing (FWM) and cross-phase modulation (XPM). After the move from dispersion shifted fiber in the mid-1990s to either standard fiber plus dispersion management or nonzero dispersion shifted fiber, the FWM is often negligible, and the XPM is the dominating nonlinear impairment. Since the XPM is known to cause fast state of polarization (SOP) changes, which we will call a cross polarization modulation (XPolM) among temporally overlapping bits in different WDM channels. Such SOP rotation will be detrimental in systems with optical PMD compensators; since these operate on slow (relative to the bit period) time scales that are determined by the polarization drifts in the systems rather than the bitwise polarization fluctuations. Most work has been devoted to two-channel (pump-probe) interaction in this respect and significantly fewer studies discuss the more practically important case with many equal-power WDM channels [8].

1.3.1 Definition of Birefringence and PMD

Birefringence is the optical property of a material having a refractive index that depends on the polarization and propagation direction of light. These optically anisotropic materials are said to be birefringent.

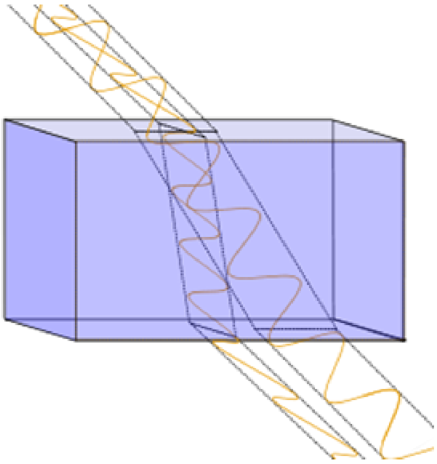

Figure 1.1: Displacement of light rays with perpendicular polarization through a birefringent material

The birefringence is often quantified by the maximum difference in refractive index within the material. Birefringence is also often used as a synonym for double refraction, the decomposition of a ray of light into two rays when it passes through a birefringent material.

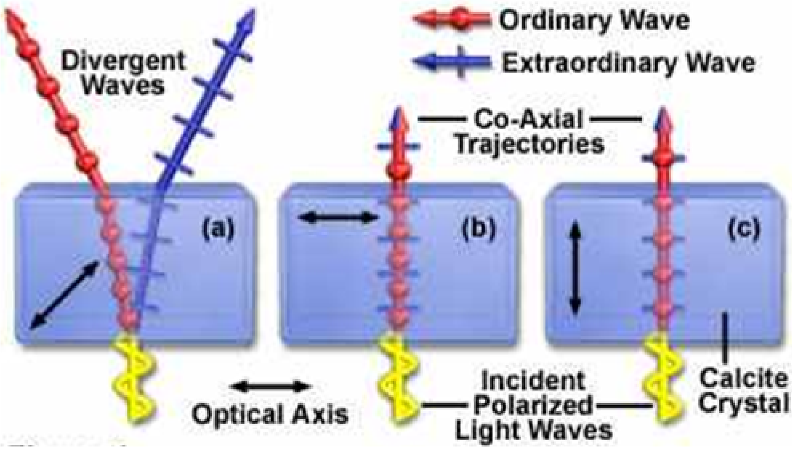

Figure 1.2: Seperation of Light Waves by a Birefringent Crystal

Crystals with anisotropic crystal structures are often birefringent, as well as plastics under mechanical stress [9].

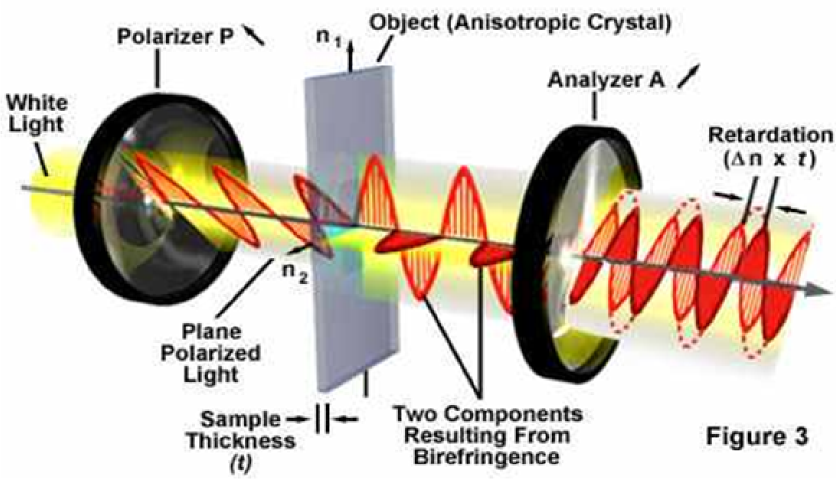

Figure 1.3: Birefringent Crystals Between Crossed Polarizers

PMD means pulse distortion due to differential group delay (DGD) between two mutually orthogonal principal states of polarization (PSP) occurring in a birefringent fiber-optic link, which is induced mainly by environment change, birefringent optical components, and asymmetric fiber core. Under a same DGD, higher bit-rate system suffers more impairment due to smaller signal pulse-width. Therefore, PMD compensation is essential for transmission systems at 40 Gb/s or beyond [10].

1.3.2 PMD Vectors

PMD phenomenon occur due to the presence of birefringence in optical fibers that are typically used for communications. This birefringence changes randomly along the fiber length. It stems from asymmetries in the fiber stress and geometry, such as elliptical cross sections, microbends or microtwists. Often, such a fiber is visualized or modeled as a sequence of random birefringent sections whose birefringence axes and magnitude changes randomly with z (along the fiber). There are different manifestations of PMD depending on the view taken. In the frequency domain view one sees, for a fixed input polarization, a change with frequency ω of the output polarization. In the time domain one observes a mean time delay of a pulse traversing the fiber which is a function of the polarization of the input pulse. These two phenomenon are intimately connected.

There exist special orthogonal pairs of polarization at the input and the output of the fiber called the PSPs. Light launched in a PSP does not change polarization at the output to first order in ω. These PSPs have group delays, τ_g, which are the maximum and minimum mean time delays of the time domain view. The difference between these two delays is called the DGD. Typical mean values of the DGD are 1 to 50 ps for a 500-km long fiber, depending on fiber type. The PMD vector $\vec{\tau}$ describes both the PSPs and the DGD in the fiber. It is a Stokes vector pointing in the direction of the slow PSP with a length equal to the DGD.

Some insight into the PMD problem can be had simply by contemplating a piece of polarization-maintaining fiber. Its PSPs are the polarizations along the principal axes of birefringence of the fiber. In this case the two axes can be treated separately, and in general have different phase shifts φ and different group delays $d\varphi/d\omega$. One can see that the different values of $\varphi(\omega)$ will also produce changes in the output state of polarization as a function of frequency unless the input is launched in one of the PSPs. It may seem surprising that PSPs occur in a fiber exhibiting random birefringence as a function of z. The DGD grows roughly as the square root of the length of fiber, as is characteristic of a random walk problem [11].

The representation uses four observable parameters, known as Stokes parameters, which are defined as

$$
\begin{aligned}
S_0 &= I_0, \\
S_1 &= I_H - I_V, \\
S_2 &= I_{+45} - I_{-45}, \\
S_3 &= I_{RCP} - I_{LCP}.
\end{aligned}
$$

In above equation, I_0 represents the intensity of the given light beam, and I_H, I_V , I_{+45}, I_{-45} , I_{RCP} , and I_{LCP} represent the transmitted intensities when the given beam is passed through a linear horizontal polarizer (LHP), a linear vertical polarizer (LVP), a linear +45-deg polarizer, a linear -45-deg polarizer, a right circular polarizer, and left-circular polarizer, respectively. Physically, S_1 gives an idea of whether the given SOP is closer to linear horizontally polarized light ($S_1 > 0$) or to linear vertically polarized light ($S_1 < 0$) or to neither ($S_1 = 0$); S_2 gives an idea of whether the given SOP is closer to the linear +45 deg ($S_2 > 0$), to linear -45 deg ($S_2 < 0$), or to neither ($S_2 = 0$); similarly, S_3 gives an idea of whether the given SOP is closer to right-circular polarized light ($S_3 > 0$), to left-circular polarized light

($S_3 < 0$), or to neither ($S_3 = 0$). Using the fact that

$$I_H - I_V = I_{-45} + I_{+45} = I_{RCP} + I_{LCP},$$

Above equations can be recast as

$$S_0 = I_0,$$
$$S_1 = 2I_H - I_0,$$
$$S_2 = 2I_{+45} - I_0,$$
$$S_3 = 2I_{RCP} - I_0.$$

The Stokes parameters are often combined into a vector, known as the Stokes vector:

$$\vec{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

The Stokes vector spans the space of unpolarized, partially polarized, and fully polarized light. For comparison, the Jones vector only spans the space of fully polarized light, but is more useful for problems involving coherent light. The four Stokes parameters do not form a preferred basis of the space, but rather were chosen because they can be easily measured or calculated.

The effect of an optical system on the polarization of light can be determined by constructing the Stokes vector for the input light and applying Mueller calculus, to obtain the Stokes vector of the light leaving the system [2].

Below are shown some Stokes vectors for common states of polarization of light.

$$\begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix} Linearlypolarized(horizontal)$$

$$\begin{pmatrix} 1 \\ -1 \\ 0 \\ 0 \end{pmatrix} Linearlypolarized(vertical)$$

$$\begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix} Linearlypolarized(+45^o)$$

$$\begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix} Linearlypolarized(-45^o)$$

$$\begin{pmatrix} 1 \\ 0 \\ 0 \\ -1 \end{pmatrix} Right-handcircularlypolarized$$

$$\begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix} Left-handcircularlypolarized$$

$$\begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} Unpolarized$$

The Jones vector describes the polarization of light.

The x and y components of the complex amplitude of the electric field of light travel along z-direction $E_x(t)$ and $E_y(t)$, are represented as

$$\begin{pmatrix} E_x(t) \\ E_y(t) \end{pmatrix} = E_0 \begin{pmatrix} E_{0x}e^{i(kz-\omega t+\phi_x)} \\ E_{0y}e^{i(kz-\omega t+\phi_y)} \end{pmatrix} = E_0 e^{i(kz-\omega t)} \begin{pmatrix} E_{0x}e^{i\phi_x} \\ E_{0y}e^{i\phi_y} \end{pmatrix}$$

Here $\begin{pmatrix} E_{0x}e^{i\phi_x} & E_{0y}e^{i\phi_y} \end{pmatrix}^T$ is the Jones vector (i is the imaginary unit with $i^2 = -1$).Thus, the Jones vector represents (relative) amplitude and (relative) phase of electric field in x and y directions [2].

The following table gives the 6 common examples of normalized Jones vectors.

Table 1.1: Common examples of normalized Jones Vector

Polarization	**Corresponding Jones vector**	**Typical ket Notation**
Linear polarized in the x-direction Typically called 'Horizontal'	$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$	$\mid H >$
Linear polarized in the y-direction Typically called 'Vertical'	$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$	$\mid V >$
Linear polarized at 45^o from the x-axis Typically called 'Diagonal' L+45	$\frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$	$\mid D > = \frac{1}{\sqrt{2}}(\mid H > + \mid V >)$
Linear polarized at -45^o from the x-axis Typically called 'Anti-Diagonal' L-45	$\frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \end{pmatrix}$	$\mid A > = \frac{1}{\sqrt{2}}(\mid H > - \mid V >)$
Right Hand Circular Polarized Typically called RCP or RHCP	$\frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -i \end{pmatrix}$	$\mid R > = \frac{1}{\sqrt{2}}(\mid H > - \mathrm{i} \mid V >)$
Left Hand Circular Polarized Typically called LCP or LHCP	$\frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ +i \end{pmatrix}$	$\mid L > = \frac{1}{\sqrt{2}}(\mid H > + \mathrm{i} \mid V >)$

The Pauli matrices are a set of three 2 x 2 complex matrices which are Hermitian and unitary. Usually indicated by the Greek letter sigma (σ), they are occasionally denoted with a tau (τ) when used in connection with isospin symmetries [11]. They are:

$$\sigma_1 = \sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\sigma_2 = \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

$$\sigma_3 = \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

1.3.3 Nonlinearities in Optical Fiber

An optical fiber looks like a thin strand of glass and consists of a central core surrounded by a cladding whose refractive index is slightly lower than that of the core. Both the core and the cladding are made off used silica, a glassy material with an ultra-low loss (about 0.2 dB/km) in the near infrared region near 1.5 μm. The refractive-index difference between the core and the cladding is realized by the selective use of dopants during the fabrication process. Dopants such as GeO2 and P2O5 increase the refractive index of pure silica and are suitable for the core, while materials such as boron and fluorine are used for the cladding because they decrease the refractive index of silica. Even a relatively small refractive-index difference between the core and the cladding (typically less than 1%) can guide the light along the fiber length through the well-known phenomenon of total internal reflection.

The response of any dielectric to light becomes nonlinear for intense electromagnetic fields. In the transparent region of optical fibers, the lowest-order nonlinear effects originate from the third-order susceptibility $\chi(3)$, which is responsible for phenomena such as third-harmonic generation, four-wave mixing (FWM), and nonlinear refraction. Among these, nonlinear refraction, a phenomenon referring to the intensity dependence of the refractive index, plays the most important role. The intensity dependence of the refractive index leads to a large number of interesting nonlinear effects; the two most widely studied are self-phase modulation (SPM) and cross-phase modulation (XPM) [12].

1.3.4 Nonlinear Schrodinger equation

Most nonlinear effects in optical fibers are observed by using short optical pulses because the dispersive effects are enhanced for such pulses. Propagation of optical pulses through fibers can be studied by solving Maxwell's equations. In the slowly varying envelope approximation, these equations lead to the following nonlinear Schrodinger equation (NSE)

$$\frac{\partial A}{\partial z} + \frac{i}{2}\beta_2 \frac{\partial^2 A}{\partial t^2} = i\gamma \mid A \mid^2 A - \frac{\alpha}{2} A$$

where A(z, t) is the slowly varying envelope associated with the optical pulse, α accounts for fiber losses, β_2 governs the GVD effects, and γ is the nonlinear parameter defined as

$$\gamma = n_2 \omega / (\mathrm{c} A_{eff})$$

Here A_{eff} is the effective core area of the fiber. This equation is appropriate for pulses wider than 5 ps. For an accurate description of shorter pulses, several higher-order dispersive and nonlinear terms must be added to the NSE [12].

1.4 Modern Digital Modulation Techniques

Fundamental to all communications is modulation, the process of impressing the data to be transmitted on the radio carrier. Most data transmissions today are digital, and with the limited spectrum available, the type of modulation is more critical than it has ever been. The main goal of modulation today is to squeeze as much data into the least amount of spectrum possible. That objective, known as spectral efficiency, measure how quickly data can be transmitted in an assigned bandwidth. The unit of measurement is bits per second per Hz(b/s/Hz).Multiple techniques have emerged to achieve and improve spectral efficiency.

1.4.1 Optical Modulation Methods

The on-going growing demand for greater capacity in optical communication systems, calls for an increase in transmission speed from 10 Gbps to 40 Gbps and beyond, while maintaining signal quality. Optical communication systems have predominantly used some form of on/off keying (OOK) as a modulation format, namely NRZ or RZ modulation. As data rates increase, the inefficiency of these modulation formats from a bandwidth point of view is becoming more apparent. With data rates moving to 40 Gbps and beyond, dispersion in the fiber limits the distance over which the data can be transmitted. Other impairments such as polarization mode dispersion or PMD become significant at 40 Gbps. Thus, inter-city transmission, which requires long-distance transmission of more than several hundred kilometers, has not been possible. Transmission links are rapidly evolving from point-to-point links to interconnected optical networks. This requires the flexibility to pass multiple optical add-drop multiplexer (OADM) nodes along the transmission link. Today, most transmission systems have a 50 GHz WDM channel spacing, which implies a 0.8 bit/s/Hz spectral efficiency for 40 Gbps transmission. For binary formats, duobinary and differential phase shift keying (DPSK) are close to the theoretical limit, which makes it difficult to cascade multiple OADMs along transmission link. The narrower optical spectrum of multi-level formats such as QPSK and differential quad phase shift keying (DQPSK) therefore enables both a high spectral efficiency as well as the possibility to cascade multiple OADM [13].

1.5 Literature Review, Motivation and Research Objectives

In the 21st century, we are seeing dramatic changes in the telecommunication industry that have far reaching implications for our lifestyles. There are many drivers for these changes. First and foremost is the continuing, relentless need for more data carrying capacity of the network. This demand is fueled by many factors. The tremendous growth of the internet and WWW, both in terms of number of users as well as the amount of time and thus bandwidth taken by each user. To satiate the demand for greater network capacity, the data rate of current optical systems has been pushed from lower bit rates to 10 Gbit/s-40 Gibt/s. However, at these data rates, the most important transmission impairments associated with long-distance optical fiber communication systems include fiber CD, Kerr effect, PMD, noise accumulation from optical amplifiers and interaction between them.

In the early years of last decade the PMD was never a major concern as most of the optical network were not being used at high bit rates. Nevertheless with the modern high-speed (i.e. 10 Gibt/s 40 Gibt/s) network PMD becomes a serious issue. Such high bandwidth requirements have pushed the network designers to include the PMD analysis before new high-speed link or network technology is purchased or installed. Thus, we have focused on the study of PMD tolerance of various modulation formats in presence of nonlinearities.

Curtis R. Menyuk and Brian S. Marks [1], reviewed aspects of the interaction of the Kerr nonlinearity and polarization mode dispersion (PMD). The basic equation that governs this interaction on the length scale of interest in optical fiber communications systems is the

Manakov-PMD equation. This equation is derived using multiple-length-scale techniques. It is shown that the scalar nonlinear Schrdinger equation is valid when PMD is absent and the signal is initially in a single polarization state. Two examples are then presented that illustrate the complexity of the interaction between nonlinearity and PMD. The first example considers the interaction of a nonlinearly induced chirp with PMD. As the power increases, one can obtain an improved eye opening relative to the case when PMD is absent. The second example considers the effect of nonlinear polarization rotation in a wavelength-division-multiplexed system. When nonlinear polarization rotation is important, the principal states of polarization become time dependent and PMD compensation becomes ineffective.

Misha Boroditsky, Marianna Bourd and Moshe Tur [14], show experimentally and theoretically that the magnitude and direction of the polarization mode dispersion (PMD) vector of a WDM channel is significantly affected by nonlinear polarization crosstalk from neighboring channels within the PMD correlation bandwidth. They use their model to estimate the effect the nonlinear interactions may have on the PMD-induced penalty.

Hanhui Li, Kun Xu, Guangtao Zhou, Jian Wu and Jintong Lin [5], use waveplate models to simulate the statistical performance of optical link with PMD and PDL in 40Gbit/s optical system. Three DPSK modulation formats are compared each other for their tolerance against PMD and PDL. The 33% RZ-DPSK is superior to the other two DPSK formats, the 50% RZ-DPSK and the CSRZ-DPSK whose duty cycle is 67% when only PMD is considered. Furthermore, the performance of two RZ-DPSK formats, whose duty cycles are 33% and 50% respectively, is superior to that of CSRZ-DPSK. This shows that modulation format with narrower pulse width owns more high tolerance against PMD and PDL, therefore the CSRZ-DPSK format shows poorer performance.

Liu Huiyang, Zhang Xiaoguang and Xu Wei [3], studied Polarization-mode dispersion compensation performance of optical DQPSK. The optical power spectra and eye diagram of different DQPSK modulation formats are obtained. Then, they adopt two pseudo random binary sequences as input data streams. In the back to back DQPSK system, by means of pre-coding, modulation and demodulation we obtain exactly the same as the original signal. The system for simulation is verified. At last, they add the polarization-mode dispersion compensation program module to the back to back DQPSK system. The result is shown that the modulation formats with smaller bandwidth have better PMD compensation performance and that PMD compensation performance of DQPSK is better than that of OOK and DPSK.

CSRZ-DPSK and CSRZ-DQPSK systems show high suitability for ultra-high spectral efficient DWDM systems and high resilience to dispersion compensation tolerances and fiber nonlinearities but a correct picture of their performance is absent. As the symbol rate is reduced, the spectral width is also significantly reduced. A DQPSK signal at bit rate B has the same spectral width as an OOK signal at bit rate B/2, for RZ waveforms. We have made an effort to quantify the effectiveness of CSRZ-DPSK and CSRZ-DQPSK in compensating PMD and also to find out their correlation.

CHAPTER 2

EFFECTS OF PMD AND NONLINEARITIES ON OPTICAL FIBER COMMUNICATION SYSTEM

2.1 General

Polarization mode dispersion (PMD) is widely regarded as a limiting impairment in high-speed optical communication systems. Since it changes unpredictably in time with temperature and other environmental conditions, active mitigation techniques are being developed based on PMD measurement on working channels. Even though PMD is often looked at as a property of a passive fiber, it is in fact affected by anything that changes the birefringence of the optical media. In multichannel long-haul systems, high optical power may cause nonlinear polarization rotation or crosstalk [14].

2.2 Overview of PMD

Polarization mode dispersion (PMD) is a form of modal dispersion where two different polarizations of light in a waveguide, which normally travel at the same speed, travel at different speeds due to random imperfections and asymmetries, causing random spreading of optical pulses. Unless it is compensated, which is difficult, this ultimately limits the rate at which data can be transmitted over a fiber [11].

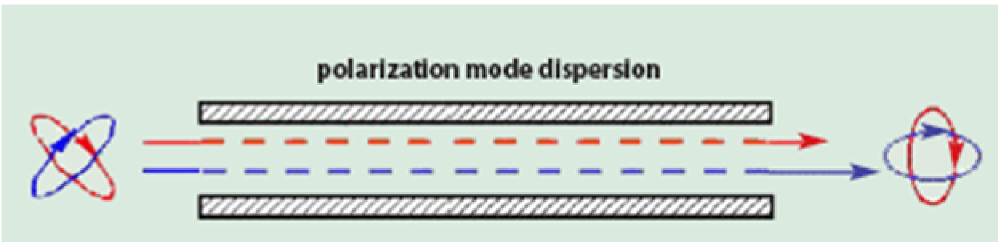

Figure 2.1: Polarization Mode Dispersion (PMD)

2.2.1 The Origin of PMD

The speed of propagation of a light wave depends on the index of refraction of the transmission medium in the direction of fluctuation of the electric field. Consider a straight, short length of single-mode fiber. Given an index difference between the X and Y-directions, a Z-traveling wave decomposes into a pair of waves having X and Y-directed electric fields. The two waves propagate at slightly different speeds, accumulating an optical phase shift and associated differential delay in proportion to distance. A transmission medium that produces a phase shift in this way is said to be birefringent. The natural birefringence of quartz and calcite account for their use in optical retarders and wave plates.

PMD in single-mode optical fiber originates with non circularity of the core (Figure-2.3a). Form birefringence is a basic characteristic of any oval waveguide. Stress birefringence, generally dominant - is induced by the mechanical stress field that is set up when the fiber is drawn to other than a perfectly circular shape. Over short lengths, fiber birefringence splits the input pulse into linear slow and fast polarization modes, behaving like a linearly birefringent crystal. The corresponding difference in propagation time is called the differential group delay (DGD), expressed in picoseconds (1 ps = 10^{-12} s). Together, the differential group delay and the orthogonal polarization modes are the fundamental manifestations of first-order PMD [11]. In practice, only relatively short, straight, undisturbed lengths of trans-

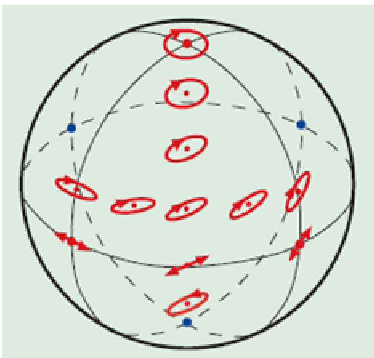

Figure 2.2: Each point on the Poincar sphere represents a unique polarization state

mission fiber behave as simple, having uniform birefringences. Spooled, cabled or deployed fiber is more accurately modeled as a chain of simple birefringent fiber segments spliced at random rotational angles (Figure-2.3b). By changing the relative phase of the local fast and slow waves, each segment transforms its input polarization state into some other output state.

This output state illuminates the following segment, where the wave again breaks down into the local fast and slow modes and the process repeats. Given the extremely weak birefringence of telecom fiber, mode coupling is easily induced in the fiber by the mechanical forces arising from spooling, cabling or installation.

The action at the interface of adjacent birefringent elements is called polarization mode coupling, and it is this phenomenon that causes the differential group delay of single-mode fiber to vary with both wavelength and environment (time). Fiber spans that contain a large number of mode-coupling events are called randomly mode-coupled. In such a fiber, the distribution of differential group delay values over wavelength tends toward a Maxwell curve. The differential group delay is also Maxwell distributed across temperature at a fixed wavelength, given sufficient temperature change. The polarization mode dispersion of a ran-

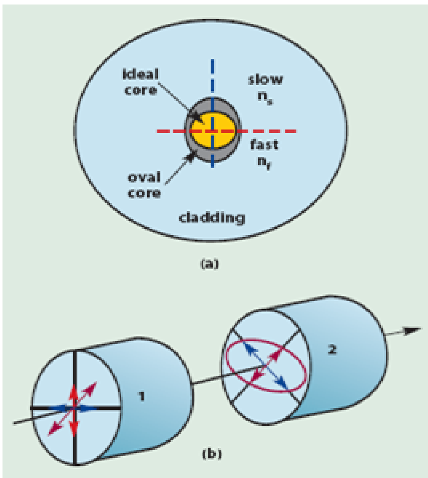

Figure 2.3: Core noncircularity (exaggerated) is the root of PMD in single-mode fiber

domly mode-coupled span is described in several ways. The differential group delay at a given wavelength and time is called the instantaneous differential group delay. The average value of the DGD over wavelength is called the PMD delay. The average DGD divided by the square root of fiber length is called the PMD coefficient. Confusion can occur when the general label ”PMD” is used alone in place of one of these more specific descriptors.

The presence of mode coupling affects more than the character of the differential group delay; the fast and slow polarization modes become elliptical states and, in addition, they vary with wavelength and time. However, at any given wavelength and time, and in the absence of polarization-dependent loss, there exist, at the input of the fiber, an orthogonal pair of states that correspond to early and late arrival of energy at the output of the fiber path.2 These special input states are called the principal states of polarization (PSPs). They are often referred to as the fast and slow polarization modes. There is another pair of principal states at the output of the fiber path. Energy coupled entirely to the fast polarization mode or principal state at the input emerges in the fast polarization mode at the output. In general, the input and corresponding output PSPs are different. Since the PSPs are the manifestation of the random configuration of birefringences and mode couplings that make up the fiber path, any change in these details causes a corresponding shift in the PSPs [11].

The defining feature of an input/output principal state pair, for example the input and output fast polarization modes, is that the transformation between these two states is independent of wavelength over a suitably narrow wavelength interval. The average value (over wavelength) of the narrow frequency interval over which PSPs are frequency independent is called the PSP bandwidth.

When the spectral width of the signal exceeds the PSP bandwidth, both the differential group delay and the PSPs vary across the signal spectrum. This produces higher order PMD effects, including both a chromatic dispersion component and a pulse distortion arising from a shift in the principal states of polarization across the pulse spectrum.

The impact of first-order PMD on an operating link depends upon both the differential group delay and the relative intensities of light in the principal states of polarization. The impairment is most severe when equal amounts of light are coupled into the input principal states of polarization, and the impairment is negligible when all of the light is coupled to a single principal state of polarization.

2.2.2 Properties of Polarization of Light

The electric and magnetic fields of a lightwave fluctuate at right angles to one another in the plane perpendicular to the direction of propagation. Polarization is defined in terms of the electric field, which interacts more strongly with most devices. The electric field of a fully polarized, monochromatic lightwave can be described as issuing from a point charge moving in an elliptical pattern in the plane of the source (Figure 2.4). Details of the ellipse - the ratio of major to minor axis, the angular orientation and handedness (direction of rotation) - describe the state of polarization of the light. Linear and circular polarizations are simply extreme cases of elliptical polarization [2].

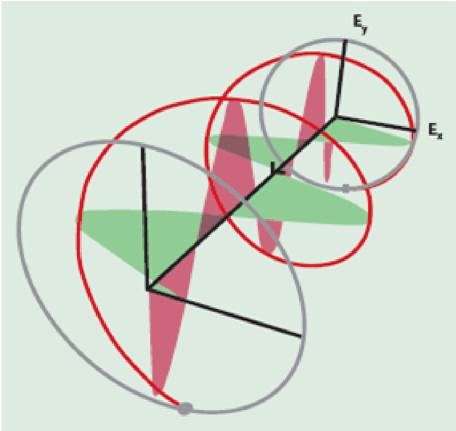

Figure 2.4: The electric field of right-hand circularly polarized light (helix), and the field components along the X- and Y-axes

A graphical shorthand representation of polarization states is provided via the Poincar sphere1 (Figure-2.2). Each point on the surface of the sphere represents a unique state of polarization. Linear states fall on the equator and circular states at the poles. Right-handed and left-handed elliptical states fall in the northern and southern hemispheres, respectively.

Polarization states diametrically opposite one another are mathematically independent, a condition called orthogonality. Linear horizontal and vertical polarizations are examples of orthogonal states; light emerging from a horizontal polarizer is blocked by a vertical polarizer. Any two orthogonally polarized, same-frequency lights can serve as the raw materials, or basis states, from which, by adjustment of relative delays and intensities, any other state can be synthesized. In Figure 2, the horizontal and vertical polarization states act as basis states to form circularly polarized light. In this case, the basis state waves are of equal intensity but are offset 90 in phase (one quarter wave of relative delay) [11].

2.2.3 Causes of PMD

In optical fibers, there is usually some slight difference in the propagation characteristics of light waves with different polarization states. A differential group delay can occur even for fibers which according to the design should have a rotational symmetry and thus exhibit no birefringence. This effect can result from random imperfections or bending of the fibers, or from other kinds of mechanical stress, and is also affected by temperature changes. Mainly due to the influence of bending, the PMD of a cabled fiber can be completely different from that of the same fiber on a spool. Modern fiber cables as used in fiber-optic links have been optimized for low PMD, but the handling of such cables can still have some influence.

In a realistic fiber, however, there are random imperfections that break the circular symmetry, causing the two polarizations to propagate with different speeds. In this case, the two polarization components of a signal will slowly separate, e.g. causing pulses to spread and overlap. Because the imperfections are random, the pulse spreading effects correspond to a random walk, and thus have a mean polarization-dependent time-differential $\Delta\tau$ (also called the differential group delay, or DGD) proportional to the square root of propagation distance L:

$$\Delta\tau = D_{PMD}\sqrt{L}$$

D_{PMD} is the PMD parameter of the fiber, typically measured in ps/$\sqrt{km}$, a measure of the strength and frequency of the imperfections.

The symmetry-breaking random imperfections fall into several categories. First, there is geometric asymmetry, e.g. slightly elliptical cores. Second, there are stress-induced material birefringences, in which the refractive index itself depends on the polarization. Both of these effects can stem from either imperfection in manufacturing (which is never perfect or stress-free) or from thermal and mechanical stresses imposed on the fiber in the field - moreover, the latter stresses generally vary over time.

The terms polarization mode dispersion (PMD) and differential group delay (DGD) are often used interchangeably, but sometimes with slightly different meanings. Some authors call the phenomenon PMD and consider DGD to be its magnitude. Others define PMD as the statistical standard deviation of DGD in some wavelength interval. Note that for optical fibers the DGD can have a substantial and complicated dependence on the optical wavelength.

Some authors use the term second-order PMD for the derivative of the differential group delay with respect to angular frequency-although there is actually no second-order derivative involved [15].

2.2.4 Detrimental Effects of PMD in Communication Systems

Polarization mode dispersion can have adverse effects on optical data transmission in fiber-optic links over long distances at very high data rates, because portions of the transmitted signals in different polarization modes will arrive at slightly different times. Effectively, this can cause some level of pulse broadening, leading to inter-symbol interference, and thus a degradation of the received signal, leading to an increased bit error rate.

In principle, one could determine the so-called principle polarization states of a fiber span, and inject the optical signals only into one such state. For a sufficiently narrow optical bandwidth, there would then be no pulse broadening, although for larger bandwidths there is a polarization-related contribution to chromatic dispersion (with its sign being different for the two principle states). However, this method is usually not practical, partly because the principle polarization states change with time.

Effects of polarization mode dispersion often need to be described statistically, concerning not only random temporal changes but also the dependence on the fiber length. For short fiber sections, the DGD is proportional to the fiber length. For longer sections, different portions of fiber contribute uncorrelated amounts of DGD, and the total r.m.s. value of the differential group delay scales only with the square root of the fiber length [15].

2.2.5 Reducing the Effects of PMD

The first measure for reducing PMD is to choose an optical fiber with reduced PMD. Modern telecom fibers have fairly stringent PMD specifications, but fibers laid in the early 1990s often exhibit much stronger PMD, which is often not even specified.

For achieving the highest possible bit rates, particularly with older fibers and in long fiber-optic links, it can be necessary to compensate the polarization mode dispersion. This is not easy, however, because temperature changes can make the PMD effect time-dependent; it is therefore often necessary to apply an automatic feedback system. If the system has multiple wavelength channels (wavelength division multiplexing), the compensation may have to be done separately for each channel, because the effect is wavelength dependent.

In principle, the problem could be solved by using well-defined polarization states in polarization-maintaining fibers, but this approach is usually not practical for various reasons: it would not only be necessary to use the more expensive and more lossy polarization-maintaining fibers for all components (including e.g. fiber amplifiers), but also the polarization directions would have to be aligned at many interfaces. Another strategy can be to limit the capacity of each transmission channel, but using many different channels in a single fiber, e.g. with the technique of wavelength division multiplexing. Finally, there are advanced modulation schemes with reduced symbol rate (for a given bit rate), which are less sensitive to PMD [15].

2.3 Overview about Nonlinearity

A relationship which cannot be explained as a linear combination of its variable inputs is known as nonlinearity. Nonlinearity is a common issue when examining cause-effect relations. Such instances require complex modeling and hypothesis to offer explanations to nonlinear events. Nonlinearity without explanation can lead to random, unforecasted outcomes such as chaos.

In physics and other sciences, a nonlinear system is the opposite of a linear system, that is a system that does not satisfy the superposition principle, which means that the output is not directly proportional to the input.

Nonlinear problems are of interest to engineers, physicists and mathematicians and many other scientists because most systems are inherently nonlinear in nature. As nonlinear equations are difficult to solve, non linear system are commonly approximated by linear equations (linearization). This works well up to some accuracy and some range for the input values, but some interesting phenomena such as chaos and singularities are hidden by linearization. It follows that some aspects of the behavior of a nonlinear system appear commonly to be chaotic, unpredictable or counterintuitive. Although such a chaotic behavior may resemble to a random behavior, it is absolutely not random [16].

For example, some aspects of the weather are seen to be chaotic, where simple changes in one part of the system produce complex effects throughout. This nonlinearity is one of the reasons why long term forecast are impossible with the current technology.

2.3.1 Nonlinearity in Optical Fiber

High optical densities in the fiber core lead to two types of non-linear effects, based on scattering and on the non-linear refractive index. Scattering processes such as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) manifest themselves as intensity-dependent gain or loss. Figure-2.5 shows the input and output spectra of a 100-channel system. The total input power is 16 dBm, travelling through 100 km of single mode fiber.

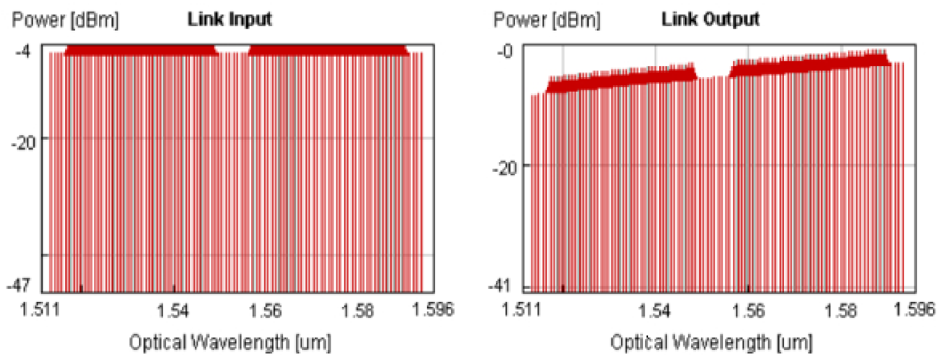

Figure 2.5: Optical spectrum of 100 channels before (a) and after (b) transmission through 100 km of optical fiber with a Raman coefficient of 0.4

The refractive index n of glass is a weak function of optical intensity, i.e.,$n = n_0 + n_2 * \frac{P}{A_e}$ where n_0 is the term independent of power, P is the optical power and A_e is the effective area of the core. The coefficient n_2 for silica fibers is approximately 2.6 x 10^{-20} m^2/W. The non-linear contribution to the refractive index results in an intensity-dependent phase change for light propagating in a fiber of

$$\varphi nl = \gamma * P * L_e, \text{ where } \gamma = 2 * \pi * n_2/(\pi * A_e) \text{ and } L_e \text{ is the effective interaction length.}$$

The intensity dependent refractive index gives rise to three effects: fluctuations in the phase of the signal on the channel, known as self-phase modulation (SPM), fluctuations in the phase of signals in other channels, known as cross phase modulation (XPM), and four-wave mixing (FWM), where the beating between two channels leads to tones and sidebands [1].

By contrast, the Kerr nonlinearity-the principal source of nonlinearity-is not difficult to model. It leads to a phase rotation that is proportional to the intensity at every point in time. However, it couples to the other transmission impairments in a complex way that is often difficult to analyze. It has been known since the late nineteenth century that even simple nonlinearities can lead to stunningly complex dynamics, including chaos, and the Kerr nonlinearity is no exception [1].

2.4 Interaction of Nonlinearity and PMD

Polarization effects and nonlinearity are usually studied separately for two reasons. First, each is hard to understand on its own. Studying them together can seem almost hopeless. Second, in practice, they usually appear separately in communications systems, with one or the other interacting with the amplified spontaneous emission noise and the chromatic dispersion to limit the transmission distance and/or the per channel data rate. However, there are good reasons for studying them together. They can interact to produce effects that are potentially harmful-like nonlinear polarization rotation, which can limit the effectiveness of polarization division multiplexing . Conversely, there are a number of cases where they interact to produce effects that are potentially useful, like all-optical switching. Polarization mode dispersion (PMD) has become increasingly important as the per-channel data rates have increased and is now arguably the most important of the polarization effects [1]. It is due to the differential rotation of the polarization states in neighboring frequencies, as will be discussed later in more detail.

The interaction between PMD and nonlinearity can be particularly complex. Sometimes, in combination with chirp, a system with both PMD and nonlinearity is less impaired than a system with the same amount of nonlinearity and no PMD. More often, the combination of PMD and nonlinearity can be harmful. Nonlinear polarization rotation can alter the polarization states of the bits, so that they vary from one bit to the next in a way that is difficult to predict. In this case, conventional PMD compensation becomes impossible [1].

Another motivation for studying the interaction of nonlinearity and polarization effects is that this interaction can provide insight into the linear properties of optical fibers. For example, if fibers are linearly birefringent, then the ratio of the crossphase modulation coefficient to the self-phase-modulation coefficient is 2/3. By contrast, in a circularly birefringent fiber, this ratio is 2. With arbitrary ellipticity, it varies between the two extremes of 2/3 and 2. This ratio has been measured to be nearly equal to 2/3, providing powerful evidence-although by no means the only evidence-that standard optical fibers are to good approximation linearly birefringent. Another example is that signals are expected to disperse linearly in exactly the same way, regardless of whether any orientation of the randomly varying axes of birefringence is equally likely, as is the case in standard communications fiber, or there is some fixed axis that is most likely, as is the case in polarization-maintaining fiber. By contrast, solitons will be stable in the former case, but they will split in two in the latter case. The stability of solitons in standard fiber thus provides strong evidence that the orientation of the axes of the birefringence is uniformly distributed to a good approximation [1].

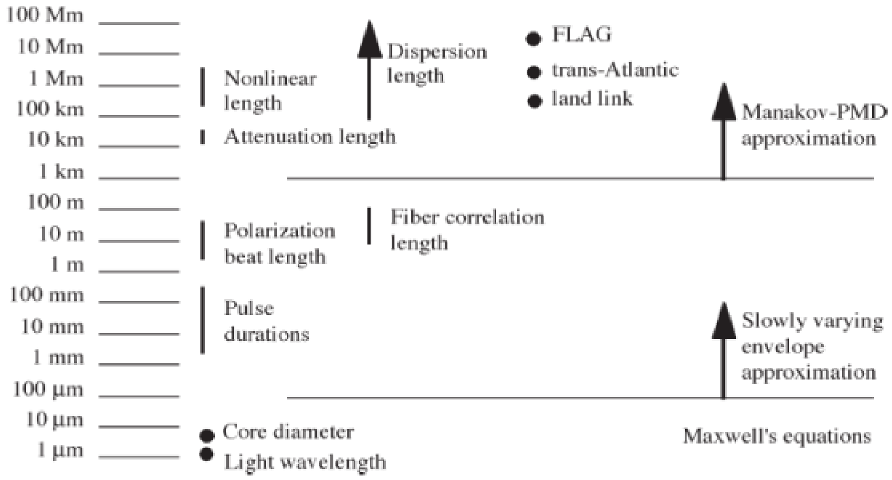

Figure 2.6: Key length scales in optical fiber communication systems (Originally from [1])

In addition to the practical reasons for studying the interaction between polarization effects and nonlinearity, there are some fundamental reasons as well. First, one of the outstanding questions in mathematical physics is understanding when the complex, chaotic behavior that is generally present in nonlinear systems can be avoided. Mathematical systems in which this behavior is never present are referred to as integrable. An example of an integrable system is the nonlinear Schrdinger equation [19], which can accurately model transmission in optical fibers in certain cases. Integrable partial differential equations like the nonlinear Schrdinger equation typically have soliton solutions. However, solitons or at least soliton-like solutions-are often also present in non-integrable systems. Indeed, for deep theoretical reasons, it has been hypothesized that solitons are robust when integrable systems are subjected to Hamiltonian deformations. Without entering into what Hamiltonian deformations are here, we will simply note that the addition of the birefringence to the nonlinear

Schrdinger equation produces a new equation-the coupled nonlinear Schrdinger equation-that is a Hamiltonian deformation of the nonlinear Schrdinger equation. The stability of solitons in this system provides evidence that the robustness hypothesis just cited is correct.

Another fundamental reason for studying the interaction of polarization effects and nonlinearity that is of more direct relevance to optical fiber technology is to determine when the nonlinear Schrdinger equation is expected to hold. To understand this issue, the reader should peruse Figure-2.6, in which the different length scales that are present in typical optical fiber communications systems are shown. The length scales vary over 13 orders of magnitude from the smallest length, the wavelength of light (1.55 μm), to the largest length, the length of a trans-global communications system (23 000 km) like fiber loop around the globe (FLAG). There is a similar large variation in time scales. The length scales shown in Figure-2.6 cluster into three groups. The shortest group, on the order of micrometers, corresponds to the wavelength of light and the fiber core diameter. The intermediate group, on the order of meters, corresponds to the fiber beat length and to the fiber correlation length-the length scale on which the fiber's axes of the birefringence change randomly. The longest group, on the order of tens of kilometers and more, corresponds to length scales for fiber attenuation and amplifier spacing, chromatic dispersion, and the Kerr nonlinearity. A point to note is that the strength of an effect is inversely proportional to its length scale. Therefore, the birefringence is a large effect compared to the chromatic dispersion [1].

Why then should the nonlinear Schrdinger equation, which completely ignores polarization effects, ever hold? The answer to this question lies in a multiple-scale analysis. While the birefringence is large, it is also rapidly and randomly varying. On a long length scale, its effects can average out. The operative word here is "can." These effects do not always average out, and one must then take into account the vector effects that are associated with the birefringence. A careful analysis shows that it is possible to use scalar equations like the nonlinear Schrdinger equation when the length scale associated with PMD is long compared to the system length and when the initial signal starts out in a single polarization state. Moreover, when the PMD length is long compared to the nonlinear length, the vector effects can be treated perturbatively and are often small [14].

2.4.1 Effect of Nonlinearities on PMD

We now consider two examples of the interaction between nonlinearity and PMD. In the first example, the nonlinearity induces a chirp in the signal, which in combination with higher order PMD can lead to pulse compression and a reduction in the eye-opening penalty that would be present in the absence of PMD. In the second example, the nonlinear interaction between two channels induces a nonlinear rotation in the principal states of the bits in each channel that varies bit to bit. While this rotation does not directly induce an eye-closing penalty, it makes it impossible to use most current PMD compensation techniques, since these techniques typically rely on each bit having the same principal states, and, more generally, the same polarization variation as a function of time within a bit slot. These two examples serve to underline two points. The first is that the impact of fiber nonlinearity can be quite complex. The second, which is closely related to the first, is that one cannot simply add the penalties due to PMD and nonlinearity without careful justification.

The basic equation that governs our investigation is the Manakov-PMD equation that we write in the form

$$i\frac{\partial U(z,t)}{\partial z} + i\Delta\beta'(z).\overline{\sigma}3(z)\frac{\partial U(z,t)}{\partial t} - \frac{1}{2}\beta''\frac{\partial^2 U(z,t)}{\partial t^2} + \frac{8}{9}\gamma \mid U(z,t) \mid^2 U(z,t) = 0$$

We do not include the nonlinear PMD term in since we will be considering pulses in the picosecond range, as is typical in optical fiber communications systems, and the nonlinear PMD term is negligible in this range. We have returned to using U as the dependent variable for the wave envelope, using it to replace W. We remind the reader that the rapid polarization evolution at $\omega = 0$ has been removed [1].

2.4.2 Improvement of a Nonlinear Chirped Signal Due to Higher Order PMD

It has been known since the early work of Poole and Giles that a chirped signal can be compressed as well as spread by its interaction with fiber PMD. While Poole and Giles focused on chirp that is due to dispersion, other mechanisms such as an initial chirp due to the laser transmitter can also produce the same effect. We show schematically the physical origin of this effect in Figure-2.7. Due to chirp, the leading edge of the pulse (earlier times) has a different frequency from the trailing edge (later times). In the case shown in Figure-

2.7 (a), the leading edge of the pulse has a frequency that differs from the mean ω_0 by $+\Delta\omega$ and the trailing edge has a frequency that differs by $-\Delta\omega$. When second-order PMD is large relative to the first-order PMD, the principal state of polarization can change significantly over the bandwidth of the signal. We show this effect in Figure-2.7 (b). Here, we show the variation of the principal state of polarization as a curve on the Poincar sphere. Thus, the state of polarization of the signal, which is shown as a dot, is primarily aligned to the fast axis when the frequency is $\omega_0-\Delta\omega$, corresponding to the trailing edge, and is primarily aligned to the slow axis when the frequency is $\omega_0+\Delta\omega$, corresponding to the leading edge, as shown in Figure-2.7 (c). As a consequence, the pulse compresses during propagation, as shown in Figure-2.7 (d).

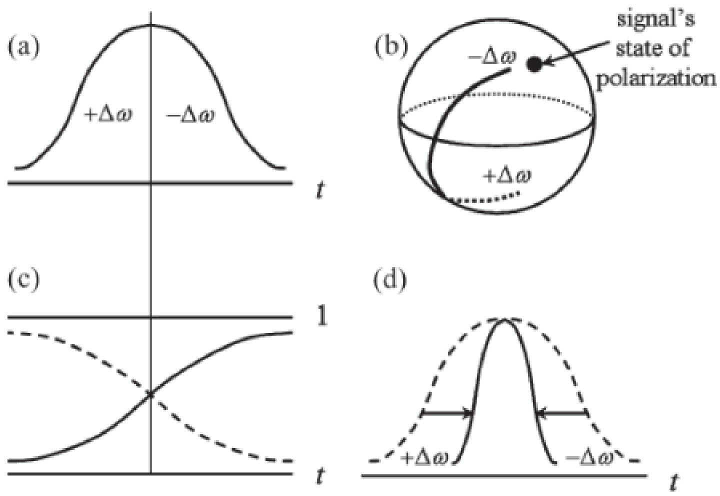

Figure 2.7: (a) Chirp leads to a time-dependent frequency variation, (b) variation of the principal states over the bandwidth of the signal, (c) time-dependent variation that is aligned with the fast (–) and slow (- - -) axes and (d) variation leads to pulse compression

We are interested here in the case when the chirp is due to nonlinearity. In contrast to other mechanisms, the pulse compression and hence the signal improvement depends on the pulse power. Systems that show no signal improvement at low powers may show signal improvement at higher powers [1].

2.4.3 Nonlinear Polarization Rotation and Its Impact

The index of refraction can be changed by the optical power in a specific polarization state, resulting in a nonlinear birefringence. In wavelength-division-multiplexed (WDM) systems, the nonlinear interaction between channels induces a nonlinear, bit-pattern-dependent phase change in an optical signal whenever there is optical power present at the other wavelengths, causing a bit-pattern-dependent change in the state of polarization. Fig.-2.8 illustrates this concept for a simple two-channel system. The bits at wavelength λ_1 that propagate alongside a long sequence of marks in the channel at λ_2 experience a small change in the fiber that changes their output state of polarization relative to the other bits in the channel. This effect becomes significant when the relative states of polarization of the channels are preserved over a distance that is long enough for the nonlinear interaction to accumulate, implying that the nonlinear change in the state of polarization is more prevalent in fibers with relatively low PMD, in which the polarization states of the channels remained correlated over a long distance [1].

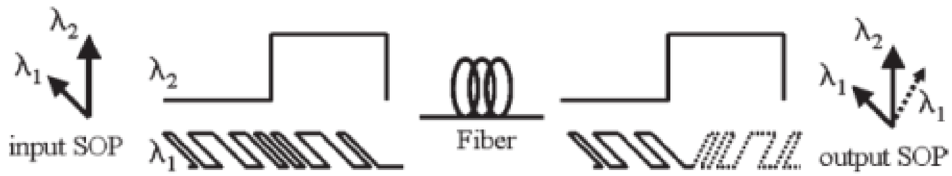

Figure 2.8: Optical power induces a small nonlinear birefringence that randomizes the state of polarization, limiting the effectiveness of the first-order PMD compensation (Originally from [1])

We thus find that while large PMD can lead to a pulse distortion in a single channel, it is actually helpful in reducing the nonlinear crosstalk between channels. The situation is analogous to the chromatic dispersion. While the chromatic dispersion may distort the signal inside a single channel, it actually reduces the nonlinear interaction between channels. It is simplest to develop the theory of nonlinear polarization rotation in the limit where PMD is negligible. In this limit, the evolution is described by the Manakov equation with gain and loss

$$i\frac{\partial U(z,t)}{\partial z} + ig(z)U(z,t) - \frac{1}{2}\beta''(\omega_0)\frac{\partial^2 U(z,t)}{\partial t^2} + \frac{8}{9}\gamma \mid U(z,t) \mid^2 U(z,t) = 0$$

including the effects of gain and loss. We consider a WDM system, and we write

$$U(z,t) = \sum_{m=1}^{N} U_m(z,t) exp(i\beta_m z - i\omega_m t)$$

where β_m is the wave number of the mth WDM channel relative to $\beta(\omega_0)$, and ω_m is the radial frequency of that channel relative to ω_0. When four-wave mixing and intra-channel chromatic dispersion can be neglected, we obtain for the lth channel

$$i\frac{\partial U_l(z,t)}{\partial z} + ig(z)U_l(z,t) + i\beta''(\omega_0)\omega_l \frac{\partial U_l(z,t)}{\partial t} + \frac{8}{9}\gamma \sum_{m=1,\neq l}^{N} \mid U_m(z,t) \mid^2$$
$$U_l(z,t) + \frac{8}{9}\gamma \sum_{m=1}^{N} [U_l(z,t).U_m^*(z,t)] U_m(z,t) = 0$$

where N is the total number of channels. Focusing on channel l, we may define a new time variable $t_l = t - z/[\beta''(\omega_0)\omega_l]$, in which the group velocity motion of the lth channel is removed [1].

CHAPTER 3

MODULATION TECHNIQUES OF OPTICAL FIBER

3.1 General

In electronics and telecommunications, modulation is the process of varying one or more properties of a periodic waveform, called the carrier signal (High Frequency Signal), with a modulating signal which typically contains information to be transmitted. In telecommunications, modulation is the process of conveying a message signal, for example a digital bit stream or an analog audio signal, inside another signal that can be physically transmitted. Modulation of a sine waveform is used to transform a baseband message signal into a passband signal. A device that performs modulation is known as a modulator and a device that performs the inverse operation of modulation is known as a demodulator (sometimes detector or demod). A device that can do both operations is a modem (from “modulator-demodulator”).

3.2 Objectives of Different Modulation Techniques

The aim of digital modulation is to transfer a digital bit stream over an analog bandpass channel, for example over the public switched telephone network (where a bandpass filter limits the frequency range to between 300 and 3400 Hz), or over a limited radio frequency band.

The aim of analog modulation is to transfer an analog baseband (or lowpass) signal, for example an audio signal or TV signal, over an analog bandpass channel at a different frequency, for example over a limited radio frequency band or a cable TV network channel.

Analog and digital modulation facilitate frequency division multiplexing (FDM), where several low pass information signals are transferred simultaneously over the same shared physical medium, using separate passband channels (several different carrier frequencies).

The aim of digital baseband modulation methods, also known as line coding, is to transfer a digital bit stream over a baseband channel, typically a non-filtered copper wire such as a serial bus or a wired local area network.

The aim of pulse modulation methods is to transfer a narrowband analog signal, for example a phone call over a wideband baseband channel or, in some of the schemes, as a bit stream over another digital transmission system [17].

3.3 Overview of NRZ, RZ, CRZ and CSRZ Modulation

A typical modulation on optical fibers is on/off, so it is RZ- return to zero. Sometimes the light is sent all the time and detected at two levels- higher and lower, but the lower level is not a zero. Then we can talk about NRZ. NRZ is typical in copper cables where you can send signals with alternating polarity, NRZ. RZ modulation is used for long reach fiber communications, because light disperses in fiber and RZ modulation provides larger headroom for dispersion. However RZ modulation requires more bandwidth because actual pulse width is shorter than one period of data. NRZ is classic on-off modulation. It is used for short reach fiber communications.

Carrier-Suppressed Return-to-Zero (CSRZ) is an optical signal format. In CSRZ the field intensity drops to zero between consecutive bits (RZ), and the field phase alternates by π between neighboring bits, so that if the phase of the signal is e.g. 0 in even bits (bit number 2n), the phase in odd bit slots (bit number 2n+1) will be π, the phase alternation amplitude. In its standard form CSRZ is generated by a single Mach-Zehnder Modulator (MZM), driven by two sinusoidal waves at half the bit rate B_R, and in phase opposition. This gives rise to characteristically broad pulses (duty cycle 67%).

We demonstrate two most used modulation formats in optical communications - nonreturn-to-zero (NRZ) and return-to-zero (RZ) - as well as two additional variants of RZ format chirped RZ (CRZ) and carrier-suppressed RZ (CSRZ). The setup is shown below:

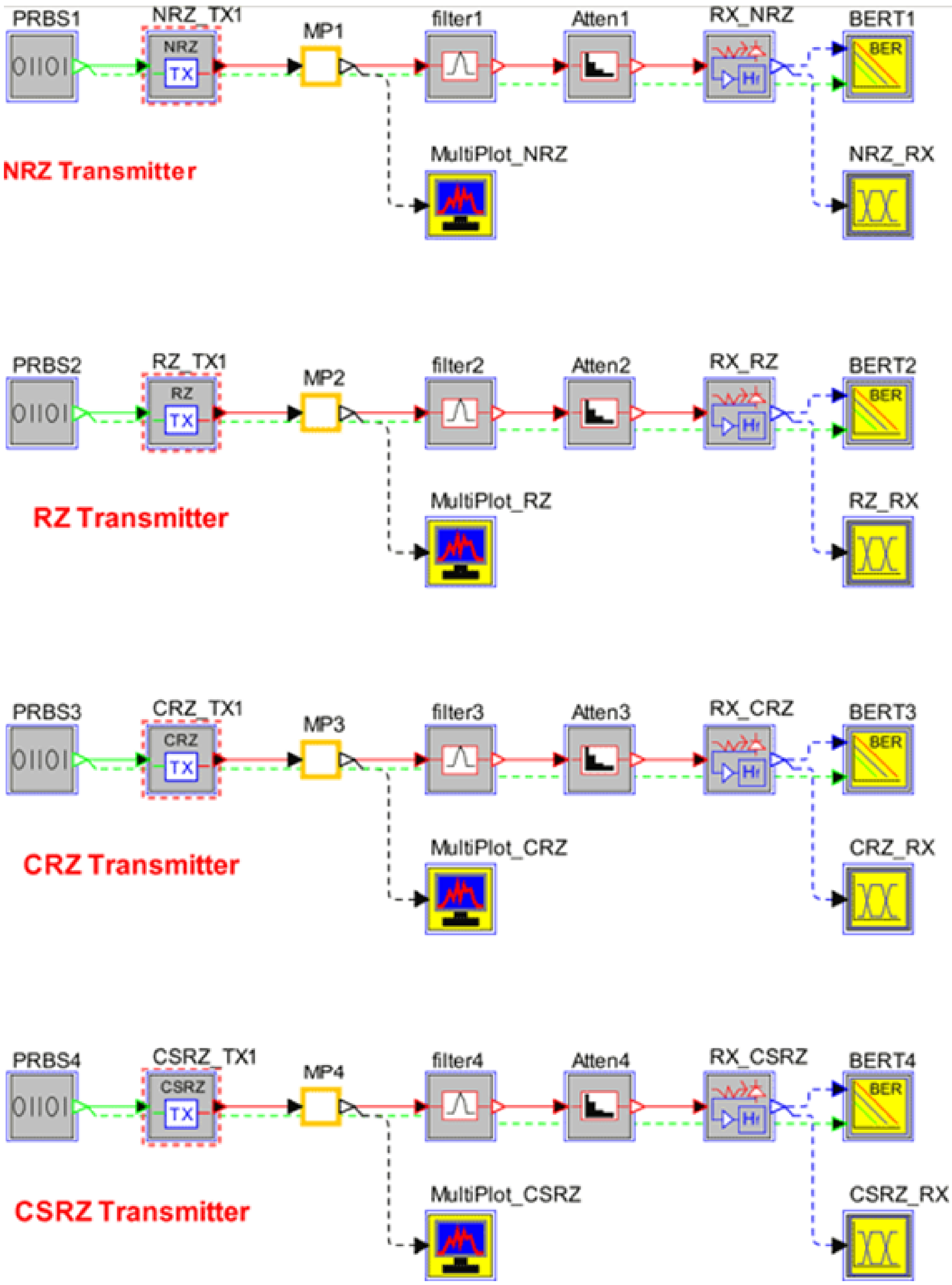

Figure 3.1: Different modulation formats (NRZ, RZ, CRZ, CSRZ) in optical communications

Each link consists of PRBS generator, transmitter, optical filter, attenuator, receiver, and BER tester. Transmitters represented as compound components blocks, i.e. combination of blocks. For example, NRZ transmitter combines CW Laser source, Electrical signal generator (NRZ driver), external Mach-Zehnder Modulator, and attenuator. The following parameters of transmitter can be set: power, wavelength, extinction ration, rise/fall time, RIN, etc. In case of RZ transmitter the electrical signal generator generate RZ signal with raised cosine shape and given duty cycle. In CRZ transmitter we add a chirp to RZ optical by applying a phase modulation. And finally in case of CSRZ transmitter the RZ optical signal after Mach-Zehnder Modulator goes through phase modulator driven by analog sine wave generator at frequency equal to half of the bit rate. That will introduce a pi phase shift between any two adjacent bits and the spectrum will be modified such that the central peak at the carrier frequency is suppressed.

Figure below shows transmitter optical spectrum for different modulation formats. One can observe the central peak suppression in case of CSRZ.

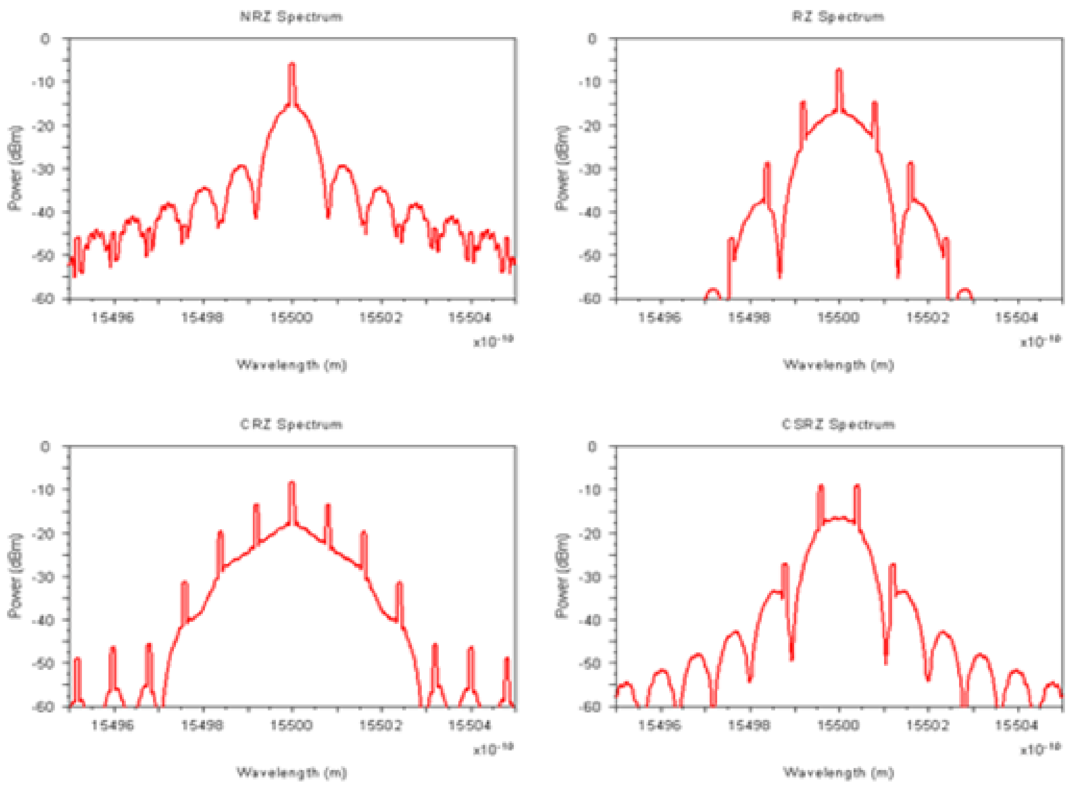

Figure 3.2: Transmitter optical spectrum for different modulation formats

Figure below gives corresponding signal waveforms. In case of NRZ format, the optical pulse representing each 1 bit occupies the entire bit slot and does not drop to zero between two or more successive 1 bits. In the RZ format, each optical pulse representing 1 bit is chosen to be shorter than the bit slot, and its amplitude returns to zero before the bit duration is over. The ratio of the pulse width to bit duration is referred to as the duty cycle of the RZ bit stream.

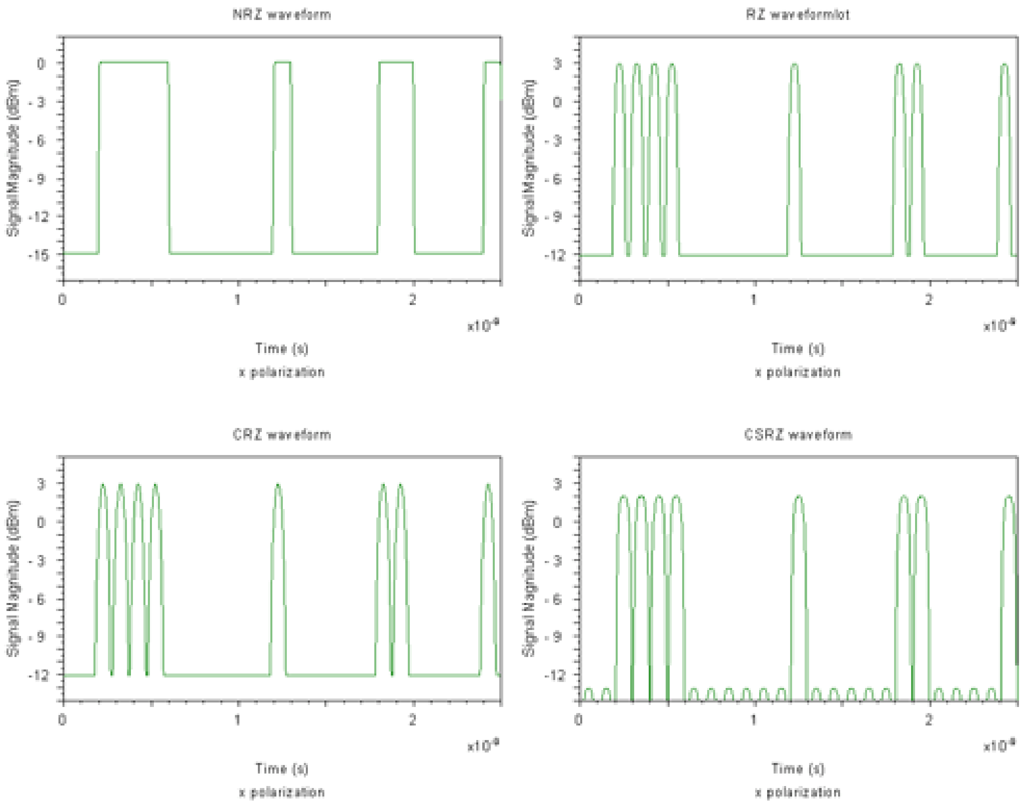

Figure 3.3: Signal waveforms of different modulation formats

Finally, figure below shows receiver eye diagrams for each of modulation formats.

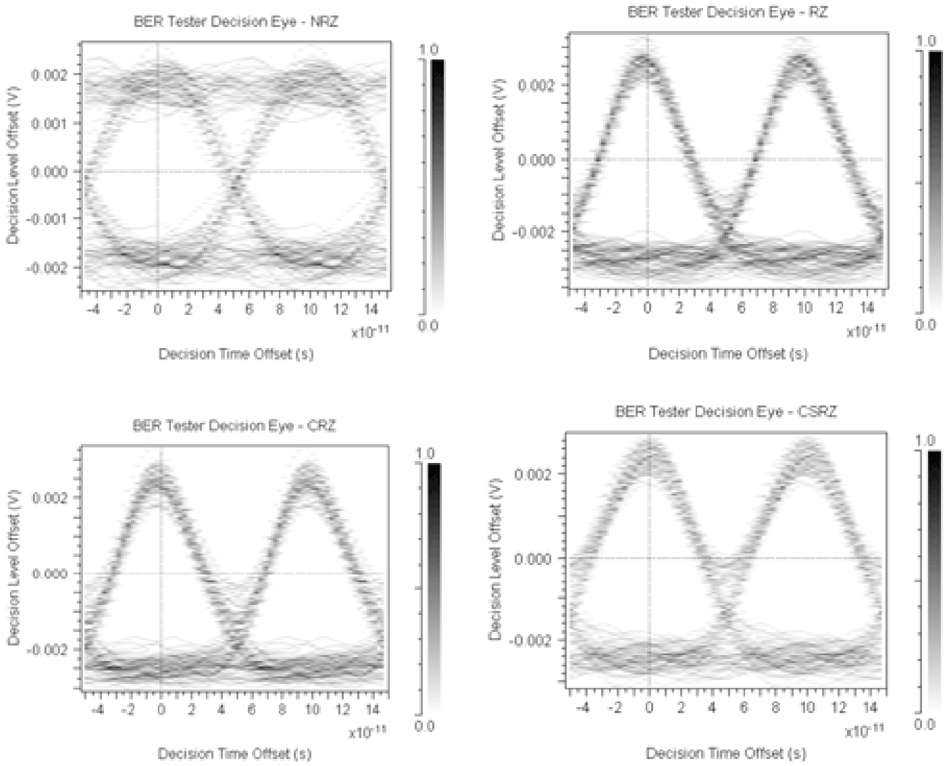

Figure 3.4: Receiver eye diagrams for each of modulation formats

CSRZ can be used to generate specific optical modulation formats, e.g. CSRZ-OOK, in which data is coded on the intensity of the signal using a binary scheme (light on=1, light off=0), or CSRZ-DPSK, in which data is coded on the differential phase of the signal, etc. CSRZ is often used to designate APRZ-OOK. The characteristic properties of an CSRZ signal are those to have a spectrum similar to that of an RZ signal, except that frequency peaks (still at a spacing of BR) are shifted by BR/2 with respect to RZ, so that no peak is present at the carrier and power is ideally zero at the carrier frequency. Compared to standard RZ-OOK, the CSRZ-OOK is considered to be more tolerant to filtering and chromatic dispersion [18].

3.4 Overview of DPSK and DQPSK

Differential phase shift keying (DPSK) is a common form of phase modulation that conveys data by changing the phase of the carrier wave. As mentioned for BPSK and QPSK there is an ambiguity of phase if the constellation is rotated by some effect in the communications channel through which the signal passes. This problem can be overcome by using the data to change rather than set the phase.

For example, in differentially encoded BPSK a binary '1' may be transmitted by adding 180^o to the current phase and a binary '0' by adding 0^o to the current phase. Another variant of DPSK is Symmetric Differential Phase Shift keying, SDPSK, where encoding would be $+90^o$ for a '1' and -90^o for a '0'.

In differentially encoded QPSK (DQPSK), the phase-shifts are 0^o, 90^o, 180^o, -90^o corresponding to data '00', '01', '11', '10'. This kind of encoding may be demodulated in the same way as for non-differential PSK but the phase ambiguities can be ignored. Thus, each received symbol is demodulated to one of the M points in the constellation and a comparator then computes the difference in phase between this received signal and the preceding one. The difference encodes the data as described above. Symmetric Differential Quadrature Phase Shift Keying (SDQPSK) is like DQPSK, but encoding is symmetric, using phase shift values of -135^o, -45^o, $+45^o$ and $+135^o$.

The modulated signal is shown below for both DBPSK and DQPSK as described above. In the figure, it is assumed that the signal starts with zero phase, and so there is a phase shift in both signals at t=0. The binary data stream is above the DBPSK signal. The individual bits of the DBPSK signal are grouped into pairs for the DQPSK signal, which only changes every T_S=$2T_B$.

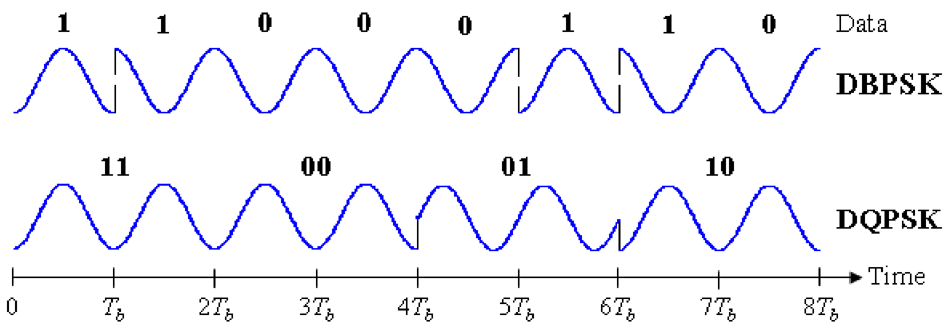

Figure 3.5: Timing diagram for DBPSK and DQPSK

Analysis shows that differential encoding approximately doubles the error rate compared to ordinary M-PSK but this may be overcome by only a small increase in E_b/N_0. Furthermore, this analysis (and the graphical results below) are based on a system in which the only corruption is additive white Gaussian noise(AWGN). However, there will also be a physical channel between the transmitter and receiver in the communication system. This channel will, in general, introduce an unknown phase-shift to the PSK signal; in these cases the differential schemes can yield a better error-rate than the ordinary schemes which rely on precise phase information [19 and 20].

3.4.1 Demodulation Technique

For a signal that has been differentially encoded, there is an obvious alternative method of demodulation. Instead of demodulating as usual and ignoring carrier-phase ambiguity, the phase between two successive received symbols is compared and used to determine what the data must have been. When differential encoding is used in this manner, the scheme is known as differential phase-shift keying (DPSK). Note that this is subtly different to just differentially encoded PSK since, upon reception, the received symbols are not decoded one-by-one to constellation points but are instead compared directly to one another.

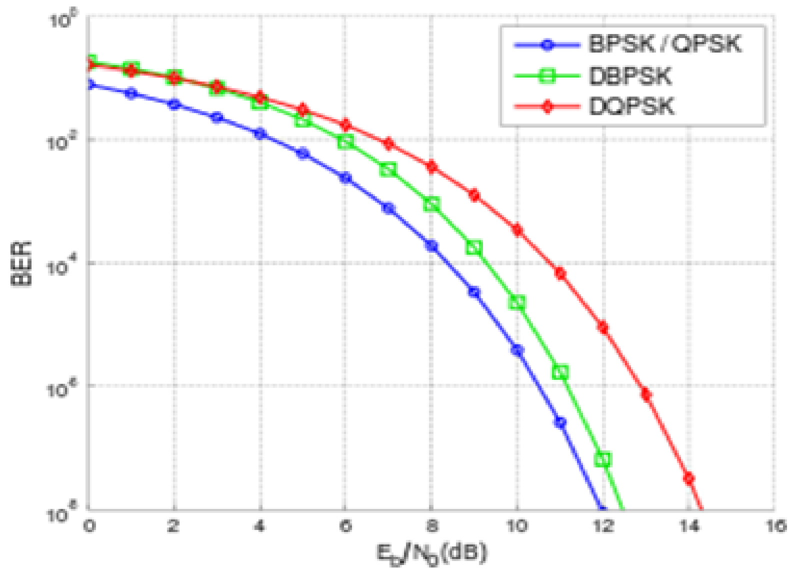

Figure 3.6: BER comparison between DBPSK, DQPSK and their non-differential forms using gray-coding and operating in white noise

Call the received symbol in the K^{th} timeslot t_k and let it have phase ϕ_k. Assume without loss of generality that the phase of the carrier wave is zero. Denote the AWGN term as n_k. Then

$$r_k = \sqrt{E_s} e^{j\phi_k} + n_k$$

The decision variable for the $(K-1)^{th}$ symbol and the K^{th} symbol is the phase difference between r_k and r_{k-1}. That is, if r_k is projected onto r_{k-1}, the decision is taken on the phase of the resultant complex number:

$$r_k r_{k-1}^* = E_s e^{j(\theta_k - \theta_{k-1})} + \sqrt{E_s} e^{j\theta_k n_{k-1}^*} + \sqrt{E_s} e^{-j\theta_{k-1} n_k} + n_k n_{k-1}$$

where superscript * denotes complex conjugation. In the absence of noise, the phase of this is θ_k-θ_{k-1}, the phase-shift between the two received signals which can be used to determine the data transmitted.

The probability of error for DPSK is difficult to calculate in general, but, in the case of DBPSK it is:

$$P_b = \frac{1}{2} e^{-E_b/N_0}$$

which, when numerically evaluated, is only slightly worse than ordinary BPSK, particularly at higher E_b/N_0 values.

Using DPSK avoids the need for possibly complex carrier-recovery schemes to provide an accurate phase estimate and can be an attractive alternative to ordinary PSK [20].

In optical communications, the data can be modulated onto the phase of a laser in a differential way. The modulation is a laser which emits a continuous wave, and a Mach-Zehnder modulator which receives electrical binary data. For the case of BPSK for example, the laser transmits the field unchanged for binary '1', and with reverse polarity for '0'. The demodulator consists of a delay line interferometer which delays one bit, so two bits can be compared at one time. In further processing, a photodiode is used to transform the optical field into an electric current, so the information is changed back into its original state.

The bit-error rates of DBPSK and DQPSK are compared to their non-differential counterparts in the graph to the right. The loss for using DBPSK is small enough compared to the complexity reduction that it is often used in communications systems that would otherwise use BPSK. For DQPSK though, the loss in performance compared to ordinary QPSK is larger and the system designer must balance this against the reduction in complexity.

3.4.2 Comparison Between DPSK and DQPSK

Some of the more bandwidth efficient schemes that have been explored in optical communications are duobinary and QPSK. The theoretical bandwidth required to transmit a signal at a rate of R symbols/sec with no inter symbol interference is R/2 Hz. Duobinary decreases the bandwidth of the transmitted signal to a value less than this limit by introducing some ISI which is unraveled later. However, it still transmits 1 bit per symbol and hence the symbol rate equals the bit rate. QPSK is more efficient because it transmits 2 bits per symbol and hence the symbol rate is half the bit rate and the theoretical bandwidth required is 1/4 of the bit rate. Hence, the effects of dispersion are considerably less for this modulation format. The drawbacks are the increased SNR required and the increase in the complexity of the system. Differential quadrature phase-shift-keying (DQPSK) format provides a promising alternative as it, like QPSK, transmits 2 bits per symbol and hence the symbol rate is half the bit rate with somewhat reduced complexity of the system. DQPSK is tolerant to chromatic dispersion (CD), polarization-mode dispersion (PMD), and has a high spectral efficiency, and thus can be used in ultra long haul transmission as well. Although the configuration of a DQPSK system is less complex compared with a QPSK system, large size and high power consumption of the optical transceivers still pose challenges to designers [20].

CHAPTER 4

EXPERIMENTAL RESULTS

4.1 General

In this chapter, firstly we established simulation models for using the above mentioned two modulation formats. Then different simulations are carried out with varied parameters. The simulations are carried out at 40Gb/s. At the end, we shall carry out a short discussion on the simulated results.

4.2 Simulation Model for CSRZ-DPSK and CSRZ-DQPSK Systems

In this experiment we analyzed the performance of two most efficient modulation formats in ultra high spectral efficient DWDM systems. For each of them, we optimized dispersion map. We used optimized parameters for a length of 100 km at 40 Gb/s. We studied the performance in a multi-span scenario.

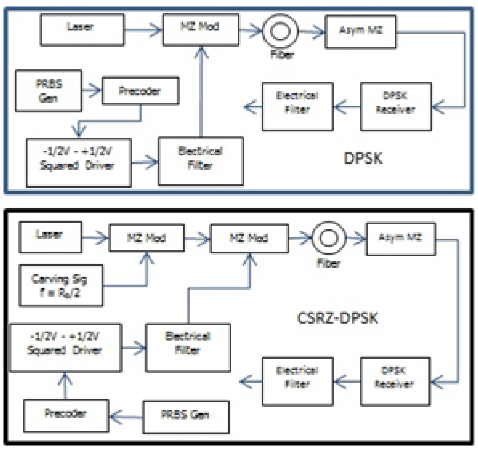

Figure 4.1: Single Channel DPSK and CSRZ-DPSK Systems

Figure-4.1 depicts detailed block diagrams of DPSK and CSRZ-DPSK systems with transmitter and receiver sections. The transmitter takes the input data of 40 Gb/s from a random data generator. The data is passed through two spans, each of 50 km. We considered a dispersion compensated fiber using appropriate fiber sections. The transmitter section of CSRZ-DPSK system is composed of two Mach-Zehnder modulators (MZMs). The receiver uses asymmetric Mach-Zender demodulator and DPSK stages to detect the data. The electrical filter finally gives the received data.

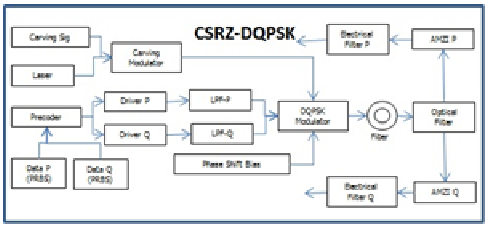

Figure 4.2: Single Channel CSRZ-DQPSK System

Figure-4.2 shows a single channel CSRZ-DQPSK setup for the multi-span configuration. A precoder converts a pair of bit streams into a pair of encoded P and Q DQPSK bit streams suitable for controlling a DQPSK modulator. Given input bit streams a and b, and encoded output bit streams p and q, the kth output bits satisfy the relationships:

$$p_k = \overline{(a_k \oplus b_k)}.(a_k \oplus p_{k-1}) + (a_k \oplus b_k).(b_k \oplus q_{k-1})$$

$$q_k = \overline{(a_k \oplus b_k)}.(b_k \oplus q_{k-1}) + (a_k \oplus b_k).(a_k \oplus p_{k-1})$$

As shown in Figure-4.2, for CSRZ DQPSK system two NRZ DPSK signals are generated from the pre-coded signals P and Q, and the signal in the upper arm is phase shifted inside the upper modulator with π/2 before both signals are combined, resulting in a four-level phase modulated signal. By this time, we obtain the NRZDQPSK signal. We added another MZM which works as a pulse carver and which is driven by another analog signal generator. The receiver section for DQPSK consists of two DPSK modules each with one symbol delay demodulators having offset of π/4. The incoming signal is split into two branches, one for each tributary. Then the signal is demodulated by a MZ interferometer with a delay of one symbol period. Balanced detection offers a 3 dB improvement in receiver sensitivity compared to single-ended reception. By applying an appropriate clock tone and adjusting the bias of the MZM, the pulse carver generates 33%return-to zero (RZ), 50% RZ, 67%

carrier-suppressed return-to-zero(CSRZ) DQPSK modulation [3]. For both the systems, dispersion compensated fiber is used where the first and second sections have opposite but equal dispersions.

4.3 PMD Modeling With/Without Nonlinearities and Simulation

In a long-distance fiber communication link, the fiber experiences stresses, bends, temperature changes, twists, etc in a random fashion along the length of the link. Therefore, the birefringence along the fiber keeps changing both in magnitude as well as in direction. As a result, the birefringence is no longer remains additive. Hence, the PMD does not grow linearly with the fiber length. Instead, it grows at a rate proportional to the square root of the propagation distance. Due to random mode coupling, the calculation of PMD becomes very complicated.

Pulses launched in principal state of polarization (PSP) or any other state, emerge into two fixed output polarization states, which are orthogonal to each other. Thus, if the input pulse is launched along one of the input PSPs, there is no splitting of the pulse. It should be noted that due to random time variation of the birefringence along a long-length fiber link, PMD also varies randomly. Hence we adopted Monte Carlo simulation technique by changing the seed. The elegant expression for the root-mean-square (rms) DGD given by

$$\Delta\tau_{rms} = \Delta\tau_0(\sqrt{2}\tfrac{L_c}{L})\ (e^{-L/L_c} - 1 + L/L_c)^{1/2}$$

where $\Delta\tau_{rms} = \sqrt{< \Delta\tau^2 >}$, L is the fiber length, and L_C is a constant known as the coupling length and is a measure of magnitude of the mode coupling along the fiber length. Further, $\Delta\tau_0$ is the DGD in the absence of mode coupling. In our simulation, we kept the L fixed at 100 km.

The scalar nonlinear Schrodinger equation (NLSE) is known to be a fairly good model for including nonlinear impairments in fiber transmission. The governing equations for the transverse electric-field components in homogeneous Kerr media are:

$$\frac{dE_x}{dz} = \mathrm{i}\gamma(|E_x|^2 + \tfrac{2}{3}\ |E_y|^2\ )\ E_x + \tfrac{i\gamma}{3}\ E_x^*\ E_y^2$$

$$\frac{dE_y}{dz} = \mathrm{i}\gamma(|E_y|^2 + \tfrac{2}{3}\ |E_x|^2\ )\ E_y + \tfrac{i\gamma}{3}\ E_y^*\ E_x^2$$

where γ is the nonlinear coefficient. Disregarding the linear propagation constant and linear birefringence, it can be shown from above equation that the optical power

$$S_0 = |E_x|^2 + |E_y|^2 \text{ is constant.}$$

In terms of the Stokes vector

$$\text{S} = [S_1, S_2, S_3] = S_0 = |E_x|^2 - |E_y|^2, 2\text{Re}(E_x E_y^*), 2\text{Im}(E_x E_y^*).$$

In form of vector equation

$$\frac{ds}{dz} = \text{w x s} = \gamma(S_1, S_2, S_3/3) \text{ x s}$$

Where the vector w equals to γS and S_3 component enters with one third of its strength which accounts for the nonlinear birefringence. Considering a field comprised of two optical wavelength channels a and b, and the wavelengths are non-overlapping, then an expression for the evolution of the absolute phase of wavelength a can be obtained from defined as

$$\frac{\partial\phi_a}{\partial z} = \gamma(P_a + \frac{3P_aP_b + s_a.s_b}{2P_a})$$

The relation for the phase of the b wave is obtained by interchanging indexes a and b. In this expression, the first term is the SPM and the remaining terms are the XPM. During the simulation the bit rate is kept fixed 40 Gb/s. The PMD coefficients and the nonlinearity coefficients are varied. Transmission fibers usually have a weak but non-negligible linear birefringence that changes randomly along the fiber length. This leads to large accumulated birefringence and PMD over long lengths of fiber.

In this simulation, this random birefringence is modeled numerically by the coarse-step method and randomly rotating the polarization state at each numeric step in the z-direction using the seed. The simulations are carried out for one channel and seven channel systems with varied PMD and nonlinear coefficients. Following figures show the system Q in contour map and Q-surface. The PMD coefficients are varied by x10^{-14} where $0.01<x>6$ and nonlinear coefficient is varied by y10^{-20} where $0.01<y>10$.

Figure-4.3 shows the contour map and Q-surface of single channel CSRZ DPSK system. As shown in Figure-4.3(a), the vertical axis represents nonlinear coefficient and horizontal axis represents the PMD coefficient. At low nonlinear coefficient, when PMD coefficient (x) is increased Q-value decreases. When x is increased beyond 3.5, the Q-value goes below the acceptable level. With increased nonlinearity, the Q-value decreases with low PMD coefficient. But the Q-value does not remain linear, rather increased nonlinear coefficient reduces the effects of PMD. For example when x is increased from 3.3 to 4.5, the increased value of y from 1 to 4 gives the same Q-value. Same data is represented in 3-D form in Figure-4.3(b). It is clear from Figure-4.3(b) that the Q-value changes rapidly.

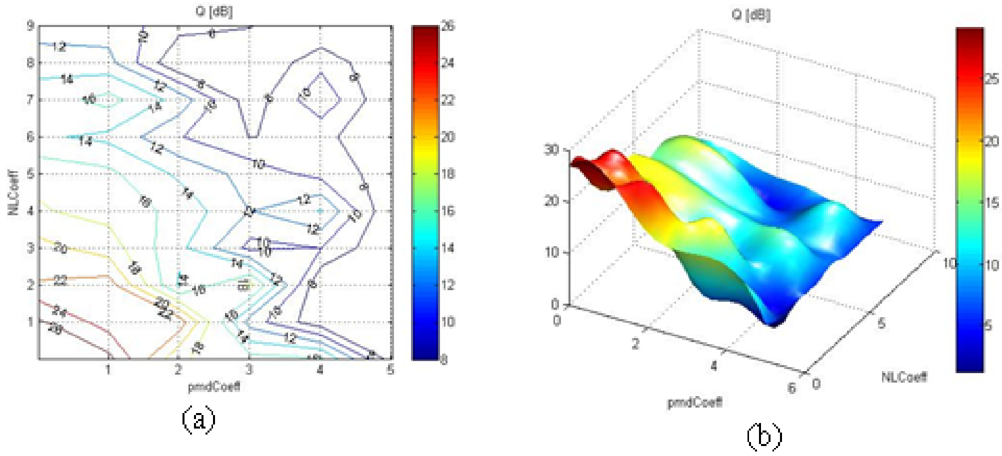

Figure 4.3: (a) Contour Map and (b) Q-Surface of Single Channel CSRZ DPSK System

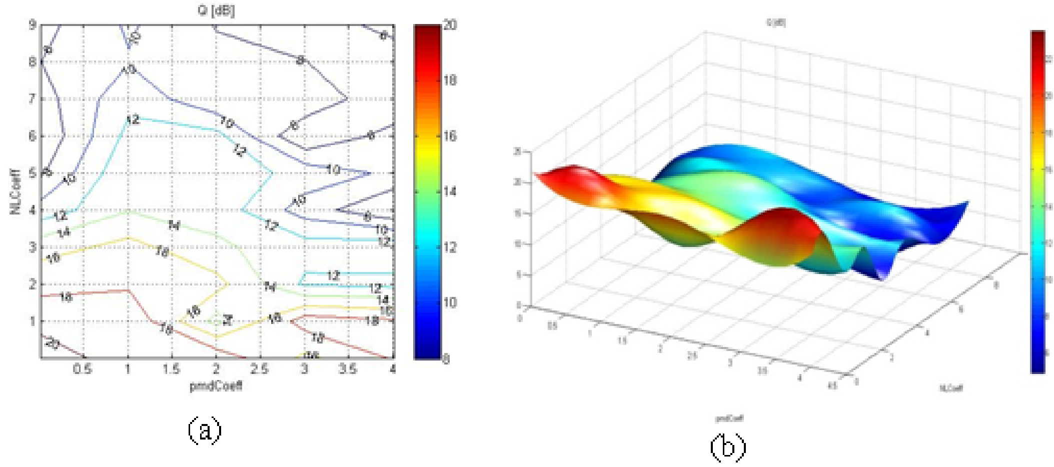

Figure 4.4: (a) Contour Map and (b) Q-Surface of Single Channel CSRZ DQPSK System

Figure-4.4 shows the contour map and Q-surface of single channel CSRZ DQPSK system. Figure-4.3 and 4.4 are the outcome of DPSK and DQPSK systems with the same parameters.

Comparing the two systems show that the Q-value of DPSK system vary very inconsistently and do not follow any gradual change pattern. It is clearly evident that DQPSK is more tolerant to PMD and nonlinearity.

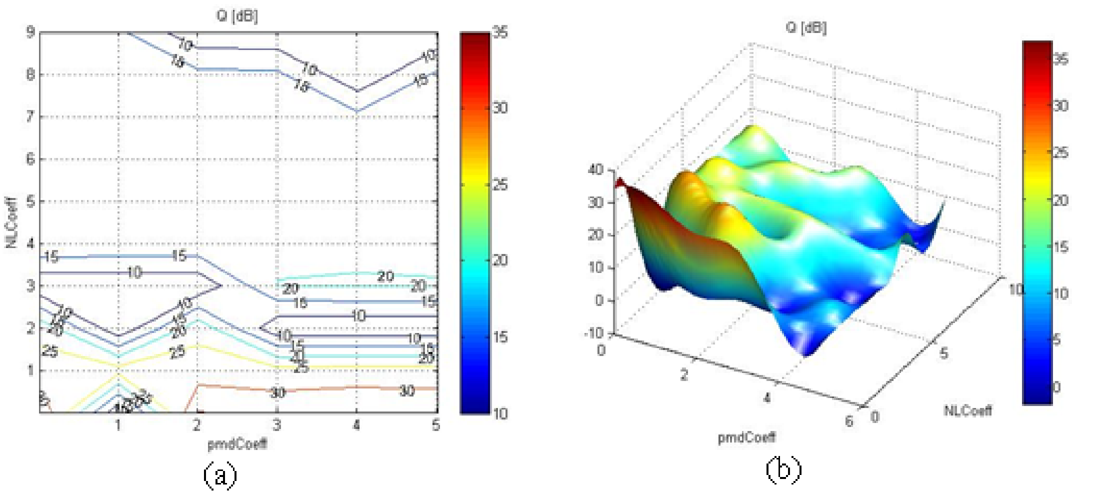

Figure 4.5: (a) Contour Map and (b) Q-Surface of Seven Channel CSRZ DPSK System

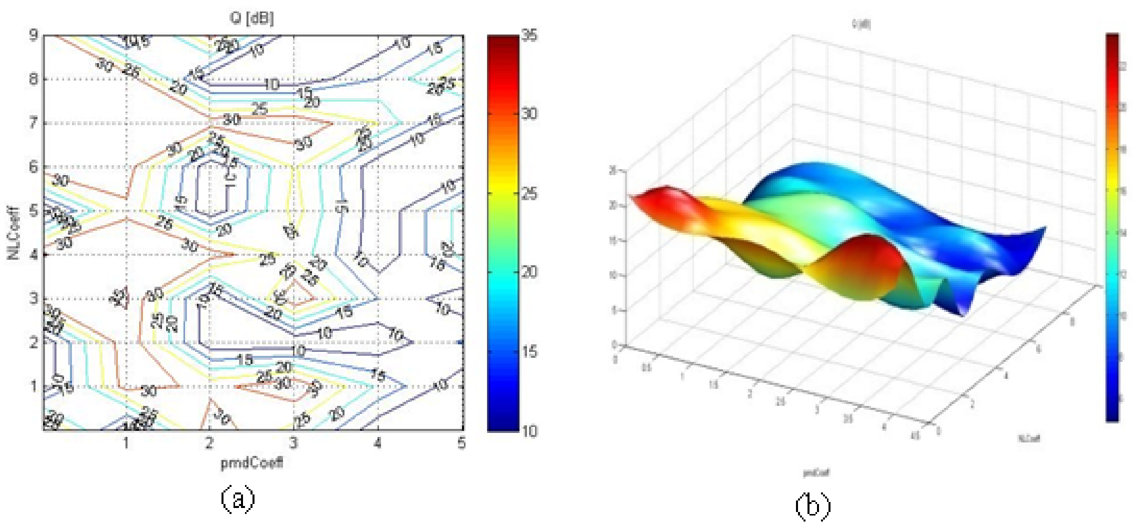

Figure 4.6: (a) Contour Map and (b) Q-Surface of Seven Channel CSRZ DQPSK System

Figure-4.5 shows the contour map and Q-surface of seven channel CSRZ DPSK system. As shown in Figure-4.5(a), the vertical axis here also represents nonlinear coefficient and horizontal axis represents the PMD coefficient. At low nonlinear coefficient up to $y<1.9$, when PMD coefficient (x) is increased Q-value almost remains static and shows consistent for higher values of PMD coefficient. The Q-value remains at acceptable level even for x>5. With increased nonlinearity, the Q-value fluctuates heavily. For seven channel system also the nonlinearity reduces the effect of PMD for certain values. For example when x is increased from 1 to 2.3, the increased value of y from 1.9 to 3 gives the same Q-value. Same data is represented in 3-D form in Figure-4.5(b). It is also clear from Figure-4.5(b) that the Q-value changes rapidly and inconsistently.

Figure-4.6 shows the contour map and Q-surface of seven channel CSRZ DQPSK system. Figure-4.5 and 4.6 are also the outcome of seven channel DPSK and DQPSK systems with similar parameters. Comparing the two systems shows that CSRZ DQPSK is more tolerant to PMD in the presence on nonlinearities.

4.4 Result of The Experiment

Simulations showed that the CSRZ DQPSK format has improved performance and better tolerance than CSRZ DPSK considering the Q-value. We have also shown that the effect of PMD is reduced for certain values and combinations of nonlinear affects. It is an interesting finding that the Q-surface is not uniform, rather there are windows with better and improved Q. The depths of such windows are more engraved and irregular in DPSK systems. We compared the PMD tolerance of single and multichannel (seven channels) systems and the graphical representations show that CSRZ DQPSK has better tolerance. The superiority of CSRZ DQPSK mainly comes from the fact that it is more efficient in utilizing the bandwidth. Results show that DQPSK modulation format can be used for data rates well beyond 40 Gb/s. It has shown better prospect in meeting the requirement of high bit transfer through optical communication networks. It is also seen that the nonlinearity helps in combating the effect of PMD. Further study is required to find out the reasons and remedies of deteriorated performances for certain combination of PMD and nonlinear coefficients.

CHAPTER 5

CONCLUSION

Transmissions in optical fiber communication systems are impaired and ultimately limited by chromatic dispersion, amplified spontaneous emission noise from amplifiers, polarization effects and fiber nonlinearities. For conventional direct-detection single-carrier systems, the impairment induced by a constant differential group-delay (DGD) scales with the square of the bit rate, resulting in drastic PMD degradation for high speed transmission systems. Polarization-mode dispersion (PMD) as well as the fiber nonlinearities has been considered as the ultimate barriers to high-speed optical transmission at and over 40 Gb/s. This scenario creates interest to look for the relationship between these two factors: PMD and nonlinearities.

Polarization mode dispersion is a form of modal dispersion where two different polarizations of light in a waveguide, which normally travel at the same speed, travel at different speeds due to random imperfections and asymmetries, causing random spreading of optical pulses. Unless it is compensated, which is difficult, this ultimately limits the rate at which data can be transmitted over a fiber. In an ideal optical fiber, the core has a perfectly circular cross-section. In this case, the fundamental mode has two orthogonal polarizations (orientations of the electric field) that travel at the same speed.

Polarization mode dispersion can have adverse effects on optical data transmission in fiber-optic links over long distances at very high data rates, because portions of the transmitted signals in different polarization modes will arrive at slightly different times. Due to random mode coupling, the calculation of PMD becomes very complicated.

The interaction between PMD and nonlinearity can be particularly complex. Sometimes, in combination with chirp, a system with both PMD and nonlinearity is less impaired than a system with the same amount of nonlinearity and no PMD. More often, the combination of PMD and nonlinearity can be harmful. Nonlinear polarization rotation can alter the polarization states of the bits, so that they vary from one bit to the next in a way that is difficult to predict. In this case, conventional PMD compensation becomes impossible.

For achieving the highest possible bit rates, particularly with older fibers and in long fiber-optic links, it can be necessary to compensate the polarization mode dispersion. This is not easy, however, because temperature changes can make the PMD effect time-dependent; it is therefore often necessary to apply an automatic feedback system.

In principle, the problem could be solved by using well-defined polarization states in polarization-maintaining fibers, but this approach is usually not practical. Another strategy can be to limit the capacity of each transmission channel, but using many different channels in a single fiber.

Optical communication systems have predominantly used some form of on/off keying (OOK) as a modulation format, namely NRZ or RZ modulation. As data rates increase, the inefficiency of these modulation formats from a bandwidth point of view is becoming more apparent. With data rates moving to 40 Gbps and beyond, dispersion in the fiber limits the distance over which the data can be transmitted. Other impairments such as polarization mode dispersion or PMD become significant at 40 Gbps. The narrower optical spectrum of multi-level formats such as QPSK and differential quad phase shift keying (DQPSK) therefore enables both a high spectral efficiency as well as the possibility to cascade multiple OADMs.

Multi-level modulation techniques allow for systems to transmit higher bits rates in densely spaced wavelength division multiplexed (WDM) channels. 40G DQPSK and 100G DP-QPSK are attractive solutions for long haul transmission with better tolerance to impairments such as Chromatic Dispersion and PMD, and higher spectral efficiency. The increased availability of components in the market is making this complex DQPSK solution possible.

At last in the experiment we analyzed the performance of two most efficient modulation formats in ultra high spectral efficient DWDM systems. For each of them, we optimized dispersion map. We used optimized parameters for a length of 100 km at 40 Gb/s. We studied the performance in a multi-span scenario.

We used carrier suppressed return to zero-differential phase shift keying (CSRZ-DPSK) and CSRZ-differential quadrature phase shift keying (CSRZ-DQPSK) to find out their comparative tolerance as polarization mode dispersion (PMD) compensator in the presence of fiber nonlinearities. Their performances are evaluated in terms of Q-factor surface diagram and contour map. We considered a dispersion compensated fiber using appropriate fiber sections. The transmitter section of CSRZ-DPSK system is composed of two Mach-Zehnder modulators (MZMs). The receiver uses asymmetric Mach-Zender demodulator and DPSK stages to detect the data. The electrical filter finally gives the received data.

CSRZ-DPSK and CSRZ-DQPSK systems show high suitability for ultra- high spectral efficient DWDM systems and high resilience to dispersion compensation tolerances and fiber nonlinearities. As the symbol rate is reduced, the spectral width is also significantly reduced. A DQPSK signal at bit rate B has the same spectral width as an OOK signal at bit rate B/2, for RZ waveforms. We have made an effort to quantify the effectiveness of CSRZ-DPSK and CSRZ-DQPSK in compensating PMD and also to find out their correlation. DQPSK has shown better PMD tolerance since it has the ability to double the spectral efficiency and relaxed dispersion management. We simulated single channel as well as multichannel optical fiber communication systems with varying parameters. The performances of the systems are evaluated with high as well as low PMD coefficients in the presence or absence of nonlinear effects. The performance of the systems will be evaluated mainly in terms of graphical representations.

Simulations showed that the CSRZ DQPSK format has improved performance and better tolerance than CSRZ DPSK considering the Q-value. We have also shown that the effect of PMD is reduced for certain values and combinations of nonlinear affects. It is an interesting finding that the Q-surface is not uniform, rather there are windows with better and improved Q. The depths of such windows are more engraved and irregular in DPSK systems. We compared the PMD tolerance of single and multichannel (seven channels) systems and the graphical representations show that CSRZ DQPSK has better tolerance. The superiority of CSRZ DQPSK mainly comes from the fact that it is more efficient in utilizing the bandwidth. Results show that DQPSK modulation format can be used for data rates well beyond 40 Gb/s. It has shown better prospect in meeting the requirement of high bit transfer through optical communication networks. It is also seen that the nonlinearity helps in combating the effect of PMD.

Further study is required to find out the reasons and remedies of deteriorated performances for certain combination of PMD and nonlinear coefficients.

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