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Title:

**Effect of Polarization Mode Dispersion on Pulse
Propagation in Optical Fiber Links**

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Dedication

First, we thank Allah, the Most Merciful, the Most Compassionate, and the Source of all wisdom and knowledge. With gratitude in our heart and humility in our words, we acknowledge that without your guidance and support, this achievement would not have been possible.

We also dedicate this work to our beloved parents, whose unwavering love, support, and sacrifices have been the cornerstone of my journey towards higher education and personal growth.

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Abstract

Polarization mode dispersion (PMD) remains one of the main sources for signal distortion in fiber optics to this day. This project focuses on studying the effects of PMD on optical signals using the Optisystem software.

To investigate the impact of the different orders of PMD, we isolated the first and second order effects by manipulating specific parameters in the PMD emulator. We tried different methods to mitigate the dispersion effects associated with first order PMD. Additionally, we explored the impact of second order PMD in the presence of PCD. Lastly, we evaluated the effects of PMD in a real-world fiber environment while employing compensation techniques for both chromatic dispersion and PMD.

The simulation results were analyzed using BER analyzers, oscilloscope visualizers and eye-diagrams. We have tested the PMD effects at three transmission bit rates (2.5 Gbps, 10 Gbps and 40 Gbps), while also varying different PMD emulator parameters (DGD, polarization rate, length, dispersion and attenuation). We have found that the first order PMD can cause detrimental pulse splitting of the signal, but it can be almost completely negated by either the PST or optical delay compensation method. As for second order effects, it can cause serious degradation of the signal at high bit rates, especially when paired with PCD. Finally, we have seen how CD and attenuation cause serious degradation to the signal. Using the FBG method alongside the PST method to compensate for PMD, CD and PCD gave satisfying outcomes resulting in a low BER signal and a high Quality factor. These obtained results were presented as tables, figures and graphs.

List of Acronyms

APD: Avalanche Photodiode.

BER: Bit Error Rate.

CD: Chromatic Dispersion.

CW: Continuous Wave.

DGD: Differential Group Delay.

DCF: dispersion compensating fiber.

EM: Electromagnetic.

LED: Light Emitting Diode.

LEP: Left Elliptical Polarization

LCP: Left Circular Polarization.

LiNb: LithiumNiobate.

MZM: Mach Zehnder Modulator.

NRZ: Non-Return to Zero.

PD: Photo Detector.

PCD: Polarization Chromatic Dispersion

PMD: Polarization Mode Dispersion.

PSP: Principal State of Polarization.

PST: Principle State Transmission

REP: Right Elliptical Polarization.

RCP: Right Circular Polarization.

RI: Refractive index.

RZ: Return to Zero.

SNR: Signal to Noise Ratio.

SOP: State of Polarization.

SOPMD: Second-order polarization mode dispersion

TCO: total cost of ownership.

TIR: Total Internal Reflection.

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INTRODUCTION

Introduction:

Communication systems are fundamental to human interaction, enabling the exchange of information, ideas, and emotions across various media. From the earliest forms of verbal communication to modern digital networks, the development of communication systems has played an important role in shaping societies and connecting people across distances.

The optical fiber communication system is a major step in this development. It is a technology that involves converting electrical signals into light signals and transmitting them through thin and flexible strands of glass or plastic fibers. Data is transmitted in the form of light pulses, which carry vast amounts of information and travel at incredible speeds, making fiber optics the preferred choice for long-distance communication.

With the evolution of the optical communication system, engineers have started facing multiple problems as the distances and speeds of transmission have increased, mainly the problems of attenuation and dispersion. Dispersion refers to the spreading of light pulses as they propagate through an optical fiber, leading to distortion and degradation of the transmitted signal.

Nowadays, researchers have successfully addressed most of the challenges related to attenuation and dispersion in optical fiber communication systems. However, with higher speeds of transmission, polarization mode dispersion remains a persistent challenge. This thesis will focus on polarization mode dispersion and its effects on the propagation of waves in optical fiber. The following chapters will outline the progression of this project:

Chapter 1: An overview of the optical fiber communication system and its characteristics, as well as the different types of dispersion.

Chapter 2: This chapter will focus on the different states of polarization and how they are represented in space, along with providing a detailed description of polarization mode dispersion.

Chapter 3: This chapter will simulate polarization mode dispersion in different situations and parameters using the OptiSystem software.

Chapter 4: A concluding chapter that summarizes the previous work and provides suggestions for future research."

Chapter 1

Optical Communication System

INTRODUCTION:

Communication systems transmit information from one place to another, whether separated by a few kilometers or transoceanic distances.

Fiber optic communication systems are a type of communication system that use optical fibers to transmit information over long distances. The system works by converting electrical signals into optical signals that are transmitted through the optical fibers. At the receiving end, the optical signals are converted back into electrical signals for processing and decoding.

Optical communication dates back to the 1800s when people used smoke signals and mirrors to transmit single pieces of information. However, the first practical and useful type of optical communication system is a system called fiber guidance, patented in 1930 by L. Baird and C. W. Hansell. They scanned and transmitted television images via uncoated fiber cables. The early practical application of optical fibers came in the 1970s with the development of fiber optic communication systems for transmitting telephone signals. In the following decades, advancements in fiber optic technology allowed for the transmission of higher data rates over longer distances with minimal losses. Today, optical fibers are widely used in a variety of applications, including telecommunications, internet and data communication, cable television, and scientific research. [1].

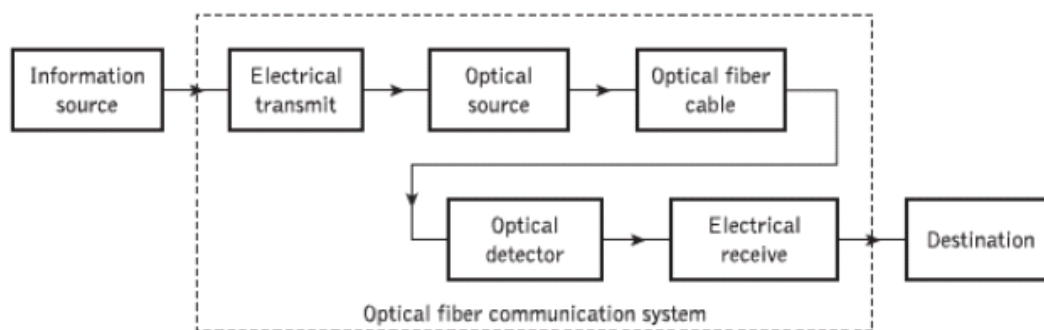


Figure 1: Optical fiber communication system

1.1 Optical transmitters:

An optical transmitter is an electronic device that converts electrical signals into modulated optical signals for transmission over optical fiber. The electrical signal to be transmitted is first converted into a digital signal, which is then fed into the optical transmitter. The transmitter converts the digital signal into an optical signal by modulating the output of the light source (laser diode or LED) with the digital signal. The modulated optical signal is then coupled into the optical fiber, where it propagates through the fiber until it reaches the receiver at the other end of the link.

The optical transmitter consists of the following components:

- Optical source
- Electrical pulse generator
- Optical modulator

1.1.1 Optical source:

An optical source refers to the device that produces and launches light into an optical fiber. The most commonly used optical sources are laser diodes and light-emitting diodes (LEDs), which emit light at specific wavelengths in the infrared region. Laser diodes offer higher output power and narrower spectral line width than LEDs, making them suitable for high-speed and long-distance communication. LEDs, on the other hand, are less expensive and have a broader spectral bandwidth, making them suitable for short-distance and low-cost application [2].

1.1.2 Electrical pulse generator:

An electrical pulse generator is a device that converts an analog signal to a digital signal in the form of short electrical pulses. There are several types of generators, which can produce many shapes of electrical signals. A very commonly used pulse generator in fiber telecommunication is the Non-return to zero pulse generator (NRZ)

NRZ is a pulse generator in which the binary low and high states, represented by numerals 0 and 1, are transmitted by specific and constant DC (direct-current) voltage. In positive-logic NRZ, the

low state is represented by the more negative or less positive voltage, and the high state is represented by the less negative or more positive voltage [3].

1.1.3 Optical modulator:

An optical modulator is a device that uses electrical signals to vary the amplitude, phase or polarization of an input optical signal. Resulting in a modulated optical signal that carries the information to be transmitted.

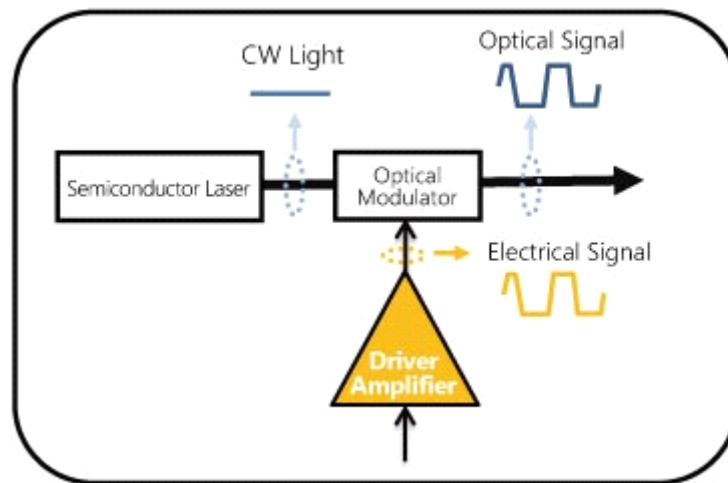


Figure 1.1.3(a): Optical modulator

A very popular optical modulator used in optical telecommunication systems is the Mach-Zehnder-modulator(MZM). The MZM is an electro-optic device with interferometric structure. It consists of two modulator arms and an input and output central waveguides. When an input optical signal enters the MZM it is split into the upper and lower arms. Applying voltage to one of those arms can cause the signal to travel at a different velocity than the signal at the other arm, which can cause a change in the amplitude of the resulting wave at the output waveguide. However applying equal voltage to both arms can cause a phase modulation at the output [1].

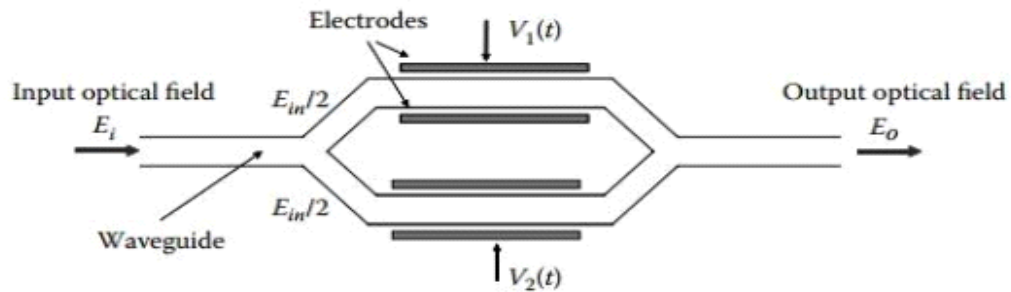


Figure 1.1.3(b): Mach Zehnder Modulator

There are two main types of MZMs: semiconductor MZMs and LithiumNiobate(LiNb) MZMs. One key difference between the two is the bandwidth. LiNb MZMs generally have a wider bandwidth than semiconductor MZMs, making them suitable for high-speed optical communication systems. Another difference is the power consumption; LiNb MZMs typically require higher voltages and consume more power than semiconductor MZMs.

1.2 Optical fibers:

Optical fiber is a type of cable used to transmit digital information over long distances through the use of light pulses that propagate along a glass or a plastic fiber. Optical fiber cables typically consist of several layers that provide different functions [4].

- Core: This is the cylindrical area in which the light rays propagate. It typically has a diameter of 8 to 10 microns for single-mode fibers and 50 to 62.5 microns for multimode fibers.
- Cladding: The layer that surrounds the glass fiber core. Its function is to provide a lower refractive index at the core interface in order to cause reflection within the core so that light waves are transmitted through the fiber.
- Coating: The coating is a protective layer that surrounds the cladding and provides protection to the fiber. It is typically made of a polymer material and is applied in a process called "buffering."

- **Strength member:** They are typically made from aramid fibers or fiberglass. They provide temperature stability and extra protection against bending or stretching due to the strong materials they are made from.
- **Outer jacket:** the outermost layer of the fiber, it is the first line of moisture, mechanical, flame and chemical defense.

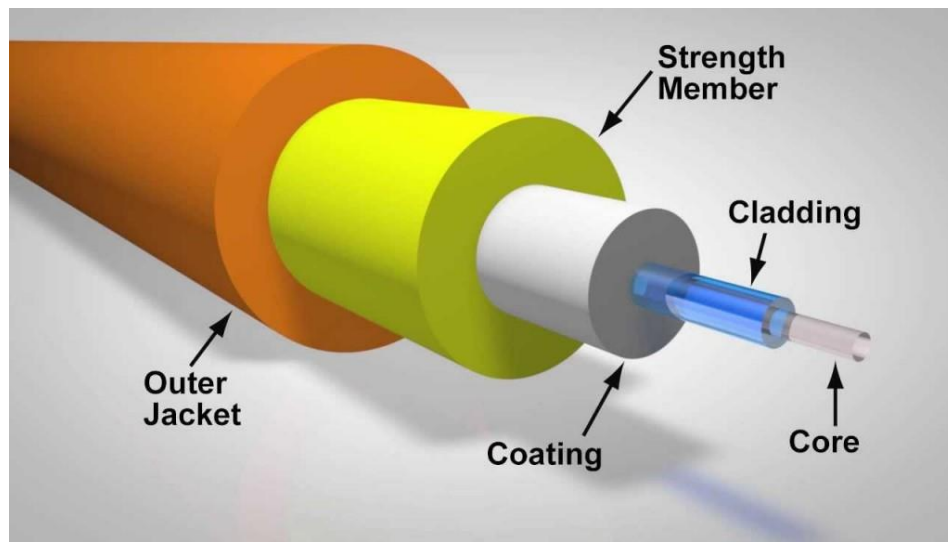


Figure 1.2: Optical fiber cable layers.

1.2.1 Wave propagation:

• **Refractive index:** the refractive index n of a medium is simply the ratio of the velocity of light in a vacuum over the velocity of light in the medium v . It depends on many factors such as temperature, wavelength and pressure

$$n = \frac{c}{v} \quad (1.1)$$

• **Ray theory:** When a ray is incident on the interface between two dielectrics of different refractive indices n_1 and n_2 refraction occurs. Snell's law of refraction states that:

$$n_1 \cdot \sin(\varphi_i) = n_2 \cdot \sin(\varphi_r) \quad (1.2)$$

Where φ_i is incident angle and φ_r is the refraction angle with respect to the normal line [5].

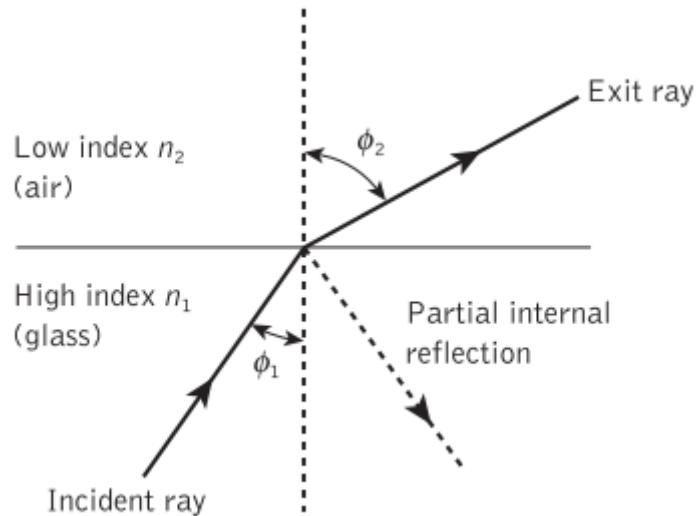


Figure 1.2.1(a): refraction

- **Total internal reflection:** When the angle of refraction is 90° , the refracted ray emerges parallel to the interface between the dielectrics, and the angle of incidence is now known as the critical angle ϕ_c . When the incident angle is greater than the critical angle the light is totally reflected, this is known as the total internal reflection (TIR) [5].

$$\phi_c = \sin^{-1} \frac{n_2}{n_1} \quad (1.3)$$

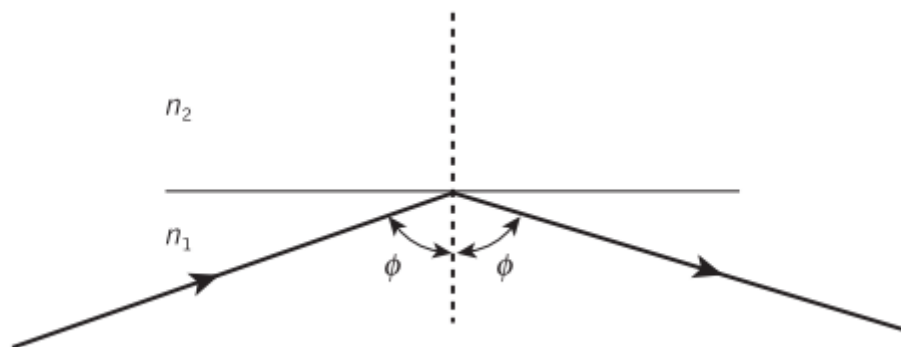


Figure 1.2.1 (b): Total Internal Reflection (TIR)

The fiber consists of a core made of a material with a high refractive index, surrounded by a cladding made of a material with a lower refractive index. The incoming light ray is incident on the core-cladding boundary at an angle greater than the critical angle, causing it to undergo total internal reflection and remain within the core.

1.2.2 Modes in fiber:

A guided mode can be described as a singular light ray that is totally internally reflected. An optical fiber can support multiple guided modes if the core diameter is large enough, or if the index difference between the cladding and core is sizeable. Each mode is identified by its speed of propagation along the fiber's main axis and its field distribution (energy) in the fiber's core. We can determine the number of guided modes the fiber can handle by calculating the normalized frequency V [1].

$$V = \frac{2\pi}{\lambda} a \cdot n_1 (2\Delta)^{\frac{1}{2}} \quad (1.4)$$

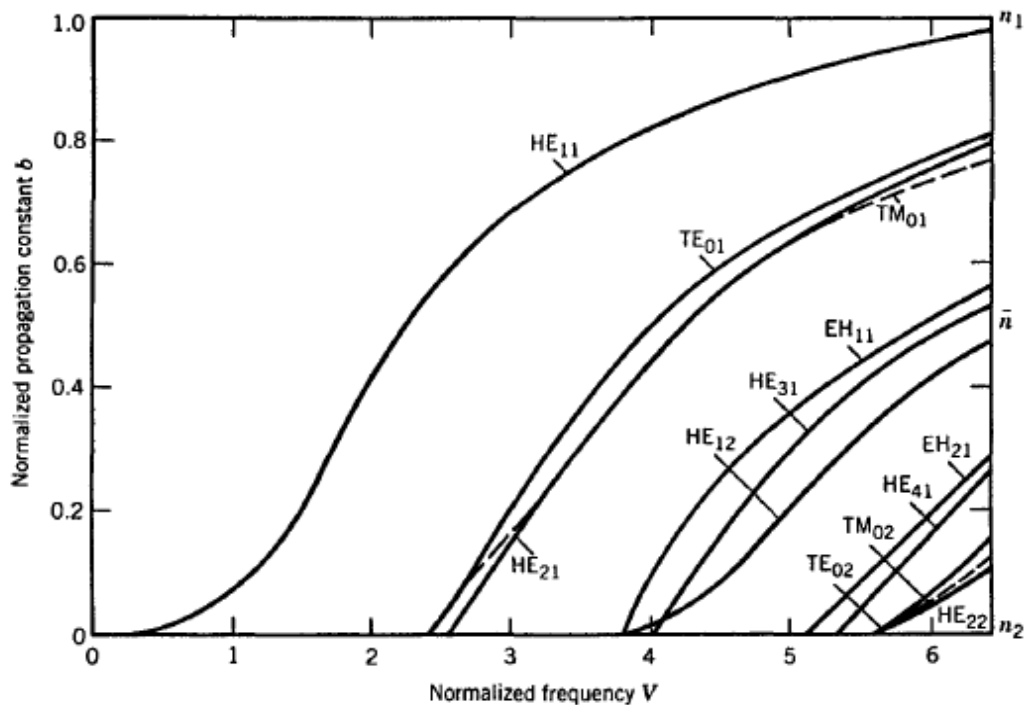


Figure 1.2.2: Normalized propagation constant b as a function of normalized frequency V for a few low-order fiber modes.

We can see that different modes have a different cutoff frequencies V_c but The first mode HE_{11} is always present. Based off the above figure we can distinguish two types of mode operation in the fiber.

a) Single mode fiber:

Single-mode fibers have a small core diameter, typically 9 microns, and allow only one mode of light to propagate through the fiber. This results in a very narrow beam of light with little dispersion, making single-mode fibers ideal for long-distance transmission of data at high speeds.

Single mode operation occurs when the normalized frequency of the fiber is less than the cutoff frequency of the second mode (TE_{01}).

For a step-index fiber, the normalized cutoff frequency value is $V_c = 2.405$, and for the graded-index fiber

$$V_c = 2.405 \sqrt{1 + \frac{2}{\alpha}} \quad (1.5)$$

Where α is the profile parameter of the fiber [1]

b) Multi-mode fiber:

Multimode fibers, on the other hand, have a larger core diameter, typically 50 or 62.5 microns, and can support multiple modes of light to propagate through the fiber. This results in a wider beam of light with more dispersion, which limits the distance and speed at which data can be transmitted.

The number of guided modes (M) that propagate through the fiber can be determined:

- For step-index fiber:
$$M_s = \frac{V^2}{2} \quad (1.6)$$

- For graded-index fiber:
$$M_g = \left(\frac{\alpha}{\alpha+2}\right) \frac{V^2}{2} \quad (1.7)$$

1.2.3 Step index and graded index fiber:

There are two types of optical fibers: Step-index and graded-index fiber. The key difference between them is the way the refractive index is distributed along the core of the fiber.

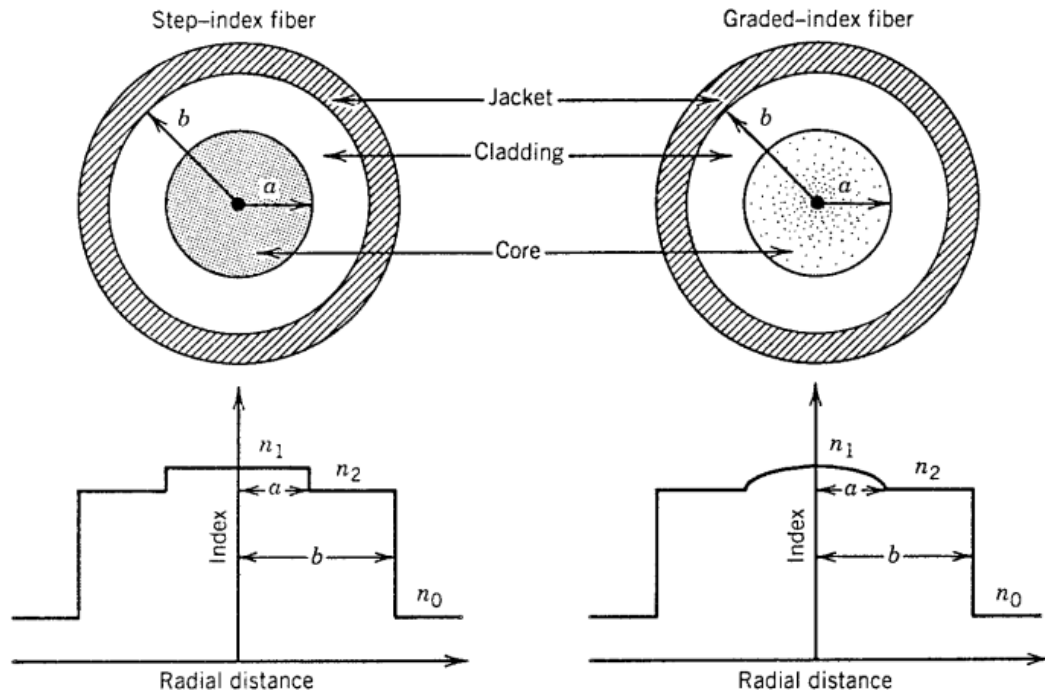


Figure 1.2.3: Cross section and refractive-index profile for step-index and graded-index fibers

1.2.3.1 Step-index fiber:

The step-index fiber has a core of constant refractive index n_1 and a cladding with slightly lower refractive index n_2 . This sudden change in refractive index is why it is called step-index. The light rays keep bouncing back and forth off the boundary between the core and cladding with an angle less than the critical one, which ensures total internal reflection [6].

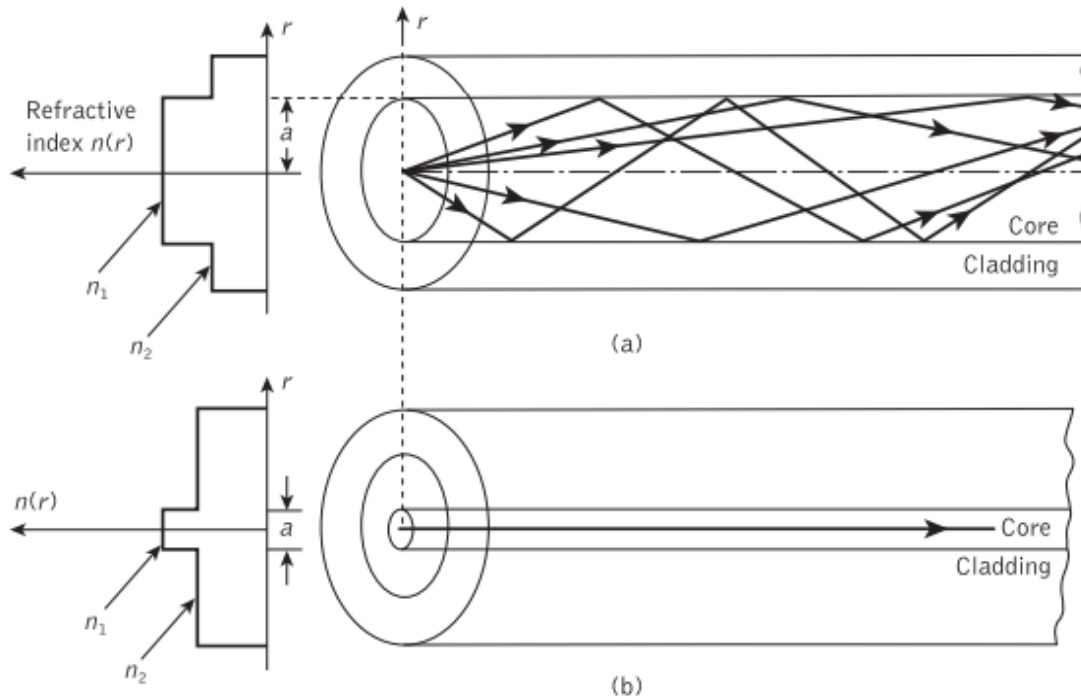


Figure 1.2.3.1: The refractive index profile and ray transmission in step index fibers: (a) multimode step index fiber; (b) single-mode step index fiber

1.2.3.2 Graded-index fiber:

The graded-index fiber has a core with a refractive index that gradually decreases with distance from the maximum value at the core axis, while the refractive index of the cladding remains constant. This index profile means that the light rays travel faster the farther away they are from the axis, which compensates for the longer path they have to travel compared to modes that travel along the core axis [1].

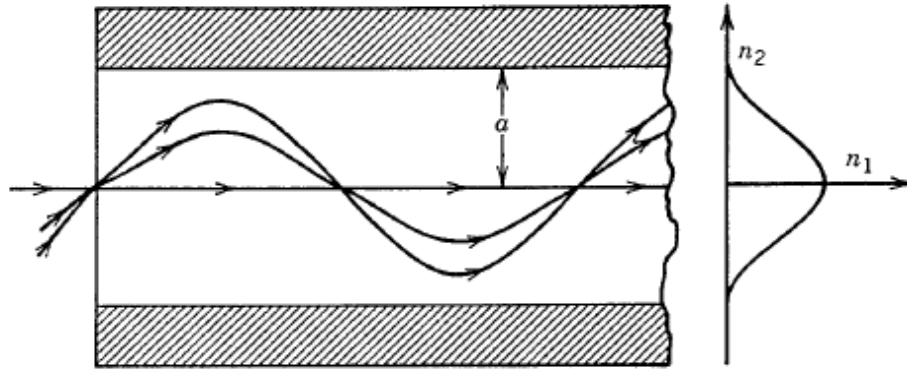


Figure 1.2.3.2: The refractive index profile and ray propagation in multimode graded-index fiber.

The light rays in figure 1.2.3.2 appear to follow curved paths through the fiber core. This is due to the gradual decrease of the refractive index, which creates many refractions. Each one of these refractions causes the rays to bend slightly towards the core axis, which ultimately give the light rays a wave-like shape.

1.2.4 Optical fiber advantages:

Optical fiber offers numerous advantages over copper wire. Firstly, it provides higher bandwidth, enabling high-speed data transmission over long distances. Unlike copper wire, optical fiber experiences minimal signal degradation due to its lower attenuation, eliminating the need for signal boosters during long-distance transmission. Additionally, while fiber optic cables may have a higher initial cost, their total cost of ownership is significantly lower. They require fewer repairs and replacements and entail less maintenance compared to other cable types. Moreover, as technology advances, the costs associated with fiber optic cables and related components continue to decrease. Optical fibers also boast a longer life cycle, lasting for over 100 years. Their thin and flexible nature allows for easier installation and routing, as they can be drawn to smaller diameters than copper wire. Furthermore, optical fiber is highly durable, withstanding more pull pressure and being less prone to damage and breakage. Its immunity to electromagnetic interference makes it particularly well suited for environments where such interference is common. In summary, optical fiber's advantages encompass higher bandwidth, minimal signal degradation, cost-effectiveness, longevity, ease of installation, flexibility,

durability, and immunity to electromagnetic interference [7].

1.2.5 Optical fiber disadvantages:

Despite its numerous advantages, optical fiber does have some disadvantages. Firstly, optical fiber is more fragile and susceptible to damage when compared to copper wires. This fragility makes splicing optical fiber more challenging than splicing copper wire, which in turn can make repairs and maintenance more difficult. Secondly, although optical fiber has lower attenuation than copper wire, it is still subject to signal loss over long distances. In such cases, the use of signal boosters, repeaters, or amplifiers might be necessary to maintain signal integrity. Lastly, optical fiber requires a power source to operate, which can limit its suitability for certain remote or low-power applications where power sources may be limited or unavailable. It's important to consider these disadvantages alongside the benefits when deciding on the appropriate use of optical fiber[8].

1.3 Optical Receiver:

An optical receiver is placed at the end of the optical fiber and is mainly used to detect the light signal transmitted through the optical fiber and convert it into an electrical signal that can be processed by electronic circuits. The receiver consists of a photo detector (PD) that converts the optical signal into an electrical current, a preamplifier that amplifies the electrical signal, and a post-amplifier that further amplifies and filters the signal.

The most common type of photodetector is the photodiode, which is a semiconductor device that converts light into electrical current based on the principle of the photoelectric effect, in which photons of light striking a material cause the emission of electrons [5].

Most common types of photodiodes are:

- PN photodiode: It consists of a p-type and an n-type semiconductor material that are joined together to form a PN junction. When light strikes the depletion region of the junction, it generates an electric current that can be measured and amplified.
- PIN photodiode: The difference between a PIN photodiode and the PN photodiode is the

intrinsic layer in the middle of the diode for which the PIN photodiode has a wider depletion region, which makes it more sensitive to longer wavelengths of light.

- Avalanche Photodiode (APD): APDs are photodiodes with internal gain produced by the application of a reverse voltage. They have a higher signal-to-noise ratio (SNR) than PIN photodiodes, as well as fast time response [6]

1.4 Transmission characteristics of the optical fiber

1.4.1 Attenuation:

Attenuation is the reduction of the strength of the light signal propagating through the fiber. It is often expressed in decibels (dB) per unit length, also known as the attenuation coefficient α .

$$\alpha = \frac{10}{L} \log_{10} \left(\frac{P_{in}}{P_{out}} \right) \quad (1.8)$$

Attenuation is a critical parameter in fiber optics because it determines the maximum distance over which a signal can be transmitted and still be reliably detected by the optical receiver. Latest developments in the fabrication of fiber cables have reduced the attenuation to 0.2dB/km.

Fiber losses heavily depend on the wavelength of the propagating light. We can see from figure 1.4.1 that the ideal wavelength for minimal attenuation is around 1550nm [9].

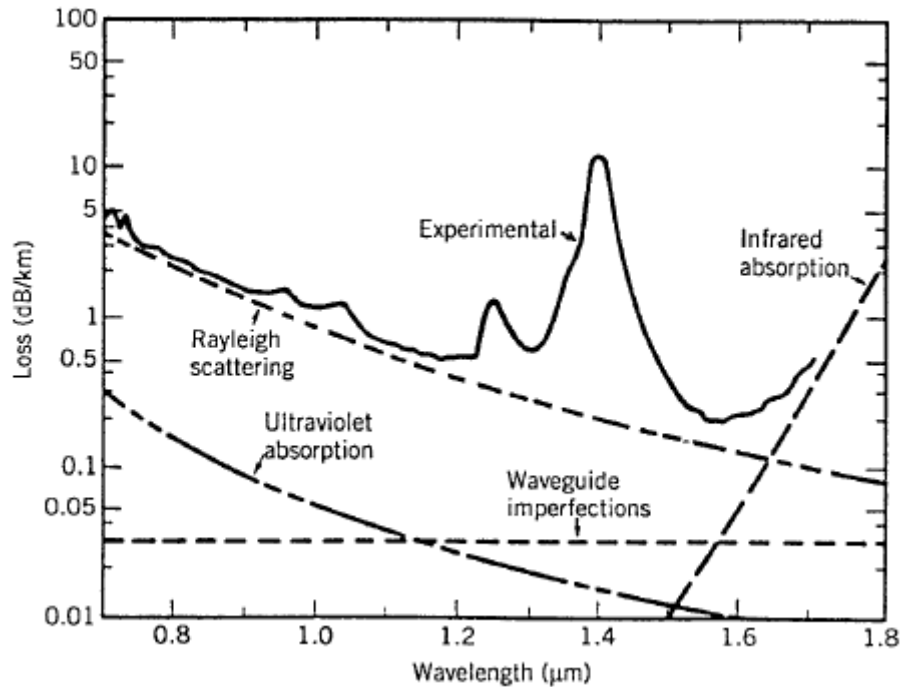


Figure 1.4.1: Loss spectrum of a single-mode fiber produced in 1979. Wavelength dependence of several fundamental loss mechanisms is also shown.

Attenuation in fiber cables can be attributed to three primary mechanisms: absorption, scattering, and bending.

1.4.1.1 Material absorption:

Material absorption is a loss mechanism related to the material composition and the fabrication process for the fiber. As all materials in nature absorb light at a certain wavelength, it occurs when the energy of the light waves is transferred to the electrons within the fiber material, causing them to transition to higher energy states. Which results in the dissipation of the light energy as heat in the fiber. We can distinguish two types of material absorption.

a) Intrinsic material absorption:

Intrinsic material absorption occurs when the light energy is absorbed by one of the main materials used to fabricate fibers. Silica glass has a high absorption rate in the infrared and ultraviolet regions of the wavelength spectrum, which leaves a window of $1.3\mu\text{m} - 1.6\mu\text{m}$ that is

commonly used in fiber communication systems, where the attenuation due to absorption is less than 0.03 dB/km [10].

b) Extrinsic material absorption:

Extrinsic material absorption occurs due to impurities in the fiberglass. Different impurities can effect light transmission at different wavelengths. Some of the most common ones are shown in the table below. [1]

Table 1.4.1.1: Absorption losses caused by some of the more common metallic ion impurities in glasses, together with the absorption peak wavelength

	<i>Peak wavelength (nm)</i>	<i>One part in 10⁹ (dB km⁻¹)</i>
Cr ³⁺	625	1.6
C ²⁺	685	0.1
Cu ²⁺	850	1.1
Fe ²⁺	1100	0.68
Fe ³⁺	400	0.15
Ni ²⁺	650	0.1
Mn ³⁺	460	0.2
V ⁴⁺	725	2.7

The main source of extrinsic absorption however is the presence of residual water vapors in silica. These hydroxyl groups and OH ion cause the three peaks seen in figure1.6.1 at 1.39, 1.24 and 0.95µm wavelengths.

Material absorption can be reduced by using high quality fiber materials. ‘Dry fiber’ can also reduce the OH concentration to insignificant levels, which almost removes the 1.39µm peak entirely.

1.4.1.2 Scattering:

Scattering losses are caused by the interaction of light with density fluctuations within a fiber. Scattering losses is the reflection of small amounts of light in all directions as it travels down the fiber. Some of this light escapes out of the core, while some travels back toward the source. Some scattering is caused by miniscule variations in the composition and density of the optical glass material itself. [6]

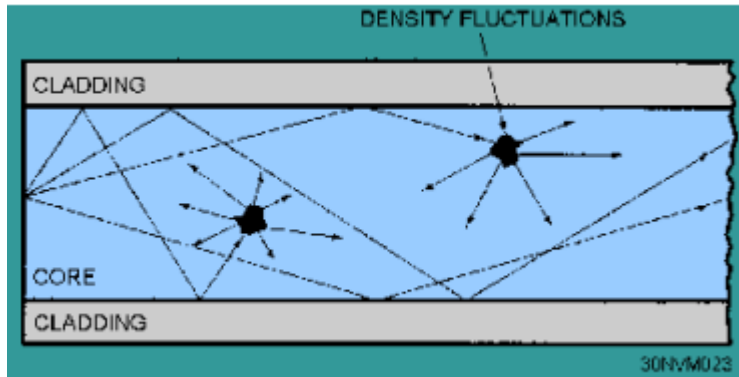


Figure1.4.1.2: light scattering

There are two main types of scattering in fiber: Rayleigh scattering and Mie scattering.

a) Rayleigh scattering

Rayleigh scattering is the dominant scattering mechanism in optical fiber. It is caused by Silica molecules moving randomly during the molten state and then freezing in place during fiber fabrication. This causes local microscopic fluctuations in density which lead to random fluctuations of the refractive index on a scale smaller than the optical wavelength.[7]

The Rayleigh scattering coefficient can be given by

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F \quad (1.9)$$

Where λ is the optical wavelength, n is the refractive index of the medium, p is the average photoelastic coefficient, β_c is the isothermal compressibility at a fictive temperature T_F , and K is Boltzmann's constant.

b) Mie scattering

Mie scattering occurs at index inhomogeneities that are comparable in size or longer than the guided wavelength. These inhomogeneities are caused by waveguide imperfections such as random core-radius variation, and non-perfect cylindrical core structure. Mie scattering can be a significant source of attenuation in fiber optic systems especially in longer wavelengths.

1.4.1.3 Bending:

When a fiber bends, the incidence angles of beams at the core-cladding boundary change, which causes some rays to be emitted from the fiber. Because the angle of incidence drops at the spots with a sufficiently small curvature radius and the criterion of total reflection is not met, a bent fiber causes emittance losses and increases attenuation. We can distinguish two types of bending losses based on the bend radius of curvature: macro bending and micro bending.[11]

a) Macro bending

Macro bends are large scale curvatures of the fiber that create angles that are too sharp for the light rays incident on them to be reflected back into the core. They can be caused by improper handling or installation of the fiber, such as excessive bending or twisting.

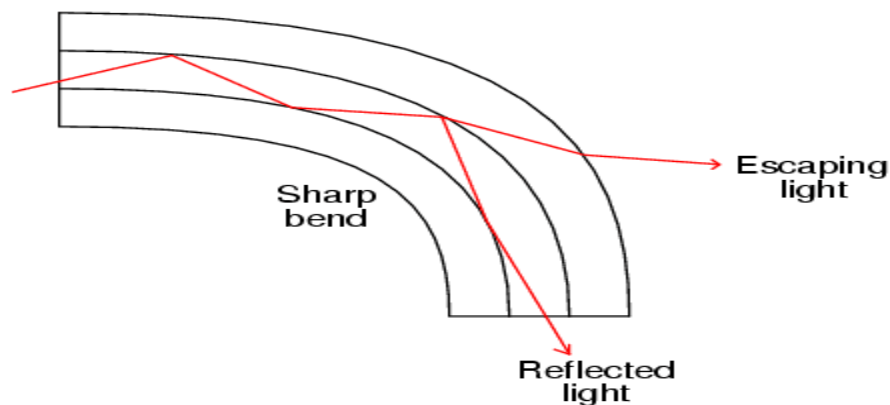


Figure1.4.1.3.a: Macrobend loss

b) Micro bending

Micro bends are bends in the fiber cable that are too small to be seen by the naked eye. They can be caused by small discontinuities or imperfections in the fiber, and when the cable is pressed against a surface that is not perfectly smooth[8]. Microbend loss increases attenuation because low-order modes become coupled with high-order modes that are naturally lossy. To minimize these losses in single mode fiber, we choose the V parameter to be as close to 2.405 as possible so that mode energy is confined primarily to the core.

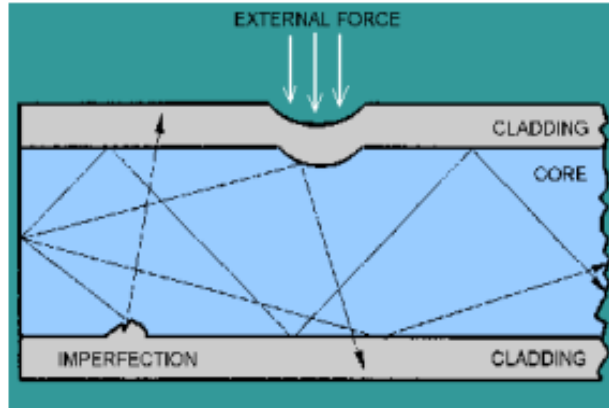


Figure 1.4.1.3.b: Microbend loss

1.4.2 Dispersion

Dispersion in an optical fiber is the spreading of light pulses when the wave travels through an optical fiber from one end to another, it is a critical factor limiting the quality of signal transmission over optical links by causing pulse broadening and increasing the bit error. In general, dispersion is a consequence of the physical properties of the transmission medium, yet different types of dispersion have different specific causes [12]

1.4.2.1 Chromatic dispersion

This type of dispersion occurs because different wavelengths of light travel at slightly different speeds through the fiber. As a result, the different wavelengths of a light pulse can become separated or spread out as they travel, causing distortion of the signal [1].

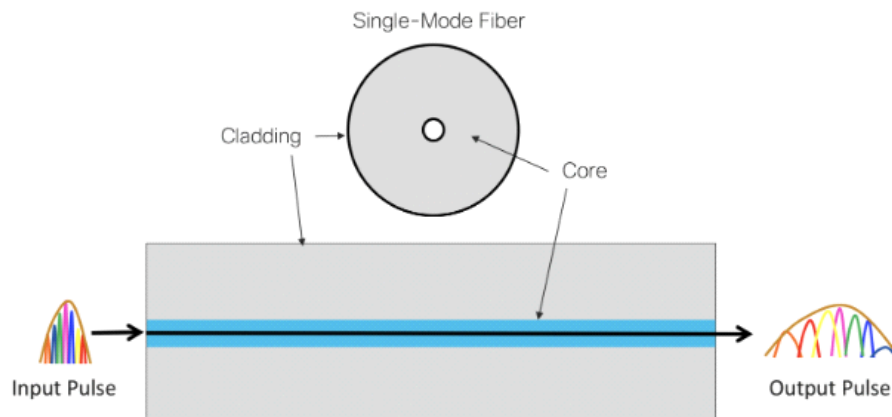


Figure 1.4.2.1: Chromatic dispersion

Two types of chromatic dispersion occur in optical fibers:

a) Material dispersion

This type of chromatic dispersion is caused by the variation in the refractive index of the fiber material with wavelength. Since different wavelengths travel at different speeds through the fiber, material dispersion can cause the different components of an optical pulse to spread out over time [13].

b) Waveguide dispersion

This type of chromatic dispersion is caused by the variation in the effective refractive index of the fiber core with wavelength. The core of a fiber acts like a waveguide, confining the light to a small region. While short wavelength lights are well confined in the core, longer wavelength lights are spread into the cladding, which cause the two wavelengths to travel at slightly different speeds through the core, causing waveguide dispersion [12].

1.4.2.2 Chromatic dispersion compensation

Chromatic and waveguide dispersion have opposite signs since one of them causes the longer wavelengths to travel faster than the short ones (Normal dispersion regime), while the other one causes shorter wavelengths to travel faster than the long ones (Anomalous dispersion regime). So they tend to counteract one another. We can see from the figure below that they cancel out around 1310nm.

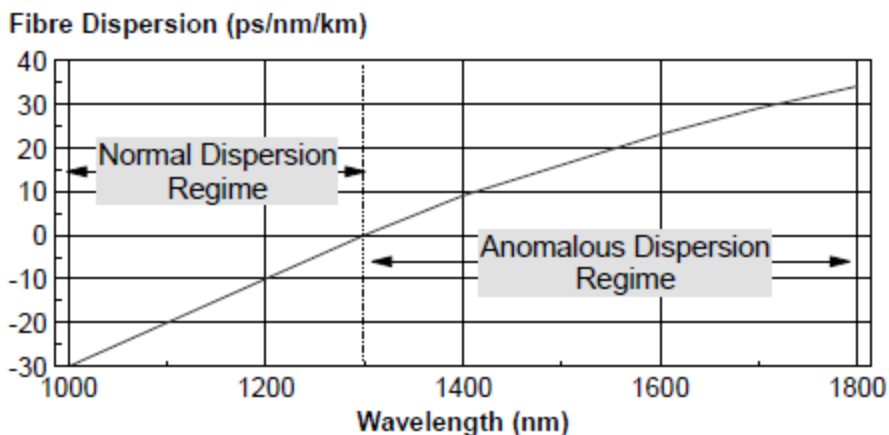


Figure 1.4.2.2: Dispersion of "Standard" Single-Mode Fibre

The 1310nm wavelength is widely used in optical telecommunication system. However, it is also useful to use the 1550nm wavelength since it provides the lowest attenuation out of any wavelengths. As seen in the above figure, at 1550nm the dispersion reaches 20ps/nm/km, which is simply unacceptable. This is why many efforts have been made to reduce and mitigate the dispersion levels at 1550nm. Some of the techniques used are:

a) Dispersion shifted fiber

Dispersion shifted and dispersion flattened fibers have their core profile created in such a way to introduce dispersion in the opposite direction (with the opposite sign) from the direction in which chromatic dispersion operates.

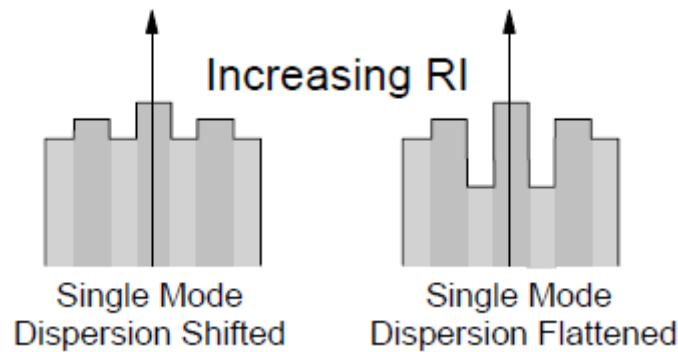


Figure 1.4.2.2a: Core profiles of Dispersion Shifted and Dispersion Flattened Fibre (RI = refractive index)

b) Dispersion compensating fiber

In many countries now, fibers operating at 1310nm wavelengths have already been installed and used [10]. As the need for 1550nm fibers grew, a solution was needed to upgrade those fibers without the huge cost of removing them and installing new ones. Simply increasing the transmission capacity by operating these fibers at 1550nm would result in significant positive dispersion. As such, new dispersion compensating fibers (DCF) have been developed. These fibers have huge negative dispersion which when added to the already existing fibers can compensate for their positive dispersion. Resulting in a zero dispersion fiber. Due to the huge negative dispersion that DCF have, only a few hundred meters of cable are needed to compensate for dispersion over tens of kilometers of the fiber in the link [14].

1.4.2.3 Modal dispersion

This type of dispersion occurs in multimode fibers where the different modes enter the fiber and reflect off the cladding wall at different angles, traveling in different paths within the fiber, each with a slightly different length. As a result, the different modes of a light pulse can arrive at the end of the fiber at slightly different times, because they exit the fiber at different times, the optical pulses broaden [15].

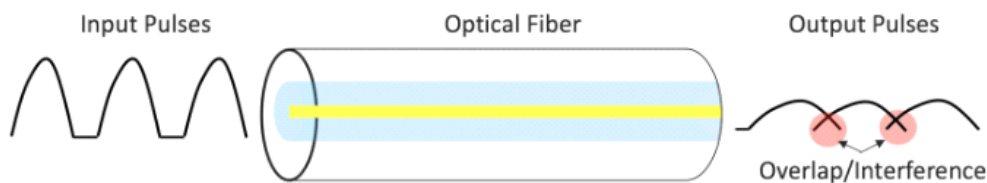


Figure 1.4.2.3 : Modal dispersion

1.4.2.4 Polarization mode dispersion(PMD):

Light is an electromagnetic wave composed of a traveling electric and magnetic field. Single-mode fiber supports one propagation mode, which in turn is comprised of two orthogonal polarization modes, or states. If traveling through a perfectly cylindrical optical fiber, both polarization states would travel at exactly the same speed. However, in the real world there are stresses and manufacturing flaws in the optical fiber causing it to be non-cylindrical. These asymmetrical variations introduce small refractive index variations between the two states. Although each variation by itself is minuscule, the accumulation over tens of kilometers of fiber causes the polarization states to travel at noticeably different speeds. This type of dispersion will be discussed further more in the following chapters, as it will be the main topic of this thesis [5].

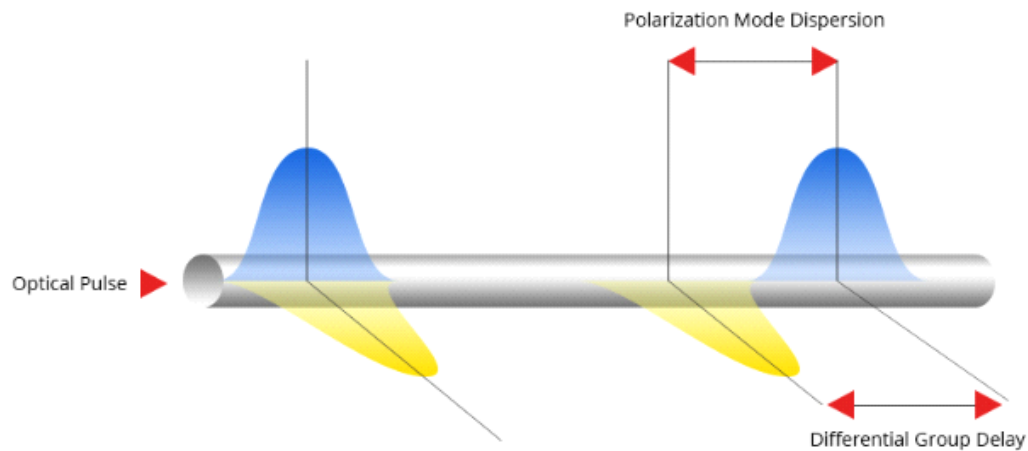


Figure 1.4.2.4 : polarization mode dispersion

Conclusion :

Over the past few decades, significant advancements have been made in the field of optical fiber communication systems. These systems are comprised of three essential components: the optical transmitter, the optical fiber itself, and the optical receiver. In the transmitter, data is initially generated as brief electrical pulses, which are then transformed into an optical signal carrying the information. This optical signal travels through the optical fiber and is ultimately converted back into an electrical signal by the receiver. However, during this transmission process, the received information can sometimes be incorrectly decoded due to certain characteristics of the optical fiber, namely attenuation and dispersion.

Attenuation refers to the loss of strength experienced by the optical signal within the fiber. This loss occurs due to three main mechanisms: absorption, scattering, and bending. The wavelength that offers the least attenuation is approximately 1550nm, and this wavelength is typically used in simulations and practical applications. On the other hand, dispersion refers to the phenomenon where light pulses spread out as they travel from one end of the optical fiber to the other. There are three types of dispersion: chromatic dispersion, modal dispersion, and polarization mode dispersion. Chromatic dispersion arises because different wavelengths of light travel at varying speeds. Modal dispersion occurs in multimode fiber when different modes of light travel at different velocities. Lastly, polarization mode dispersion emerges because the two orthogonal

modes of the electromagnetic wave travel at different speeds. A more detailed discussion of polarization mode dispersion will be provided in the subsequent chapter.

Chapter 2

Polarization Mode Dispersion

Introduction:

As the bit rates and distance continue to increase, polarization mode dispersion (PMD) has emerged as a key factor limiting high-speed transmission in optical fiber links. PMD is caused by the birefringence of optical fiber and the random variation of its orientation along the fiber length. The existence of this birefringence in the fiber implies that the fiber supports two orthogonally polarized modes that have different effective indices and hence propagate with different group velocities in the fiber. The two modes thus reach the output end of the fiber at slightly different times and with different phases. The superimposition of these two modes leads to the generation of pulse broadening. With the bit rates increasing it becomes more likely that the input pulses cannot be perceived correctly at the output end [5].

2.1 Polarization:

The polarization of light represents the oscillation direction of the electric field vector of the light waves as they propagate through a medium. If the electric field varies randomly with time, then the wave is said to be unpolarized, while if it varies in a predictable manner, the wave is said to be polarized. The nature of variation of the electric field of a polarized light with time defines the state of polarization (SOP) of the electromagnetic (EM) wave. The SOP refers to the shape that the propagation of the electric field vector makes on the plane that is perpendicular to the direction of propagation [16].

2.1.1 State of polarization:

The three types of polarization state that a polarized wave may take are linear, circular, and elliptical.

a) Linear polarization:

An electromagnetic wave is said to be linearly polarized if the electric field vector changes in a line on the plane of propagation. Linear polarization is the easiest of the three to describe mathematically. In general, when the electric field vector make an angle θ with the x-axis, we can describe the electromagnetic wave as the superposition of two orthogonal and linearly polarized components along the x and y axes.

$$E_x = A \cdot \cos\theta \cdot \cos(\omega t - kz + \phi).$$

$$E_y = A \cdot \sin\theta \cdot \cos(\omega t - kz + \phi). \quad (2.1)$$

Where A is the amplitude of the wave, ω is the angular frequency, ϕ is the initial phase, and $k = (2\pi / \lambda_0) n$, with n being the refractive index of the medium, λ_0 the free space wavelength, and z the direction of propagation.

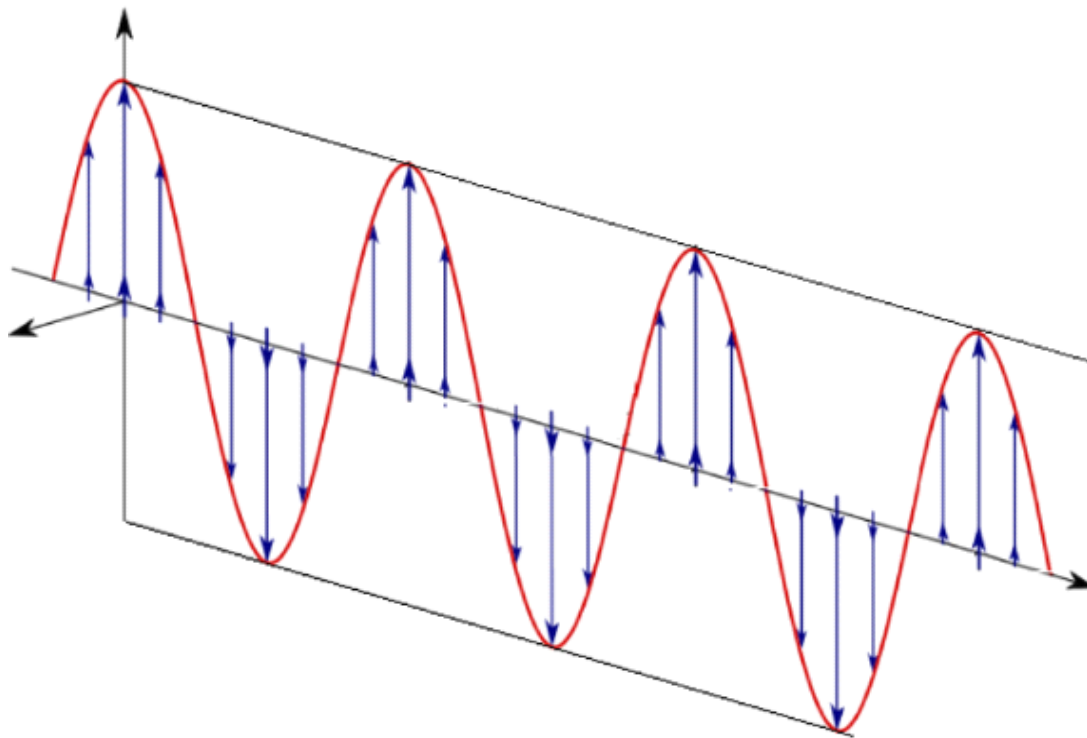


Figure 2.1.1.a: linear polarization

b) Circular polarization:

An electromagnetic wave is said to be circularly polarized if the electric field vector changes on a circle on the plane of propagation. This electromagnetic wave can be described as the superposition of two orthogonal and linearly polarized components along the x and y axes.

$$E_x = A \cdot \cos(\omega t - kz + \phi).$$

$$E_y = A \cdot \cos(\omega t - kz + \phi \pm \frac{\pi}{2}). \quad (2.2)$$

The term $\pm \frac{\pi}{2}$ refers to the phase difference. The sign may be positive if the y component leads the x component in the case of right circular polarization (RCP) or negative if the y component lags behind the x component in the case of left circular polarization (LCP).

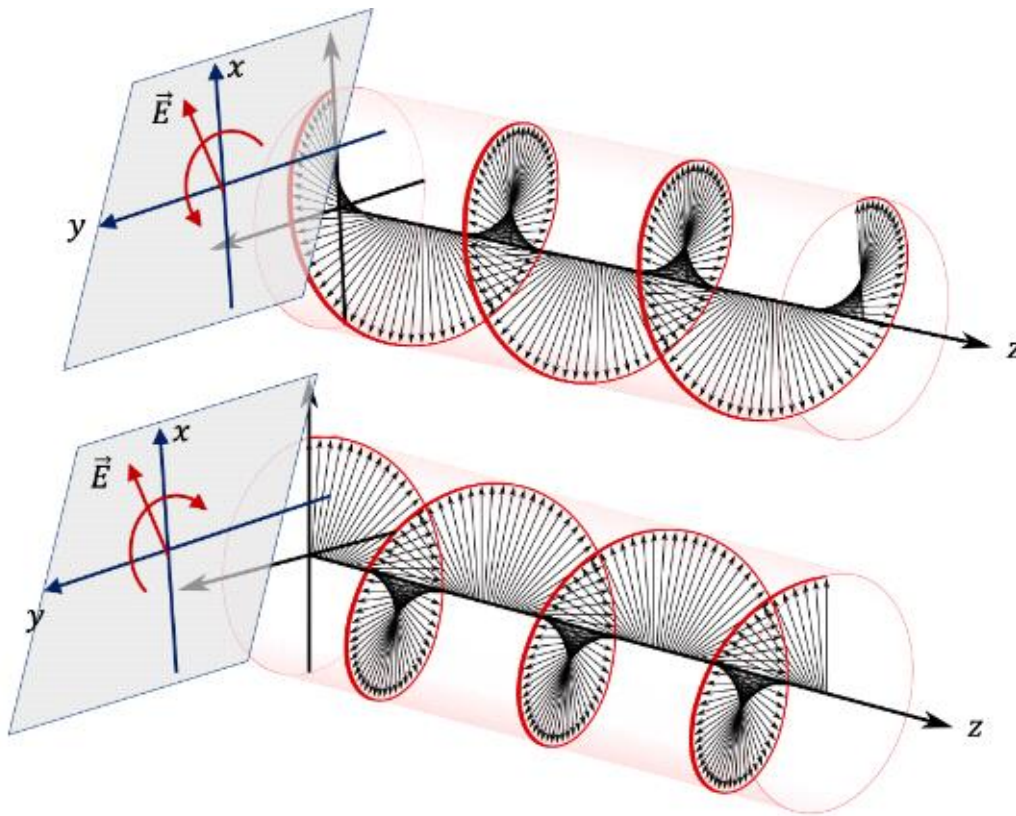


Figure 2.1.1.b: Comparison between right hand circular polarization and left hand circular polarization

c) Elliptical polarization:

Same as the previous discussed SOPs, an electromagnetic wave is said to be elliptically polarized if the electric field vector changes on an ellipse on the plane of propagation. Elliptical polarization represent the general case of the SOP as other SOP can be considered special cases of the elliptical polarization state. An elliptically polarized electromagnetic wave can be described as the superposition of two orthogonal and linearly polarized components along the x and y axes.

$$E_x = A_x \cdot \cos(\omega t - kz + \phi_x).$$

$$E_y = A_y \cdot \cos(\omega t - kz + \phi_y). \quad (2.3)$$

The shape of this ellipse varies from a circle when the amplitudes of the x and y component are equal and the phase difference between them is 90° , to a line when the two components are in phase or out of phase. Similar to circular polarization, elliptical polarization can be either left handed or right handed, if the y component leads the x component it will be right elliptical polarization (REP), if the y component lags behind the x component in that case it is called left hand elliptical polarization (LEP) [17].

2.1.2 Parameters of the SOP:

As said before elliptical polarization is considered to be the general state of polarization, from this we can define two new angles or parameters that describe the ellipse. Firstly, the azimuthal angle θ , which is also called the orientation angle, it represents the angle between the major axis of the ellipse and the positive direction of the x-axis. The angle θ varies from -90° to 90° . The other angle that describe the ellipse is the ellipticity angle χ , which is a measure of both the ellipticity and the sense of rotation of the SOP. The ellipticity angle varies from -45° to 45° and can be computed using the following formula

$$\chi = \tan^{-1} \pm \frac{b}{a} \quad (2.4)$$

Where b/a is the ratio of the minor axis over the major axis. A positive value of χ represents a right sense of rotation, while a negative value of χ represents a left sense of rotation.

Geometrically, χ is the angle between the major axis of the ellipse and the diagonal of the rectangle enveloping the ellipse. Therefore if $\chi=0$ the wave is linearly polarized, and would be circularly polarized when $\chi = \pm 45^\circ$ [18].

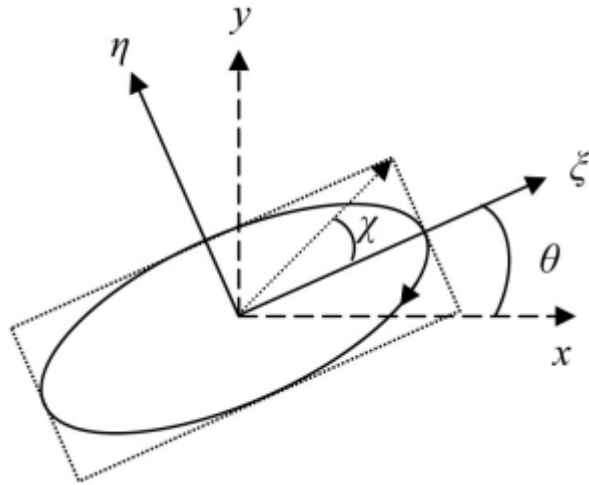


Figure 2.1.2: azimuthal and ellipticity angles

2.1.3 Representation of a polarized light:

A polarized electromagnetic wave can have different representation the most common ones are Jones vector, Stokes parameter, and the Poincaré sphere.

2.1.3.1 Jones vector representation:

Jones vector can be considered the simplest way to represent the SOP of an electromagnetic wave. It consist of using a 2×1 matrix with two components that represent the magnitude of the x and y component of the wave and the phase difference between them. This matrix is in the form

$$J = \begin{bmatrix} a_x \\ a_y \cdot e^{i\delta} \end{bmatrix} \quad (2.5)$$

Where a_x , and a_y are the magnitude of the x and y component respectively and δ is the phase difference between the two component. This matrix can be normalized by dividing both magnitudes over $\sqrt{a_x^2 + a_y^2}$ [19].

2.1.3.2 Stokes vector representation:

Another way to represent the SOP is the Stokes parameters. Unlike Jones vector which is straight forward, Stokes parameters is a more versatile method to represent the SOP. There are four stokes parameters and they are S_0 , S_1 , S_2 , and S_3 .

In terms of power, S_0 represents the total power, S_1 is the power difference between 0° linear and 90° linear polarization states, S_2 is the power difference between 45° linear and 135° linear states and S_3 is the power difference between RCP and LCP.

For a completely polarized light, stokes parameters can be written in terms of magnitude of the x and y component and the phase difference between them.

$$S_0 = a_x^2 + a_y^2,$$

$$S_1 = a_x^2 - a_y^2,$$

$$S_2 = 2 a_x a_y \cos\delta,$$

$$S_3 = 2 a_x a_y \sin\delta, \tag{2.6}$$

The Stokes parameters can be arranged vertically in the form of a column vector in order to form the Stokes vector of an electromagnetic wave. [18,20].

2.1.3.3 Poincaré sphere representation:

The Poincaré sphere representation is a simple and extremely useful geometrical representation of various polarization states and their evolution through a birefringent medium. Any SOP can be represented on a sphere with unit radius. As discussed earlier any SOP has two angle parameters which are the azimuthal angle Θ and the ellipticity angle χ , that same SOP can be represented on the Poincaré sphere on the surface of the sphere by a point whose longitude and latitude have the values 2θ and 2χ respectively.

Points that are on the upper half of the sphere represent a right-handed SOP, while points on the lower half represent a left handed SOP. The set of points that constitute the equator represent linear SOPs with different rotation angles [21].

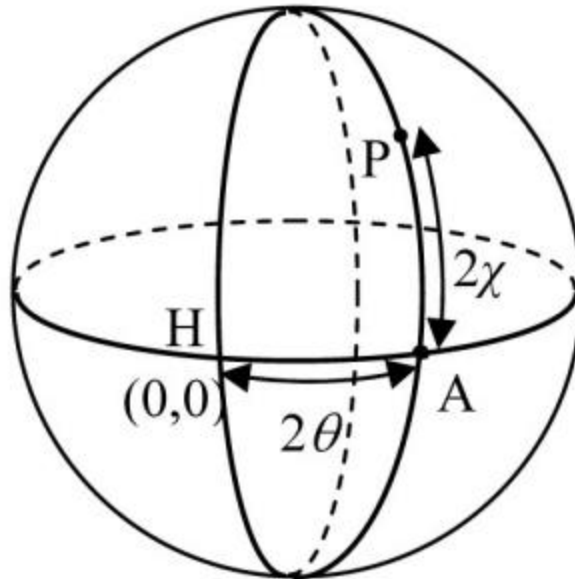


Figure 2.1.3.3: poincaré sphere representation

In the above figure, the point H represents the horizontal linear SOP and the reference point A represents the linear SOP with the azimuthal angle θ , while P represents the SOP with the azimuthal and ellipticity angles θ and χ respectively.

2.2 Birefringence

Single mode fibers actually have two orthogonal modes propagating in the core. In an ideal cylindrical fiber, these two modes travel with the same velocity as they experience the same refractive index. In reality, manufactured fibers have at least some asymmetry in their core geometry due to imperfections in the manufacturing process or external factors such as bending, twisting and stress. This asymmetry causes the two modes to ‘see’ different refractive indices, which makes them travel at different speeds. The difference between the two velocities is called birefringence. [18]

In the figure below, the RI of the x-axis is higher than the y-axis. Thus, light polarized along the X-axis propagates with a speed slower than that of the light polarized along the Y-axis. Typically, the polarization that propagates with lower speed is called the “slow axis” whereas the polarization that propagates with the higher speed is called the “fast axis”.

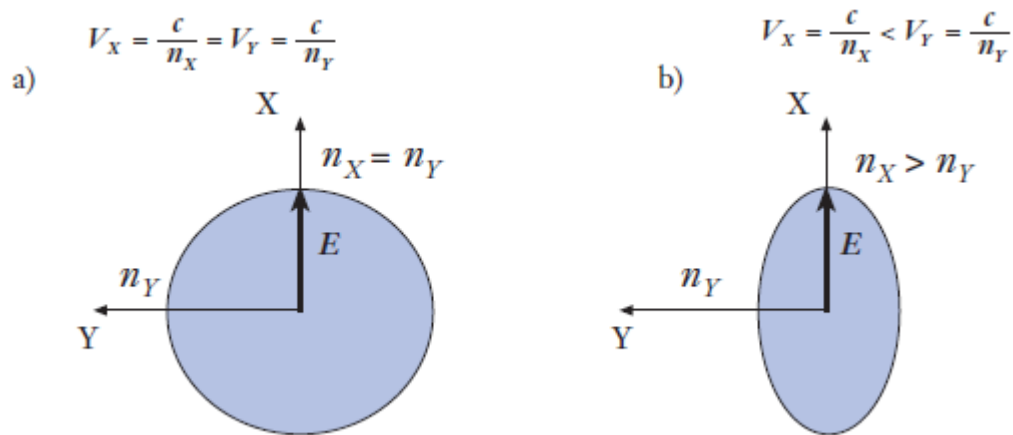


Figure 2.2.a: (a) Representation of a perfectly symmetrical fiber where the index ellipse is a circle and the speed of light does not depend on its polarization and (b) representation of the fiber with birefringence where X-polarized light propagates slower than Y-polarized light.

Birefringence causes a differential group delay (DGD) between the two polarization states. This means that they arrive on the output at a slightly different time, which causes the distortion of the light signal at the output. At high bit rates and distances, this can be a huge problem. As if the DGD is large enough, two distinct pulses appear at the output. This is known as pulse splitting. Such distortion can cause the receiver to not be able to distinguish between 1's and 0's [22].

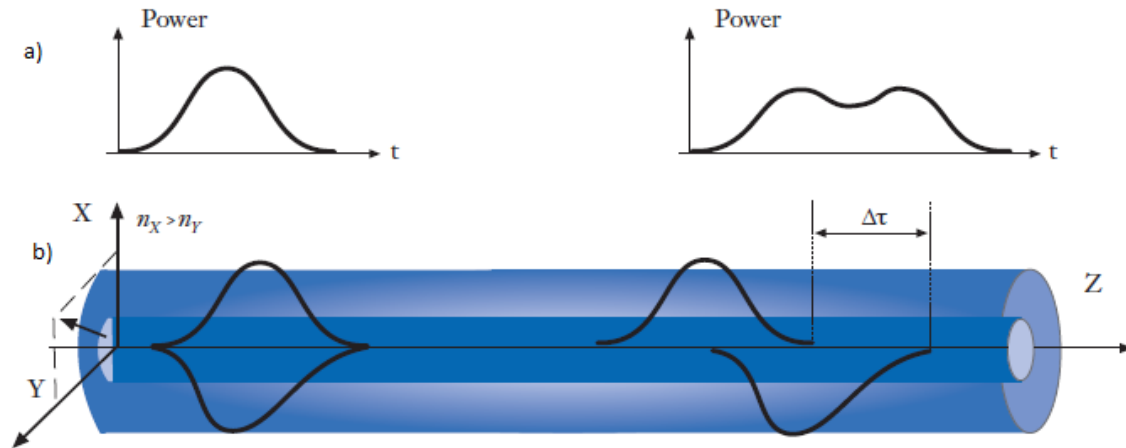


Figure 2.2.b: The impact of birefringence on an optical pulse. a) Pulse splitting and b) DGD

2.3 Beat length

When a linearly polarized light is launched into the fiber, it goes through polarization changes in cyclic fashion as it is propagating through the fiber. From linear to elliptical to circular and back through elliptical to a linear state orthogonal to the launch state. The beat length is known as the distance it takes for a light wave's polarization to go through a full cycle and go back to the original launch state. It is given by:

$$L_b = \lambda / \Delta n \quad (2.7)$$

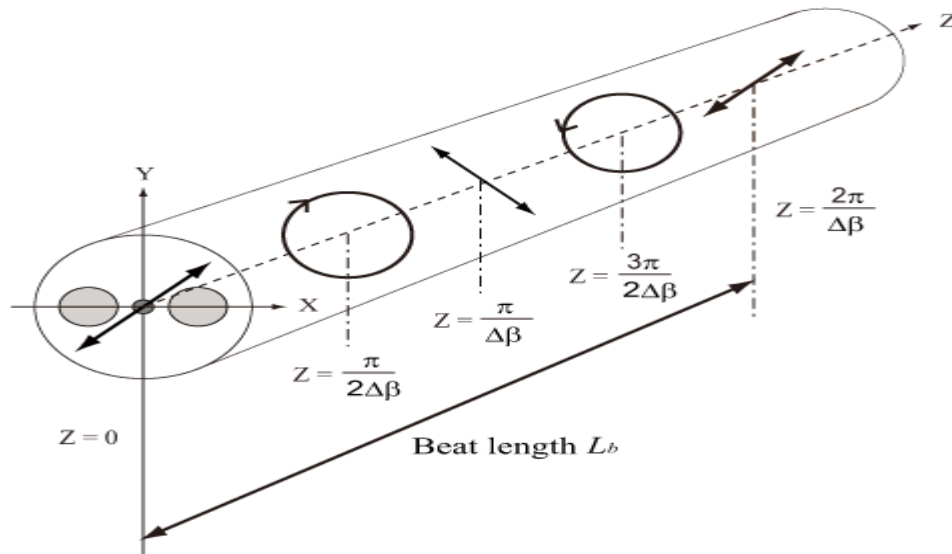


Figure 2.3.a: Evolution of the polarization state of light guided along a birefringent fiber when the x- and y-polarized modes are equally excited.

In the frequency domain viewpoint, for a fixed-input polarization state, if the light frequency is varied, the output polarization state from a short length of birefringent fiber will cycle in the same way through the various states. The output polarization \hat{t} traces a circle on the surface of the Poincaré sphere [23].

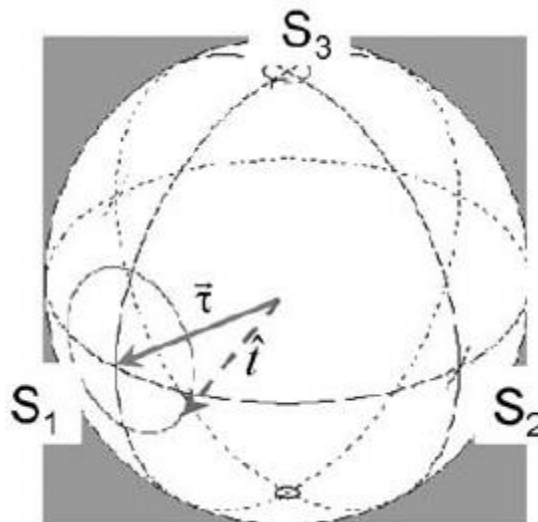


Figure 2.3.b: Frequency-domain behavior of PMD in a short birefringent fiber, where the fiber's birefringent axis τ is aligned with the S_1 axis.

2.4 Polarization mode coupling

In a short-length fiber, the birefringence can be considered uniform and the average DGD increases linearly with fiber length. However, in long distances, the birefringence changes randomly due to the fiber's environment variations (temperature, stress...). Different sections of the fiber exhibit different levels of birefringence both in terms of levels of refractive index asymmetry, and the relative orientation of the slow and fast axis which, causes polarization mode coupling. These different sections can either add or subtract from the total average DGD, which means it does not increase linearly with fiber length. Rather, it increases with the square root of distance as shown in multiple experiments [18, 24].

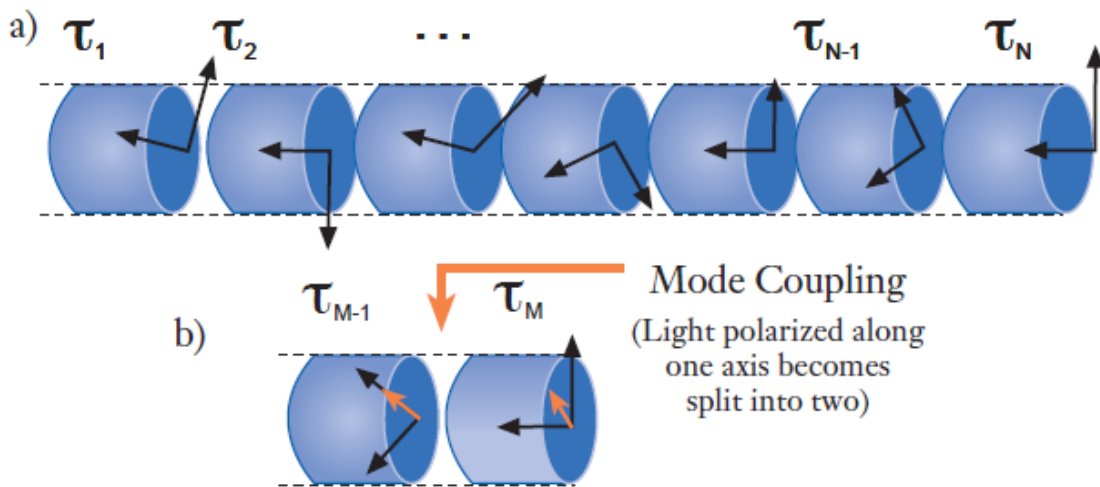


Figure 2.4: (a) Physical model of fiber PMD as a concatenated series of birefringent fibers with a certain length and (b) separated by mode coupling sites where the birefringent section is “rotated” with respect to the adjacent sections.

2.5 Correlation length

To distinguish between the short and long length regimes of the fiber, we define a correlation length parameter L_c . Assuming a fixed input polarization of $\langle p_x \rangle = 1$ and $\langle p_y \rangle = 0$ (power averages in the x and y polarizations), it is expected that for a large distance all the polarizations have the same probability to be observed. L_c is defined as the length where the power difference has decayed to $\langle p_x \rangle - \langle p_y \rangle = 1/e^2$ [23].

The correlation length L_c can be linked to the mean squared DGD and L_b with the following expression:

$$\langle \Delta\tau^2 \rangle = 2(\Delta\tau_b \frac{L_c}{L_b})^2 (L/L_c + e^{-L/L_c} - 1) \quad (2.8)$$

Where $\Delta\tau_b$ is the DGD for a beat length and $\langle \Delta\tau^2 \rangle$ is the mean squared DGD.

For fiber transmission lengths that satisfy $L \ll L_c$, the fiber is considered to be in the short length regime. The root mean square of the DGD $\sqrt{\langle \Delta\tau^2 \rangle} = \Delta\tau_{rms}$ simplifies to:

$$\Delta\tau_{rms} = \Delta\tau_b L/L_b \quad (2.9)$$

For fiber lengths that satisfy $L \gg L_c$, the fiber is considered to be in the long-length regime. The root mean square of DGD simplifies to:

$$\Delta\tau_{rms} = (\Delta\tau_b/L_b)\sqrt{2LL_c} \quad (2.10)$$

2.6 Principle states of polarization

As mentioned above, pulse propagation through a long-length fiber can be very complicated and unpredictable due to random changes in the magnitude and direction of the birefringence, causing polarization mode coupling. Fortunately, even in long fibers we can still find two orthogonal input SOPs (state of polarization) that result in two orthogonal output SOPs that are undistorted to the first order of frequency. These polarization states are known as principle states of polarizations (PSP). Pulses launched in these polarization states emerge into two fixed output polarization states, which are also orthogonal to each other. Thus, if the input pulse is launched along one of the input PSPs, there is no splitting of the pulse.

In the figure 2.6, we can see that the two input SOPs that minimize BER are relatively undistorted compared to the polarization launch that maximized BER at the output. Those two SOPs are the slow and fast PSPs [25].

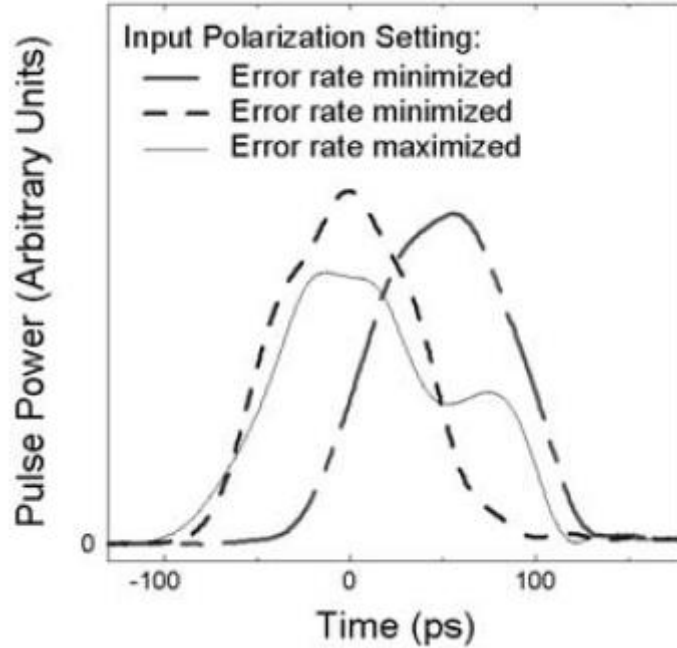


Figure 2.6: Output pulse shapes for three polarization launches of a 10 Gbps signal through a 48-km fiber with 60 ps PMD.

The input and output PSPs, designated by the unit Stokes vectors \hat{p}_s and \hat{p} , respectively. \hat{p} points in the direction of the slow PSP. While $-\hat{p}$ indicates the fast PSP. They are 180° apart from each other in the stokes space.

2.7 Representation of PMD

There exists three ways to represent PMD mathematically. Stokes space, jones space and energy space. The stokes space is the most common and intuitive representation of PMD. However, it has its drawbacks as it ignores the isotropic dispersion and it cannot predict the transmission eye-diagram [18].

2.7.1 Stokes space

Using the PSP model, we can represent PMD in stokes space by a vector $\hat{\tau}$ which points in the direction of the slow PSP \hat{p} and has a magnitude $\Delta\tau$ which is the DGD.

$$\hat{\tau} = \Delta\tau \hat{p} \quad (2.11)$$

The fast PSP is represented by $-\hat{p}$ which is 180° from \hat{p} . Moreover, the DGD in this case refers to the difference in arrival time between the fast and slow PSPs.

Assuming a fixed input polarization \hat{s} . The output polarization $\hat{t} = R\hat{s}$ at a certain fixed distance z will vary with frequency following the infinitesimal law of rotation.

$$\frac{d\hat{t}}{d\omega} = \tau \times \hat{t} \quad (2.12)$$

The above equation shows that the output polarization \hat{t} will precess around τ as the frequency is varied. The angle of precession (rotation around the axis) is $\Delta\delta = \Delta\tau\Delta\omega$

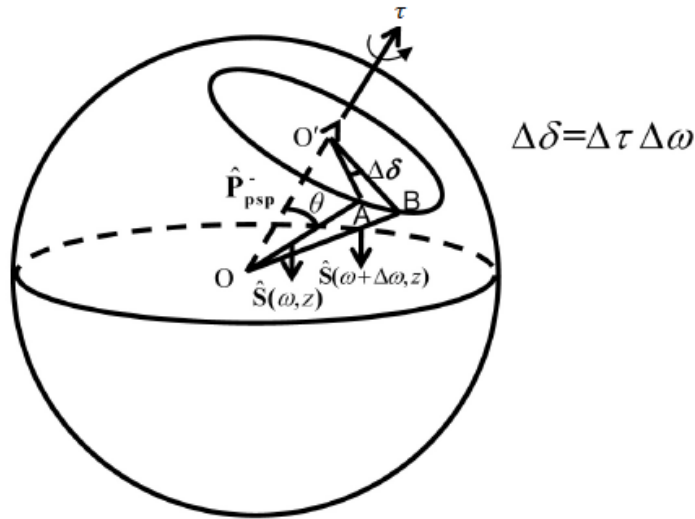


Figure 2.7.1: Precession of the SOP from A to B by an angle of $\Delta\delta = \Delta\tau\Delta\omega$ after the frequency is changed by $\Delta\omega$ in the poincaré sphere

We also notice that if we launch \hat{s} along one of the PSPs, there will be no precession and the output polarization remains the same as the frequency varies. This aligns perfectly with our definition of a PSP.

This PMD vector model uses the PSPs of the entire fiber length, which is usually in the long-length regime. However, as we move along the fiber from z to $z + \Delta z$, the local birefringence changes direction as well as the local PSPs. To include this effect we define the birefringence vector $\hat{\beta}$.

$$\hat{\beta} = \Delta\beta \hat{p}_{local} \quad (2.13)$$

Where $\Delta\beta = \hat{\alpha}_f - \beta_s$ is the difference between the propagation constants of the fast and slow PSPs. \hat{p}_{local} is the stokes vector of the slow PSP corresponding to a piece of fiber that is in short-length regime.

Similar to the PMD vector, for a fixed frequency, the SOP as the distance increases will process around the birefringence vector with an angle of $\Delta\delta' = \Delta\beta\Delta z$ following this differential equation:

$$\frac{d\hat{t}}{dz} = \beta \times \hat{t} \quad (2.14)$$

If the fiber is in the short-length regime, the PMD and birefringence vectors will have the same PSPs and therefore the same direction in the poincaré sphere. However, if the fiber is in the long-length regime, the PMD vector takes into account the entire fiber length to determine its PSP. While the birefringence vector only considers the PSP of a certain section of the fiber which belongs to the short-lengths regime. As we move along the fiber length the birefringence vector changes direction from section to section (see figure 2.4) [18,24].

Using the previous two differential equations of the PMD and birefringence vectors, we can derive the dynamical equation of PMD:

$$\frac{d\tau}{dz} = \frac{d\beta}{dz} + \beta \times \tau \quad (2.15)$$

2.8 First and second order PMD

From equation 2.11 and knowing that the PMD vector is frequency dependent. We use Taylor series expansion around the carrier frequency ω_0 and we obtain:

$$\tau(\omega_0 + \Delta\omega) = \tau(\omega_0) + \tau'(\omega_0)\Delta\omega + \dots, \quad (2.16)$$

Where the prime on τ' refers to the derivative with respect to the frequency.

From the equation 2.16, the first term on the right refers to the first order PMD, which is considered to be frequency independent. The second term refers to the second order PMD, and can be written as:

$$\tau'(\omega_0) = \frac{d(\Delta\tau)}{d\omega}(\omega_0) \cdot \hat{p}(\omega_0) + \Delta\tau(\omega_0) \cdot \frac{d\hat{p}}{d\omega}(\omega_0) \quad (2.17)$$

The other terms of the equation 2.16, represent higher order PMD. Because the effects of higher order PMD starts at very high bit rate (above 40Gbits/s), it is often neglected when simulating using an optical fiber simulator (Optisystem in next chapter). Considering only first and second orders PMD, the PMD vector can be represented as the sum of vectors as shown in figure 2.8.

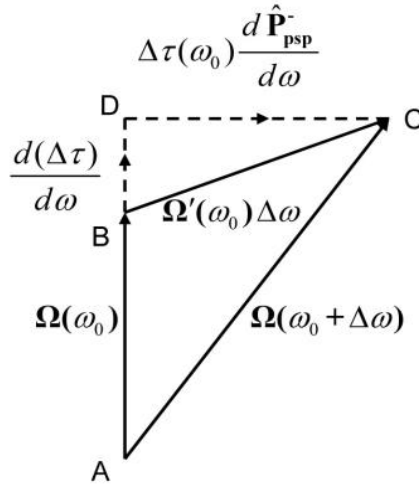


Figure 2.8: Schematic representation of the PMD vector, and its first and second-order PMD components.

Where in the precedent figure \overline{AC} represents the PMD vector, \overline{AB} and \overline{BC} represent the first and second orders PMD respectively. As for \overline{BD} and \overline{DC} , they represent the two components of the second order PMD.

2.9 Conclusion:

In summary, this chapter provides a comprehensive overview on the mathematical representation of Polarization Mode Dispersion (PMD) in optical fiber communication systems. It covers the basics of polarization, including different representations like stokes parameters and poincaré sphere. The concepts of birefringence, polarization mode coupling and principle states of polarization were explored. Furthermore, many important PMD parameters were studied like correlation and beat lengths. This knowledge is crucial for understanding and mitigating the impact of PMD on optical signals, leading to improved performance and reliability in optical fiber systems.

chapter 3

Optisystem Simulation

Introduction:

This chapter will provide a detailed exploration of how polarization mode dispersion affects the transmission of electromagnetic waves through fiber, including first order PMD and second order PMD. Next, we intend to provide a solution that compensate the first order PMD. To simulate the signal transmission under the influence of PMD, we will utilize the Optisystem software mainly focusing on the PMD emulator component. Additionally, we will define various parameters related to the PMD emulator and observe how changes in these parameters influences the electromagnetic wave.

3.1 Optisystem:

The purpose of developing the OptiSystem software was to provide the academic community with a powerful tool for teaching and research, which can reduce the time spent on preparing lectures. The software enables an efficient learning process by offering samples that can be simulated during class hours, additionally supports researchers in comprehending the fundamentals of optical devices and networks by allowing them to simulate and analyze their designs before creating an actual test setup. Furthermore, Optisystem has various applications, such as designing optical fiber characteristics, studying the impact of dispersion and attenuation, comprehending optical components, and modeling optical networks.

3.2 BER Analyzer:

The Quality factor (Q factor) and bit error rate (BER) play a crucial role in determining the maximum achievable transmission distance in optical communication systems. To enable signal transmission over long distances, it is imperative to maintain a low BER and a high Q-factor within the optical fiber. The BER analyzer is the visualizer that allows the user to calculate and display the Quality factor and BER of an electrical signal automatically. Additionally this visualizer display the Eye Diagram, the Height, and Threshold. Using the BER analyzer the user can determine the quality of the signal transmitted and the impact of various factors such as noise, dispersion, and impairments on the system's error rate.

3.2.1 Quality Factor (Q):

Q factor measures the quality of an analogue transmission signal in terms of its signal to noise ratio (SNR). The eye pattern oscilloscope will typically generate a report that shows what the Q factor number is. The Q factor is defined as the difference of the mean values of the two signal levels (level for a “1” bit and level for a “0” bit) divided by the sum of the noise standard deviations at the two signal levels. A larger number in the result means that the pulse is relatively free from noise. Mathematically Q factor is measured using the equation

$$Q = \frac{|\mu_1 - \mu_2|}{\sigma_1 + \sigma_2} \quad (3.1)$$

Where μ_1 and μ_2 are the means, and σ_1 and σ_2 are the standard deviations on the zeros and the ones.

3.2.2 Bit Error Rate:

Before data is transmitted in optical fiber, this data is encoded into ‘0’s and ‘1’s each ‘0’ or ‘1’ represent a bit. When data is received it will be decoded based on those ‘0’s and ‘1’s. Yet due to dispersions and noises errors may happen during the decoding process .the bit error rate (BER) refers to the measure of the number of erroneous bits in this data transmission compared to the total number of transmitted bits. The BER is typically expressed as a ratio or percentage, representing the probability of bit errors occurring during transmission. A lower BER means relatively less noise and dispersion.

The BER is inversely proportional to the quality factor and can be calculated using the following formula.

$$BER = \frac{1}{2} \operatorname{erfc}\left(\frac{Q}{\sqrt{2}}\right) \quad (3.2)$$

Where Q is the Quality factor and

$$\operatorname{erfc}(x) = \frac{2}{\delta} \int_x^{\infty} e^{-t^2} dt \quad (3.3)$$

3.3 PMD Emulator:

In the process of simulating the process of PMD on pulse propagation using Optisystem, one of the needed tool is going to be the PMD emulator. The PMD Emulator component is used to demonstrate the distortions in the transmitted signal, caused by first and second order PMD effects. This emulator simulate the effect of PMD of given parameters such as length, attenuation, dispersion, Differential Group Delay, depolarization rate and polarization chromatic dispersion. While the Differential Group Delay (DGD) simulate the effects of first order PMD, the depolarization rate simulate the effects of the second order PMD.

3.4 Simulation Setup:

In this simulation, we will be focusing on the PMD emulator. As for the setup, we will be building a transmitter structure using a pseudo-random Bit Sequence Generator, connected to an NRZ Pulse Generator, connected to a Low Pass Gaussian Filter with a cutoff frequency equal to 85% of the Bit rate, connected to a 1x2 Fork. As for the optical source, we will be using a Continuous Wave (CW) Laser. All three outputs including the two outputs from the Fork and the one from the CW Laser are connected to a LithiumNiobate (LiNb) Mach-Zehnder modulator. Figure 3.1 shows the structure of the transmitter.

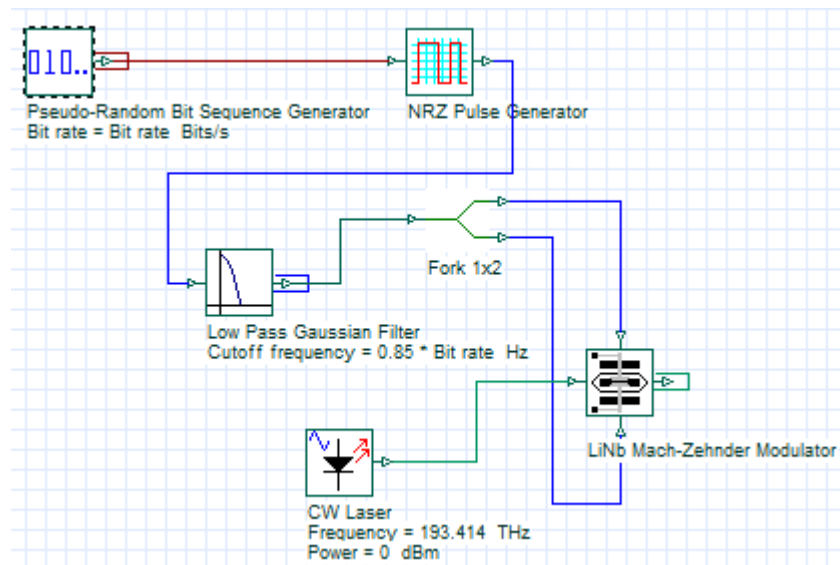


Figure 3.1: structure of the transmitter.

As for the transmission line, we will be using a PMD Emulator. The output of the PMD Emulator is connected to the receiver, which is simply a PIN Photodetector. Adding visualizers, the complete structure is represented in figure 3.2.

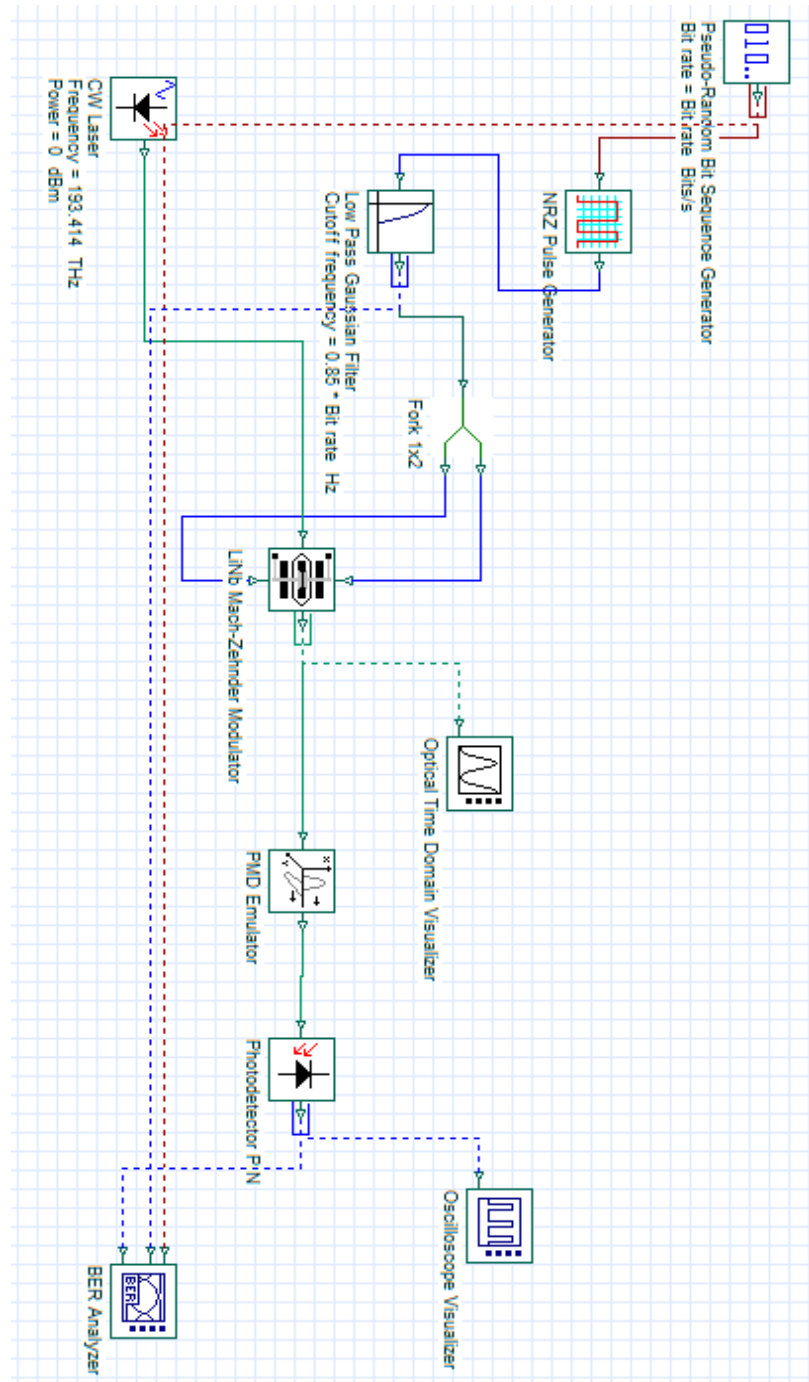


Figure 3.2: PMD Emulator simulation design.

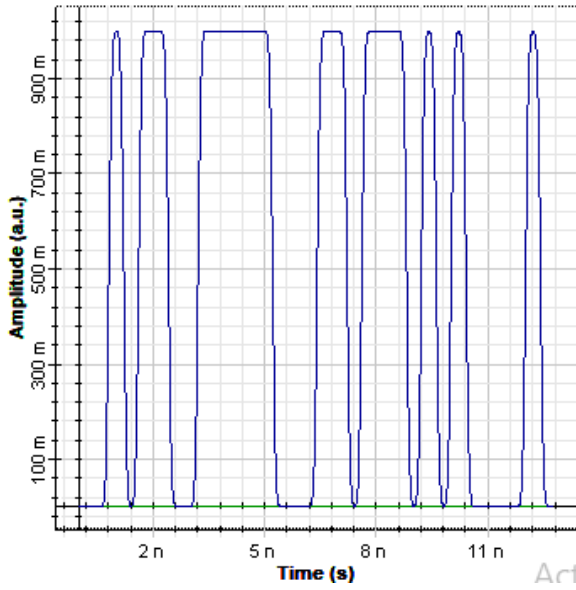
3.4.1 Effect of Bit Rate on PMD:

In order to analyze how the effect of PMD on pulse propagation changes with bit rate we employ the previous simulation design. Parameters on both the CW Laser and the PMD Emulator are fixed as shown in figure 3.3, while we will be varying the bit rate from 2.5 GBits/s to 40 GBits/s.

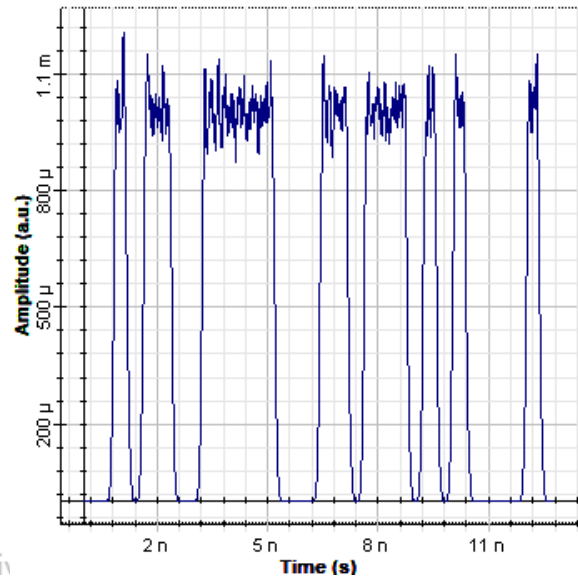
Table 3.3: system Parameters for Bit rate effect.

Parameter	Value
Power	0 dBm
Attenuation	0 dB/Km
Dispersion	0 ps/km
DGD	71 ps
Depolarization Rate	10.8 deg/GHz
Polarization Chromatic Dispersion	1.3 ps/GHz

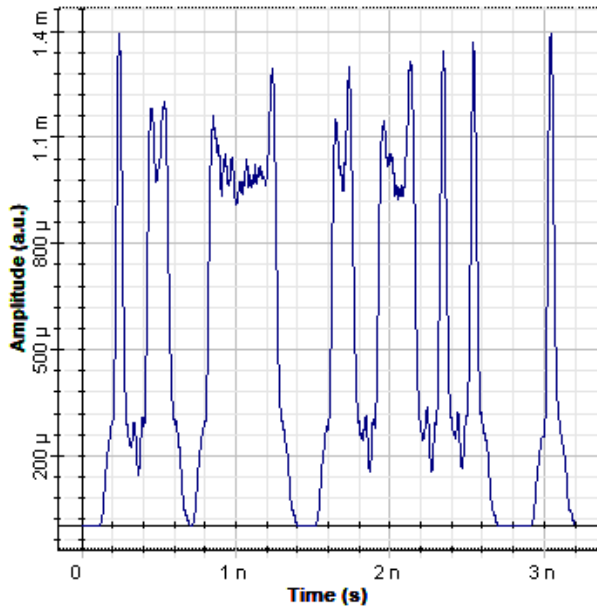
Figures 3.4, 3.5, and 3.6 are the result of the simulation. We will be looking for the result shown in both the oscilloscope visualizer and the BER analyzer when the simulation is performed with a Bit rate of 2.5 GBits/s, 10 GBits/s, and 40 GBits/s. we will summarize with a graph that shows the change in the Quality factor with the Bit Rate.



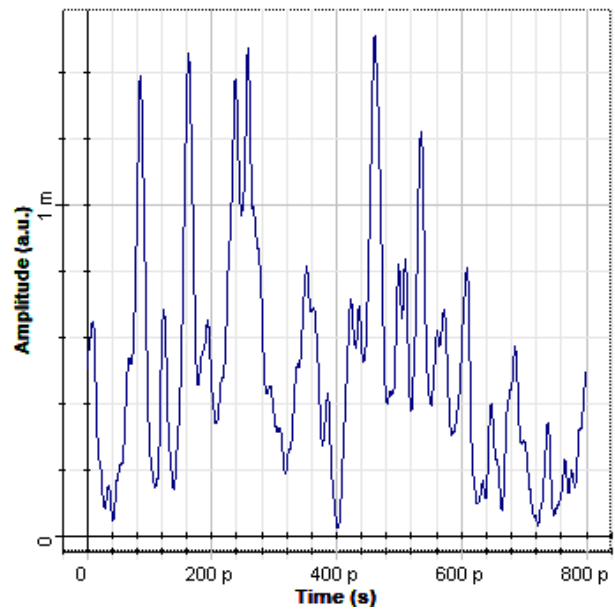
a) Input signal



b) 2.5 GBits/s

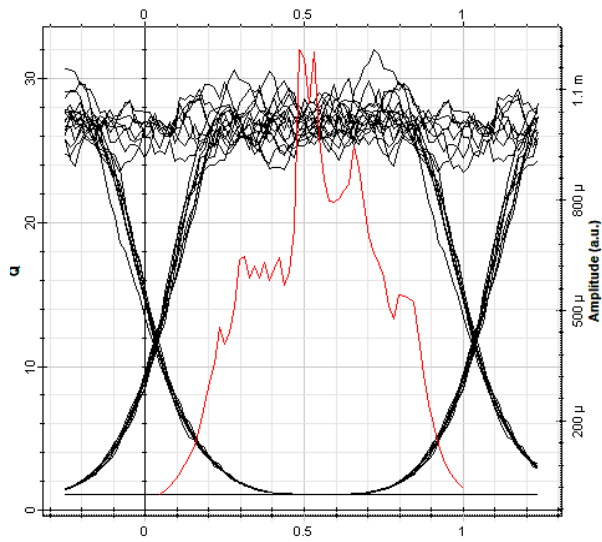


c) 10 GBits/s

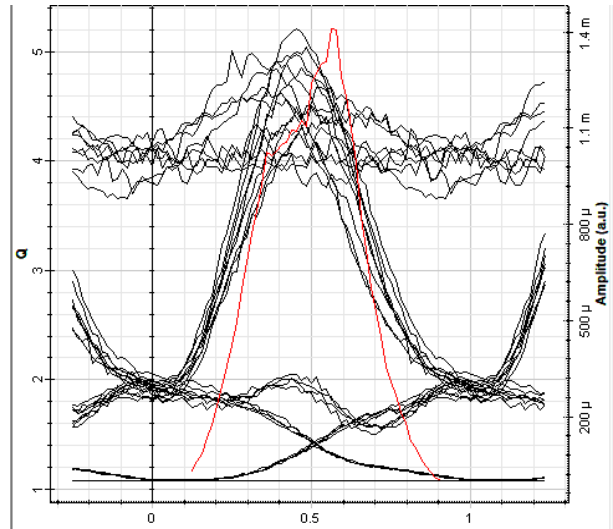


d) 40 GBits/s

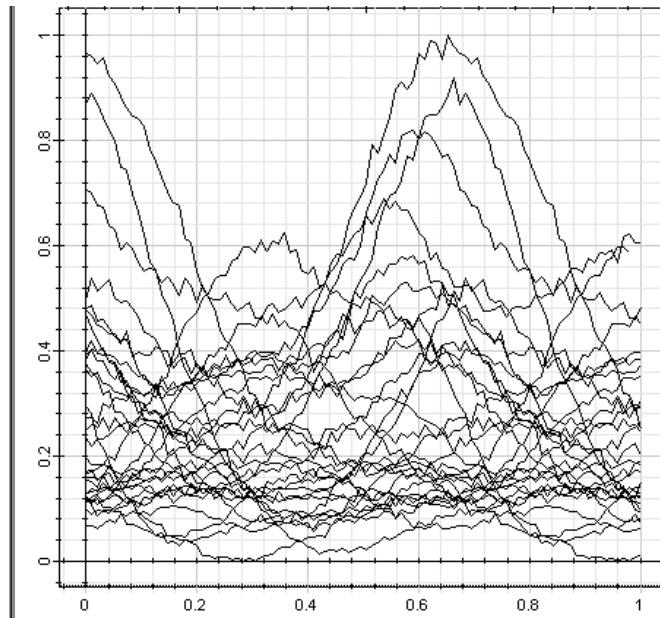
Figure 3.4: The effect of bit rate on a PMD affected signal



a) 2.5 Gbps



b) 10 Gbps



c) 40 Gbps

Figure 3.5: Eye Diagram of a PMD affected signal at different bit rates

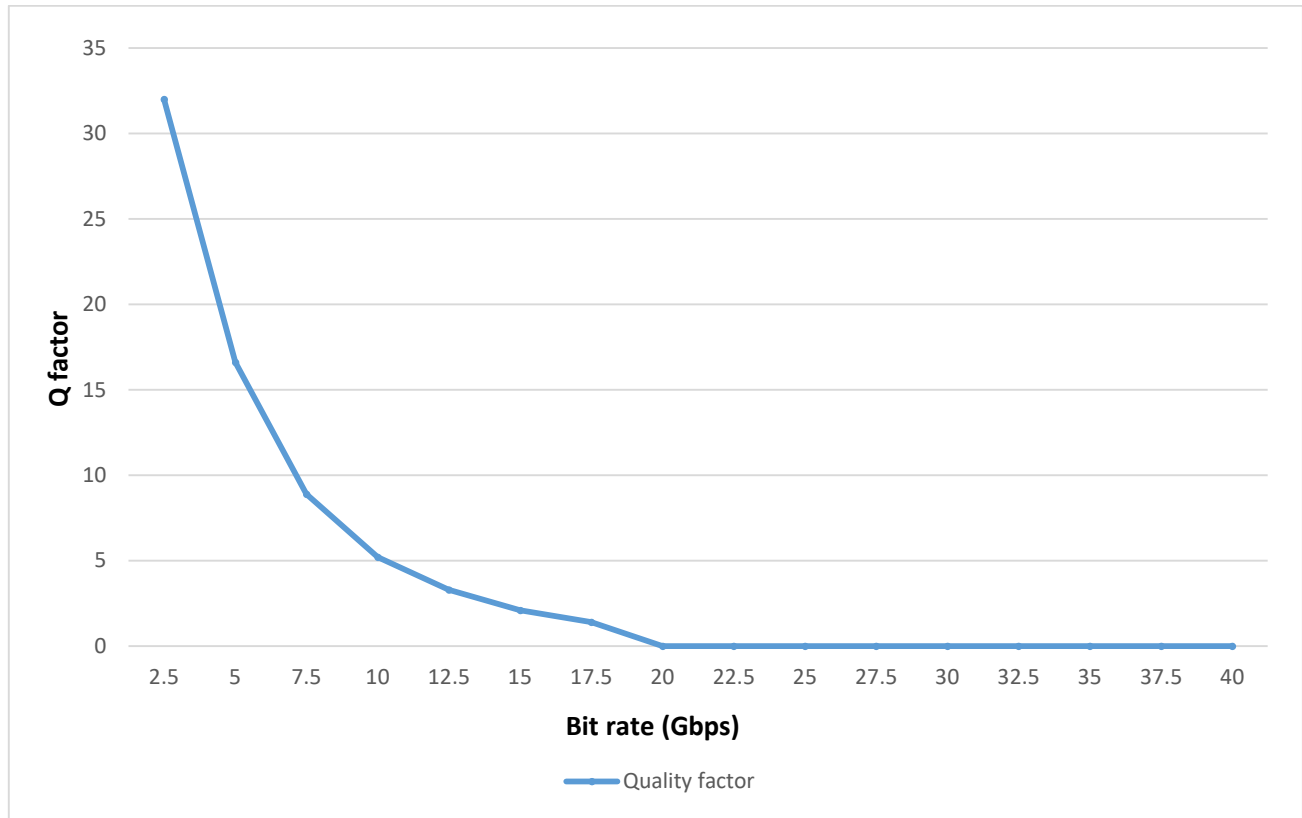


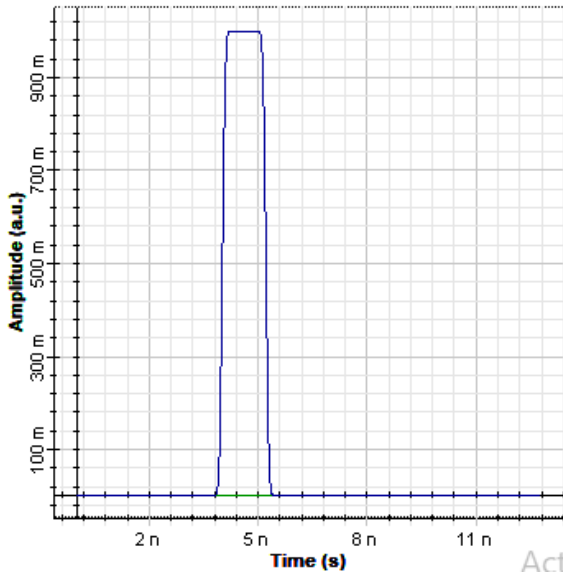
Figure 3.6: the Q factor of a NRZ signal with respect to the bit rate

Analyzing the results from figure 3.4 and figure 3.5 the output displayed by the oscilloscope visualizer and the BER analyzer demonstrate that the effect of the PMD is negligible at 2.5 Gbps. When the bit rate reaches 10 Gbps, the PMD's impact becomes evident in the eye diagram, as the signal distortion becomes increasingly noticeable. At very high Bit rates (40 Gbits/s) the decoding of the signal at the output end is no longer possible due to the high impact caused by the PMD. From figure 3.6, we can see that the Q factor is decreasing dramatically as the Bit rate increase until it reaches zero at around 20Gbit/s.

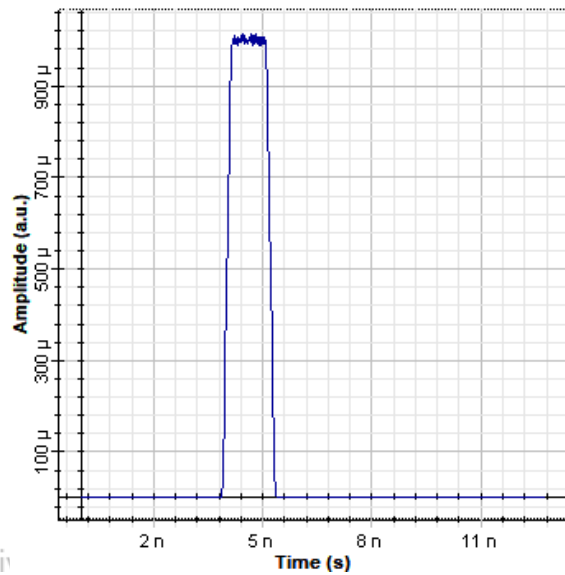
3.4.2 Effect of first order PMD:

First, we use the setup presented in figure3.2 combined with a user defined bit sequence generator in order to send a pulse to the PMD emulator with the worst-case input polarization (azimuthal= 45°) to see the effect that first order PMD will have on it. We try three different bit rates: 2.5 Gbps, 10 Gbps and 40 Gbps. We have set the attenuation and other dispersions and the

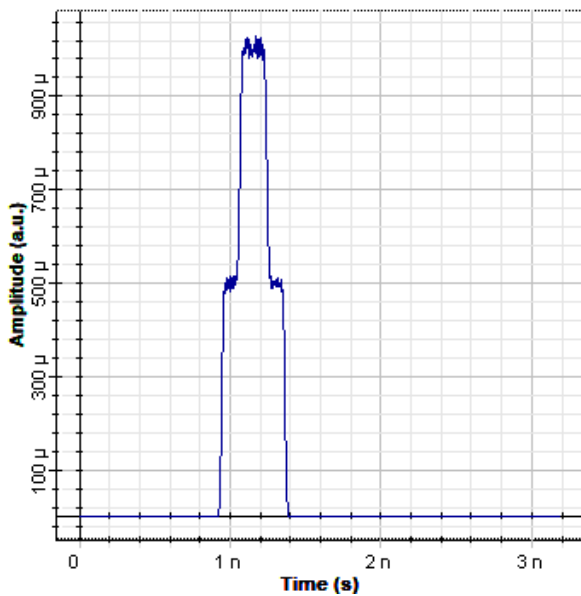
second order PMD parameter all to zero to isolate the effect of first order PMD. Although typical mean DGD values in modern low PMD fibers are usually around 20 ps. In a 100km cable, we use 100 ps to emphasize the pulse splitting effect that PMD can have on our system.



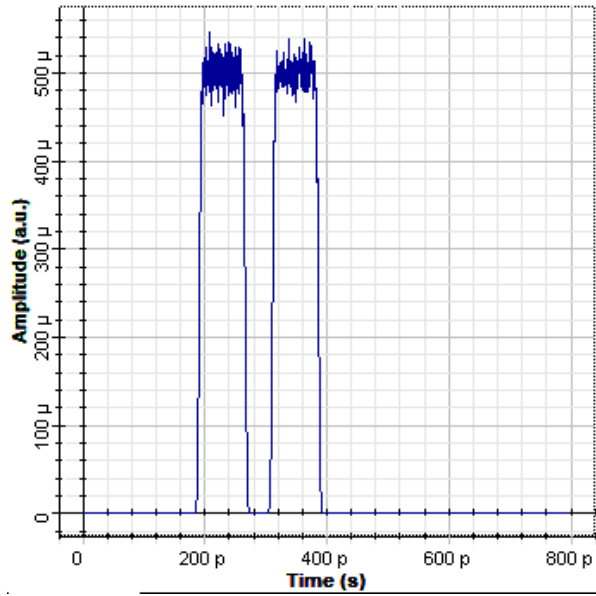
a) The input pulse



b) Output at 2.5 Gbps

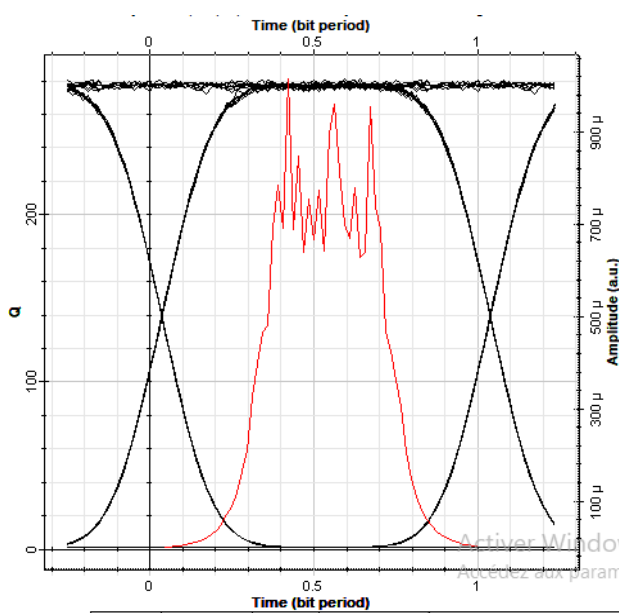


c) Output at 10 Gbps

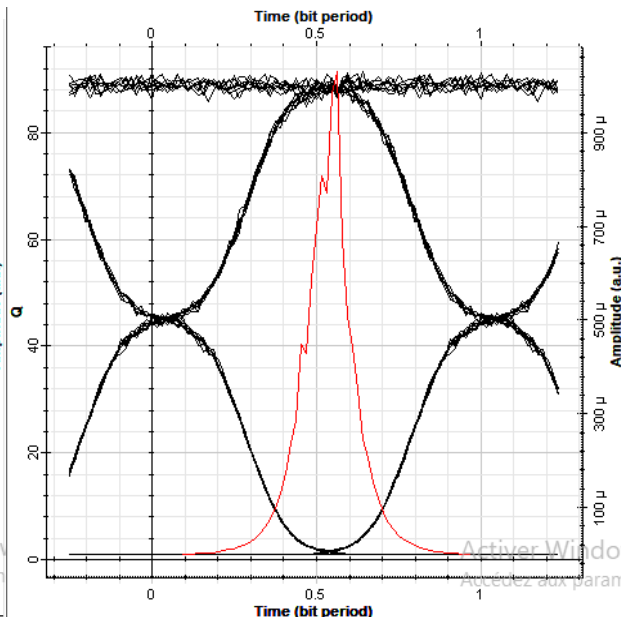


d) Output at 40 Gbps

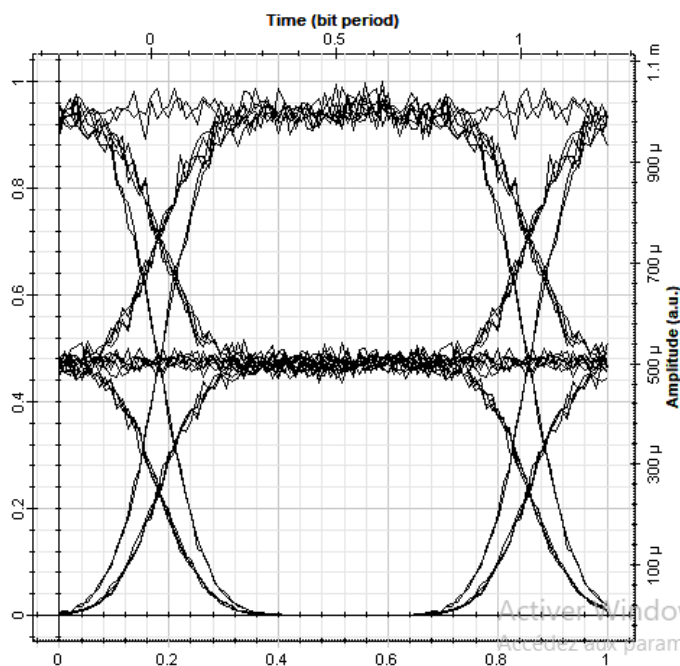
Figure 3.7: The impact of first-order PMD on a pulse with the mean DGD=100 ps at different bit rates



a) 2.5 Gbps



b) 10 Gbps



c) 40 Gbps

Figure 3.8: Eye-diagram of a first-order PMD affected signal with a mean DGD = 50 ps at different bit rates

We can see from figures 3.7 and 3.8 that the first order PMD can have a devastating effect of the signal quality even at a low DGD value. While this effect can be ignored at lower bit rates, it can cause significant distortions to the signal as we use higher bit rates, which is why we will focus in the following section on how we can compensate first order PMD.

3.4.3 First order PMD compensation:

The main effect of first order PMD is the pulse splitting that happens due to the two polarization components travelling at different speeds. Therefore, the ‘fast’ axis component arrives first and the difference in arrival times between the fast and slow axis is called DGD. However, as we have previously seen in section 2.6, launching a pulse where its input polarization is aligned with the PSPs of the fiber can lead to a relatively undisturbed output signal. Now, to find the direction of the PSPs of the PMD emulator that we use, we send a signal with varying azimuth angle and a fixed ellipticity = zero and measure the output Q factor.

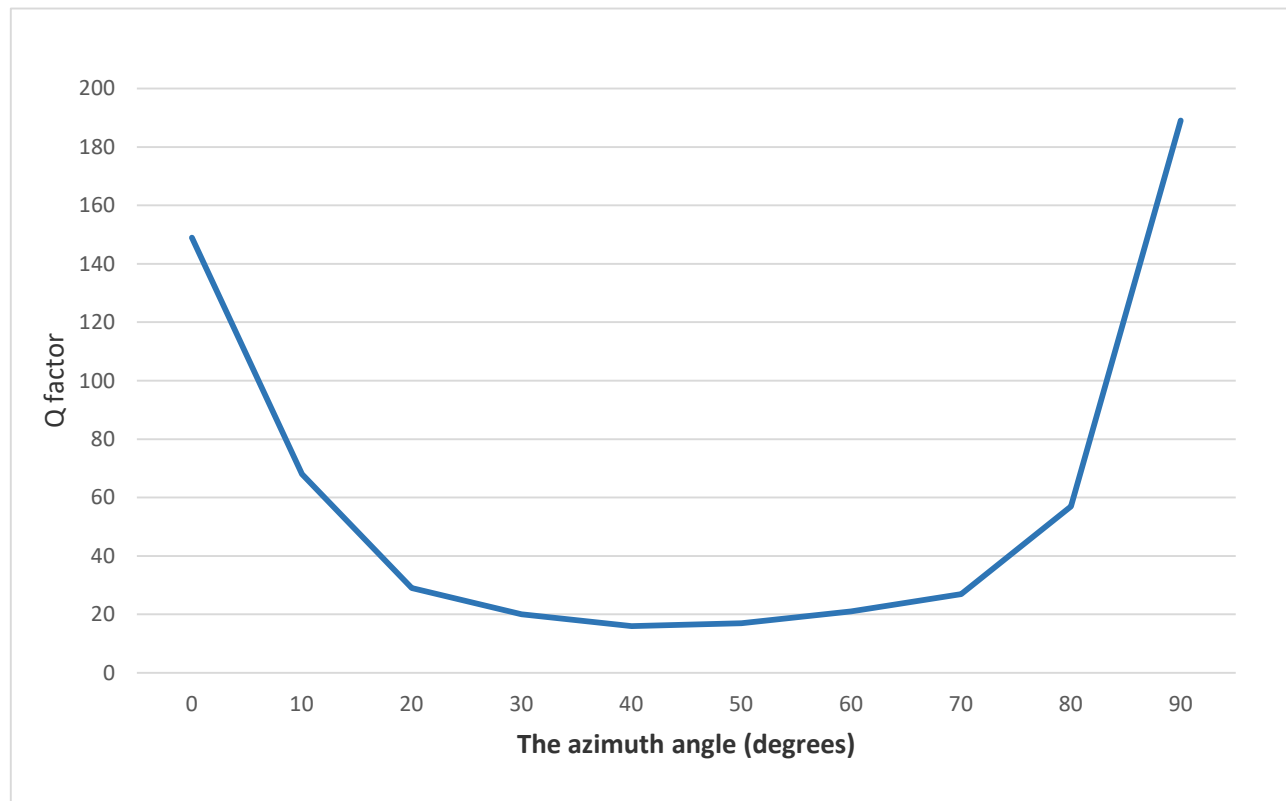


Figure 3.9: Q factor of a signal with respect to the input polarization

We can see from figure 3.9 has two peaks around 0° and 90° . Therefore, the PSPs most likely are the 0° and 90° axis. Which aligns well with section 2.6 that says the PSPs must be perpendicular. This means that if we send a pulse with its input polarization aligned with one of the PSPs it should arrive relatively undistorted. This can be confirmed with figure 3.10.

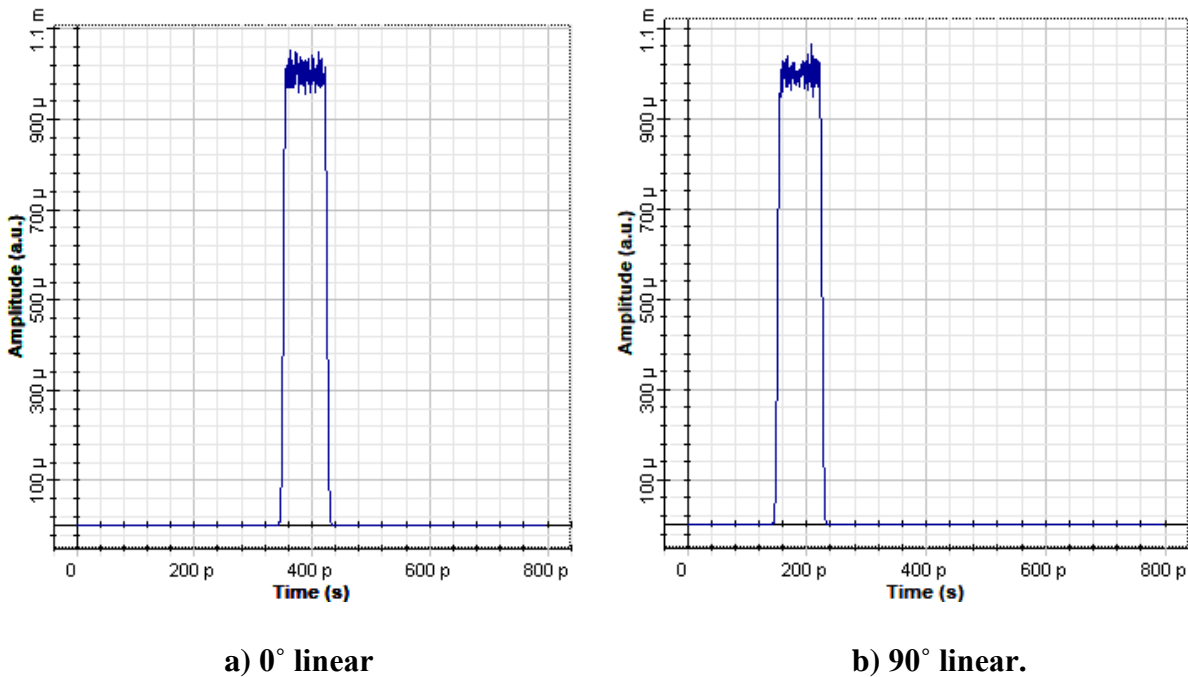


Figure 3.10: The output pulse shapes of a 10 Gbps signal through a PMD emulator with 200 ps DGD for two polarization launches

We notice from figure 3.10 that the difference in arrival times between the two polarization launches is exactly 200 ps, which is the DGD. We also see that the 90° PSP arrives first at the output meaning it is the fast PSP, while the other one is the slow PSP.

Now that we have seen the effect that the input polarization has on the signal and found out the direction of the PSPs of the PMD emulator, we can try two compensation methods and compare their effectiveness.

a) Polarization state transmission method (PST):

We can compensate the first order PMD effect by adding a polarization controller as demonstrated in figure 3.11. This device will make sure the input polarization of the signal stays aligned with the PSP of the emulator. The result of such simulation as displayed by the BER analyzer in shown in figure 3.12.

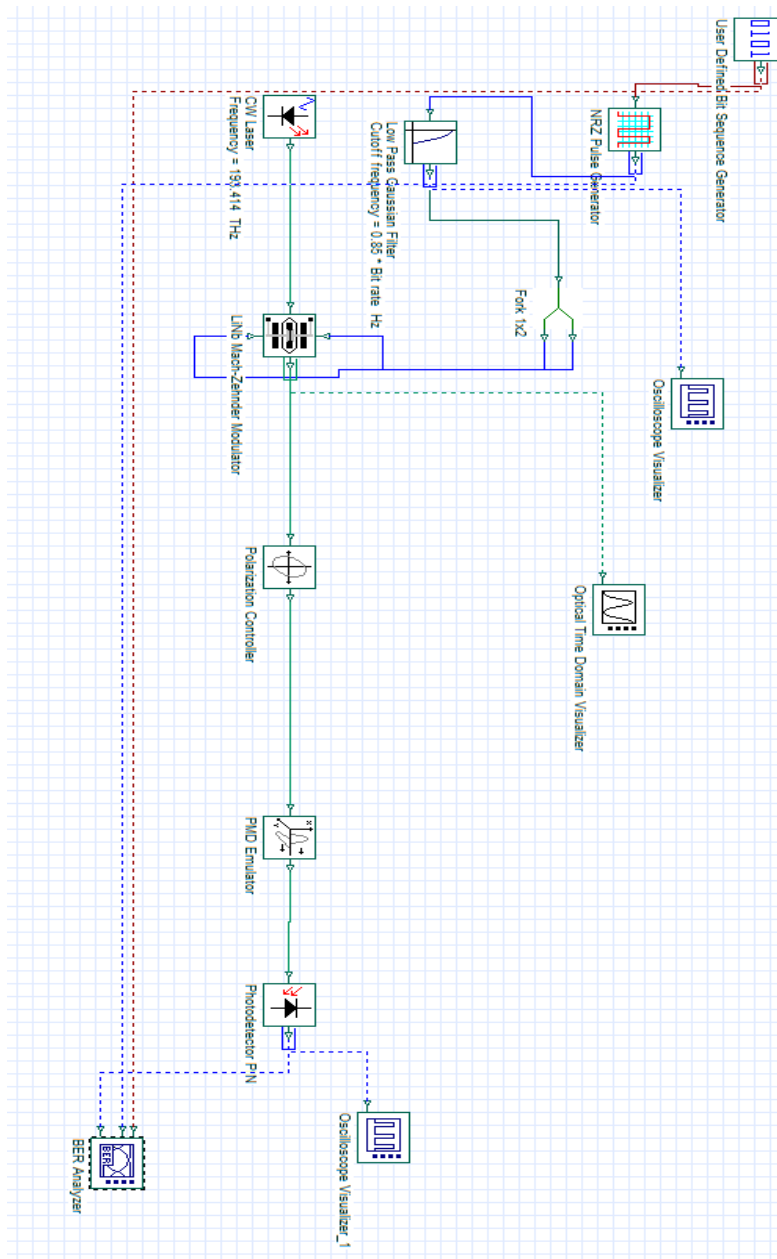
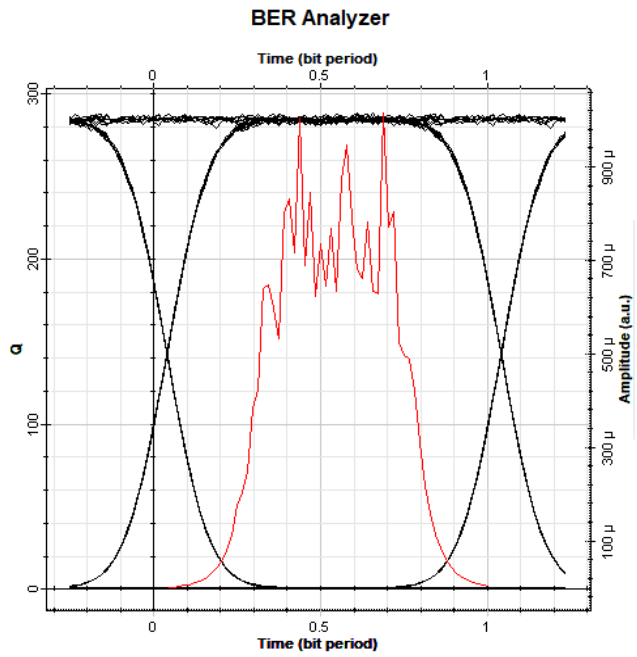
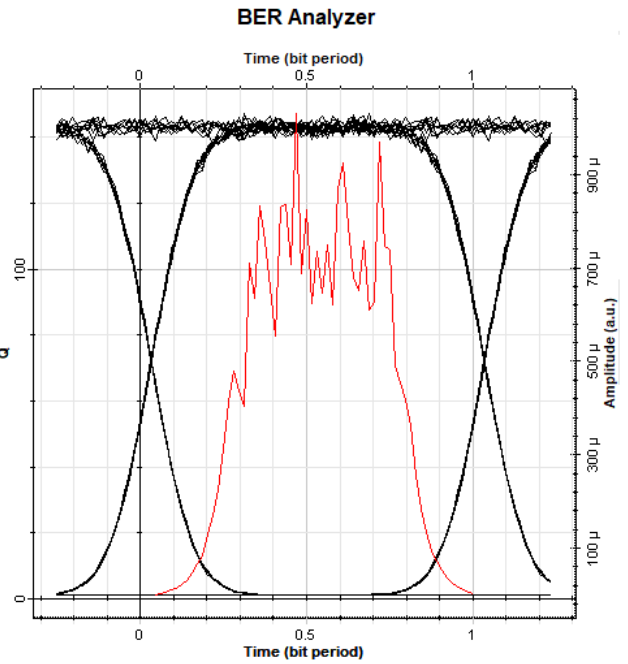


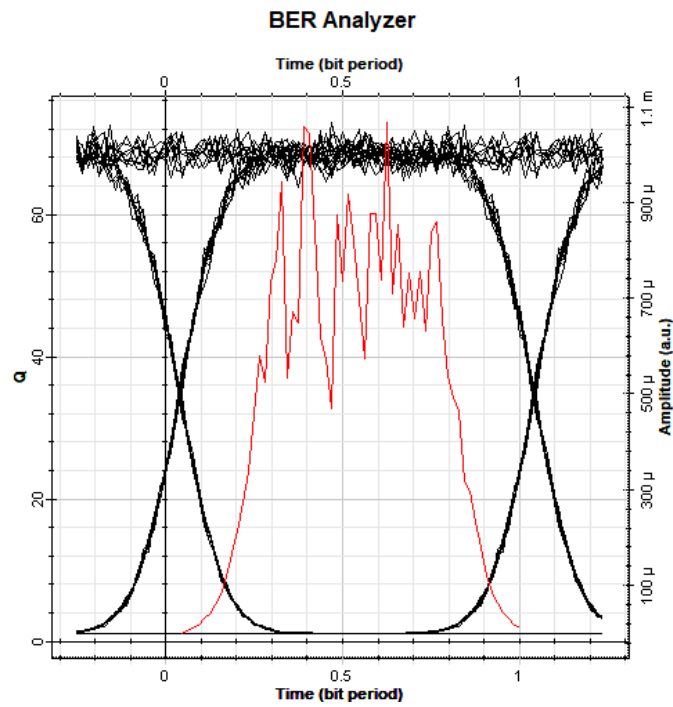
Figure 3.11: Simulation setup for first order PMD compensation



a) 2.5 Gbps



b) 10 Gbps



c) 40 Gbps

Figure 3.12: Eye diagram of a PMD affected signal compensated using the PST method at different bit rates

b) Optical delay method:

Unlike the PST method where we adjust the signal before sending it, in the optical delay method, we manipulate the signal after it has gone through the fiber. As presented in figure 3.13, the PMD-distorted signal is separated into two components using a polarization beam splitter. By adjusting the angle of the polarization splitter, the two resulting components are along the two PSPs. after introducing an adjustable delay in the branch with the fast PSP, the components are recombined using a polarization combiner.

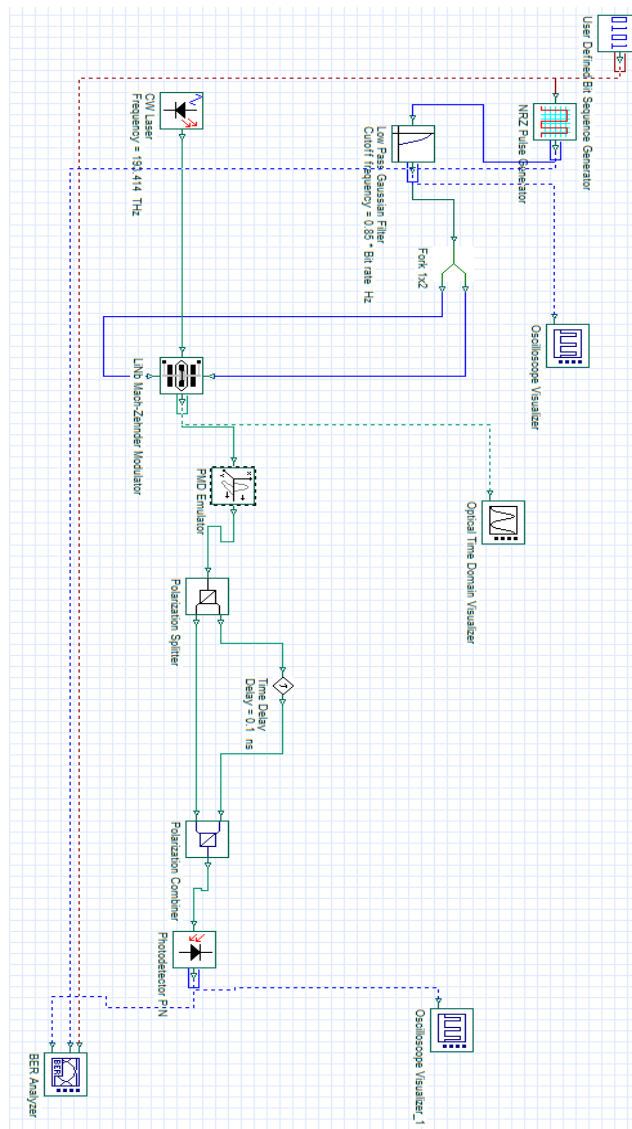
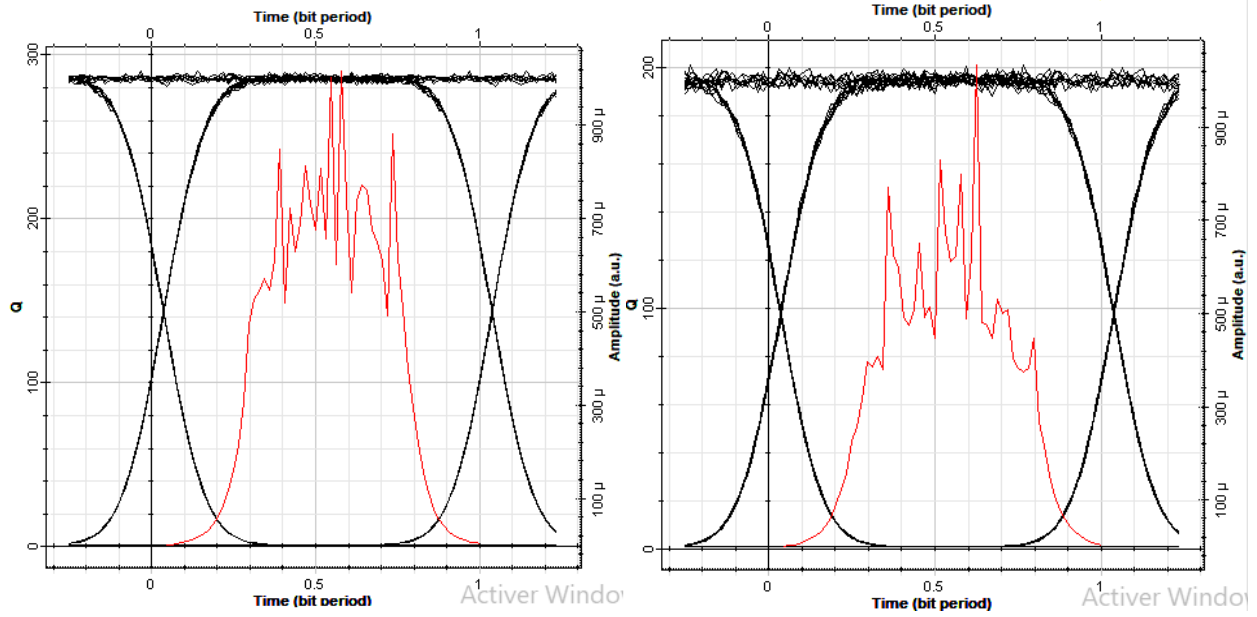
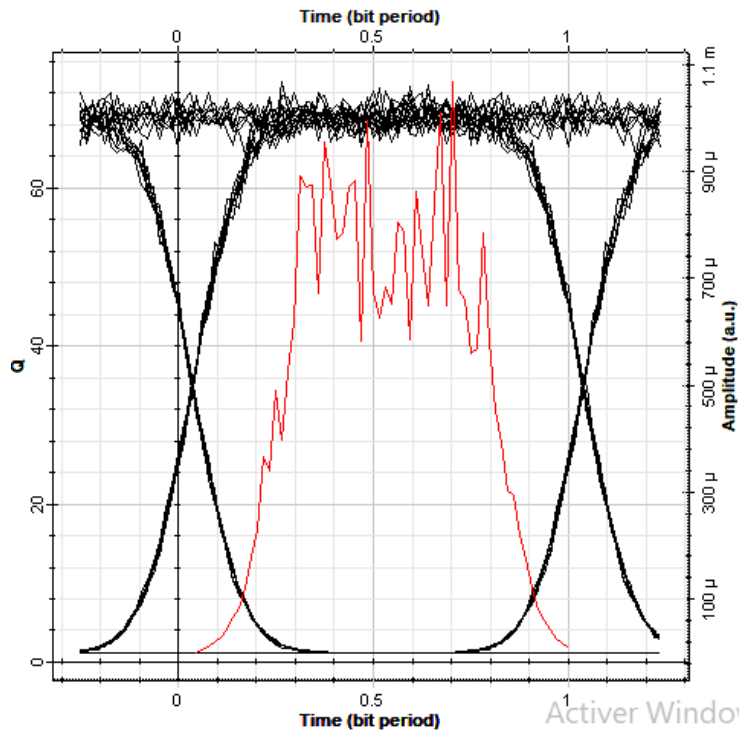


Figure 3.13: Simulation setup for first order PMD compensation using the optical delay method



a) 2.5 Gbps

b) 10 Gbps



c) 40 Gbps

Figure 3.14: Eye diagram of a PMD affected signal with the mean DGD=100 ps compensated using optical delay method at different bit rates

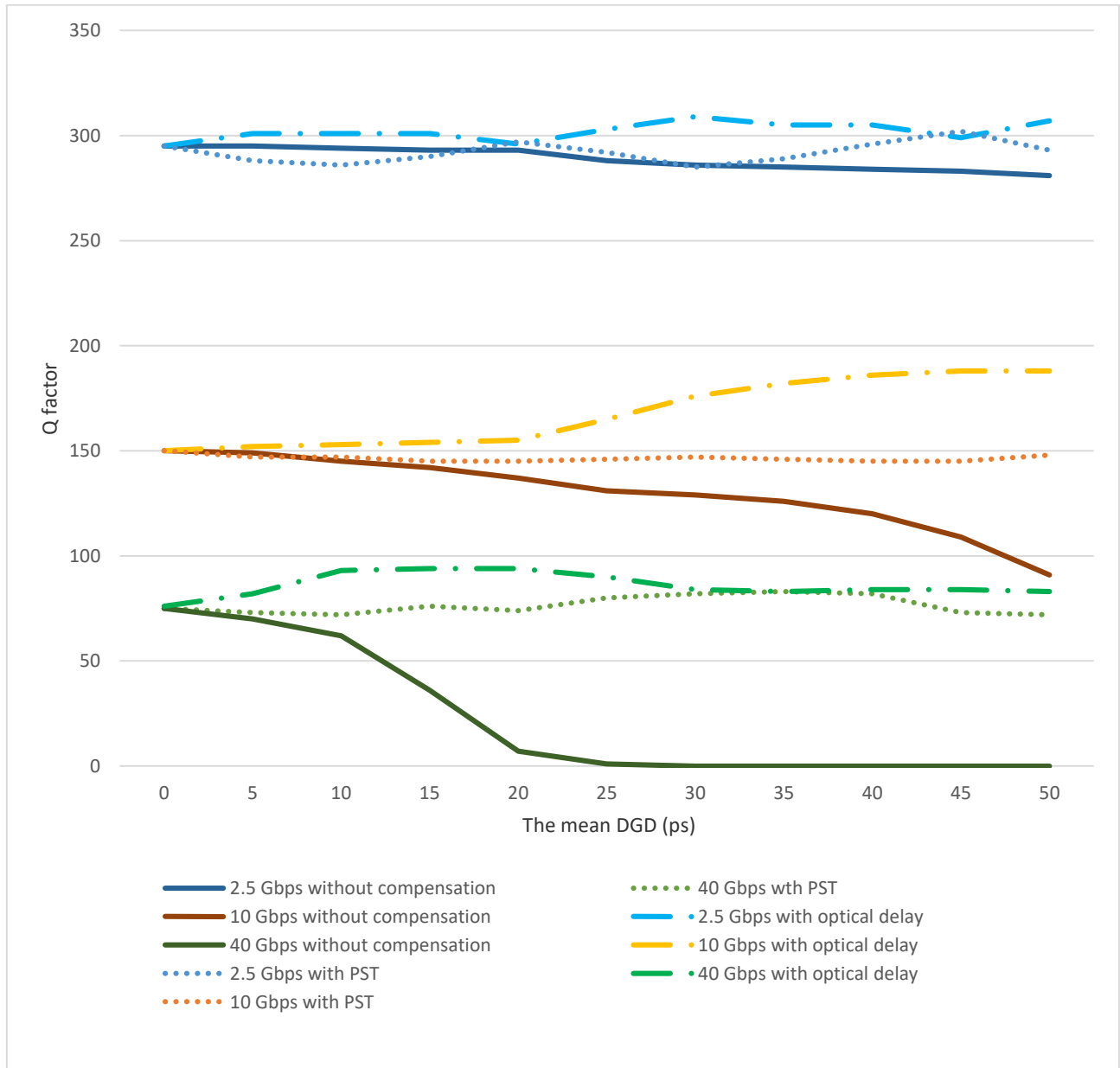


Figure 3.15: Q factor at different Bit rates before and after compensation

Discussion:

We notice from figure 3.15 that at low DGD values (≤ 10 ps) the signal is relatively undistorted and the Q factor is almost the same as the compensated signal. This means that high quality fibers with very low PMD coefficients can be used without the need for compensation. However, as the DGD increases, the Q factor starts decreasing rapidly and the higher bit rates signals drop faster than the lower ones. Meanwhile, the compensated signal's Q factor remains

stable even at high DGD values. Therefore, we can see that the principle state transmission (PST) compensation method nullifies almost all first order PMD effects. The downside to this technique is that the birefringence – and therefore, the PSPs – of a fiber in the field varies with time due to environmental changes and external stress. To solve this problem, the polarization controller needs to be updated regularly so that it is always aligned with the PSPs of the fiber. This process can be automated using a feedback circuit that updates the controller about the position of the PSPs.

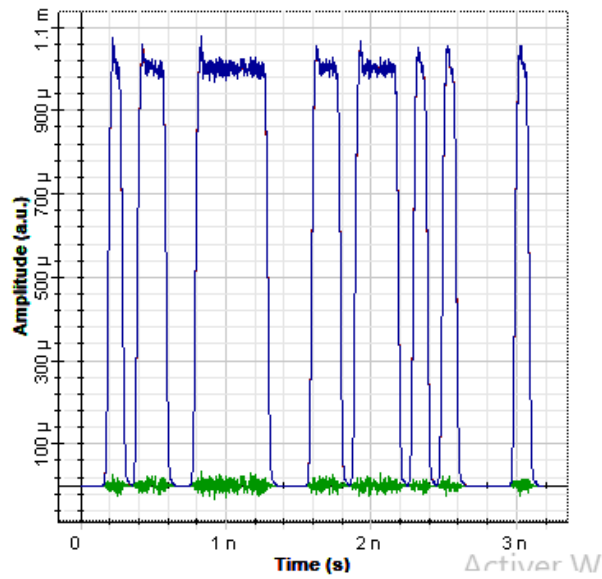
As for the optical delay method, it resulted in a consistently better signal quality than the PST method. However, similar to the other method, we still need a feedback loop to constantly update the polarization splitter's angle to align with the changing PSPs of the fiber. Another advantage to the optical delay is that due to the compensation devices being placed at the receiver end of the fiber, the feedback would have a shorter distance to travel, leading to less system outage and better capability to handle sudden birefringence changes in the fiber. The only disadvantage to this technique is that its success is dependent on the ratio L/L_{pmd} not exceeding four [26]. Where L is the length of the fiber and $L_{pmd} = (T_0/D_p)$, T_0 is the pulse width and D_p is the PMD coefficient.

To conclude, first order PMD can have a detrimental effect on optical signals and even though modern fibers inherently have low PMD coefficients, compensation techniques are still widely used today due to their effectiveness in almost completely negating first order effects.

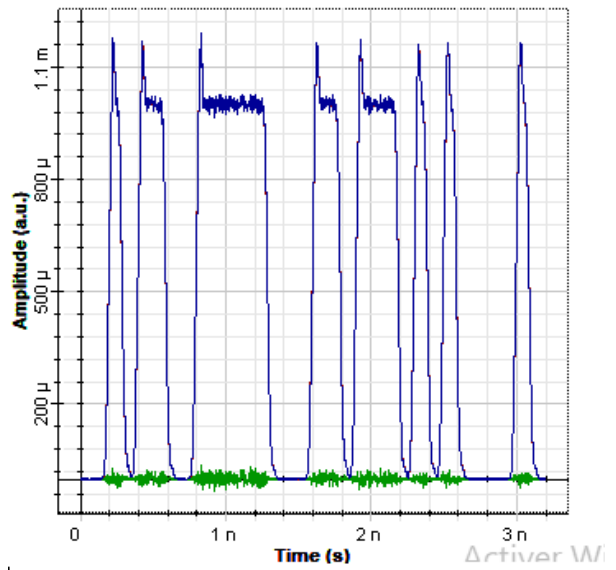
3.4.4 Effect of Second order PMD:

Unlike first order PMD, the second order PMD is a more complex phenomenon due to its tendency to induce partial loss of polarization in the wave. In OptiSystem, the depolarization rate serves as the governing parameter for second order PMD, which can be modified using the PMD emulator component. Using the same simulation design shown in figure 3.11. We fix the DGD at 30 ps, and the polarization chromatic dispersion to 0 ps/GHz, and then we adjust the value of the depolarization rate ranging from 0 deg/GHz to 10 deg/GHz.

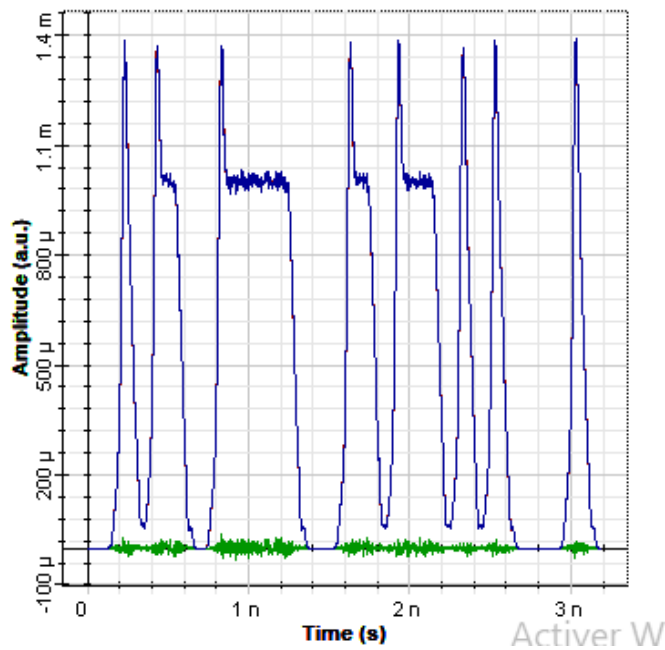
Figures 3.16 and 3.17 will show the result displayed by the oscilloscope visualizer and the BER analyzer respectively at 10 GBits/s as the depolarization rate changes.



a) 2.5 deg/GHz

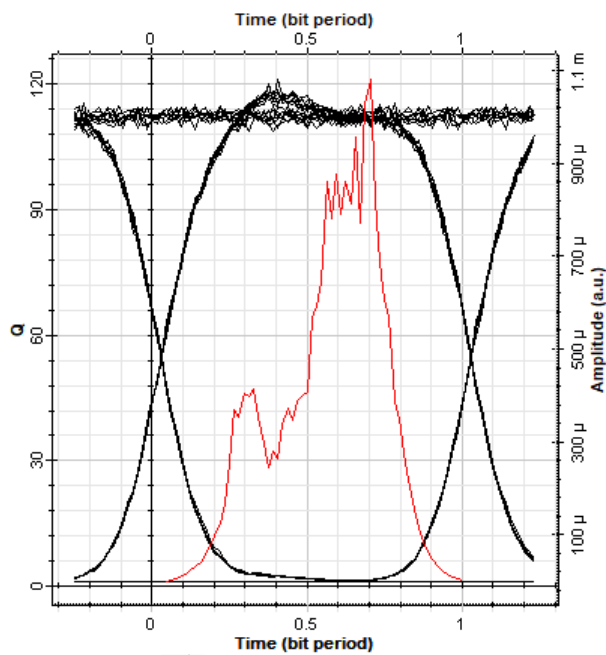


b) 5 deg/GHz

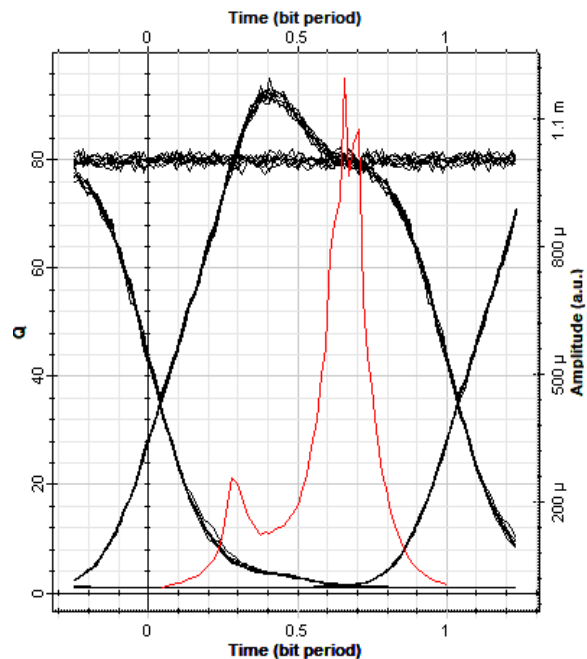


c) 10 deg/GHz

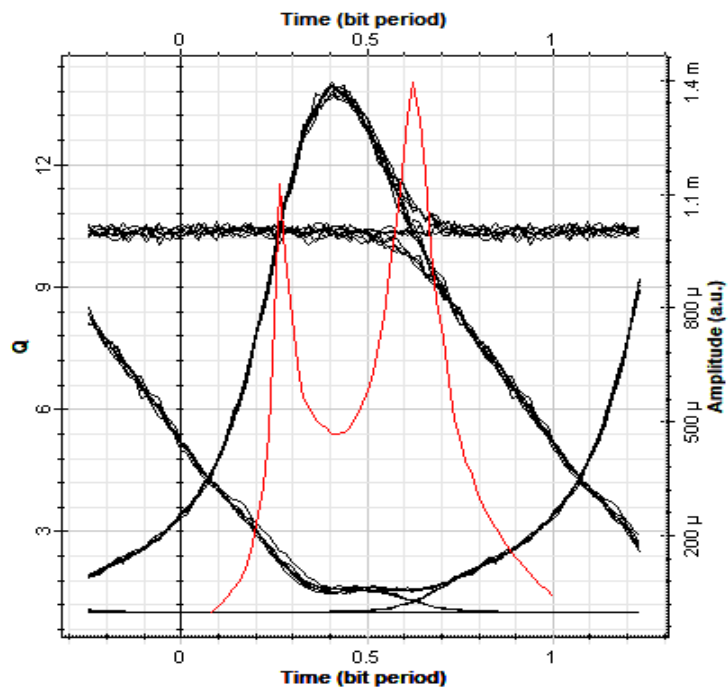
Figure 3.16: Oscilloscope output of 10 GBits/s second-order PMD affected signal for different depolarization rates



a) 2.5 deg/GHz



b) 5 deg/GHz



c) 10 deg/GHz

Figure 3.17: Eye Diagram of a 10 GBits/s second-order PMD affected signal for different depolarization rates

To gain a broader understanding of the impact of second order PMD, we will utilize a graph that shows the variation in the Q factor as the depolarization rate increases. This analysis will be conducted across various bit rates, specifically 2.5 GBits/s, 10 GBits/s, and 40 GBits/s.

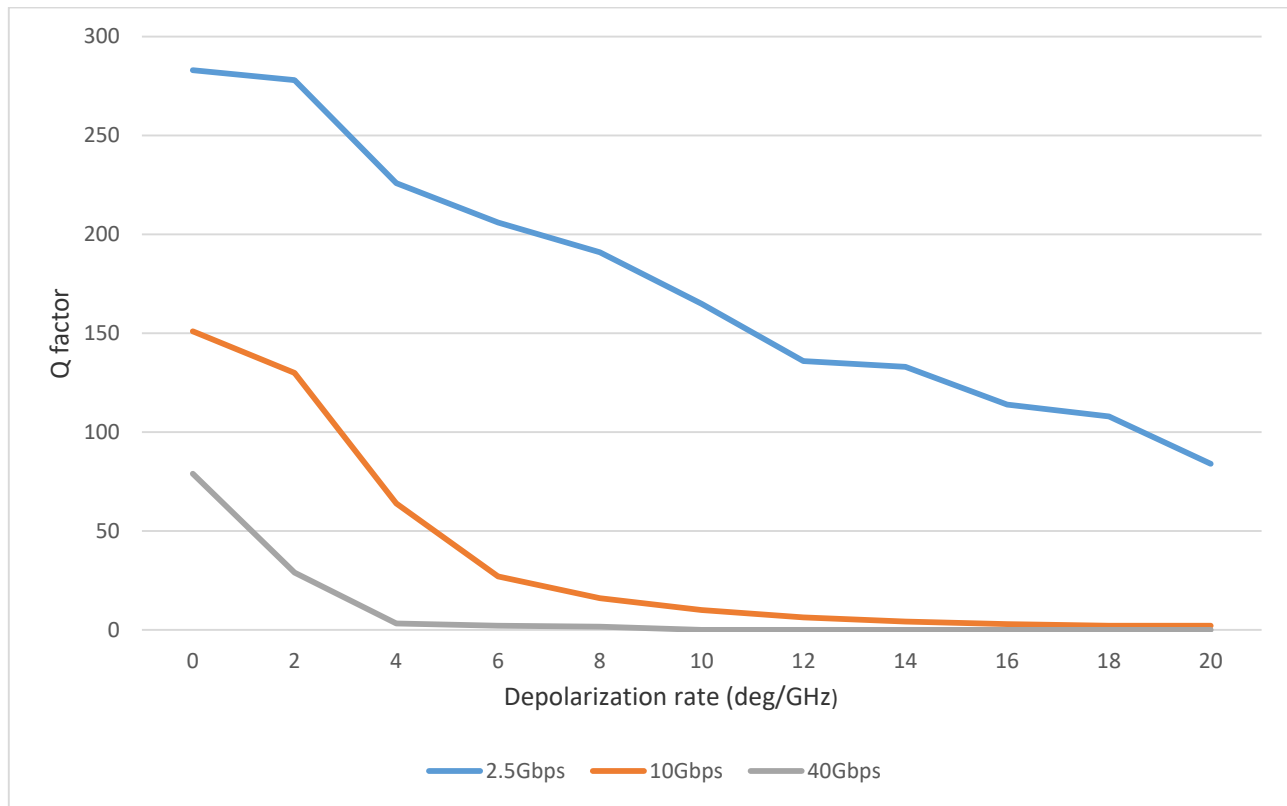


Figure 3.18: Q factor of a NRZ signal with respect to the depolarization rate at Bit rates of 2.5 GBits/s, 10 GBits/s, and 40 GBits/s

By analyzing the result given by the Oscilloscope analyzer and the BER analyzer shown in figures 3.16 and 3.17 respectively, we can see how the distortion in the signal is increasing as the depolarization rate increase. For a transmission speed of 10 GBits/s the figures show that for a depolarization rate of 2.5 deg/GHz the output signal still has a good quality. As the depolarization rate increase the distortion in the signal become more noticeable. At around 5 deg/GHz the signal has a relatively high BER, yet still can be decoded as shown by the eye Diagram. Going further with the depolarization rate until it reaches 10 deg/GHz will lead to a very poor signal with a BER close to 1. Moving to the chart shown in figure 3.18, as previously mentioned, the effect of PMD shines in higher Bit rates. This is evident from the 2.5 GBits/s line chart, the Q factor

remain relatively high even for 20 deg/GHz. On the other hand, when the Bit rates reaches 10 GBits/s the Q factor fall down faster, reaching a value of 10 at a depolarization rate of 10 deg/GHz. As for the simulation done with a 40 GBits/s bit rate, we can see how the second order PMD completely disturbed the signal starting from a depolarization rate of 4 deg/GHz.

3.4.5 Polarization dependent chromatic dispersion (PCD):

In the preceding discussion on second-order PMD, the influence of polarization-dependent chromatic dispersion was not taken into account. However, it is crucial to acknowledge the substantial role that PCD plays in pulse broadening and compression of signal components propagating in the principal polarization states. PCD intensifies the dispersion effects caused by SOPMD, thereby serving as the primary factor behind the adverse impact that SOPMD can impose on signal quality.

To explore the effects of SOPMD in the presence of PCD on the system performance, we first use the setup presented in figure 3.11 to test different PCD values without worrying about the first order PMD.

The results will be analyzed using a BER analyzer and the Q factor of the signal at different PCD and SOPMD values will be presented in figure 3.19.

Table 3.19: Q factor of a NRZ signal with the mean DGD = 30 ps at 10Gbps with respect to the PCD and depolarization rate.

Depolarization rate (Deg/GHz)	PCD (ps/GHz)				
	0	1	2	3	4
2	118	57	23	17	21
4	103	90	21	19	16
6	72	29	20	20	12
8	32	20	15	15	10
10	15	11	10	14	9

Discussion:

We notice from figure 3.19 that on average, the signal deteriorates as both the PCD and second order PMD increase and that the degradation due to depolarization rate builds up with chromatic dispersion. However, we also notice that the system performance improves at certain points. This is because the second order PMD in the presence of PCD can either compensate or accumulate the distortion caused by PCD [26]. To conclude, SOPMD can have a detrimental impact on optical transmission in the presence of PCD. Therefore, it is essential to address its impact. In the subsequent section, we will discuss the compensation methods employed to mitigate PCD.

3.4.6 Effect of PMD in real scenarios:

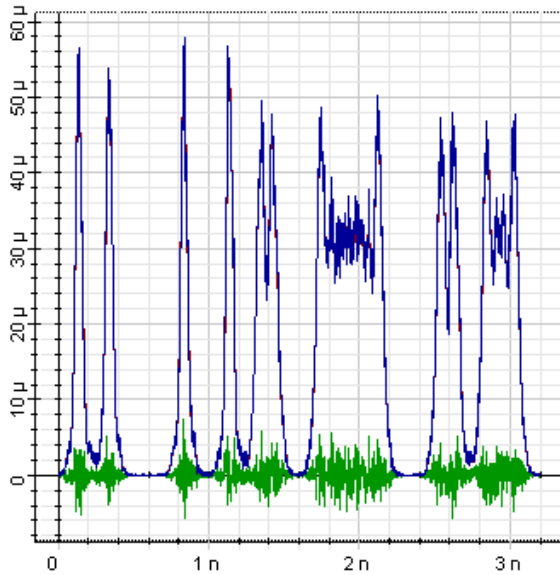
In the previous simulation the effect of attenuation and other type of dispersions were neglected, contrariwise, real fibers are affected by those effect in addition to the effect of PMD. In the next simulation we will be showing the effect of attenuation and other dispersion. Using the setup shown in figure 3.11, so that the first order PMD will be compensated, and the other effects will be shown clearly. The parameters of this simulation are shown in the figure 3.20:

Table 3.20: System Parameter for attenuation and dispersion effects

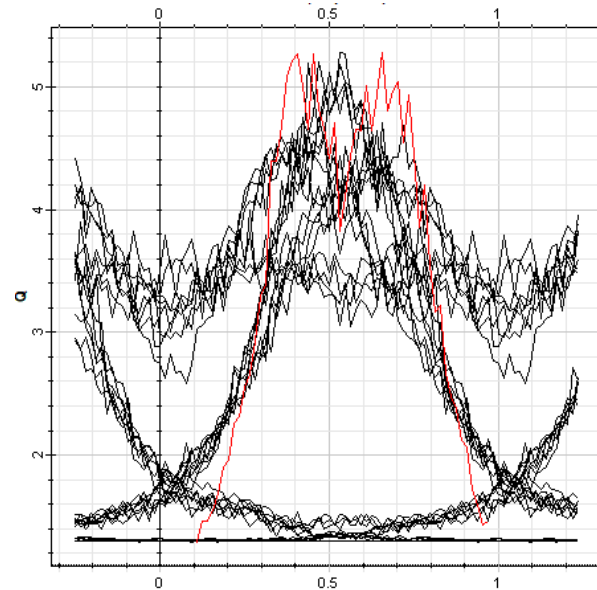
Parameter	Value
Bit rate	10 GBit/s
Length	100 Km
Power	15 dBm
Attenuation	0.3 dB/Km
Dispersion	4 ps/km
DGD	30 ps
Depolarization Rate	3.6 deg/GHz
PCD	3 ps/GHz

After running the simulation, the output of the oscilloscope visualizer and the BER analyzer are shown.

- From the oscilloscope it can be seen that the signal is under high distortion due to the chromatic dispersion, attenuation and SOPMD, as it is impossible to read the output signal. This same result can be seen from the BER analyzer that shows a quality factor value of around 5.3 and a highly distorted eye diagram.



(a)



(b)

Figure 3.21: simulation of dispersion and attenuation effects output of a) the oscilloscope visualizer b) BER analyzer

In order to solve this problem we will be using the Fiber Bragg Grating technique (FBG) method to compensate the chromatic dispersion as well as the PCD. As stated before the effect of SOPMD is directly related to the PCD, this means that compensating the PCD will reduce the impact of the SOPMD on the signal. For this purpose, we will use an Ideal Dispersion Compensation Fiber Bragg Grating (IDCFBG), which will be added before the PMD emulator component. In addition, we will add an optical amplifier in order to compensate for the attenuation. Figures 3.22 and 3.23 will show respectively:

- The complete setup for this simulation after adding the IDCFBG component and the optical amplifier.
- Output of the oscilloscope visualizer and the BER analyzer after the compensation.

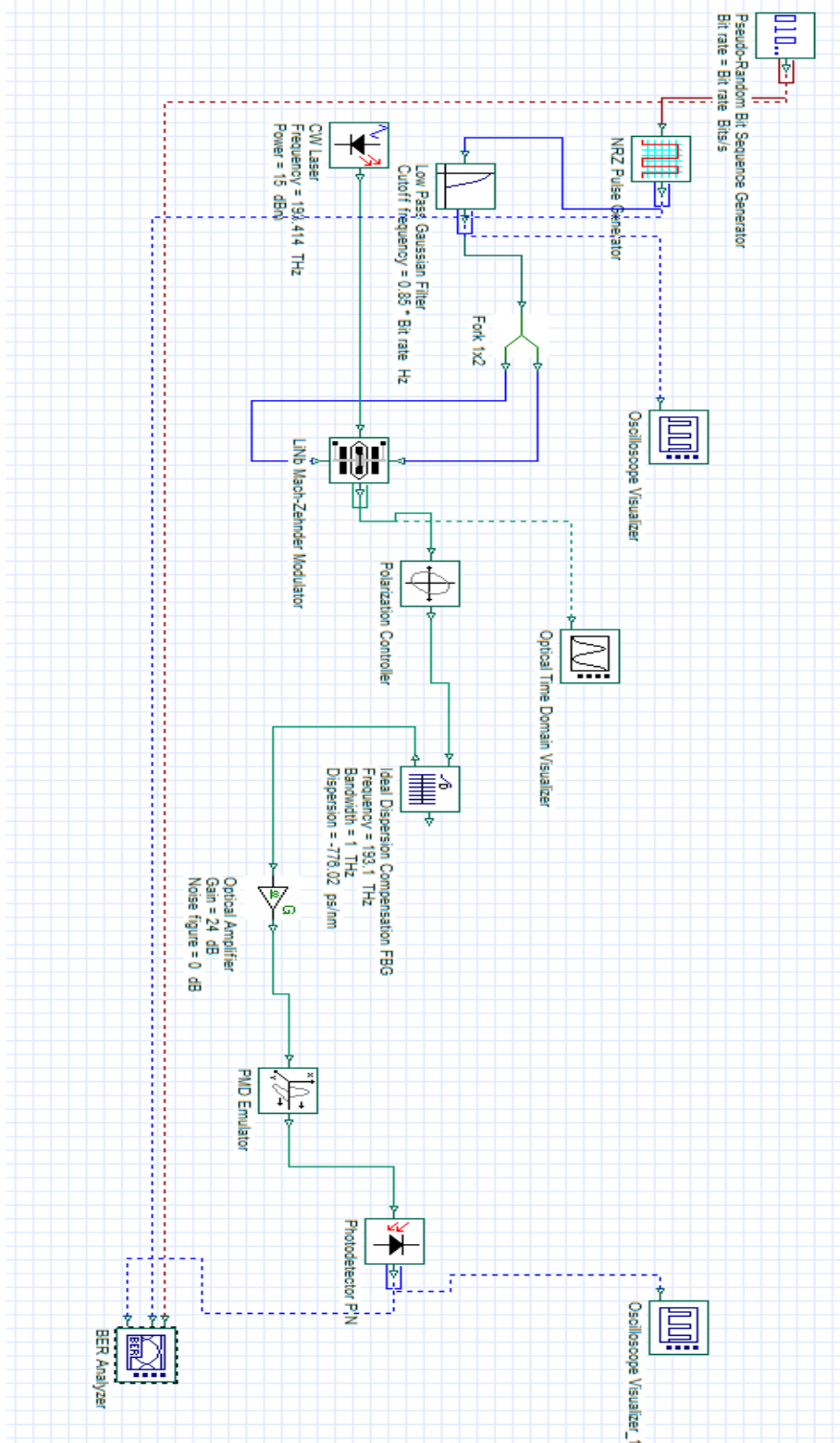


Figure 3.22: attenuation and dispersion simulation design

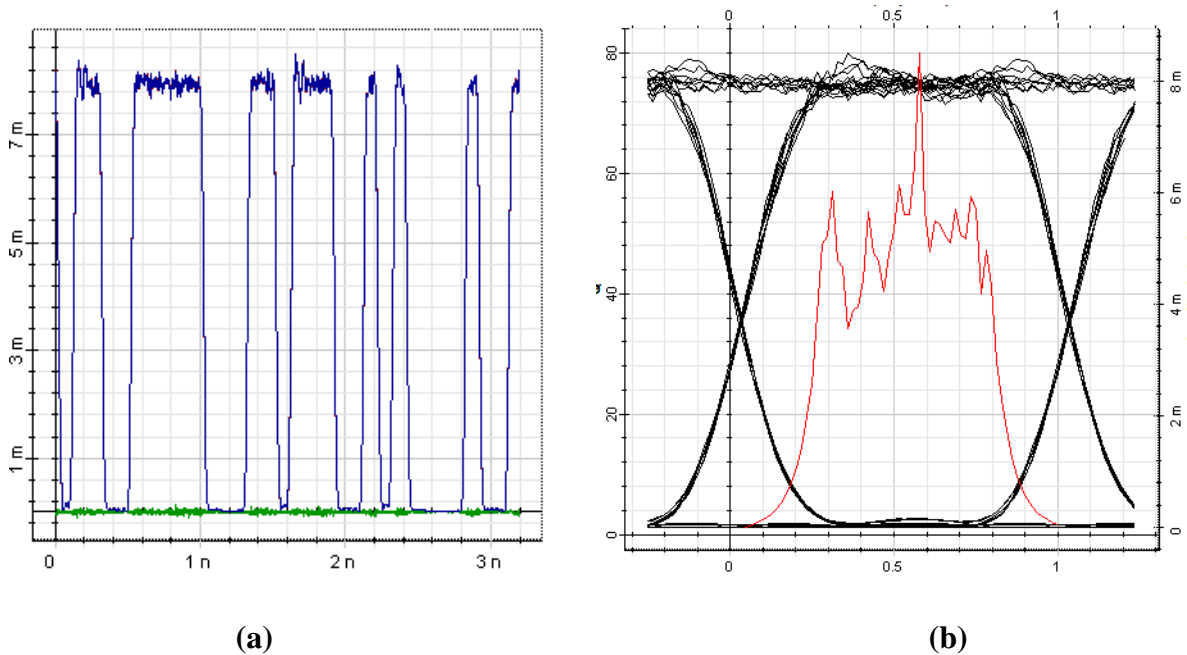


Figure 3.23: result of compensation displayed by a) oscilloscope b) BER analyzer

The oscilloscope visualizer show how the signal distortion has been erased, as the signal is now clear and similar to the input signal but shifted by 30ps due to the first order PMD. The BER analyzer show a high quality factor of 80, the diagram show also how the bit error rate is negligible.

The IDCFBG technology is designed to counteract the chromatic dispersion that occurs in optical fiber communication systems. FBGs are periodic variations in the refractive index of an optical fiber that act as wavelength-selective reflectors. They can be used to create dispersion compensators by introducing specific wavelength-dependent phase shifts to counterbalance the dispersion effects. From the previous simulation, the effectiveness of the IDCFBG became clearer as it totally solved the problem of chromatic dispersion within the fiber and indirectly reduced the effect of SOPMD by compensating the PCD. As for the optical amplifier, it was used in order to compensate for the attenuation that was simulated using the PMD emulator component.

Chapter 4

Conclusion

Polarization Mode Dispersion (PMD) poses a significant threat to optical signals, particularly in long-haul and high-speed communication systems. Over the years, researchers have dedicated considerable efforts to address and mitigate this issue, and new methods of mitigation continue to be explored to this day.

PMD can be classified into multiple orders. Higher order PMD effects become more significant the higher the bit rate we use. In our project, we focused on analyzing the impact of PMD, specifically its first and second order effects, which are the primary sources of signal distortion. We isolated these orders individually and studied their influence at various bit rates (2.5 Gbps, 10 Gbps, and 40 Gbps). Next, we introduced the PCD and analyzed the variation in the SOPMD effects on the signal as the PCD changes. Furthermore, we employed two first order compensation techniques (PST and optical delay method) to assess their effectiveness and observe each method's advantages and disadvantages. To simulate real-world scenarios, we introduced chromatic dispersion and attenuation, observing how they influence the signal transmission. To achieve comprehensive compensation for all types of dispersions and attenuations, we combined the PST compensation technique with the FBG method.

Our analysis involved several essential tools, including BER analyzers, eye-diagrams, and oscilloscope visualizers. The results of our simulations revealed that first order PMD effects are relatively tolerable at low bit rates but exhibit exponential growth at higher bit rates. However, both the PST and optical delay compensation techniques demonstrated remarkable effectiveness in completely mitigating the first order effects. To illustrate our findings, we presented a graph comparing uncompensated and compensated signals across different bit rates, which revealed that the optical delay was slightly more effective than the PST. In the simulation of the second order PMD, we saw how it is directly connected to the PCD; higher values of the PCD intensify the distortion caused by the SOPMD. Remarkably, the combination of the FBG method with the PST compensation technique yielded excellent results, effectively reducing the signal Bit Error Rate (BER) to an insignificant level. In addition to effectively compensating for chromatic dispersion, the FBG method also successfully compensated the PCD resulting in a significant reduction in the impact of the SOPMD. Finally, the issue of attenuation can be easily resolved by incorporating an optical amplifier to compensate for power loss.

Looking towards future work, we recommend further enhancing the PSP compensation technique by implementing a feedback circuit to continuously update the polarization controller. Additionally investigating other methods for second order compensation is an intriguing avenue for future research.

By conducting this study, we have contributed to the ongoing efforts in combating PMD-induced distortions in optical communication systems. The insights gained from our project highlight the importance of effective compensation techniques and pave the way for future advancements in this field.

Appendix

Eye diagrams :

The eye diagram technique is a valuable measurement method to evaluate the data-handling capability of digital transmission systems. It is widely used for assessing the performance of both wire systems and optical fiber data links. This technique employs time domain measurements to display the immediate impact of waveform distortion on standard BER test equipment screens.

In Figure 1, we can observe a common visual representation referred to as an eye pattern or eye diagram. This display pattern illustrates the upper and lower limits determined by the logic 1 and 0 levels, represented as b_{on} and b_{off} respectively [9].

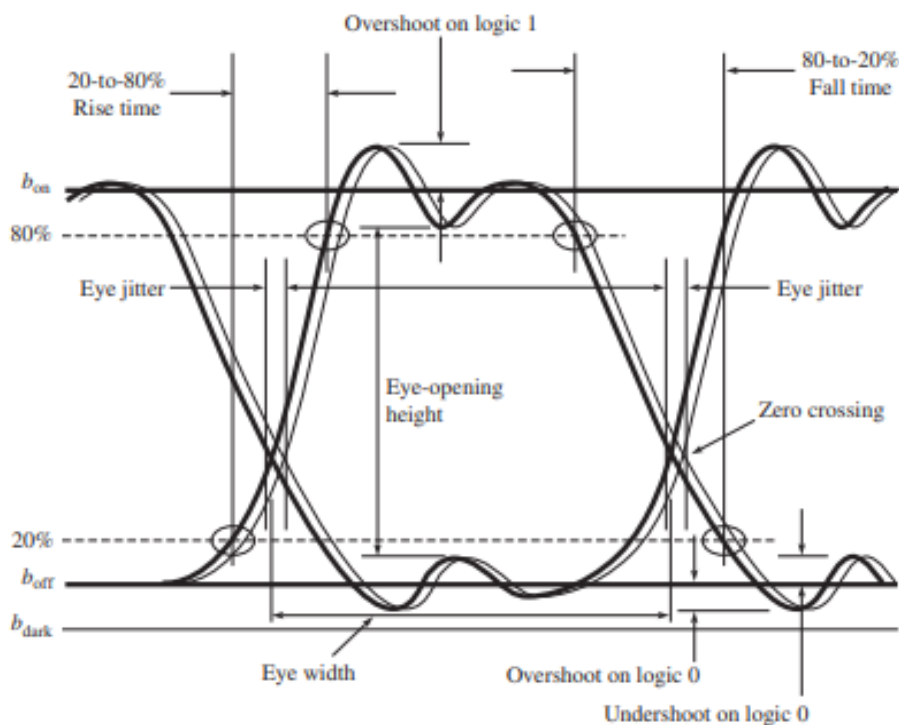


Figure 4: General configuration of an eye diagram.

Figure 1 show the fundamental measurement parameters of an eye diagram. The following is a brief definition of those parameters.

- **Eye width:** the time period during which the received signal can be accurately sampled without any interference caused by neighboring pulses.
- **Height of the eye opening:** the vertical distance between the top of the eye opening and the maximum signal level on the display. It indicates the degree of amplitude distortion in the data signal. When the height of the eye opening is largest, it signifies the optimal time to sample the received waveform. As the height of the eye opening reduces, it indicates increased distortion, making it more challenging to differentiate between 1s and 0s in the signal.
- **Eye jitter:** the mean value of a thin vertical histogram window centered on the crossing point of the eye diagram. The eye jitter is then calculated using the following equation:

$$\text{Eye jitter}(\%) = \frac{\Delta T}{T_b} \times 100\%$$

Where ΔT is the amount of distortion at the threshold, and T_b is the bit interval.

- **Rise time:** the time interval between the points where the rising edge of the signal reaches 10 percent of its final amplitude to the time where it reaches 90 percent of its final amplitude. However, because these points are often obscured by noise and jitter effects, the rising time is generally measured at the more distinct values at the 20 percent and 80 percent threshold points
- **Fall time:** the time interval between the points where the falling edge of the signal reaches 90 (or 80) percent of its maximum amplitude to the time where it reaches 10 (or 20) percent of its maximum amplitude.

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