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Design and performance analysis of QPSK transceiver for high speed coherent optical communication systems

Defense Committee Members:

Pr. MEDJOURI Abdelkader

Pr. Mohamed Nadjib Kateb

Pr. Abdelkader Hima

Presented by:

Houamed Ziad

Mebarki Imad Eddine

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إهداء

بسم الله الرحمن الرحيم

أهدي ثمرة هذا العمل المتواضع إلى من كانا سبب وجودي بعد الله، إلى من غرسا في نفسي حب العلم والاجتهاد، إلى من سهرا الليالي وتحمّلا المشاق من أجل أن أصل إلى ما أنا عليه اليوم،

إلى والديّ العزيزين، حفظهما الله وأطال في عمرهما، جزاءً لما قدماه لي من حب وتضحية وعطاء لا يُقدَّر بثمن.

إلى إخوتي وأخواتي، سندي في الحياة ورفقاء دربي، الذين كانوا مصدر قوة ودعم في كل خطوة من خطواتي.

إلى عائلتي الكريمة، التي أحاطتني بالمحبة والتشجيع والدعاء.

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وإلى كل أستاذ علّمني حرفًا، وأسهم في تكويني العلمي والمعرفي.

إليكم جميعًا أهدي هذا العمل عربون وفاء وتقدير وامتنان

حوامد زياد

بسم الله الرحمن الرحيم

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مباركي عماد الدين

Abstract

This thesis presents a study of optical fiber communication systems and digital modulation schemes, focusing on the design and simulation of a coherent optical QPSK transceiver. In this work, we first addressed an overview of fiber-optic communication systems, covering their basic components, historical evolution, and fiber characteristics. We then explored digital modulation techniques and optical modulators, examining line coding, pulse shaping, and advanced schemes such as ASK, PSK, FSK, and QPSK. Finally, we presented the full simulation of the coherent QPSK transceiver, analyzing the obtained results including NRZ waveforms, eye diagrams, and the constellation diagram.

Keywords

Optical Fiber Communication, Coherent Optical Communication, QPSK Modulation, Optical Transceiver, Coherent Detection, Optical System Simulation, Performance Analysis

ملخص

تقدم هذه الأطروحة دراسة لأنظمة الاتصالات عبر الألياف الضوئية وتقنيات التضمين الرقمي، مع التركيز على تصميم ومحاكاة جهاز إرسال واستقبال ضوئي متماسك بتقنية QPSK. في هذا العمل، تطرقنا في البداية إلى نظرة عامة على أنظمة الاتصالات بالألياف الضوئية، من خلال تناول مكوناتها الأساسية وتطورها التاريخي وخصائص الألياف. ثم تطرقنا إلى تقنيات التضمين الرقمي والمعدِّلات الضوئية، باستعراض أساليب الترميز الخطي وتشكيل النبضات والمخططات المتقدمة كـ ASK و PSKو FSKو QPSK. وأخيراً قدمنا المحاكاة الكاملة لجهاز إرسال واستقبال QPSK المتماسك، مع تحليل النتائج المتحصل عليها بما فيها أشكال موجات NRZ ومخططات العين ومخطط الإشارة.

كلمات المفتاحية :

الاتصالات بالألياف الضوئية ، الاتصالات الضوئية المتماسكة ، تضمينQPSK، المرسل والمستقبل الضوئي، الكشف المتماسك، محاكاة الأنظمة الضوئية ، تحليل الأداء

Résumé

Cette thèse présente une étude des systèmes de communication par fibre optique et des techniques de modulation numérique, axée sur la conception et la simulation d'un émetteur-récepteur optique cohérent QPSK. Dans un premier temps, nous proposons une vue d'ensemble des systèmes de communication par fibre optique, en abordant leurs composants de base, leur évolution historique et les caractéristiques des fibres. Nous explorons ensuite les techniques de modulation numérique et les modulateurs optiques, en examinant le codage en ligne, la mise en forme d'impulsions et des techniques avancées telles que l'ASK, le PSK, le FSK et le QPSK. Enfin, nous présentons la simulation complète de l'émetteur-récepteur cohérent QPSK et analysons les résultats obtenus, notamment les formes d'onde NRZ, les diagrammes de l'œil et le diagramme de constellation.

Table of Contents

List Figures :

CHAPTER 01

CHAPTER 02

CHAPTER 03

List Tables :

General introduction

The rapid growth of global data traffic has placed enormous demands on modern communication infrastructure, driving the need for faster, more efficient, and higher-capacity transmission systems. Optical fiber communication has emerged as the dominant technology to meet these demands, offering exceptionally low signal attenuation, immunity to electromagnetic interference, and the ability to carry vast amounts of data over long distances. This thesis investigates the design and simulation of a coherent QPSK optical transceiver system operating at 25 Gbit/s. The work is organized into three chapters, each building upon the previous to provide a comprehensive understanding of the system from its theoretical foundations to practical simulation and results. Chapter One presents a broad overview of optical fiber communication systems, covering their historical evolution, basic structure, fiber characteristics, and the fundamental principles of transmission, reception, and optical networking. Chapter Two examines the digital modulation techniques used in optical communications, with a focus on line coding, pulse shaping, and advanced modulation schemes including ASK, PSK, FSK, and QPSK, as well as the optical modulators and coherent receivers required to implement them. Chapter Three presents the full simulation of the QPSK optical transceiver using software, detailing each system component and analyzing the obtained results including NRZ waveforms, eye diagrams, and the constellation diagram.

CHAPTER 01

Overview On Fiber-Optic Communication Systems

1.Introduction

Optical communication systems have become a fundamental technology for high-speed and efficient data transmission, as they rely on light propagation through optical fibers to carry information over long distances with minimal loss and high immunity to interference.[1]This chapter provides an overview of these systems, starting with their basic components such as the transmitter, channel, and receiver, followed by their historical development and significance in modern applications .It also examines the characteristics of optical fibers and the main factors affecting signal quality during transmission, highlighting their essential role in the advancement of modern communication networks.

2. Historical overview of optical fiber communication

Optical fiber communications have a long history, dating back to the 19th century when people first attempted to transmit information using light. They faced difficulties controlling the light, but a major breakthrough occurred in the 1960s with the invention of the laser, which enabled stable light transmission. [1] However, transmitting light through the air was not entirely reliable due to environmental interference. Therefore, researchers began exploring the use of fibers to guide light.

Optical fibers are made of transparent glass and guide light through the phenomenon of total internal reflection. Initially, optical fibers were used for lighting and other applications. In 1966, Charles Kao recognized their potential for use in communications, and their practical application became possible in the 1970s as fiber quality improved and signal loss decreased .[2]

CHAPTER 01

In subsequent years, new technologies such as laser diodes, optical signal amplifiers, and wavelength division multiplexing (WDM) significantly enhanced the strength and reliability of optical fiber communications. These new technologies allowed for the efficient transmission of multiple signals simultaneously over long distances. Today, optical fibers are an integral part of communication, including the internet, massive data centers, and networks spread across the globe. Fiber optics are characterized by their ability to transmit enormous amounts of information with minimal signal loss and are unaffected by electromagnetic interference. [3]In the future, optical communications are expected to see further advancements with the development of fully optical networks, which aim to increase speed and efficiency by reducing reliance on electronic components.

3. Basic structure of an optical fiber communication system

Optical fiber communication systems are really good at sending information from one place to another. They use light to do this. Optical fiber communication systems work by turning an electronic signal into a light signal. Then they send this signal through a special kind of wire that does not lose much of the signal. At the end they turn the light signal back into a regular electronic signal. [2]An optical fiber communication system has three parts that work together: the optical transmitter, the optical fiber channel and the optical receiver. The optical transmitter and the optical fiber channel and the optical receiver all work together to make sure that information is sent quickly and without getting messed up. Optical fiber communication systems are good, at sending information and they do not lose much of the information when they send it.

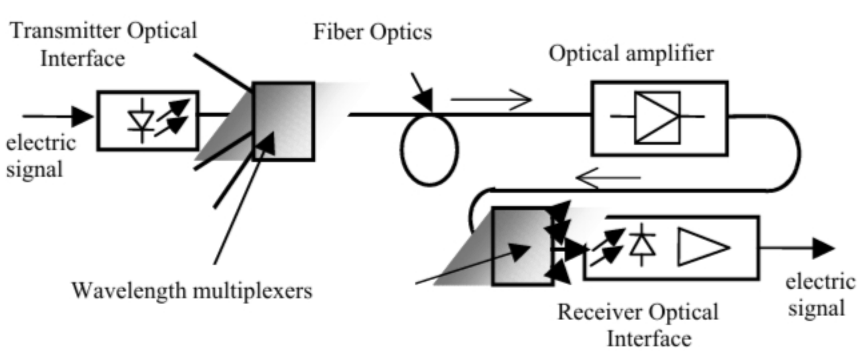

Figure 1.1: Point-to-point fiber-optic link

CHAPTER 01

3.1 Optical transmitter

The optical transmitter is the starting point of the communication system, where the electrical signal carrying the information is converted into an optical signal that can be transmitted through the optical fiber. This component comprises several essential elements, including the light source, the modulator, and the interface for coupling with the fiber. [1] [5]

3.1.1 Light Source (Optical Source)

The light source is the essential element in the transmission process, as it is where the optical signal is generated. Among the most important sources used are:

• Light Emitting Diode (LED)

The light-emitting diode, or LED, is a fundamental component in optical communication systems. LEDs are used as light sources to convert electrical signals into optical signals.

The operating principle of an LED is based on the phenomenon of recombination within a cf negative region. When an electrical voltage is applied, electrons recombine with holes, emitting energy in the form of photons, which are visible or invisible light depending on the type of material. LEDs possess several characteristics that make them suitable for use in this field. These characteristics include their small size, low power consumption, long lifespan, and acceptable data transmission speed.

However, the light emitted by an LED is incoherent, making it less efficient than a laser diode in applications requiring long-distance, high-speed data transmission.[2] Nevertheless, LEDs remain an economical and efficient option for short- to medium-distance systems.

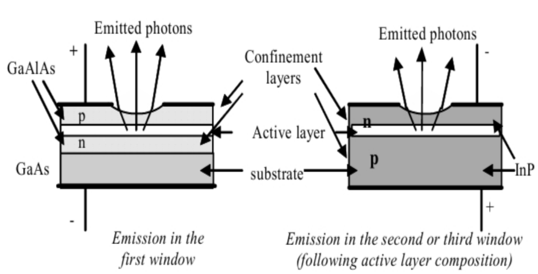

Figure 1.2:

Light-emitting diodes

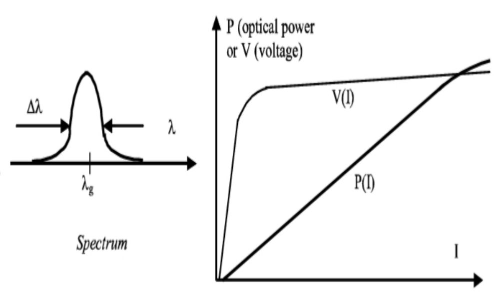

Figure 1.3:

Characteristics of a lightemitting diode

• Laser Diode (LD)

The laser is a key component in coherent communication systems as it functions both as a carrier in the transmitter and as a local oscillator (LO) in the receiver. Commonly، diode lasers due to their efficiency and reliability are favored to be used at both the transmitter and the receiver.

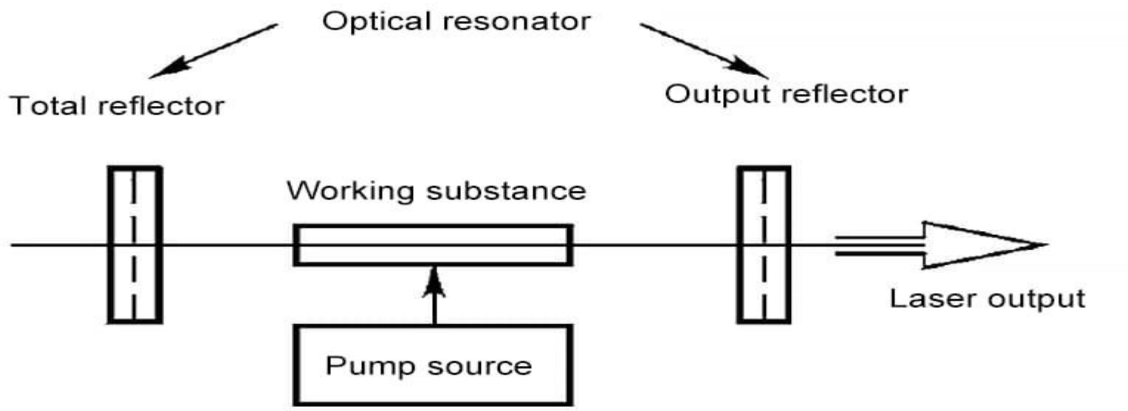

Figure 1.4: Schematic diagram of the basic structure of the laser

The lasers' efficiency relies on several factors such as wavelength stability, launch power, and line width.The laser's launched power determines the amplifier (or repeater) spacing. Increasing the launch power extends the spacing between the amplifiers, saving costs by reducing the number of required amplifiers. However, the nonlinear effects of the fiber limit the extent to which the launch power can be raised. Typically, launched power is denoted in dBm units, with 1 mW acting as the reference level.

The laser line width determines the spread of optical frequencies around the laser's nominal output frequency, which directly impacts the phase noise of the laser. [5] Thus، narrower line width implies more stable frequency emission and larger line width indicates higher frequency deviation.

3.1.2 The Modulator

A modulator is a device that encodes an information signal onto a high-frequency carrier by varying its amplitude, frequency, or phase for transmission. It includes analog (AM, FM, PM) and digital (ASK, FSK, PSK, QAM) techniques depending on system needs. Its performance is evaluated by metrics such as spectral efficiency and bit error rate (BER)..

3.1.3 Coupling

This stage involves inserting the light signal into the optical fiber with minimal loss. It is a delicate process requiring precise alignment between the light source and the fiber's properties.

3.2 Optical fiber channel

Optical fibers are narrow strands made of silica glass which carry the optical signal from one end to the other. Step-index fibers consist of a core made of glass with a refractive index n1 that is higher than the refractive index of the surrounding cladding layer nc, as shown in Figure 1.5.

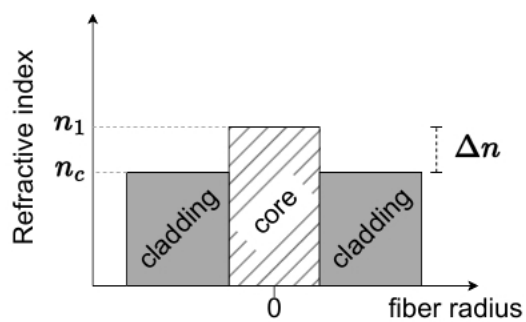

Figure 1.5: Refractive index profile.

This configuration traps light propagating inside the fiber by continuously bouncing the light against the boundary separating the core and cladding . The refractive index difference can be achieved by either increasing the refractive index for the core silica through germanium-oxide (GeO2) doping, or by decreasing the refractive index of the cladding through fluoride (F) doping. [1] [2]Additionally, the polymer coating is sometimes considered as a third layer. However, this layer does not interfere with the signal propagation; its primary purpose is to provide protection for the glass fiber against external abrasion, environmental factors, micro-bending loss, and stress corrosion or fatigue Within these optical fibers, the light can travel according to one or several modes. Here, the term 'mode' denotes the unique routes or patterns that the light follows as it propagates within the fiber. These modes correspond to varied spatial arrangements of the light waves as they reflect and traverse along the fiber. The number of modes that a fiber can accommodate is dependent on several parameters, including the size of the core, the refractive index distribution, and the operational wavelength. This multiplicity of modes leads to the

classification of optical fibers into two fundamental categories: single mode fibers and multi-mode fibers. Single mode fibers permit the propagation of a single signal mode, whereas multi-mode fibers supports multiple orthogonal modes. The capability of a fiber to support single or multi-mode propagation at a given wavelength primarily hinges on the difference in refractive index between the core and the cladding, denoted as $\Delta n = n1 - nc$, in conjunction with the diameter of the core. Conversely, a smaller refractive index disparity and a smaller core diameter result in a fiber that can support fewer modes.

The principal impairments that occur during long-haul transmissions can be broadly categorized into two groups: linear and nonlinear effects. Linear transmission effects en compass phenomena such as chromatic dispersion that causes pulse spreading, attenuation leading to signal power loss, and polarization mode dispersion. On the other hand, nonlinear transmission effects arise due to interaction between the optical signal and fiber's nonlinear characteristics resulting in signal distortion and degradation. These nonlinear effects include phenomena such as self and cross-phase modulation, four-wave mixing, cross polarization modulation, stimulated Raman and Brillouin scattering . These impairments can greatly affect the quality of the transmission and must be carefully considered in the design and operation of long-haul optical networks. In the subsequent sections, we delve into the various impairments that affect long-haul transmissions.

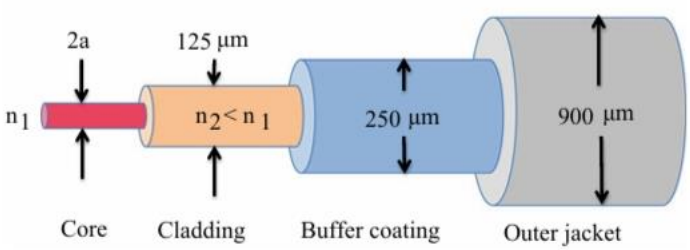

Figure 1.6: Schematic of a generic optical fiber structure; nominal core diameters are 2a = 9 μm for single-mode and 50 μm for multimode fibers

3.2.2 Phenomena affecting the signal

Despite its high efficiency, the optical signal is affected by several factors, including

•Attenuation

This is the weakening of the signal with distance. Its causes include:

-Absorption by the material, especially due to OH impurities.

-Rayleigh scattering due to variations in glass density.

-Bending loss when the cable is bent sharply.

And The optimal operating windows are 1310 nm and 1550 nm (minimum attenuation) [1] [2]

• The Dispersion

Dispersion is a phenomenon that causes the light pulse to spread out and its time dilation as it travels through the fiber, resulting in signal interference. (ISI) Dispersion is one of the most important factors limiting transmission speed and distance . [1]

• Nonlinear effects

It appears at high power levels and affects signal quality.

3.2.1 Types of optical fibers

•Single-Mode Fiber (SMF)

Suitable for large areas and characterized by low correlation.

• Multimode Fiber (MMF)

Suitable for short distances, characterized by ease of installation and lower cost. [2]

Property	Single-mode fiber (SMF)	Multimode fiber (MMF)
Heart diameter	8-10 µm	50-62,5 µm
Distance	Up to 100 km+	Up to 2 km
Distraction	Very small	higher
Cost	most expensive	Cheapest
Usage	International Internet networks	Building and center networks

Table 1.1: The difference between SMF and MMF

3.3 Optical receiver

The optical receiver is the final stage in the system, where the light signal is received and the original information is retrieved from it.

3.3.1 Photodetector

A Photodetector converts light energy into an electric current, relying on the photoelectric effect. Some of its main types include:

• PIN photodiode

This uses photodetection (conversion of a photon into a hole-electron pair) in a semiconductor. and only photons with energy hv higher than Eg can be detected. In order to obtain a good performance, a PIN diode reverse-biased structure, is used (Figure 1.10) photons are absorbed in the intrinsic (i) zone which, because of bias, does not have mobile carriers (depleted zone); electrons and holes thus created have a low probability of recombining. They are separated by the electric field E which is in the intrinsic zone and directs them toward zones n and p where they are a majority. The zone receiving the light must be thin and protected by an anti-reflection coating which increases external efficiency and protects material. [5]

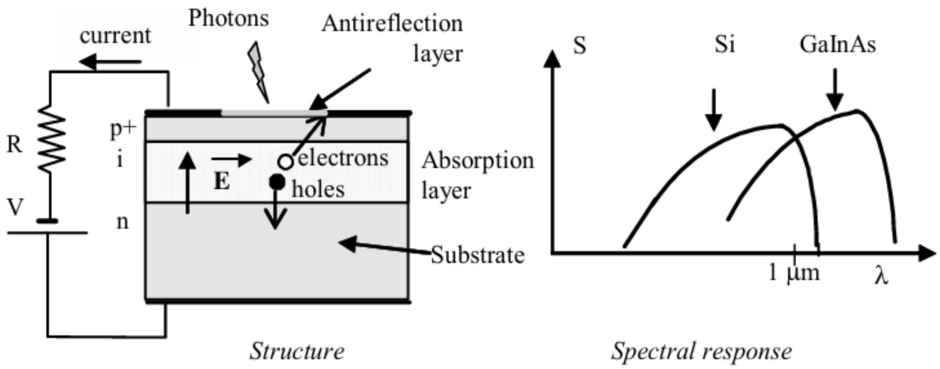

Figure 1.7: PIN photodiode

Photodiode characteristics

When light falls on the photodiode junction under reverse bias, a reverse current is generated. This current consists of two components: the photocurrent, which is directly proportional to the received optical power, and the dark current, which flows through the junction even in the absence of any illumination. The responsivity of the photodiode, expressed in amperes per watt (A/W), quantifies the efficiency of converting optical power into electrical current. It depends on the quantum efficiency of the material and the frequency of the incident light. Responsivity increases gradually with wavelength until it reaches a maximum value, beyond which it drops sharply near the cutoff wavelength of the material, where the semiconductor becomes transparent to the incoming light. The dark current originates from leakage and thermal generation within the junction. It increases with both temperature and applied bias voltage. In the absence of dark current, the photodiode operates as a pure current source driven solely by the received optical power. Under these conditions, if the photocurrent flows through a load, a direct voltage appears across it this is known as photovoltaic operation, which is the principle used in solar cells and optical power meters. However, this mode is characterized by a slow response time, making it unsuitable for high-speed optical transmission. When the photodiode is operated under reverse bias even with only a few volts its response time becomes very short, typically less than one nanosecond for standard surface-illuminated devices. This response time decreases further as the reverse bias voltage increases. In this configuration, the photodiode behaves as a current source in parallel with the junction capacitance, which is the standard operating mode in optical communication receivers

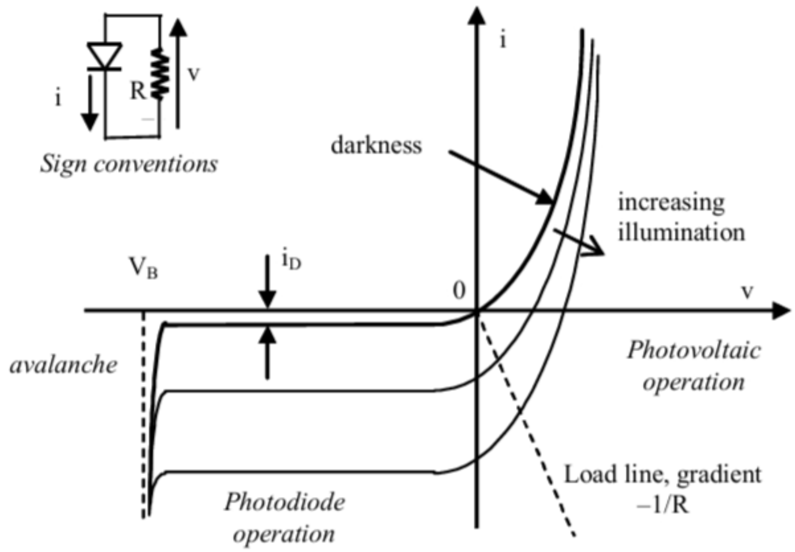

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Figure 1.8: Characteristic of a photodiode

• Avalanche photodiode

The photocurrent must be amplified because the signal received is often very low. Since the preamplifier noise can be predominant, it may be interesting to use an internal gain component called an avalanche photodiode (APD). Its principle is chain ionization by carrier impact caused by a very intense electric field. The avalanche effect, if it is not controlled, leads to junctionbreakdown for a reverse voltage VB (see Figure 1.11). Each primary carrier will produce m secondary carriers. This electric field is obtained with high reverse bias voltage, in a pn abrupt junction, generally separated from the absorption zone, which is thick and slightly doped; this is the pπpn structure principle (Figure 1.12), mostly used in silicon APD (π corresponds to p-). High multiplication coefficients M are then obtained: M is the average number of secondary carriers created (i.e. the average value of m).

The photocurrent then becomes:

$$i's = M.S.P \quad (1)$$

The dark current is multiplied by a factor that is slightly lower than M. It increases with bias voltage and temperature simultaneously. Thanks to high zone resistivity, the gain can be controlled. For reasons due to material, germanium APDs generally adopt a simple pn structure;

the gain is lower but obtained under lower voltage. In this case, a law of the following type is used

$$M = \frac{1}{1-(V/V)Bm'} \qquad (2)$$

in which m' has a typical value from 3 to 6.

Also defined are the ionization coefficients of electrons ‹αn, and holes ‹αp, which are the probability of each carrier creating a second carrier by ionization, which equals αdx in a material depth dx. Carriers with the highest ionization factor must be injected (this is the case with electrons in silicon). The use of avalanche photodiodes is decreasing due to the development of erbium-doped fiber optical preamplifiers. [5]

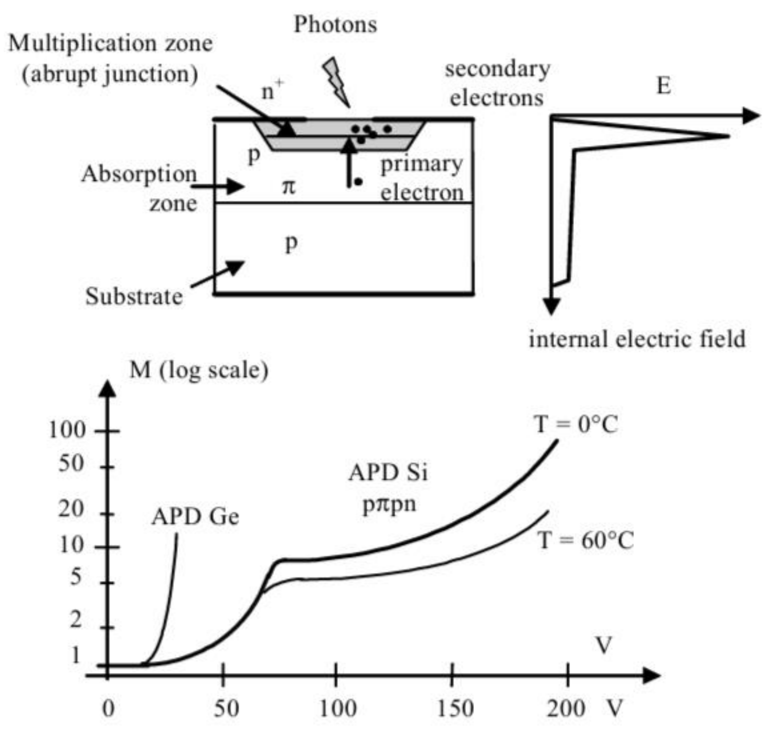


Figure 1.9: Avalanche photodiode and gain-voltage curve

• Materials used in photodetection

Contrary to emission, the semiconductor used does not have to be direct. Silicon which is an indirect semiconductor widely used for image sensors and solar cells, is used up to the limit of its responsivity (approximately 1 μm). Its performances are very good and cost is low, hence the interest of the "first transmission window." However, silicon APDs require large bias voltages and are now used mainly for instrumentation applications (reflectometry, spectroscopy, image intensifiers, etc).

Beyond 1 μm, other material must be used. Germanium is a traditional material that is mediocre in performance. It has progressively been replaced by III-V semiconductors (GaInAs over InP), with much better performance because they can be developed as heterojunction structures (Figure 1.13). Illumination through the substrate, in particular, increases performance and decreases leakage currents because it is transparent to the detected wavelength.

Edge illumination in high speed photodiodes uses the active layer as a guide (of great depth for photons but low transit time for carriers) and also requires a heterojunction. Combined with a matched propagation line structure, these components have a bandwidth that is larger than 40 GHz, but their connection with fiber optics is as tricky as for edge transmission laser diodes. In addition, III-V material enables the integration of detectors, transmitters، integrated optical devices (couplers and optical switches) and electronic components in the same substrate. In this way a complete transmission module, with monitoring photodiode, control circuit and even optical multiplexer can be monolithically integrated.

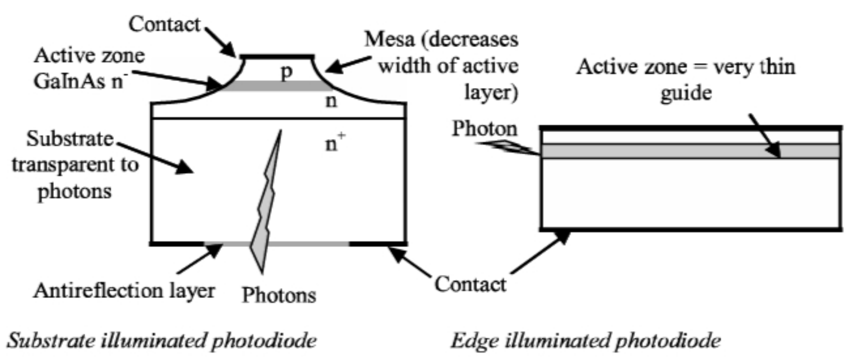


Figure 1.10: GaInAs photodiodes

Table 1.14 illustrates the main characteristics of the different material. HgCdTe, a II-VI compound, is mainly used in infrared instrumentation and very little in telecommunications.

Germanium has seen a renewed interest in the form of SiGe alloy, for the development of high speed components which can be integrated with silicon circuits. However, SiGe compositions compatible with a silicon substrate have a low germanium content, in order for there not to be too much lattice mismatched (they are constrained layers), and can mostly be used in the first window up to 0.98 µm.

Research projects concerning germanium photodiodes bonding on SoI (Silicon on Insulator) substrate are also being carried out.

Window	First	Second and third		
Material	Si	Ge	GaInAs	HgCdTe
λ_{lim} (µm)	1.0	1.6	1.7	1.7 to 2.2
S_{max} (A/W)	0.6	0.7	0.8	0.9
i_D (nA)	1 to 5	500	1 to 5	10
Avalanche: V_B (V)	100 to 200	25	100 to 160	100
max gain	100	10	20	30
exponent x	0.5	1	0.7	0.5

Table 1.2: Photodiode characteristics according to their material

Signal processing

After detection, the signal goes through several stages:

•Amplification

•Filtering

• Data Recovery

These processes aim to improve signal quality and reduce the impact of noise and distortion.

4.Optical networks

Optical networks are an integral part of modern communication. Their use is increasing due to the enormous volume of data being transmitted and the speed at which it is transmitted. Unlike electrical systems, optical networks use optical fibers that transmit information as light, enabling the simultaneous transmission of large amounts of data without interference. For example, a technology called Wavelength Division Multiplexing (WDM) significantly improves the performance of optical networks, allowing multiple messages to be transmitted over a single optical fiber at once. For this reason, optical networks are crucial for the internet and for communicating with people in remote locations. [4][6]

This section presents some general concepts of networks, their types, and some of their terminology and layers, concluding with a detailed explanation of the optical layer.

4.1 General network concepts

To understand the concepts of optical networks better, this section illustrates different types of networks, notes who owns and operates them, defines some network terminology, and describes what the terms physical layer and optical layer mean.

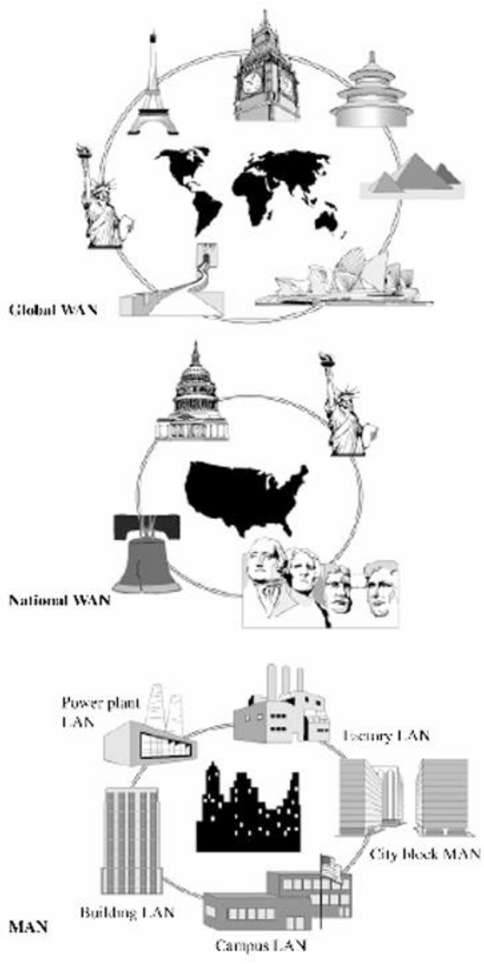


Figure 1.11: Examples of broad categories of networks ranging from LANs to WANs.

4.1.1. Types of networks

Networks can be divided into the following broad categories, as Fig. 1.15 illustrates:

CHAPTER 01

1. Local-area networks (LANs) interconnect users in a localized area such as a room, a department, a building, an office or factory complex, or a campus. Here the word campus refers to any group of buildings that are within reasonable walking distance of each other. For example, it could be the collocated buildings of a corporation, a large medical facility, or a university complex. LANs usually are owned, used, and operated privately by a single organization, which is referred to as an enterprise.

2. Metropolitan-area networks (MANs) span a larger area than a LAN. The size of a MAN could range from interconnections between buildings covering several blocks within a city or it could encompass an entire city and the metropolitan area surrounding it. There is also some means of inter connecting the MAN resources with communication entities located in both LANs and wide-area networks. MANs are owned and operated by many organizations. They commonly are referred to as metro networks.

3. Wide-area networks (WANs) span a large geographic area. The links can range from connections between switching facilities in neighboring cities to long-haul terrestrial transmission lines running across a country or between countries. WANs are owned and operated by either private enterprises or telecommunication service providers.

4. Undersea networks (not shown explicitly in Fig. 1.15) use undersea cables to connect continents. These cables could be several thousand kilometers in length, such as those running across the Atlantic Ocean between North America and Europe or those crossing the Pacific Ocean.

When a network is owned and deployed by a private enterprise, it is referred to as an enterprise network. The networks owned by the telecommunication carriers provide services such as leased lines or real-time telephone connections to other users and enterprises. Such networks are referred to as public networks. [6]

4.1.2. Network terminology

Before we examine network details, let us define some terms, using Fig. 1.16 for guidance.

■ Stations. Collections of devices that users employ to communicate are called stations. These may be computers, terminals, telephones, or other equipment for communicating. Stations are also referred to as data terminal equipment (DTE) in the networking world.

■ Networks. To establish connections between these stations, one deploys trans mission paths running between them to form a collection of interconnected stations called a network.

■ Trunk. The term trunk normally refers to a transmission line that runs between nodes or networks and that supports large traffic loads.

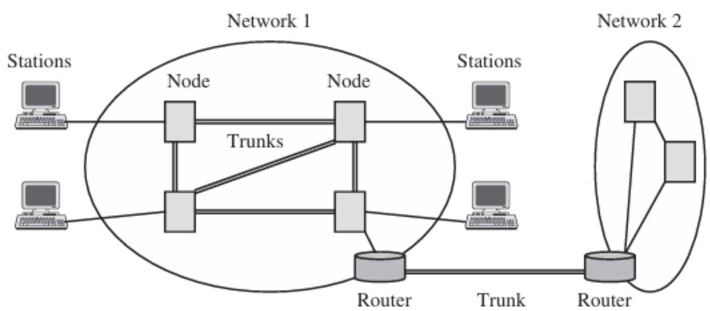


Figure 1.12: Definitions of various elements of a network.

■ Topology. The topology is the logical manner in which nodes are linked together by information transmission channels to form a network.

■ Central office. A node in a public network is called a central office(CO) or a point of presence(POP). The CO houses a series of large switches that establish temporary connections for the duration of a requested connection time between subscriber lines which terminate at the switch.

■ Access network. The access network encompasses connections that extend from the CO to individual businesses, organizations, and homes. Its function is to concentrate the information flows which originate in the access network prior to their entering a long-haul or backbone network.

■ Backbone network. The term backbone means a network that connects multiple LAN, MAN, or WAN segments. Thus a backbone handles internetwork traffic, that is, traffic that originates in one segment and is transmitted to another segment.

4.1.3. Optical layer

When dealing with optical network concepts, one hears the words optical layer used to describe various network functions or services. The optical layer is a wavelength-based concept, and it lies just above the physical layer, as shown in Fig. 1.19. This means that whereas the physical layer provides a physical connection between two nodes, the optical layer provides light path services over that link. A light path is an end-to-end optical connection that may go through one or more intermediate nodes. For example, in an eight-channel WDM link there are eight light paths, which may go over a single physical line. Note that for a specific light path the wavelengths between various node pairs may be different. As shown in Fig. 1.20, the optical layer may carry out processes such as wave length multiplexing, adding and dropping of wavelengths, and support of optical cross-connects or wavelength switching. Networks which have these optical layer functions are referred to as wavelength-routed networks. [6][3]

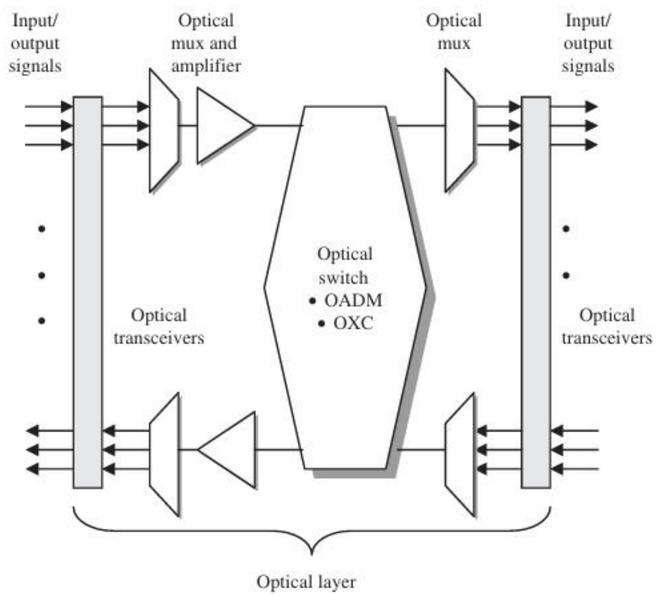


Figure 1.13: The optical layer carries out processes such as multiplexing, adding/dropping of wavelengths, and support of optical cross-connects or wavelength switching.

CHAPTER 01

5.Conclusion.

In conclusion, this chapter has presented a comprehensive overview of optical fiber communication systems, highlighting their fundamental principles and importance in modern telecommunications. The historical evolution of optical communication has been discussed, showing how technological advancements have led to the widespread adoption of optical fibers as the backbone of global communication networks. Furthermore, the basic structure of an optical fiber communication system has been detailed, including the roles of the optical transmitter, the fiber channel, and the optical receiver. The interaction between these components ensures efficient transmission of information with high speed and reliability. Overall, optical fiber communication systems offer significant advantages over conventional transmission technologies, making them essential for supporting the ever-growing demand for high-capacity and high-speed data transmission. The next chapter will focus on modulation techniques used in optical communication systems, providing a deeper understanding of how information is encoded and transmitted over optical channels.

CHAPTER 02

Modulation Formats Techniques

1.Introduction

To convey a message, the amplitude, frequency, and phase of an optical carrier are switched in accordance with the message data. For example, bits '1' and '0' can be transmitted by turning a laser diode on and off, respectively. Typically, the message signal is in the form of binary data in an electrical domain, and optical modulators are used to convert the data into an optical domain. This chapter reviews the various line coders, pulse shapes, and digital modulation schemes. Furthermore, we deal with different types of optical modulators and generation of modulated signals using optical modulators.

2. Line coder

Digital data can be represented by electrical waveforms in a number of ways. This process is called *line coding*. In the binary case, bit '1' is sent by transmitting a pulse $p(t)$ and bit '0' is sent by transmitting no pulse. This line code is known as *unipolar* or *on–off*, as shown in Fig. 2.1(a). If a bit '1' and bit '0' are represented by $p(t)$ and $-p(t)$, respectively, such a line code is *polar*. This is shown in Fig. 2.1(b). If a bit '0' is represented by no pulse and a bit '1' is represented by $p(t)$ and $-p(t)$, such a line code is known as *bipolar*. In a bipolar line code, bit '1' is encoded by $p(t)$ if the previous bit '1' is encoded by $-p(t)$ and bit '1' is encoded by $-p(t)$ if the previous bit '1' is encoded by $p(t)$, as shown in Fig. 2.1(c). [6]

CHAPTER 02

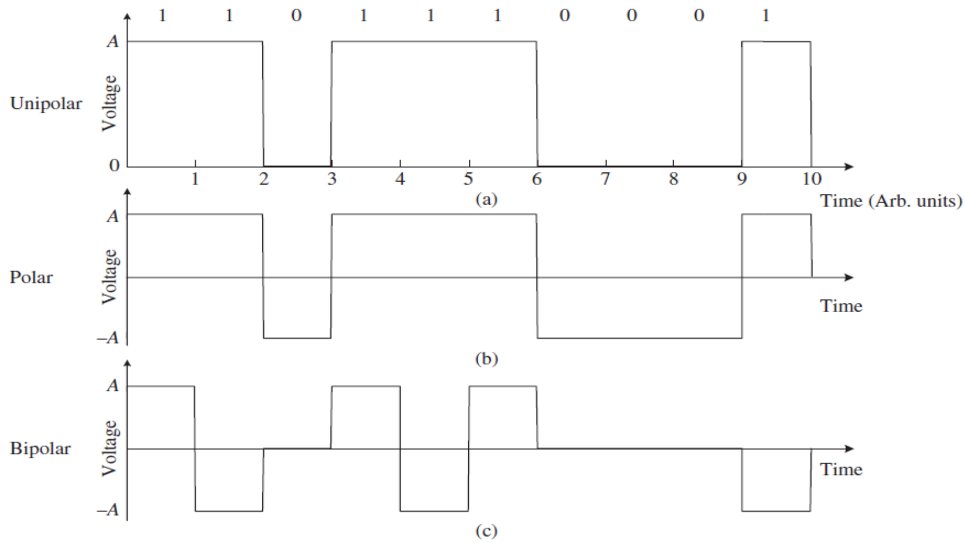


Figure 2.1: Various line codes: (a) unipolar, (b) polar, and (c) bipolar.

3. Pulse shaping

The message signal can be the internet data, voice data after analog-to-digital conversion (ADC), or any other form of digital data in an electrical domain. The widely used pulse shapes ($p(t)$) are *non-return-to-zero* (NRZ) and *return-to-zero* (RZ). In the case of NRZ, the signal does not return to a zero level if there are two consecutive '1's in a bit stream, whereas in the case of RZ, the signal returns to zero at the end of each bit slot (Fig. 2.2). The advantage of NRZ is that fewer transitions between '0' and '1' are required compared with RZ, since the signal amplitude remains the same if consecutive bits are '1' or '0'. Therefore, the bandwidth of a NRZ signal is less than that of a RZ signal. [6]

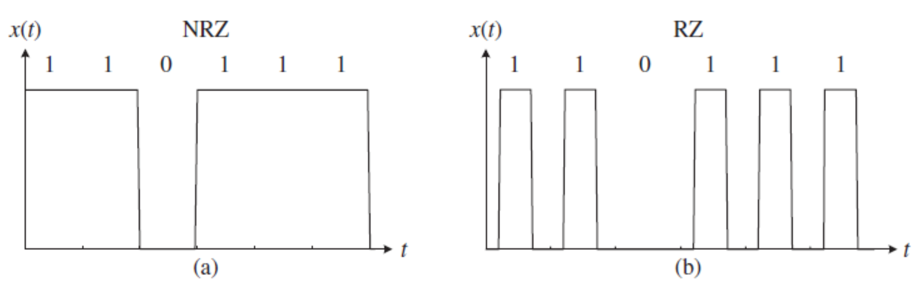


Figure 2.2: Pulse shapes: (a) NRZ, and (b) RZ.

CHAPTER 02

4. Digital modulation schemes

4.1 Amplitude-Shift Keying

A laser is an optical carrier whose amplitude and/or phase can be varied in accordance with a message signal by means of an optical modulator. Let the laser output be $c(t) = Acos(2\pi f_c t + \theta)$ where the amplitude A, frequency f_c, and phase factor θ are constants. When the amplitude A is varied in accordance with a message signal $m(t)$ while keeping f_c and θ constant, the resulting scheme is known as *amplitude modulation*. The modulated signal can be written as:

$$s(t) = k_a m(t) \cos(2\pi f_c t + \theta) \qquad (1)$$

When the message signal $m(t)$ is a digital signal, the modulation scheme is known as *amplitude-shift keying* (ASK) or *on–off keying* (OOK). In general, to transmit bit ‘1’, a sinusoid of certain amplitude A_1 is sent and to transmit bit ‘0’, a sinusoid of amplitude A_2 is sent. [6]

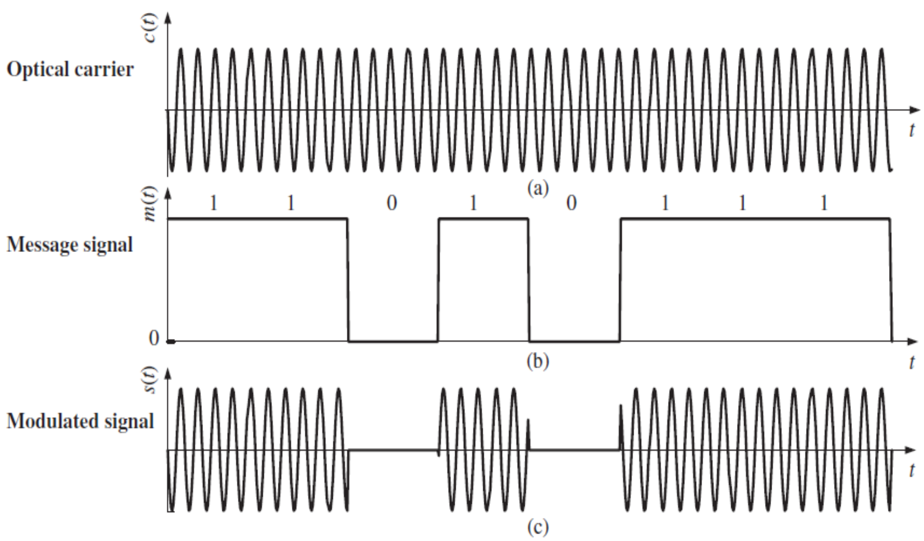


Figure 2.3: Modulation of the optical carrier by digital data: (a) carrier, (b) data, and (c) modulated signal.

CHAPTER 02

4.2 Phase-Shift Keying

When the phase θ of the carrier is varied in accordance with the message signal $m(t)$ while keeping the amplitude A and frequency f_c constant, the resulting scheme is known as *phase modulation*. Suppose the phase is proportional to the message signal, $\theta(t) = k_p m(t)$, where k_p is called the phase sensitivity. Now, the optical carrier is said to be phase modulated. The modulated signal can be written as:

$$s(t) = A\cos\left[2\pi f_c + k_p m(t)\right] \qquad (2)$$

When the message $m(t)$ is a digital signal, the modulation scheme is known as *phase-shift keying* (PSK) or binary phase-shift keying (BPSK). Fig. 2.4(b) shows the modulated signal when the modulation scheme is PSK. Note that there is a 180° phase jump at the bit boundaries if the digital data in the consecutive bit intervals are different. In general, PSK can be described as a scheme in which a bit '1' is transmitted by sending a sinusoid of phase θ_1 and a bit '0' is transmitted by sending a sinusoid of phase θ_2. [9]

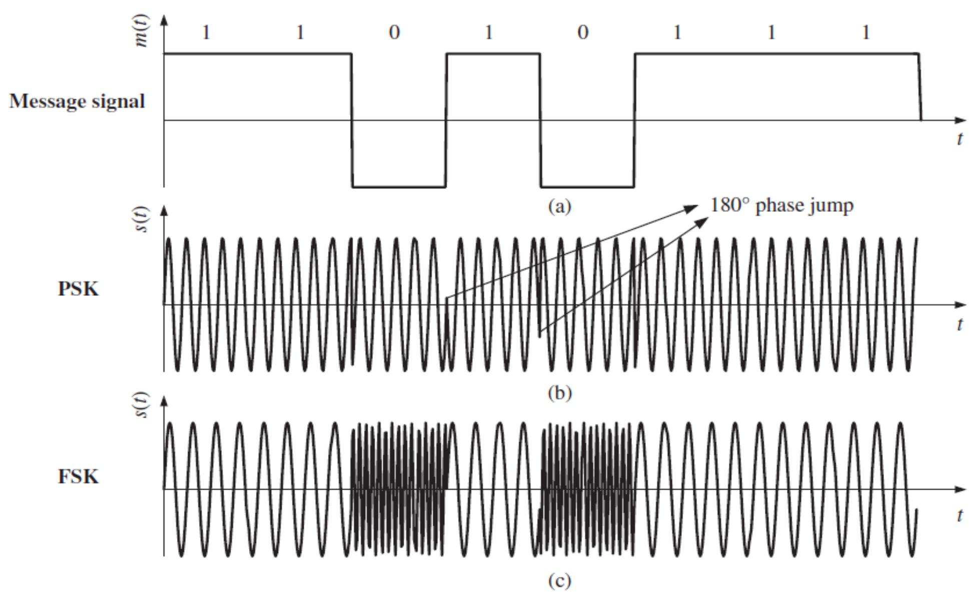


Figure 2.4: Phase and frequency modulation of an optical carrier. (a) Message signal, (b) Phase-shift keying, and (c) Frequency-shift keying.

CHAPTER 02

4.3 Frequency-Shift Keying

FSK can be described as a scheme in which a bit '1' is transmitted by sending a sinusoid of frequency f_1 and a bit '0' is transmitted by sending a sinusoid of frequency f_2. [6] Let the message signal be binary data, The transmitted signal within a bit interval $[0, T_b]$ can be written as $s(t) = A\cos[\phi(t)]$, where:

$$\phi(t) = \begin{cases} 2\pi f_1 t \; for \; bit \; '1' \\ 2\pi f_2 \;\; for \; bit \; '0' \end{cases} \qquad (3)$$

4.4 Differential Phase-Shift Keying

When a PSK signal is transmitted, it requires a complex receiver architecture to detect the phase. This is because the optical signal acquires a phase due to propagation, which fluctuates due to temperature, stress, and other factors. Therefore, to estimate the transmitted phase, we need a reference at the receiver which is provided by a laser known as a local oscillator (LO), whose phase is aligned with that of the received optical carrier. The phase alignment is achieved by phase estimation in digital domain using digital signal processing (DSP) techniques. Instead of using the LO as a reference, the phase of the previous bit can be taken as a reference for the current bit. This is known as *differential phase detection*. [9]

5. Optical modulators

The simplest optical modulator we could think of is the switch of a flash light. Suppose we turn on a flash light for 1 second and turn it off for 1 second. We generate digital data '1' and '0', respectively. Optical modulation techniques can be divided into two types: direct modulation of lasers and external modulation of lasers.

5.1 Direct modulation

The laser drive current can be modulated by a message signal, as shown in (Fig. 2.5). For example, when the message signal is bit '0' (bit '1'), the laser is turned off (on) and, therefore, the information in the electrical domain is encoded onto the optical domain. [5]

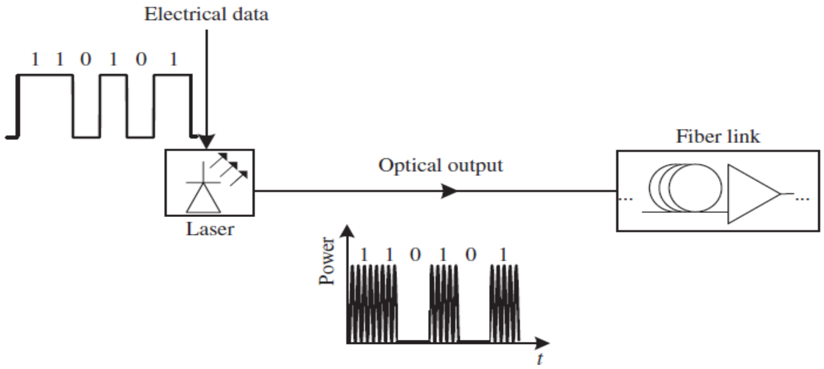


Figure 2.5: Direct modulation of a laser.

Directly modulated lasers are usually used for transmission systems operating at low bit rates (≤ 10 Gb/s) and for short-haul application (<100 km). The pulse distortion and frequency chirp prevent the use of directly modulated lasers for high-bit-rate applications.

5.2 External modulators

Fig. 2.6 shows the schematic of a transmitter using external modulators. Widely used external modulators are: the phase modulator, the Mach–Zehnder (MZ) interferometer modulator, and the electroabsorption (EA) modulator. [7]

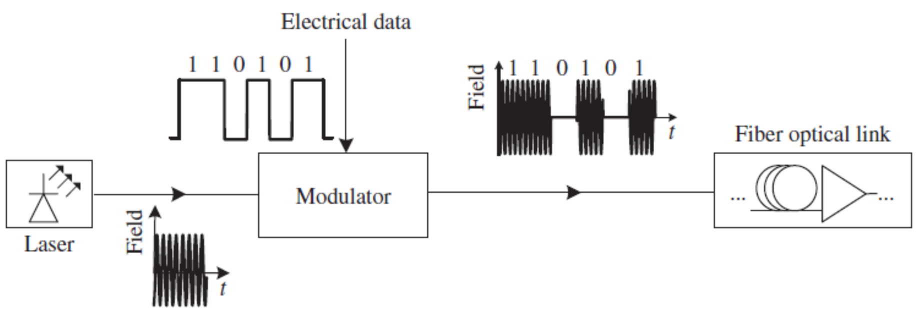


Figure 2.6: A transmitter using an external modulator.

5.2.1 Phase modulators

The phase modulation of an optical carrier can be achieved in a number of ways. When an electric field is applied to an electro-optic crystal, the refractive index of the crystal changes and, therefore, the phase (∝ refractive index) of an optical carrier propagating in the crystal also changes. The refractive index change is directly proportional to the applied electric field intensity. This effect is known as the *Pockels effect* or *linear electro-optic effect*.

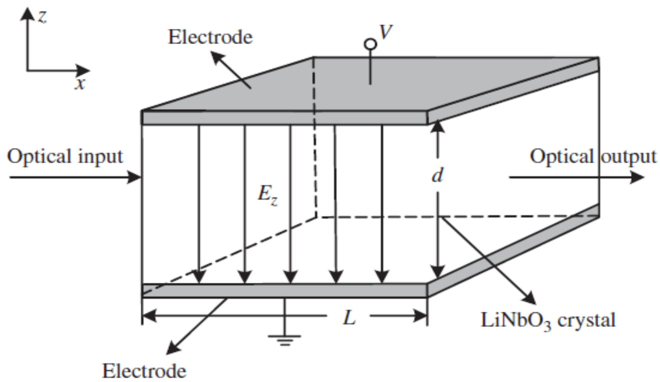


Figure 2.7: Phase modulation of an optical signal in a $LiNbO_3$ crystal.

5.2.2 Dual-Drive Mach–Zehnder Modulators (MZMs)

A MZM consists of two arms, as shown in Fig. 2.8. Voltages V_1 and V_2 are applied to the upper and lower arms, respectively. The first *y*-branch splits the input wave into two optical beams of equal power. The optical beams in the upper and lower arms undergo a phase shift of φ_1 and φ_2, respectively, in the presence of applied voltages. The optical beams in the upper and lower arms are recombined via a second *y*-branch. The power is conserved when $\varphi_1 = \varphi_2$. When $\varphi_1 = \pi + \varphi_2$ optical fields coming from two branches of the second *y*-branch do not excite a guided mode in the output waveguide; instead, radiation modes are excited which go out of the waveguide. [5]

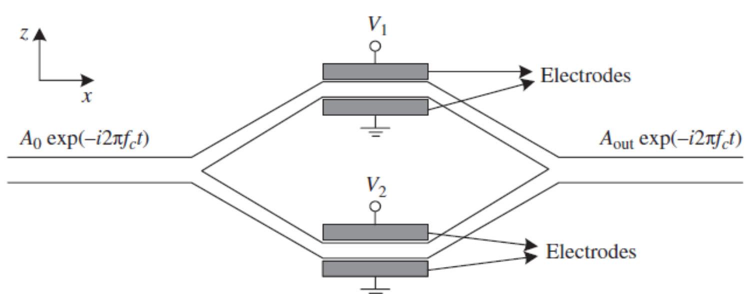


Figure 2.8: A dual-drive MZM.

5.2.3 Electroabsorption Modulator (EAM)

Electroabsorption refers to the dependence of the absorption coefficient of a semiconductor on the applied electric field. The band gap of a semiconductor decreases as the applied field increases. Electroabsorption refers to the dependence of the absorption coefficient of a semiconductor on the applied electric field. The band gap of a semiconductor decreases as the applied field increases. Consider an optical carrier with frequency $f_c < E_{g0} / h$, where E_{g0} is the band gap in the absence of the applied electric field. Let the driving voltage $V(t)$ vary from 0 to V_0 volts. When $V(t) = 0$, the photon energy is less than the band gap and the optical carrier is not absorbed. When $V(t) = V_0$, the band gap decreases. Now the photon energy could be larger than the band gap and the optical carrier is absorbed, which generates electron-hole pairs. Thus, the information in the electrical domain is translated into the optical domain. [7]

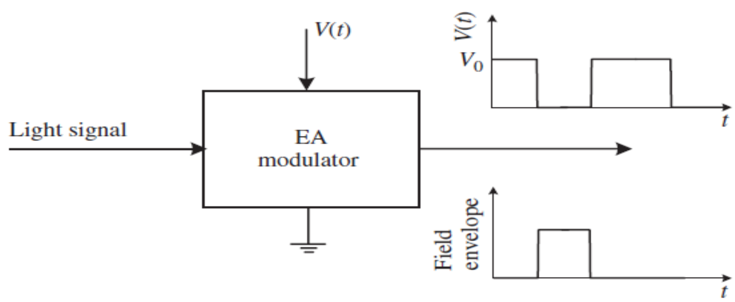


Figure 2.9: Amplitude modulation using an EAM.

6. Optical realization of modulation schemes

6.1 Amplitude-Shift Keying

The optical ASK signal can be generated using a MZM, as shown in Fig. 2.10. The optical power of the MZM output may be written as:

$$P_{out} = P_0 cos^2 \left[\frac{m(t)\pi}{V_\pi} - \frac{V_{bias}\pi}{2V_\pi}\right] \qquad (4)$$

Let the message signal be a polar NRZ,

$$\mathrm{m}(t) = \begin{cases} +V \ for\ bit\ '1' \\ -V \ \ for\ bit\ '0' \end{cases} \qquad (5)$$

The desired Mach–Zehnder output power is:

$$P_{out} = \begin{cases} P_0 \; for \; bit \; '1' \\ 0 \; \; for \; bit \; '0' \end{cases} \qquad (6)$$

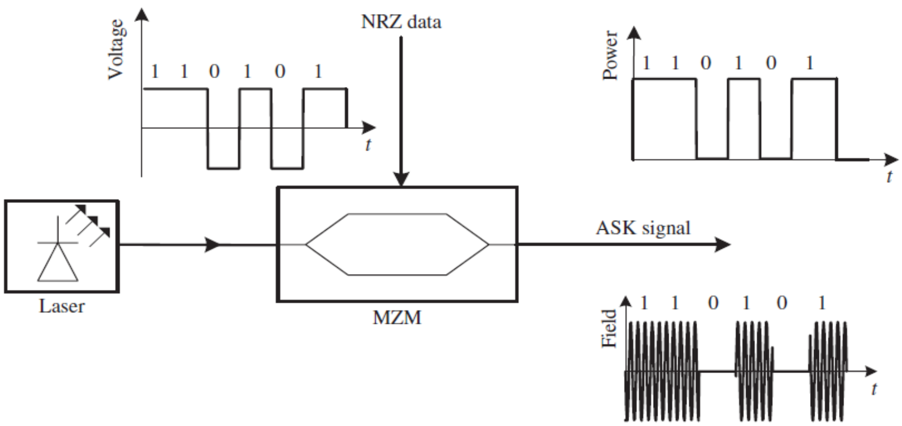


Figure 2.10: Generation of ASK signal using a MZM.

Thus, the polar NRZ in an electrical domain becomes a unipolar NRZ in an optical domain. There are two approaches for the generation of RZ-ASK. The first approach is to apply the message signal, which is a polar RZ. The second approach is to introduce a RZ pulse carver in series with a MZ modulator. The advantage of the second approach is that higher bit rates (≥40 Gb/s) can be realized.

6.2 Phase-Shift Keying

The optical field envelope of the MZM output can be written as:

$$A_{out} = A_0 cos^2 \left[\frac{m(t)\pi}{V_\pi} - \frac{V_{bias}\pi}{2V_\pi}\right] \qquad (7)$$

Let the message signal be a polar NRZ given by Eq. (5). desired field envelope of the Mach–Zehnder output is:

$$A_{out} = \begin{cases} +A_0 \; for \; bit \; '1' \\ -A_0 \; \; for \; bit \; '0' \end{cases} \qquad (8)$$

After simplifying we obtain the conditions for voltages V and V_{bias}. Fig. 2.11 shows a schematic of the PSK signal generation. RZ-PSK can be generated using a RZ pulse carver in series with a

MZM, similar to RZ-ASK. PSK can also be generated using a phase modulator. When the message signal corresponds to bit '1', the phase modulator provides no phase change and when it corresponds to bit '0', the phase modulator changes the carrier phase by π.

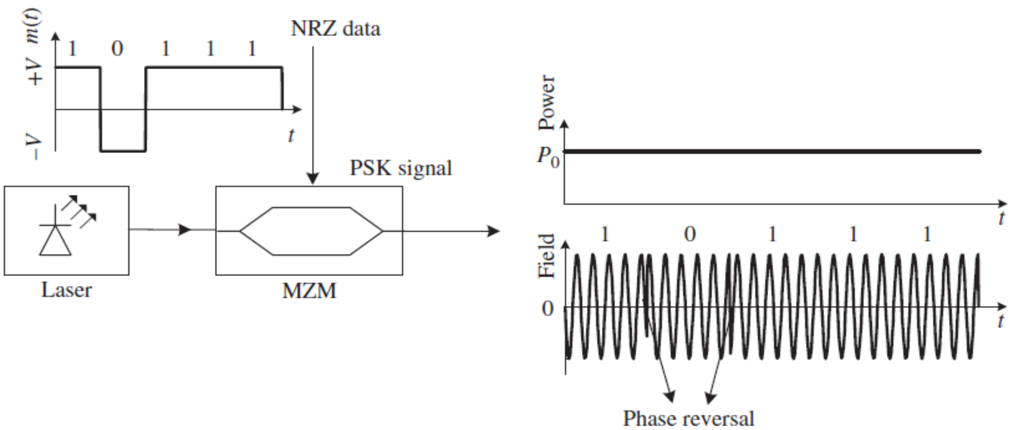


Figure 2.11: Generation of optical PSK signal.

6.3 Differential Phase-Shift Keying

The DPSK signal generation is analogous to PSK generation except for a precoder which provides differential coding. The differentially encoded signal $m(t)$ is used to drive a PM or a MZM.

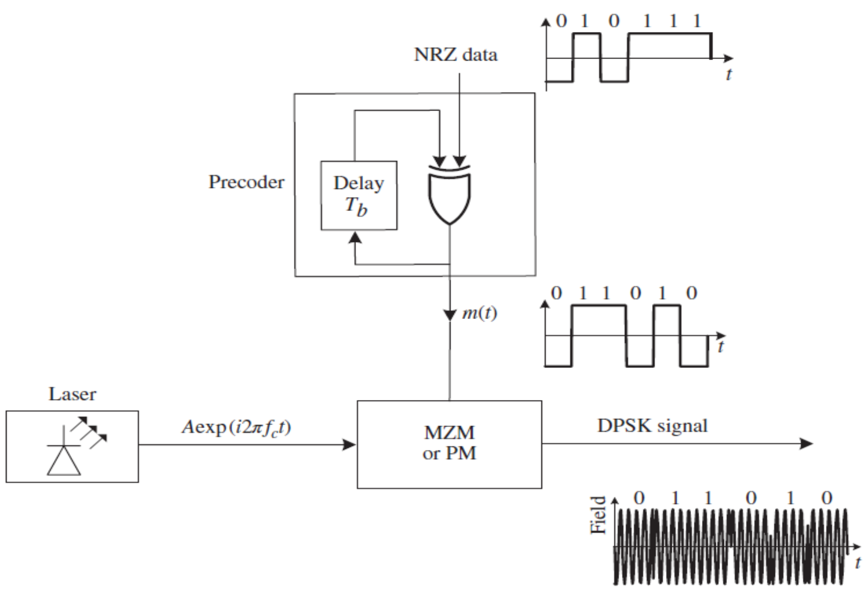


Figure 2.12: Optical DPSK signal generation.

CHAPTER 02

7. Multi-Level signaling

So far, we have assumed that the message signal is binary data with two levels represented by the symbols ‘0’ and ‘1’. Instead, the message signal could consist of multiple levels. For example, we could have four levels with voltages −3 V, −1 V, 1 V, and 3 V. These four levels can be represented by four symbols, ‘00’, ‘01’, ‘10’, and ‘11’. We may do the following mapping: −3 V → ‘00’, −1 V → ‘01’, 1 V → ‘11’, and 3 V → ‘10’. These four symbols could correspond not only to four amplitude levels (4-ASK), but also to four phase levels (4-PSK), or a combination of amplitude and phase levels (4-QAM).

7.1 M-ASK

Here *M* stands for the number of symbols or levels. The simplest example we could think of is the switch of a flash light with two levels of brightness and an off button. In total, there are three power (or amplitude) levels corresponding to 3-ASK. When $M = 4$, the four symbols can be represented by four amplitude levels $\pm 3A$, $\pm A$. The smallest separation between any two amplitude levels is $2A$, to ensure equal noise immunity. When $M = 8$, we need three binary digits or bits to represent eight symbols: ‘000’, ‘001’, …, ‘111’ and eight amplitude levels: $\pm 7A$, $\pm 5A$, $\pm 3A$, and $\pm A$.

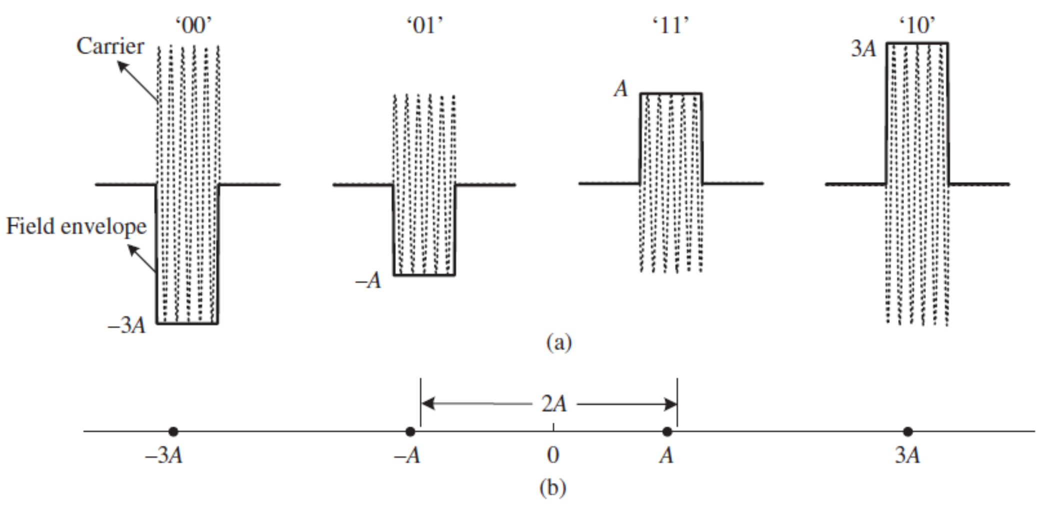


Figure 2.13: (a) Amplitude levels of 4-ASK. (b) Constellation diagram.

CHAPTER 02

7.2 M-PSK

When M = 2, we have a binary PSK or BPSK signal with two phase levels 0 or π. When M = 4, the signal is called quadriphase-shift keying (QPSK). The phase of the carrier takes on one of four values, 0, $\pi/2$, π, and $3\pi/2$.

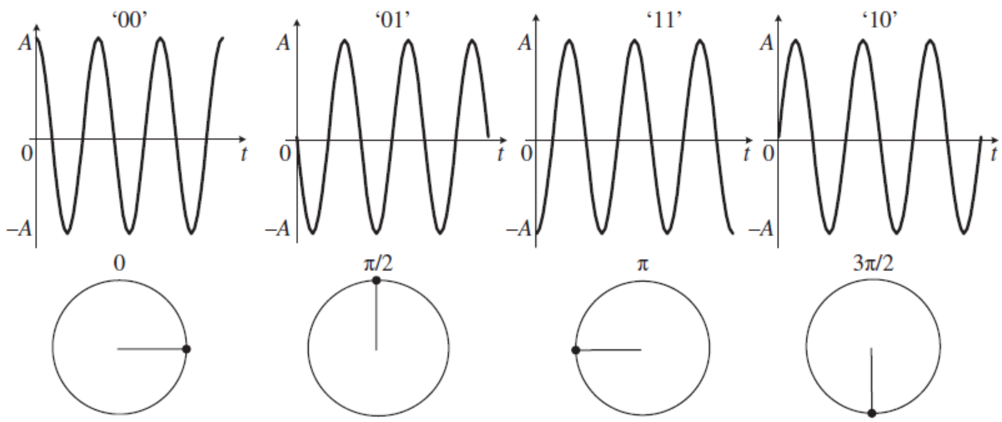


Figure 2.14: QPSK symbols.

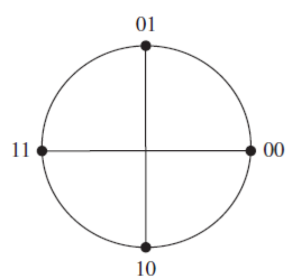


Figure 2.15: Constellation diagram of QPSK.

In general, the M-PSK signal in an interval $kT_s \leq t \leq (k + 1)T_s$ may be written as:

$$s_j(t) = A[m_I(t)cos(2\pi f_c t) + m_Q(t)sin(2\pi f_c t)] \quad (9)$$

Where: $m_I(t) = p(t)cos[k_p m_j(t) + \theta_0]$ and $m_Q(t) = -p(t)sin[k_p m_j(t) + \theta_0]$. $m_I(t)$ and $m_Q(t)$ can be imagined as two message signals modulating an in-phase carrier, $cos(2\pi f_c t)$ and a quadrature carrier, $sin(2\pi f_c t)$, respectively. $m_I(t)$ and $m_Q(t)$ are called the *in-phase* and *quadrature* components of the message signal, respectively. QPSK signal can be generated using two polar NRZ data streams. The optical realization of QPSK can be achieved using a phase modulator. An alternative is to use the optical IQ modulator shown in Fig. 2.16. The output of the laser passes through the pulse carver and its output is split into two equal parts using a 3-dB coupler. The upper arm is known as the in-phase (I) arm and the lower arm is known as the quadrature (Q) arm. In the I-arm, the optical signal amplitude is modulated using a MZM. In the Q-arm, the optical signal is first phase-shifted by $-\pi/2$ and then its amplitude is modulated using a MZM. The optical signal is recombined using a 3-dB coupler to obtain the QPSK signal. The advantage of this scheme is that both $m_I(t)$ and $m_Q(t)$ are binary NRZ data streams. An 8-PSK signal can be obtained from a QPSK signal after passing through a phase modulator which changes the phase of the QPSK signal by $\pi/4$ or 0 depending on whether the electrical driving signal is $V_\pi/4$ or zero, respectively. This is because an 8-PSK signal is nothing but a phase-modulated QPSK signal.

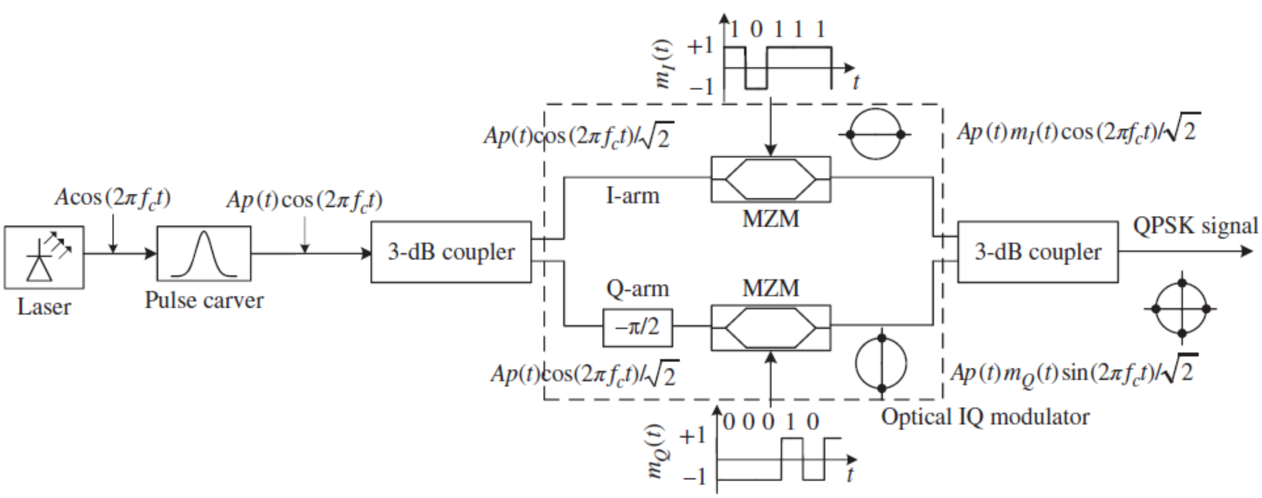


Figure 2.16: Optical QPSK generation using two MZMs.

7.3 Coherent receivers

In the 1990s, coherent detection was pursued mainly because the fiber-optic systems were then loss limited. Coherent receivers have higher sensitivity than direct detection receivers and, hence, coherent detection is more attractive for loss-limited systems. However, with the development and deployment of EDFAs in the mid-1990s, fiber loss was no longer a problem and coherent receivers were not pursued due to the technical hurdles associated with aligning the phase and polarization of the local oscillator (LO) with those of the received signal. Owing to the rapid advances in digital signal processing (DSP), coherent detection has drawn renewed interest recently. The polarization and phase alignment can be performed using DSP, which is easier than optical phase-locked loop (PLL) used in 1990s' coherent receivers. Unlike direct detection, coherent detection allows us to retrieve both amplitude and phase information. The advantages of the coherent receiver are the following. (1) In the case of direct detection, the detection process is nonlinear–photocurrent is proportional to the absolute square of the optical field. Since the phase information is lost during the detection, it is hard to compensate for dispersion and polarization mode dispersion (PMD) in an electrical domain. In the case of coherent detection, the detection process is linear–the complex optical field envelope is linearly translated into an electrical domain and, therefore, the inverse fiber transfer function can be realized using DSP to compensate for dispersion and PMD. (2) With coherent detection, higher spectral efficiencies can be realized using multi-level modulation formats that make use of both amplitude and phase modulation. [12] [13]

7.3.1 Single-Branch IQ coherent receiver

We consider the case which $s(t)$ is complex (multi-level PSK and QAM for example). To recover the real part of $s(t)$, the LO phase should be aligned with that of the optical carrier. Similarly, to recover the imaginary part of $s(t)$, the LO phase should be shifted by $\pi/2$ with respect to the optical carrier. The received signal and LO outputs are divided into two parts using power splitters and are mixed together.

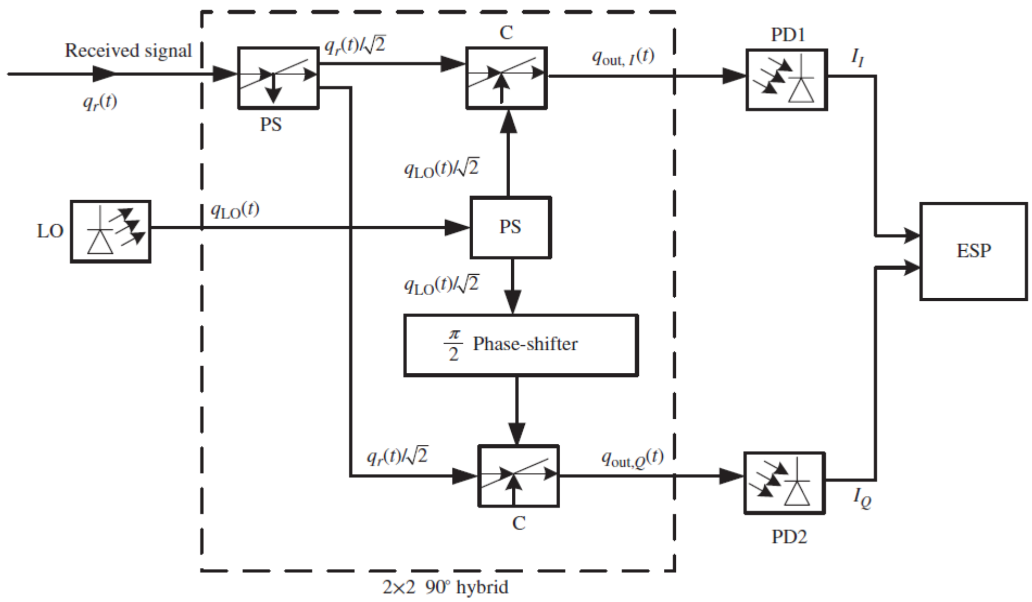


Figure 2.17: Block diagram of a single-branch IQ receiver.

PS = power splitter, C = combiner, LO = local oscillator, PD = photodetector, ESP = electrical signal processor.

Let us first consider the in-phase component. The corresponding photocurrent after ignoring the intermodulation cross-talk and DC terms is:

$$I_I(t) \approx \frac{RA_rA_{LO}}{2}|s(t)|cos(\omega_{IF}t + \phi_s(t) + \Delta\phi) \qquad (10)$$

The other part of the LO is 90° phase-shifted and is mixed with the received signal. The corresponding photocurrent is:

$$I_Q(t) \approx \frac{RA_rA_{LO}}{2}|s(t)|sin(\omega_{IF}t + \phi_s(t) + \Delta\phi) \qquad (11)$$

The electrical signal processing unit forms the complex current $I(t) = I_I(t) + iI_Q(t) = RA_rA_{LO}s(t)/2$. Thus, the transmitted complex signal could be retrieved.

7.3.2 Balanced IQ receiver

It is straightforward to modify the block diagram of Fig. 2.17 to obtain the balanced IQ receiver, shown in Fig. 2.18.

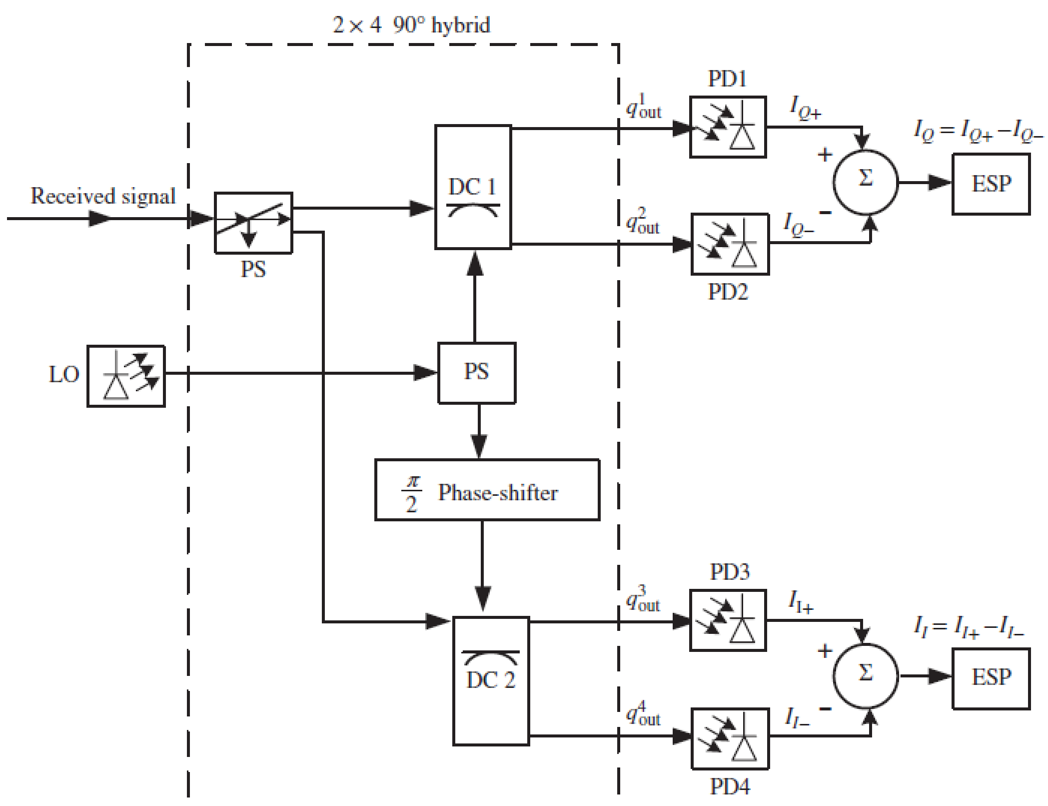


Figure 2.18: Block diagram of a balanced IQ receiver.

DC = directional coupler, PS = power splitter, LO = local oscillator, PD = Photodetector.

Proceeding as before, the quadrature current I_Q is given by:

$$I_Q = -RA_rA_{LO}Im\{s(t)exp[-i(\omega_{IF}t + \Delta\phi)]\} \qquad (12)$$

For the I-branch, the LO output is phase-shifted by 90°. The in-phase component of the current is:

$$I_I = RA_rA_{LO}Re\{s(t)exp[-i(\omega_{IF}t + \Delta\phi)]\} \ (13)$$

Finaly, we get the complex current $I(t) = I_I(t) - iI_Q(t) = RA_rA_{LO}s(t)$.

8.Conclusion

In this chapter we have discussed a number of modulation formats commonly used for optical communication systems. Traditionally binary NRZ has been the most popular choice for high-speed optical systems because it has relatively narrow spectral bandwidth and high tolerance to chromatic dispersion of the fiber. The relatively narrow electric bandwidth also makes it easier for the design of transmitters and the receivers. However, RZ coding has more concentrated signal peak power at the decision point of each bit, which helps improving the receiver sensitivity.

Basic optical phase modulation formats such as BPSK and DPSK have been introduced. While BPSK requires coherent detection, DPSK can be received by both coherent detection and direct detection. Coherent detection helps improving the receiver sensitivity, but direct detection without the need of an optical local oscillator can be much simpler, and the receiver sensitivity can be improved by employing an optical pre-amplifier in the receiver. Multilevel phase shift keying (PSK) modulation and complex optical field modulation such as QAM, help further increase optical spectral efficiency, which are now quite commonly used for high-capacity optical transmission with dense WDM.

CHAPTER 03

Simulation & Results

1.Introduction

Phase-shift keying (PSK) is a digital modulation scheme that conveys message information by modulating the phase of the carrier wave. Quadrature Phase-Shift Keying (QPSK) can encode two bits per symbol by using four different phases. In this chapter, the phase modulation of the signal is done with an interferometer that contains balanced Mach-Zehnder Modulators (MZM) on each of the arms and a 90-degree phase shifter on one of the arms. Demodulation of the QPSK signal is done with an optical hybrid receiver with a local oscillator (LO).

2. System design

an Optical QPSK transceiver circuit is implemented in the simulator using a coherent detection architecture. At its core, the transmitter generates a phase-modulated signal by encoding data onto an optical carrier using a nested Mach-Zehnder Modulator (MZM) structure with a 90-degree phase shifter to create the four distinct phase states that represent two bits per symbol. On the receiver side, the signal is demodulated using a 90-degree optical hybrid, which mixes the incoming signal with a continuous-wave Local Oscillator (LO) laser. This mixing effectively separates the in-phase (I) and quadrature (Q) components of the signal, allowing the original data to be recovered. The performance of this circuit is commonly evaluated by measuring quality metrics such as the Q-factor and constellation diagrams from the recovered signal. Figure (1) gives the structure of the QPSK transceiver circuit.

3. System metrics

There are a number of factors we want to measure for QPSK modulation transceiver.

- **Bit/Symbol Error Rate (BER/SER)**: BER is the number of error bits divided by the total number of transmitted bits in a studied time interval it is a unitless performance measurement. The BER/SER can be affected by a number of elements in the system, but the key factors are the received signal power and the noise level in the channel.
- **Eye Diagram**: eye diagram is an oscilloscope display formed by horizontally sweep the repeatedly sampled received digital data signal. Several system performance measurements, such as Q-factor and time jitter, can be derived by analyzing the eye diagram.
- **Q-factor**: Q-factor is a dimensionless parameter that describes the eye opening in optical communication systems, it can be derived from the eye diagram and measures the system's quality.
- **Error Vector Magnitude (EVM)**: EVM is a measurement used to qualify the performance of the receiver or transmitter in communication systems. Informally, it is a measure of the variance of the constellations from their ideal positions. Noise, phase noise and distortion can all degrade EVM, hence EVM provides a comprehensive

measure of the quality of the receiver or transmitter.

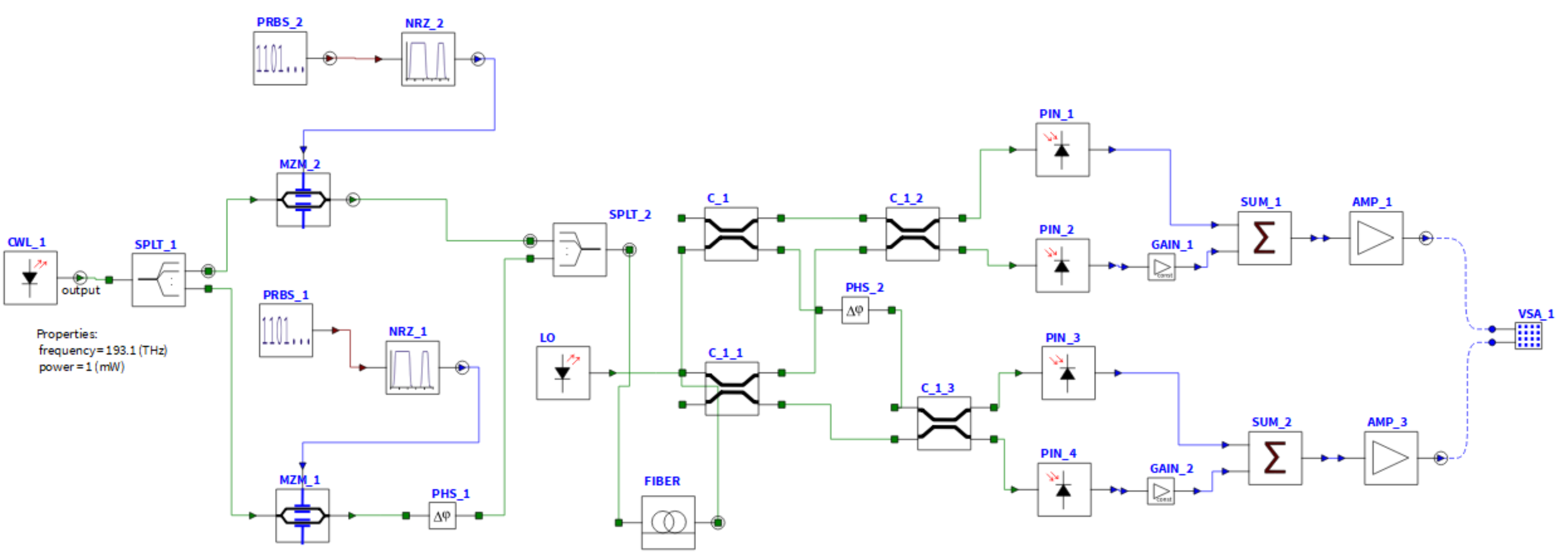


Figure 3.1: Structure of the QPSK transceiver circuit.

CHAPTER 03

4. System performances and impact of system parameters

The system is a coherent optical transmission link using QPSK modulation. It operates over a 1 km standard single-mode fiber (SSMF) with minimal linear impairments due to the short distance. The laser source has a power of 1 mW (0 dBm) and a frequency of 193.1 THz (corresponding to a wavelength of approximately 1552.5 nm, in the C-band). The bit rate is set to be 25 Gb/s and the sequence length is set to be 64. Figure .2 depicts the signal at the fiber input (a), fiber output (b), eye diagram for the in-phase component (c) and the quadrature phase component (d).

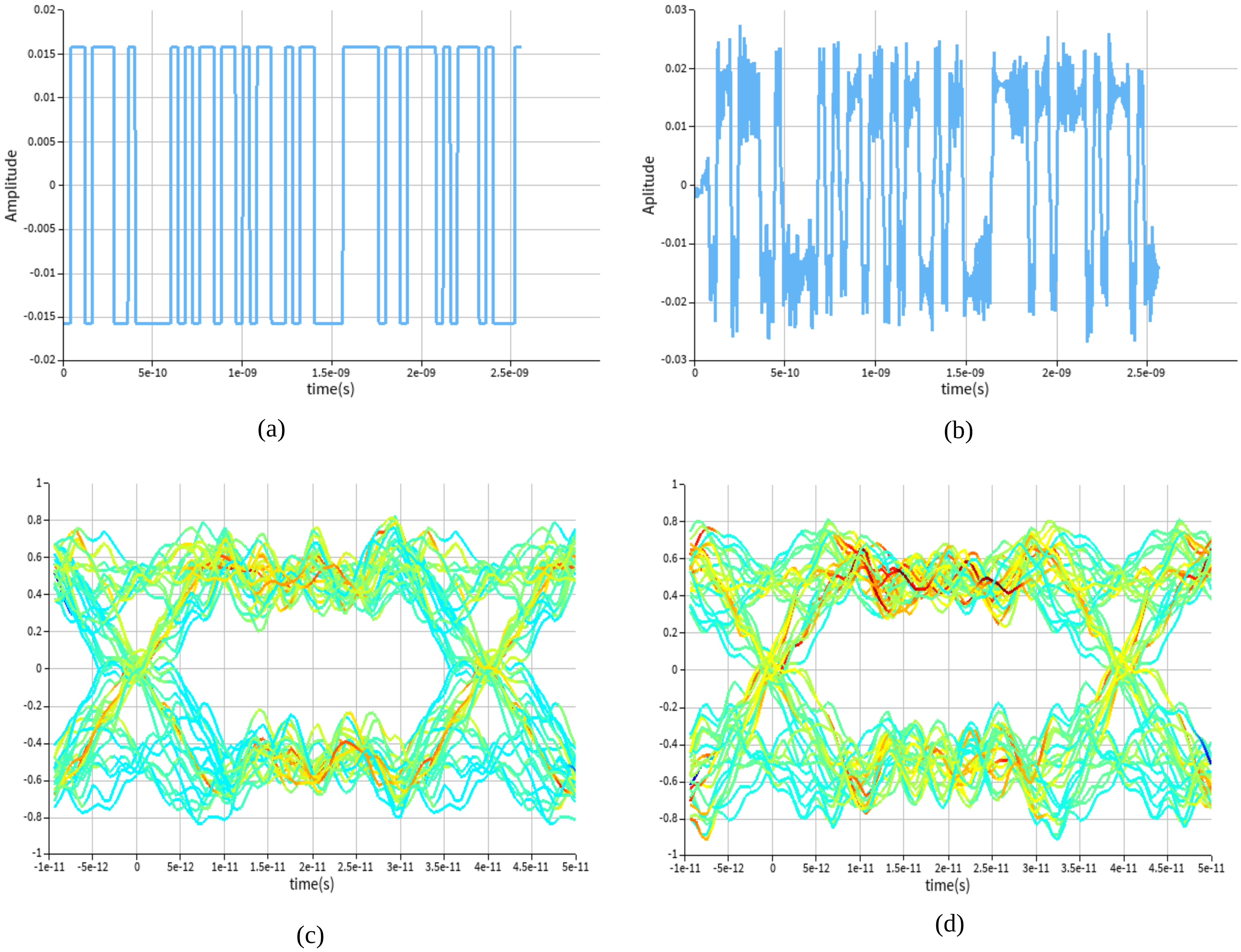


Figure 3.2: Signal at the fiber input (a), fiber output (b), eye diagram for the in-phase component (c) and the quadrature phase component (d).

4.1 Effect of the transmitter parameters

First, we consider the impact of both the input laser power and spectral linewidth on the system performances.

4.1.1 Effect of the input laser power

The input laser power exerts a dominant, non-monotonic influence on the system quality metrics-namely the Q factor, symbol error rate (SER), and error vector magnitude (EVM)-in the proposed 1 km optical QPSK link operating at 1.55 µm as depicted in figure 2, 3 and 4. At low input powers (substantially below 1 mW), the received signal is primarily degraded by additive white Gaussian noise (AWGN) from thermal and shot noise sources at the coherent receiver, resulting in a low Q factor, high SER, and elevated EVM due to poor phase estimation in the presence of noise. As the laser power increases towards the specified 1 mW and slightly beyond, the optical signal-to-noise ratio (OSNR) improves proportionally, leading to a marked enhancement in the Q factor (typically exceeding 7 for error-free operation), a reduction in SER into the range of 10^{-12} or lower, and a decrease in EVM to within standard constellation thresholds (e.g., below 15%). However, for this short fiber span, exceeding an optimum power threshold (approximately 5–8 mW for standard single-mode fiber) introduces detrimental nonlinear phase noise through self-phase modulation (SPM), which differentially rotates the QPSK constellation points. [1][9]

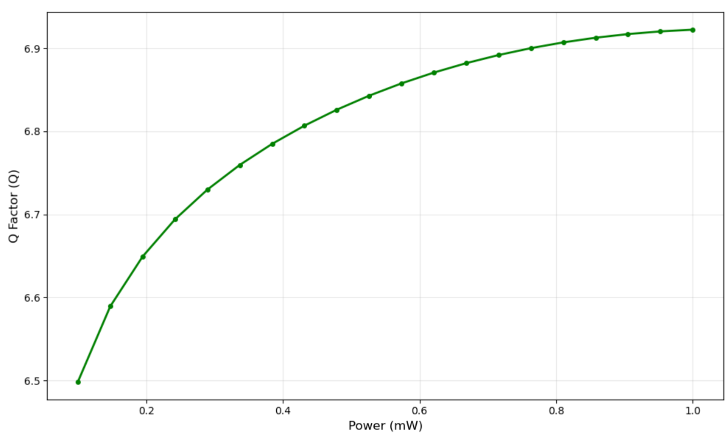


Figure 3.3: Effect of the laser power on the Q factor.

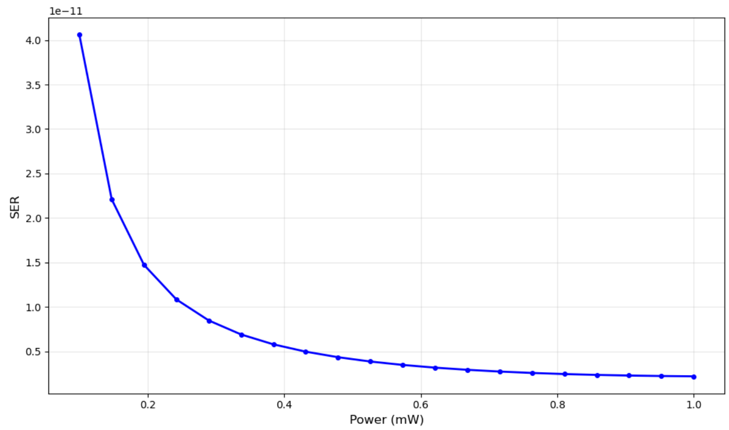


Figure 3.4: Effect of the laser power on the SER.

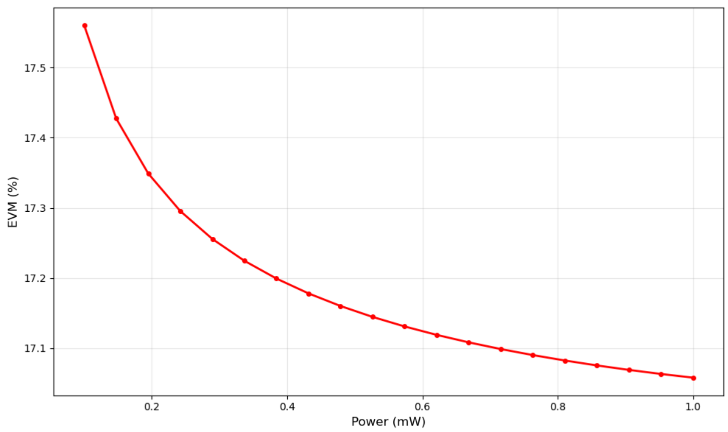


Figure 3.5: Effect of the laser power on the EVM.

Considering the eye diagram, figure (3.6) gives the eye diagram for the case of 0.1 mW and 1 mW.

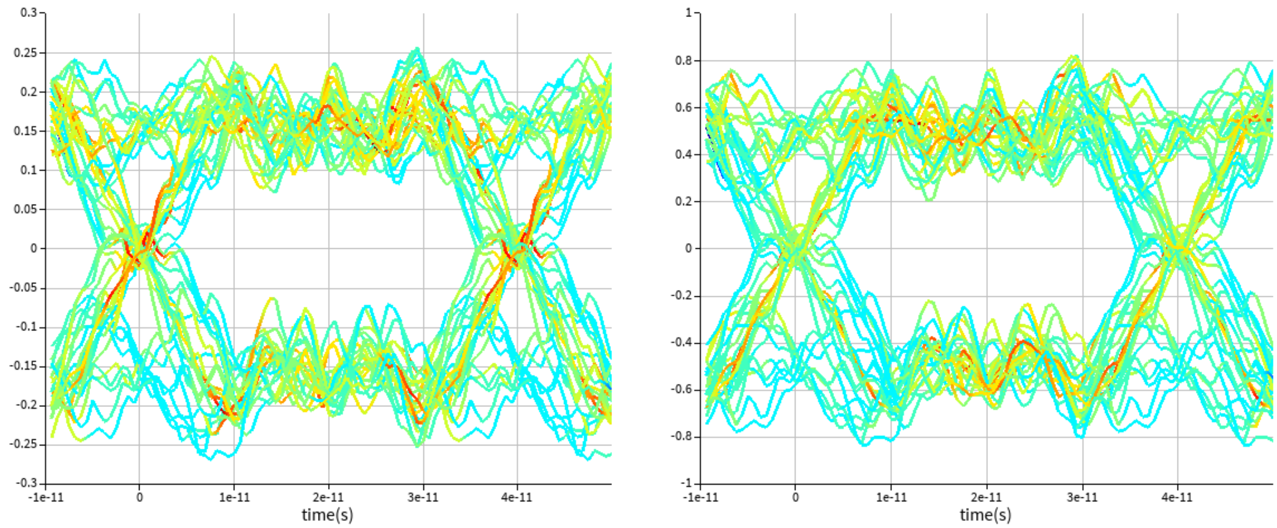


Figure 3.6: Eye diagram for the case of 0.1 mW (left) and 1 mW (right).

4.1.2 Effect of the input laser linewidth

The spectral linewidth of the input laser significantly impacts QPSK transceiver performance by introducing phase noise, which directly degrades the signal's error vector magnitude (EVM). In a QPSK system, information is encoded in the phase of the optical carrier—with states separated by 90 degrees. Excessive laser linewidth (relative to the symbol rate) causes random phase fluctuations that the receiver's carrier phase estimation (CPE) algorithm cannot fully track, leading to increased bit error rates (BER). For high-order QPSK systems, the laser linewidth must typically be less than ~10^{-4} times the symbol rate (e.g., a few hundred kHz for 10 Gbaud) to keep the phase noise penalty below 1 dB. Narrowing the linewidth improves coherent detection sensitivity and link margin, but requires trade-offs in laser design (e.g., longer cavities or lower feedback). [11][14]

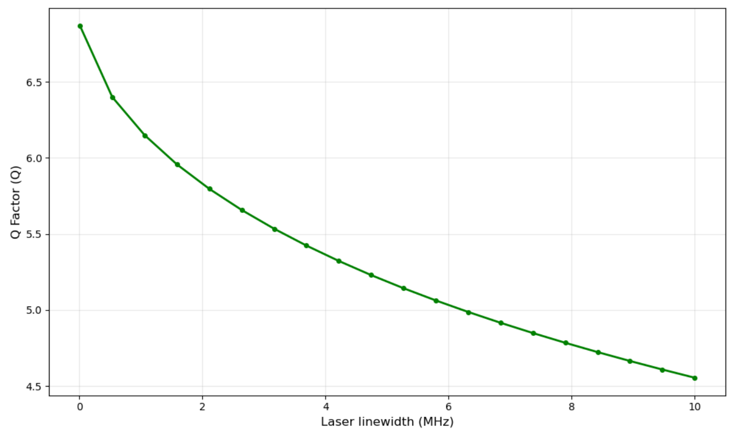


Figure 3.7: Effect of the laser spectral linewidth on the Q factor.

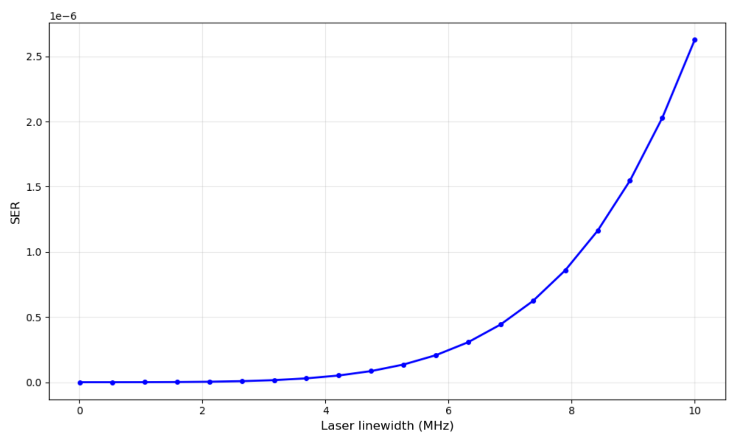


Figure 3.8: Effect of the laser spectral linewidth on the SER.

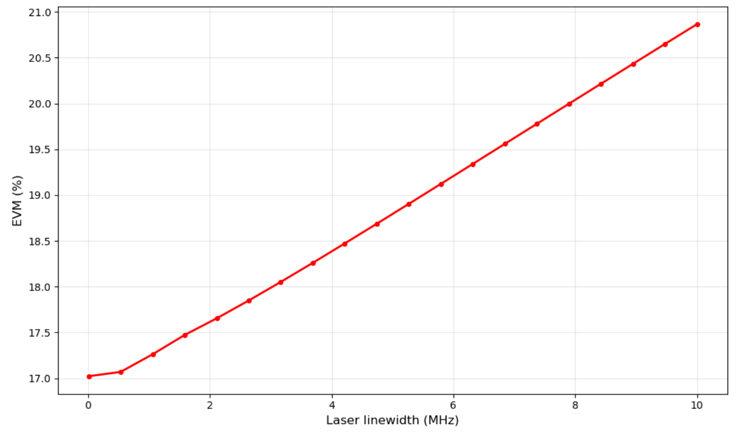


Figure 3.9: Effect of the laser spectral linewidth on the EVM.

Considering the eye diagram, figure (3.10) gives the eye diagram for the case of 10 KHz and 10 MHz.

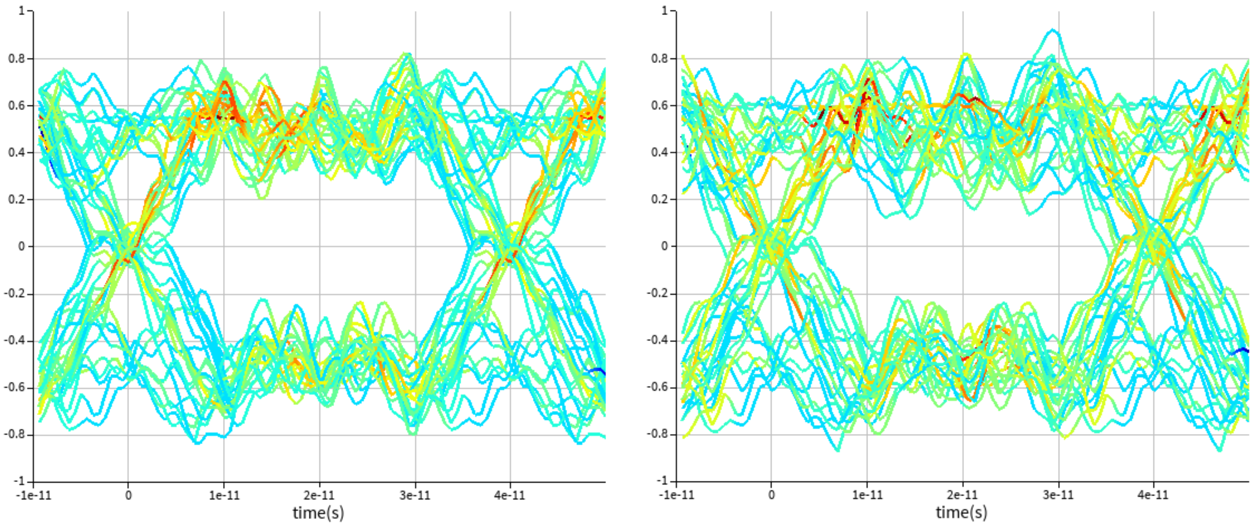


Figure 3.10: Eye diagram for the case of 10 KHz (left) and 10 MHz (right).

4.2 Effect of the channel attenuation

Channel attenuation is the reduction of a signal's strength as it travels through a communication channel. This phenomenon occurs due to factors such as distance, obstacles, and the physical properties of the transmission medium. As attenuation increases, the received signal becomes weaker, which can lead to data errors, lower transmission quality, and reduced communication range. To overcome attenuation, communication systems often use amplifiers, repeaters, or error-correction techniques to maintain reliable signal transmission. [4]

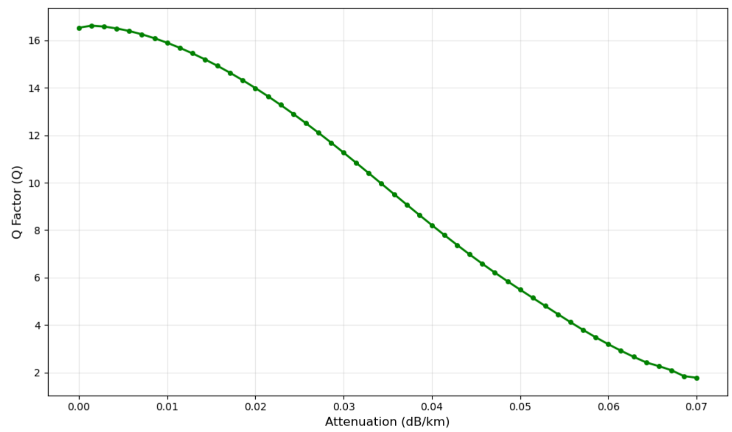


Figure 3.11: Effect of the Attenuation on the Q factor.

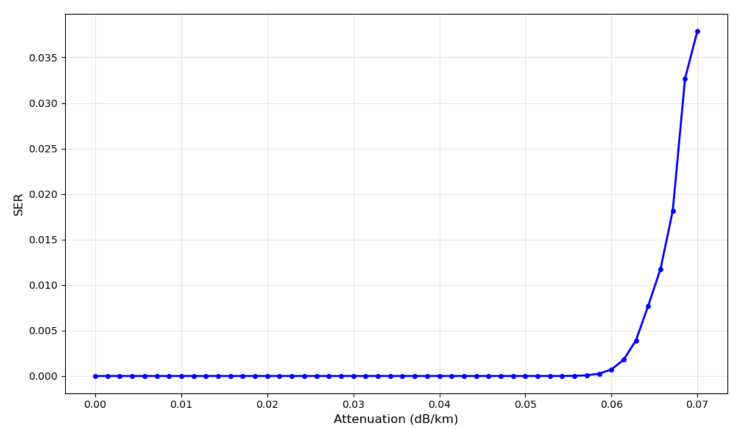


Figure 3.12: Effect of Attenuation on the SER.

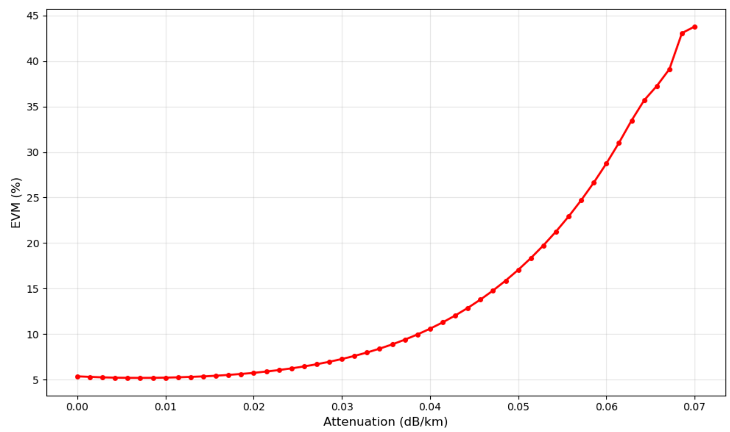
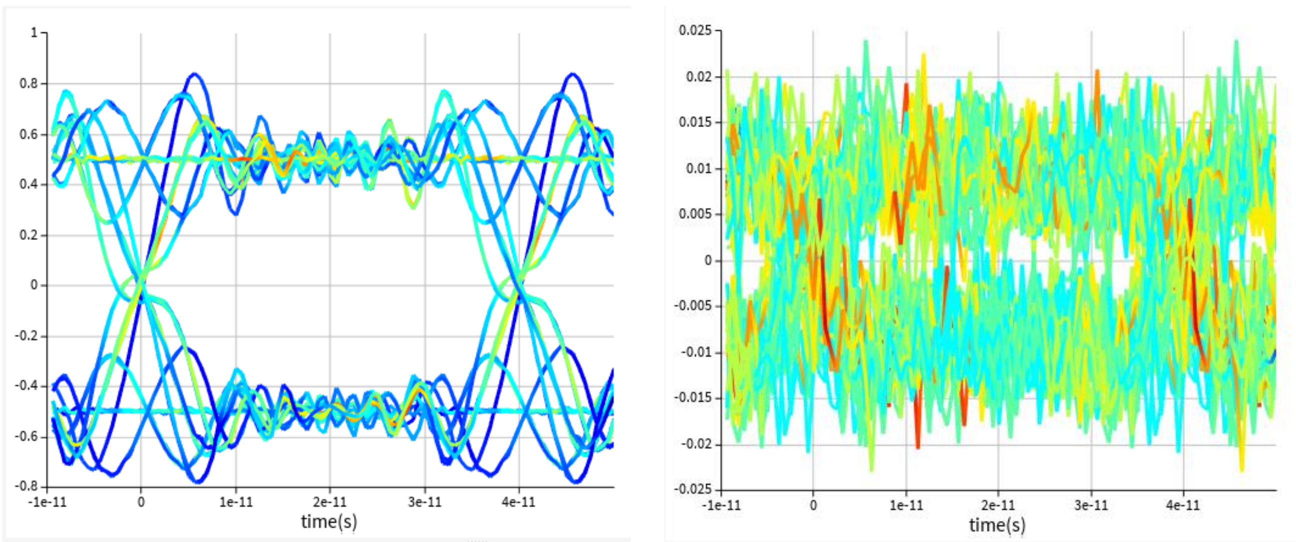


Figure 3.13: Effect of the Attenuation on the EVM.

Considering the eye diagram, figure (3.14) gives the eye diagram for the case of 0 mW and



70mW.

Figure 3.14: Eye diagram for the case of 0 mW (left) and 0.7 mW (right).

4.3 Effect of the receiver parameters

Finaly, we consider the impact of both the local laser oscillator power and spectral linewidth on the system performances.

4.3.1 Effect of the LO power

The Local Oscillator (LO) power plays a crucial role in the performance of communication and RF systems, especially in mixers. Adequate LO power ensures efficient frequency conversion and improves signal quality. If the LO power is too low, the mixer may not operate properly, leading to higher conversion losses and reduced output signal strength. On the other hand, excessively high LO power can cause distortion, increased noise, and unnecessary power consumption. Therefore, maintaining the optimal LO power level is essential for achieving reliable and efficient system performance. [12][13]

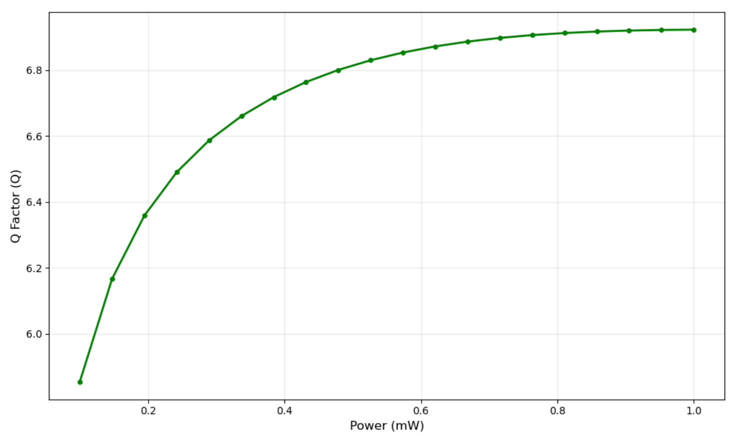


Figure 3.15: Effect of the LO power on the Q factor**.**

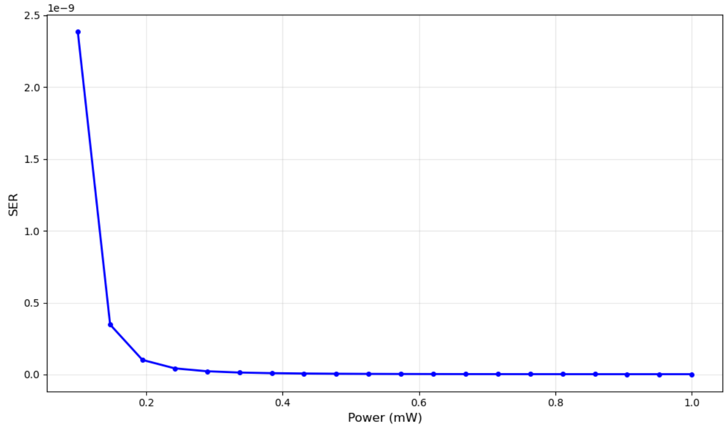


Figure 3.16: Effect of LO power on the SER.

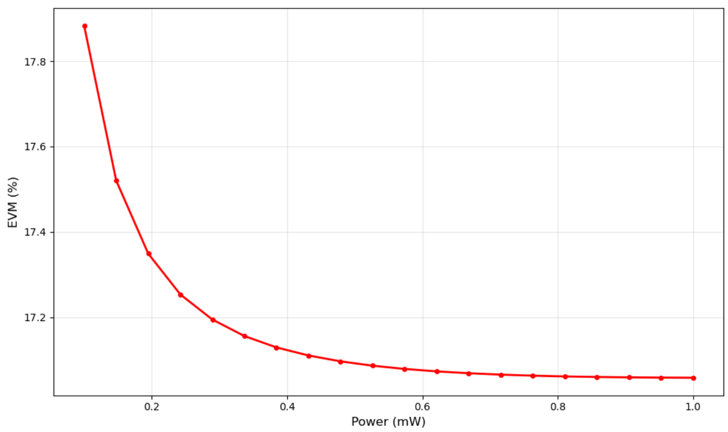


Figure 3.17: Effect of the LO power on the EVM.

Considering the eye diagram, figure (3.18) gives the eye diagram for the case of 0.1 mW and 1mW.

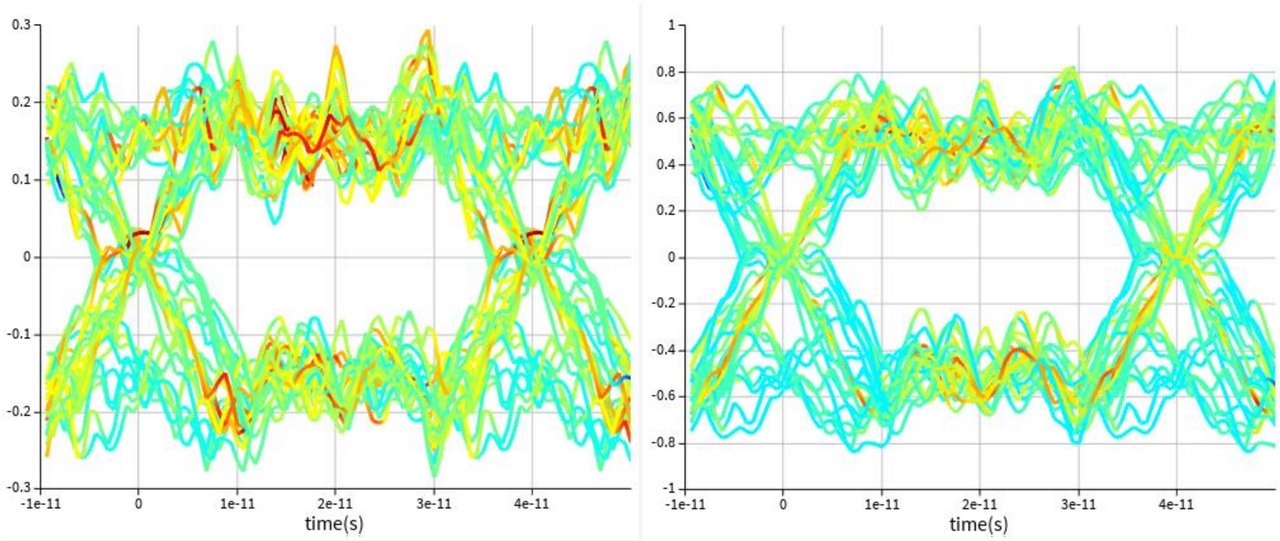


Figure 3.18: Eye diagram for the case of 0.1 mW (left) and 1 mW (right).

4.3.2 Effect of the LO linewidth

The linewidth of the Local Oscillator (LO) represents the spectral purity and frequency stability of the oscillator. A narrow LO linewidth indicates lower phase noise and better frequency stability, resulting in improved signal quality and more accurate frequency conversion. In contrast, a wider LO linewidth introduces higher phase noise, which can degrade system performance by increasing signal distortion, reducing signal-to-noise ratio, and causing errors in communication systems. Therefore, minimizing the LO linewidth is important for achieving high-performance and reliable RF and optical communication systems. [11][16]

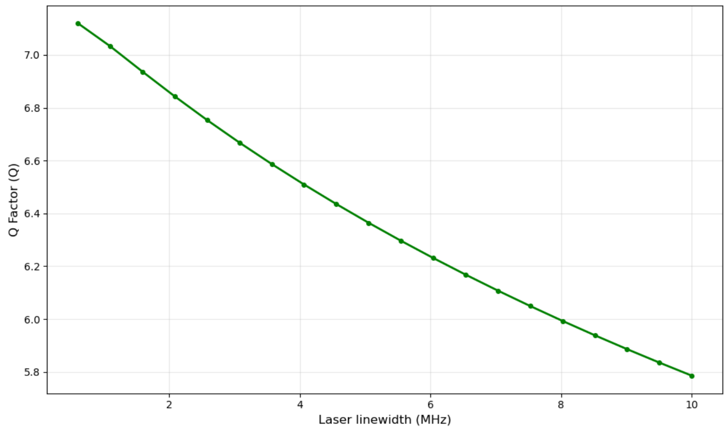


Figure 3.19: Effect of the LO linewidth on the Q factor**.**

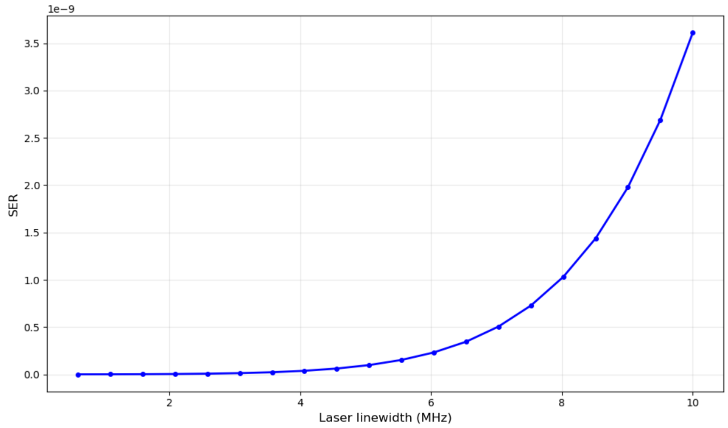


Figure 3.20: Effect of LO linewidth on the SER.

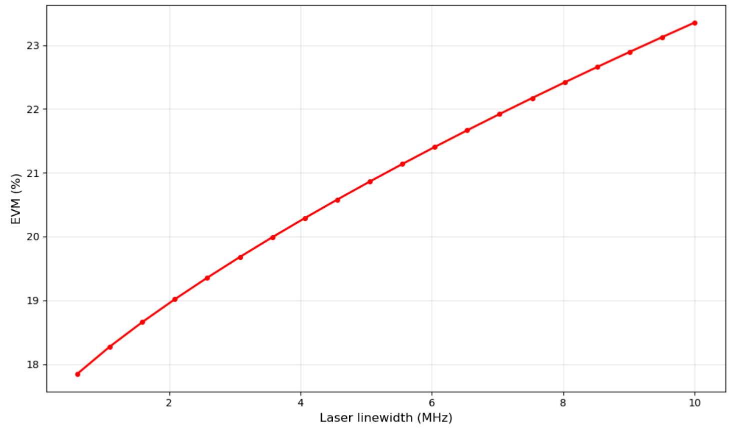


Figure 3.21: Effect of the LO linewidth on the EVM.

Considering the eye diagram, figure (3.22) gives the eye diagram for the case of 0.6 MHz and 10 MHz.

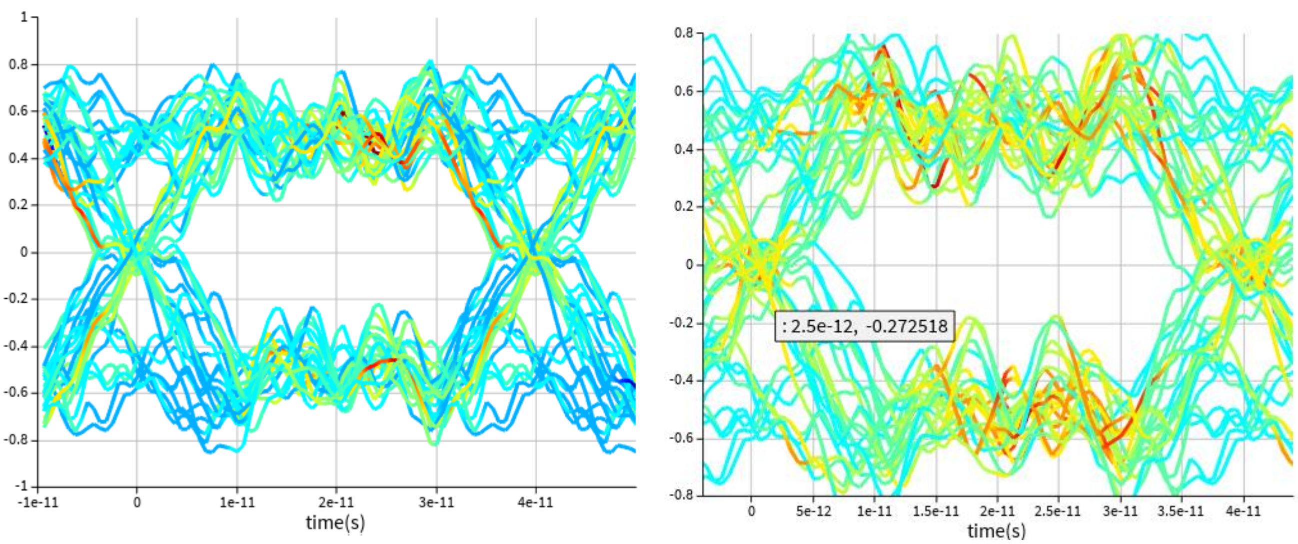


Figure 3.22: Eye diagram for the case of 0.6 MHz (left) and 10 MHz (right).

CHAPTER 03

5.Conclusion

In this chapter, the design and performance evaluation of the QPSK transceiver were presented and analyzed through numerical simulations. The transmitter architecture was implemented by mapping the input binary data stream into four distinct phase states, allowing the transmission of two bits per symbol and consequently improving spectral efficiency compared to binary modulation formats. The receiver section was investigated to assess its ability to recover the transmitted information accurately. The obtained results demonstrated the correct generation, transmission, and detection of the QPSK signal. Time-domain waveforms, eye diagrams, and other performance metrics confirmed the effectiveness of the modulation and demodulation processes.

General Conclusion

This thesis has presented a complete study of a coherent QPSK optical transceiver system, covering both the theoretical foundations and the practical simulation and performance evaluation of the system. A coherent QPSK transceiver operating at 25 Gbit/s over an optical carrier of 193.1 THz and a 1 km standard single-mode fiber link was successfully designed and simulated. The NRZ waveforms, eye diagrams, constellation diagrams, and performance metrics all confirmed the correct operation of every system component, from data generation to coherent demodulation.

The simulation results revealed that the system performance is highly sensitive to several key parameters. Regarding the effect of the input laser power, increasing the power from low levels toward the optimal range (around 1 mW) leads to a significant increase in the Q-factor and a notable decrease in both the SER and the EVM, as the optical signal-to-noise ratio improves. However, exceeding the optimal power threshold (approximately 5–8 mW) causes the Q-factor to decrease and the SER and EVM to increase again due to nonlinear effects such as self-phase modulation. Similarly, the laser spectral linewidth has a direct impact: as the linewidth increases, the Q-factor decreases and the SER and EVM increase due to the growth of phase noise, which the carrier phase estimation algorithm cannot fully compensate. Conversely, narrowing the linewidth improves all three metrics.

With respect to channel attenuation, increasing the fiber loss reduces the received signal power, causing the Q-factor to decrease and both the SER and EVM to increase, ultimately degrading system reliability. On the receiver side, the Local Oscillator (LO) power also plays a critical role: at low LO power levels, the Q-factor is reduced and the SER and EVM are elevated due to insufficient mixing gain. As the LO power increases toward its optimal value, the Q-factor improves and the SER and EVM decrease. Excessive LO power, however, introduces distortion that again degrades performance. Likewise, increasing the LO linewidth introduces additional phase noise at the receiver, leading to a decrease in the Q-factor and an increase in the SER and EVM.

The eye diagrams and constellation plots obtained from the simulator confirmed these observations visually, showing clearly open eyes and well-separated phase states under optimal conditions, and progressively degraded patterns as parameters deviated from their optimal values. In summary, this thesis confirms that coherent QPSK optical transceivers represent a mature and reliable technology for high-capacity optical communications. The combination of phase modulation efficiency, coherent detection sensitivity, and the availability of advanced photonic simulation tools makes this approach well-suited for deployment in future high-speed optical networks. Future work may extend this study to longer fiber spans, higher-order modulation formats, and the investigation of digital signal processing algorithms for further performance improvement.

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