Democratic and People's Republic of Algeria
Ministry of Higher Education and Research Scientific

University of Hamma Lakhder EL-OUED

Faculty of Science and Technology

Department of Electrical Engineering

Final thesis

Presented for the graduation of

ACADEMIC MASTER

Field: Science and technology

Sector: Electrical Engineering

Specialization: Telecommunications

The topic

Numerical investigation of an electro-absorption based optical modulator

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2023/2024

Dedication

I dedicate this modest work to those who are
the source of my inspiration and my
courage.
To my dearest mother, who always gives me
the hope of living that never ceased
to pray for me.
To my dearest father who acrifies throughout my
God bless them for their moral support
and financially, for their encouragement and sacrifices
and especially for his sacrifice so that nothing hinders
The course of my studies.
To my dear brothers.
To my sister.
To all my friends.

Gratitude

First, we would like to thank our GOD "Allah" our creator for giving us the strength to accomplish this work.

My sincere thanks go above all to my teacher ***MADJOURI Abdelkader*** *who guided and supported me in this research. For having diligently engaged us throughout of this work, for its understanding, patience, competence , and these remarks that have been precious to us.*

We offer our warm thanks to the teachers of the Department of Electrical Engineering Our last thanks, go to all those who contributed near or far to the end of this work.

Abstract

This study conducts a thorough numerical investigation of an electro-absorption based optical modulator using computational simulations and analysis. The focus lies on exploring how the modulator performs under various operational conditions, particularly in response to different voltage inputs and input signals. The ultimate aim is to optimize the modulator's design to achieve desired performance metrics such as modulation depth and bandwidth. Furthermore, potential challenges and limitations encountered during the modulator's operation are identified and addressed to improve its efficiency and reliability. The study's findings contribute significantly to advancing electro-absorption based optical modulators, offering valuable insights that can drive enhancements in optical communication technology.

Key words: electro-absorption, the modulator, optical modulators, optical communication.

Résumé

Cette étude conduit une étude numérique approfondie d'un modulateur optique basé sur l'électro-absorption en utilisant des simulations et des analyses informatiques. L'accent est mis sur l'exploration de la façon dont le modulateur fonctionne dans diverses conditions opérationnelles, en particulier en réponse à différentes entrées de tension et signaux d'entrée. L'objectif ultime est d'optimiser la conception du modulateur pour atteindre les mesures de performance souhaitées telles que la profondeur de modulation et la bande passante. En outre, les défis et les limites potentiels rencontrés au cours de l'exploitation du modulateur sont identifiés et abordés pour améliorer son efficacité et sa fiabilité. Les résultats contribuent de manière significative à faire progresser les modulateurs optiques à base d'électro-absorption, offrant des informations précieuses qui peuvent conduire à des améliorations dans la technologie de communication optique.

Mots clés : l'électro-absorption, le modulateur, les modulateurs optiques, la communication optique.

الملخص

تجري هذه الدراسة تحقيقًا عدديًا شاملاً لمعدل بصري قائم على الامتصاص الكهربائي باستخدام المحاكاة والتحليل الحسابي. ينصب التركيز على استكشاف كيفية أداء المحول في ظل ظروف تشغيلية مختلفة، لا سيما استجابة لمدخلات الجهد المختلفة وإشارات المدخلات. الهدف النهائي هو تحسين تصميم المعدل لتحقيق مقاييس الأداء المطلوبة مثل عمق التعديل وعرض النطاق الترددي. علاوة على ذلك، يتم تحديد التحديات والقيود المحتملة التي تتم مواجهتها أثناء تشغيل عامل التغيير ومعالجتها لتحسين كفاءته وموثوقيته. تساهم نتائج الدراسة بشكل كبير في تطوير المعدلات البصرية القائمة على الامتصاص الكهربائي، مما يوفر رؤى قيمة يمكنها دفع التحسينات في تكنولوجيا الاتصالات البصرية.

الكلمات المفتاحية: الامتصاص الكهربائي، المغير، المغيرات البصرية، الاتصالات البصرية.

List Of Abbreviations

PCs : Personal Computers.

LED : Light Emitting Diode.

LASER : Light Amplification by Stimulated Emission of Radiation.

LD : Laser Diode.

MSM : Metal–Semiconductor–Metal.

MZI : Mach-Zehnder Interferometer.

EO : Electro-Optical.

EA : Electro-Absorption.

TM : Transverse Magnetic.

TE : Transverse Electric.

GaAs : Gallium Arsenide.

AMI : Alternate Mark Inversion.

ADC : Analog-to-Digital Converter.

NRZ : Non-Return-to-Zero.

RZ : Return-to-Zero.

FWHM : Full Width at Half Maximum.

ASK : Amplitude Shift Keying.

OOK : On-Off Keying.

PSK : Phase Shift Keying.

BPSK : Binary Phase Shift Keying.

FSK : Frequency Shift Keying.

CPFSK : Continuous Phase Frequency Shift Keying.

DMLs : Directly modulated lasers.

MZ : Mach-Zehnder.

EAM : Electro-Absorption Modulator.

EAMs : Electro-Absorption Modulators.

QCSE : Quantum Confined Stark Effect.

PRBS : Pseudo-Random Binary Sequence.

OSC : Oscilloscope.

CWL : Continuous Wave Laser.

OOSC : Optical Oscilloscope.

SPAR : Optical Time Variant S-Parameter.

GENERAL INTRODUCTION

General introduction

The era of speed, is a label we often hear today. Indeed, in most fields, we find that researchers and scientists are looking for ways to accomplish tasks faster and cheaper, and the field that falls under this label is data communications. With the advent of the internet and its diffusion throughout the world, the needs in bandwidth have become increasingly important in order to convey the growing mass of information on the various networks, with reliability and preserving a good quality of service. Indeed, this has required the development of communications systems that are efficient and reliable enough to interconnect a constantly growing number of users around the world. At present, the most efficient and widespread technology relies on fiber optic transmission systems.

In theory, optical fiber offers bandwidth of several hundred gigahertz. Nevertheless, the amount of information transmitted is limited in part by the modulation technique. For speeds above 10 Gbps, commercial transmitters today use external modulation. This technique, less sensitive to chromatic dispersion and offering greater spectral purity, is performed from a continuous laser source and an optical modulator.

My research work presented in these sections is particularly relevant to a numerical study of an optical modulator based on electrical absorption. We divided this work into three important chapters:

Chapter 1 presents generalities on optical communication systems as well as optical communication system structure, fiber optic, optical transmitter, optical receivers and optical modulator.

In chapter II, I will talk about optical modulators in addition to the basic operation principle of electro-optic modulators, line coder, pulse shaping, digital modulation schemes, direct modulation, external modulators, phase modulation, electrical absorption modulator.

Finaly, we present the main results of numerical simulations in chapter III. Here, we use a multiple softwares to accomplish an optoelectronic simulation of a GaAs based electro-absorption modulator.

CHAPTRE I

Optical Communication System

I.1. Introduction

A communication system transmits information from one place to another, whether separated by a few kilometers or by transoceanic distances. Information is encoded on an electromagnetic carrier wave, whose frequency can vary from a few megahertz to several hundred terahertz. Optical communication systems employ high frequencies (∼200 THz) in the near-infrared region of the electromagnetic spectrum. They are also called light wave systems to distinguish them from microwave systems, whose carrier frequency is typically smaller by five orders of magnitude (∼1 GHz). Fiber-optic communication systems are light wave systems that employ optical fibers for information transmission. Such systems have been deployed worldwide since the year 1980 and have revolutionized the field of telecommunications. Indeed, light wave technology, together with microelectronics, led to the advent of the “information age” during the 1990s. The emphasis is on the fundamental aspects, but relevant engineering issues are also discussed. In this introductory chapter, we present the basic concepts and provide the background material. [1]

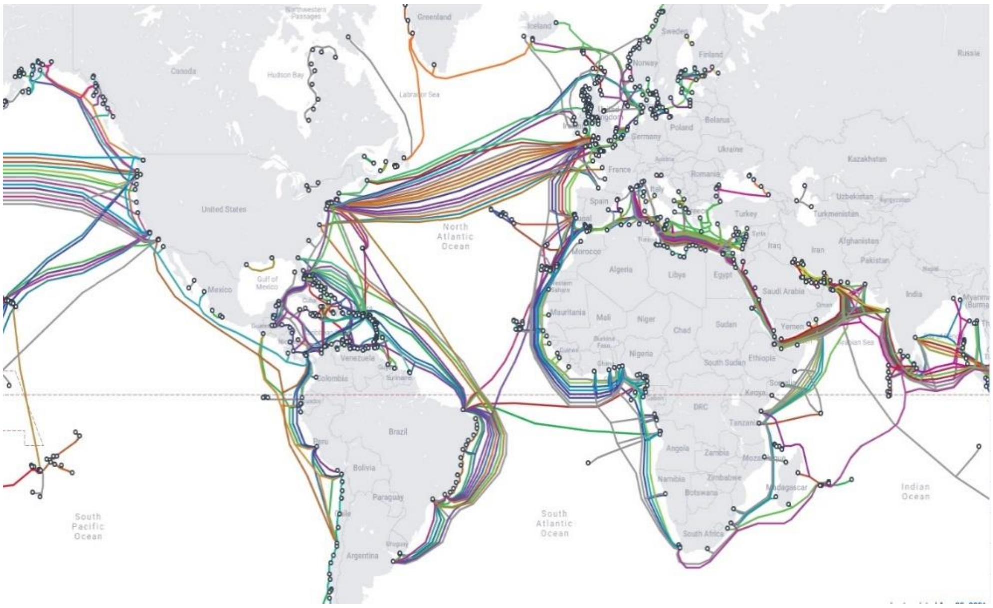


Figure (I.1): Global-fiber-optic-cable-network-map.

I.2. Structure of Optical communication system

Optical communication systems differ in principle from microwave systems only in the frequency range of the carrier wave used to carry the information. The optical carrier frequencies are typically ∼200 THz, in contrast with the microwave carrier frequencies (∼1 GHz). An increase in the information capacity of optical communication systems by a factor of up to 10,000 is expected simply because of such high carrier frequencies used for light wave systems. This increase can be understood by noting that the bandwidth of the modulated carrier can be up to a few percent of the carrier frequency. Taking, for illustration, 1% as the limiting value, optical communication systems have the potential of carrying information at bit rates ∼1 Tb/s. It is this enormous potential bandwidth of optical communication systems that is the driving force behind the worldwide development and deployment of light wave systems. Current state-of-the-art systems operate at bit rates ∼10 Gb/s, indicating that there is considerable room for improvement. Optical communication systems can be classified into two broad categories: guided and unguided. As the name implies, in the case of guided light wave systems, the optical beam emitted. In addition, Figure (I.2) shows the general optical communications structure that is applicable and common to all communications systems. [2]

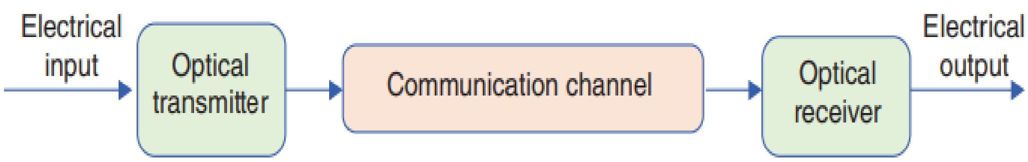


Figure (I.2): A general structure of an optical communication system.

I.3. Optical fibers

Figure (I.3) shows the schematic of a conventional optical fiber structure. Most other fiber constructions are based on material, size, and layering variations of this fundamental configuration. A standard fiber consists of a solid glass cylinder called a core. The core is the region in which light propagates along the fiber. This is surrounded by a dielectric cladding, which has a different material property from that of the core in order to achieve light guiding in the fiber. A standard cladding diameter is 125 µm for most types of fibers. A polymer buffer coating with a nominal 250 µm diameter surrounds these two layers to protect the fiber from mechanical stresses and environmental effects. Finally, an outer protective polymer jacket with a nominal 900 µm diameter encapsulates the fiber. A standard cladding diameter is 125 µm for most types of fibers. A polymer buffer coating with a nominal 250 µm diameter surrounds these two layers to protect the fiber from mechanical stresses and environmental effects. Finally, an outer protective polymer jacket with a nominal 900 µm diameter encapsulates the fiber. The first-generation optical fiber had a 50µm core diameter and a 125µm cladding diameter. Six such buffered fibers were enclosed in a single optical cable, which was used in the first installed optical fiber links in the late 1970s. These commercial links were used for transmitting telephony signals at about 6 Mb/s over distances of around 10 km. As research and development progressed, the sophistication and capabilities of these systems increased rapidly during the 1980s to create links carrying aggregate data rates beyond terabits per second over distances of hundreds of kilometers. These achievements were based on new technology developments using single-mode optical fiber with nominally 9 µm core diameters. This demand was fueled by the rapid proliferation of personal computers (PCs) and sophisticated smart phones coupled with a phenomenal increase in their storage capacity and processing capabilities. [3]

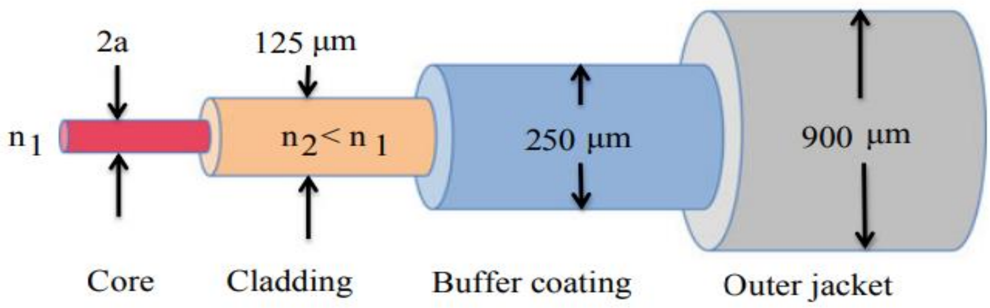


Figure (I.3): Structure of a conventional optical fiber.

The phenomenon of total internal reflection, responsible for guiding of light in optical fibers, has been known since 1854 [4]. An optical fiber is the core component of an optical fiber communication link. Popularly known as optical fiber cables, they are the most promising type of guided transmission medium for virtually all forms of digital and data communications applications. With optical fibers, electromagnetic light waves propagate through the media composed of a transparent material without using electrical current flow. Optical fibers are mostly made of glass or plastic material having properties such that the phenomena of total internal reflection take place that enables light waves to propagate within it in a properly guided manner similar to that of electromagnetic waves through a metallic transmission medium. this an easy-to-understand ray model of the propagation of light through optical fibers. where a discussion on the concept of modes and the modal analysis of step-index as well as the graded-index type of fibers. [5]

I.3.1. Step-index optical fiber

A step-index optical fiber cable has a central core having a uniform index of refraction (i.e., constant density throughout the core) which is surrounded by a cladding that too has a uniform index of refraction but of lesser value as that of the core. Thus, there is an abrupt change in the refractive index at intersection of the fiber core and the cladding of the optical fiber cable. A typical index profile of a step-index optical fiber is illustrated. [4]

I.3.2.Graded-index optical fiber

Graded-index optical fiber, as the name suggests, is different from step-index optical fiber with respect to the nature of their index profile. It has a central core with a non-uniform index of refraction. This simply means that the refractive index of the fiber core is maximum in the middle and then it gradually decreases towards its outer edge up to core–cladding interface. Thus, graded-index optical fibers do not possess a constant refractive index even within the fiber core. [6]

I.4. Optical transmitter

The role of an optical transmitter is to convert an electrical input signal into the corresponding optical signal and then launch it into a fiber cable serving as the communication channel. A major component of optical transmitters is the optical source. Lightwave systems employ semiconductor sources such as a light-emitting diode (LED) or a semiconductor laser because of several advantages offered by them. These advantages include compact size, high efficiency, good reliability, right wavelength range, and possibility of direct modulation at relatively high frequencies. The use of semiconductor lasers became practical after 1970, when continuous operation of such lasers became possible at room temperature [4]. They are also known as laser diodes or injection lasers, and their properties have been discussed in several books [7–8].

I.4.1. Laser diodes

Recall the acronym for LASER as Light Amplification by Stimulated Emission of Radiation. As compared to incoherent and wide spectral emission characteristics of LED optical source, a laser diode (LD) exhibits much better performance in terms of high transmission data rate for long-haul optical fiber communication networks. However, it has the disadvantage of having complex drive circuits, temperature-dependent optical power output, lower reliability and being expensive. Some of the distinct advantages of laser diodes are given below:

1. Higher optical power output (of the order of mW), mainly due to amplifying effect of stimulated emissions.
2. Narrow bandwidth (less than or equal to 1 nm) which helps to minimize the impact of material dispersion (for example, group velocity dispersion).
3. Modulation capabilities up to GHz range.
4. Coherent output which allows heterojunction coherent detection in high-capacity system.
5. Efficient coupling of optical power output into the low numerical aperture fibers by focusing the light into a tiny spot by using an external lens.

6. Size of injection laser diode is compatible with optical fiber.

7. Better error performance. [9]

I.4.2 Modulation techniques

Optical transmitters are designed to output a data-encoded optical signal and thus need a modulator that transfers an electrical bit stream into the optical domain. In the case of direct detection systems, this modulator generates an optical pulse train (in the RZ or NRZ format) representing a coded sequence of 0 and 1 bits. Two techniques, known as (a) direct modulation and (b) external modulation, can be used to generate such an optical bit stream. [10]

I.5. Optical receivers

The role of an optical receiver is to convert the incoming optical signal into an electrical form and recover the data transmitted over a fiber cable. Its main component is a photodetector, which converts light into current through the photoelectric effect. The requirements for a good photodetector are similar to those for an optical source at the transmitter side. It should have low noise, high sensitivity, low cost, and high reliability, and its size should be compatible with the fiber's core size. These requirements are best met by photodetectors made of semiconductor materials [11–12]. We introduce in Section 4.1, the basic concepts related to such photodetectors and discuss in Section 4.2 about several types of photodetectors used for optical receivers. The components of an optical receiver are described in Section 4.3.

I.5.1 Basic Concepts

The physical mechanism behind the photodetection process is the absorption of photons by a semiconductor material. This section introduces basic concepts such as responsivity, quantum efficiency, rise time, and bandwidth that are common to all photodetectors and are used to characterize them. [11]

I.5.2 Common Photodetectors

The semiconductor slab of Figure (I.4) is useful for illustrating the basic concepts but such a simple device is rarely used in practice. This section focuses on reverse-biased p–n junctions that are commonly used for making optical receivers. Metal–semiconductor–metal (MSM) photodetectors are also discussed briefly [12].

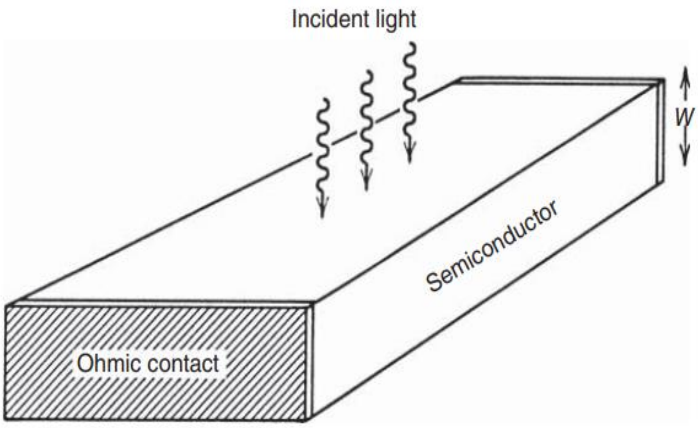


Figure (I.4): A semiconductor slab used as a photodetector.

I.5.3 Receiver Design

The design of an optical receiver depends on the modulation format used by the transmitter. As many light wave systems employ intensity modulation with direct detection, we focus in this section on optical receivers used for such systems. Figure (I.5) shows a block diagram of such a receiver with its components arranged into three groups. The detectors developed for coherent systems make use of a heterodyne technique [12].

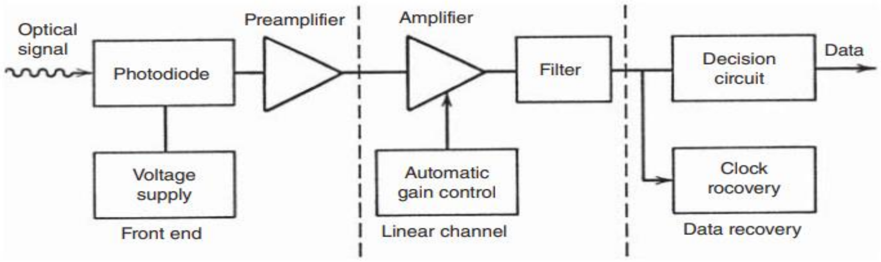


Figure (I.5): Diagram of a digital optical receiver showing various components. Vertical dashed lines group receiver components into three sections.

I.6. Optical modulators

In an optical transmitter, encoding electrical signals into optical domains can be accomplished either by directly modulating the injection current of a laser diode, known as direct modulation, or by electro optic (EO) modulation using an external modulator, known as external modulation.

The speed of direct modulation is primarily limited by the carrier lifetime of the laser source, which is typically in the sub-nanosecond level. Meanwhile, a more important concern of direct current modulation is that it not only modulates the intensity but also modulates the frequency of the optical signal through the carrier density-dependent refractive index of the semiconductor material [13]. This effect is known as the frequency chirp, which broadens the spectral width of the optical signal and may significantly degrade the transmission performance of a high-speed fiber-optic system when chromatic dispersion is considered. The broadened signal optical spectrum also reduces the bandwidth efficiency when wavelength division multiplexing (WDM) is used. On the other hand, an external modulator manipulates the optical signal after the laser, and ideally it does not affect the laser operation. Nowadays, a commercial, high-speed external EO modulator can have >100 GHz modulation bandwidth with well-controlled frequency chirp [14]. Because of their high performances, external modulators have been widely adopted in long-distance and high-speed optical communication systems. Depending on the device configuration and system requirement, an external modulator can perform intensity modulation and optical phase modulation, as well as complex optical field modulation, which is the combination of amplitude and phase modulation. Both the EO effect and electro-absorption (EA) have been used to make external optical modulators. The former relies on the modulation of refractive index by the applied electric field, whereas the latter is the attenuation that is dependent on the applied electric field. This chapter starts by discussing basic operation principles and configurations of EO modulators, including phase modulators and intensity modulators. Among various EO materials, lithium niobate ($LiNbO_3$) is most often used to make external modulators in fiber-optic systems because of the high EO coefficient and low attenuation in the optical communications wavelength window. While the EO effect is capable of directly introducing optical phase modulation through the applied electric voltage waveform, optical circuit configuration such as a Mach-Zehnder interferometer (MZI) can convert the phase modulation into intensity modulation, so that EO amplitude modulators can be made. The relationship between phase modulation and amplitude modulation in a modulator based on a single MZI can be explored to create single-sideband as well as carrier-suppressed optical modulation. A more sophisticated optical circuit based on the combination of three MZIs, known as the I/Q modulator, can provide more flexibility of modulating the optical phase and optical amplitude independently. This ability of complex optical field modulation is required in many coherent optical communication systems that encode data into both the amplitude and the phase of the optical signal to enhance the transmission capacity. A commercially available $LiNbO_3$ based on I/Q modulator with input and output fiber pigtails is shown in Figure (I.6) A. Although EO modulators based on $LiNbO_3$ can have excellent performance, they are usually expensive and traditionally cannot be monolithically integrated with diode laser sources. EA modulators, on the other hand, are based on pn-junction structures made of III–V semiconductor materials, which are the same materials as those used to make laser diodes. Instead of forward biasing with injection current such as in-diode lasers, the pn-junction of an EA modulator is reversely biased (similar to a photodiode), which absorbs photons and converts them into electrons. The optical absorption of an EA modulator is thus proportional to the applied reverse bias voltage, directly allowing intensity modulation of the optical signal. Because of the use of the same material platform and the similar pn-junction and waveguide structures, an EA modulator can be monolithically integrated with a diode laser to reduce the cost and to miniaturize the footprint of an optical transmitter. A commercially available laser diode integrated with and EA modulator is shown in Figure (I.6) B; it only needs a single output fiber pigtail. However, the change of electro-absorption is often associated with a change of signal optical phase in the semiconductor material when modulated with an electric voltage waveform, which often introduces a modulation chirp. In addition, directly integrating an EA modulator with a diode laser source without sufficient isolation between them may cause an optical reflection back into the laser diode, affecting the coherence property of the optical signal [1].

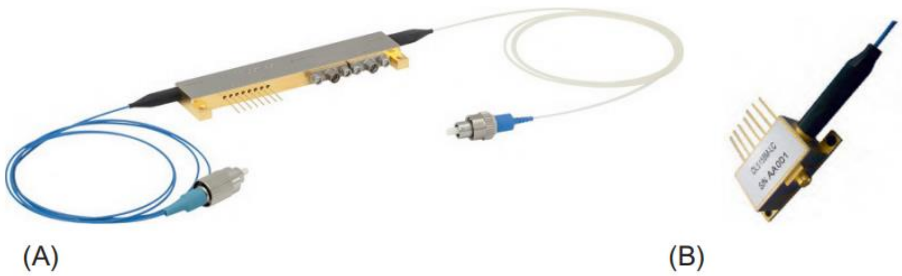


Figure (I.6): Examples of commercial EO modulator based on $LiNbO_3$ (A), and EA modulator integrated with a laser source (B).

I.7. Conclusion

In this chapter, we delved into studying the optical fiber communication system as a means of transmitting information from one place to another. An optical communication system consists of a transmitter and a receiver that are separated by an optical fiber. Furthermore, information is encoded by modulating an optical signal carrier generated by the laser. The aim of the next chapter is to present with details the various techniques to realize external modulation.

CHAPTRE II

Optical Modulators

II.1. Introduction

The electro-optic effect can be used in optical waveguide devices to control the phase or amplitude of a guided wave. Typically, these devices use this effect to control polarization or interference of guided-light beams, with the most important application being in integrated optical modulators. These devices operate on the electro-optical coupling of TE and TM modes in a waveguide, or pure phase retardation of waveguide modes. This coupling can be understood and treated via coupled-mode theory. In addition, electro-optic control of phase retardation of the guided light enables polarization splitting, optical switching, a wavelength-selective coupling. The electro-optic effect results from a redistribution of bound charges in a dielectric waveguide upon the application of a voltage across the optical guide [15]. Deformations of the lattice from the applied electric field also contribute to the effect. These perturbations cause a change in the optical impermeability tensor relating the displacement vector, $\vec{D}$, and the electric field, $\vec{E}$, of the optical wave. Equivalently, the application of an electric field causes a change in the index of refraction of the crystal. In this chapter, we will first briefly review the fundamentals of the electro-optic effect and consider two model–material systems, which are used heavily for the E/O devices: GaAs (or other III–V semiconductor material) and LiNbO3. In addition, electro-optical devices have been made in a variety of other material systems , including polymers, etc.; these secondary materials are mentioned throughout. The chapter will then present a detailed discussion of optical modulators [16].

II.2. Basic operation principle of electro-optic modulators

EO modulators rely on EO materials in which the refractive indices are functions of the electrical field applied on them. More specifically, for an EO material, the index change δn is linearly proportional to the applied electric field E as $\delta n = \alpha_{EO}E$, where α_{EO} is the linear EO coefficient, which is a material property. The most popular EO material used so far for an EO modulator is LiNbO3, which has a high EO coefficient and low attenuation in the telecommunication's optical wavelength window. [17, 18]

II.3. 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. (II.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. (II.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. (II.1) (c). In other words, pulses representing consecutive bit '1's (no matter how many '0's are between the '1's) alternate in sign. Hence, this line code is also called alternate mark inversion (AMI). [19, 20]

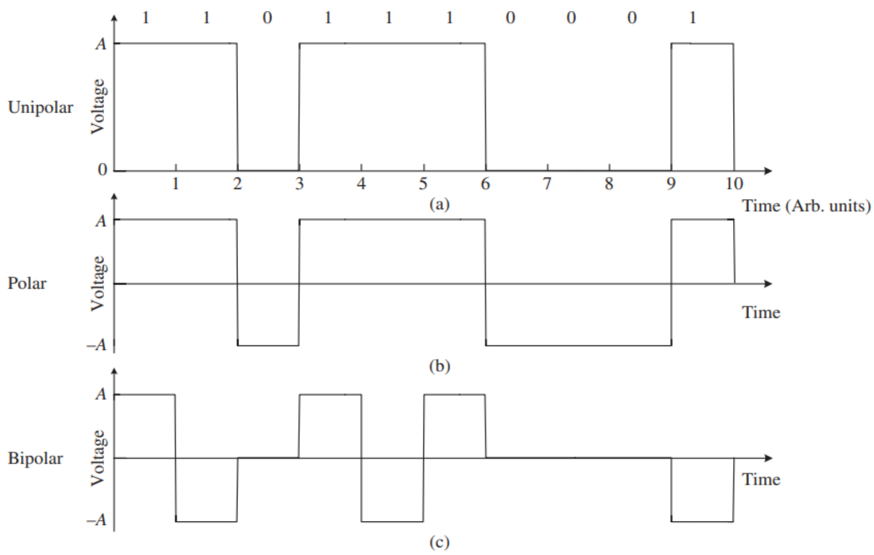


Figure (II.1): Various line codes: (a) unipolar, (b) polar, and (c) bipolar.

II.4. 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, as shown in Fig. (II.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. The wider spectral width of a RZ signal can also be understood from the fact that the pulse width of RZ pulse is shorter than that of a NRZ pulse. The message signal may be written as

$$m(t) = A_0 \sum_{n=-\infty}^{\infty} a_n p(t - nT_b) \qquad (1.1)$$

where an is the binary data in the bit slot, p(t) represents the pulse shape, and A0 is a real constant. An important parameter that characterizes a RZ signal is the duty cycle. This is defined as the time for which the light is turned on in a bit interval divided by the bit interval, i.e., the fraction of time over which the light is on “duty” within a bit interval. For example, for a 10-Gb/s system, the bit interval Tb is 100 ps and if the duration of the signal pulse is 30 ps, the duty cycle is 30%. The duty cycle of a NRZ signal can be considered to be 100%. In the above definition, we have assumed rectangular pulses. For pulses of arbitrary shape, the duty cycle x can be defined as the ratio of the FWHM of a pulse to the bit interval Tb [21].

$$x = \frac{FWHM}{T_b} \qquad (1.2)$$

When rectangular pulses are used, a RZ pulse in a bit interval [−Tb⁄2, Tb⁄2] may be written as

$$\mathrm{p(t)} = 1 \text{ for } |\mathrm{t}| < \mathrm{xT_b}/2 \qquad (1.3)$$

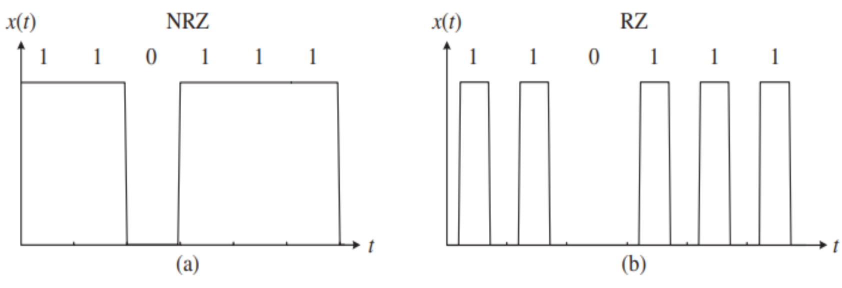


Figure (II.2): Pulse shapes: (a) NRZ, and (b) RZ.

II.5. Digital Modulation Schemes

II.5.1. 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 (Fig. (II.3) (a))

$$c(t) = A\cos(2\pi f_c t + \theta) \quad (1.4)$$

In Eq. (1.4), the amplitude A, frequency fc, and phase factor θ are constants. When the amplitude A is varied in accordance with a message signal m(t) while keeping fc and θ constant, the resulting scheme is known as amplitude modulation. Suppose the amplitude is proportional to the message signal m(t),

$$A(t) = k_\alpha m(t) \quad (1.5)$$

where ka is amplitude sensitivity. Now, the carrier is said to be amplitude modulated. The modulated signal can be written as

$$s(t) = K_\alpha m(t)\cos(2\pi f_c t + \theta). \quad (1.6)$$

When the message signal m(t) is a digital signal, such as shown in Fig. (II.3) (b), 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 A1 is sent and to transmit bit ‘0’, a sinusoid of amplitude A2 is sent. [22]

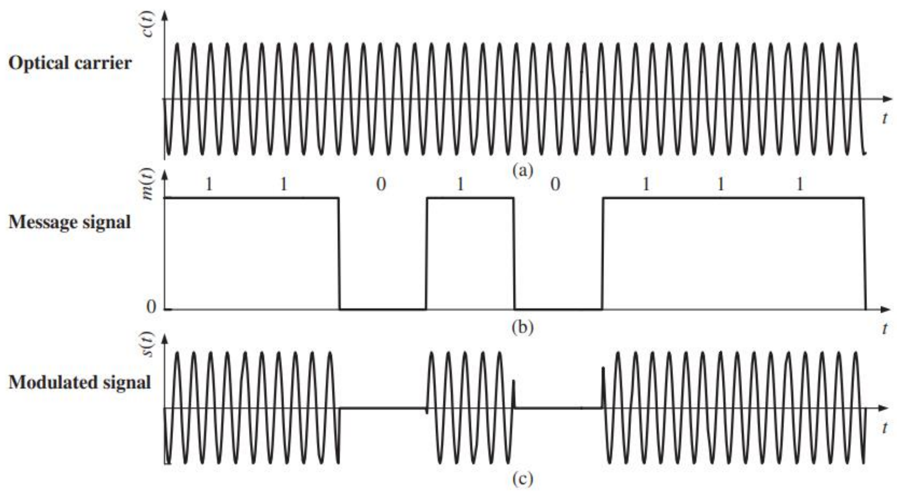


Figure (II.3): Modulation of the optical carrier by digital data: (a) carrier, (b) data, and (c) modulated signal.

II.5.2. 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 fc constant, the resulting scheme is known as phase modulation. Suppose the phase is proportional to the message signal,

$$\theta(t) = k_\rho m(t), \quad (1.7)$$

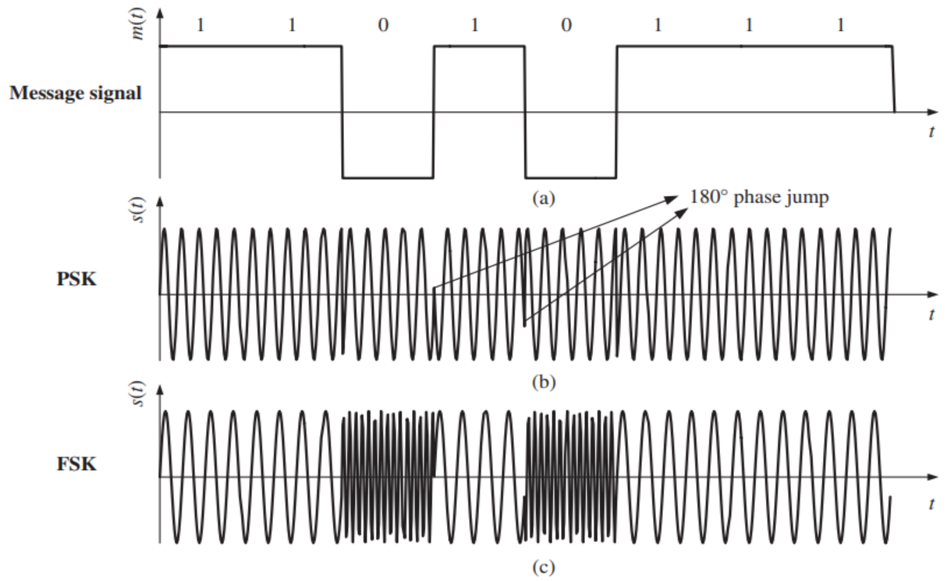


Figure (II.4): Phase and frequency modulation of an optical carrier. (a) Message signal, (b) Phase-shift keying, and (c) Frequency-shift keying.

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

$$s(t) = A\cos[2\pi f t + k_p m(t)]. \quad (1.8)$$

For example,

$$m(t) = \begin{cases} A\sin(2\pi f_C t) & for\ bit\ `1' \\ -A\sin(2\pi f_C t) & for\ bit\ `0'. \end{cases} \quad (1.9)$$

When the message m(t) is a digital signal, such as shown in Fig. (II.4) (a), the modulation scheme is known as phase-shift keying (PSK) or binary phase-shift keying (BPSK). Fig. (II.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. Fig. (II.4) shows the schematic of PSK generation. [23]

II.5.3. Frequency-Shift Keying

FSK can be described as a scheme in which a bit '1' is transmitted by sending a sinusoid of frequency f1 and a bit '0' is transmitted by sending a sinusoid of frequency f2, as shown in Fig. (II.4) (c). Let the message signal

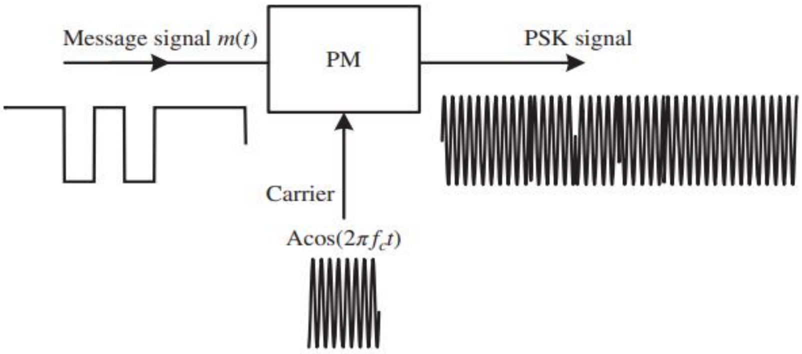


Figure (II.5): Generation of a PSK signal. PM = phase modulator.

be binary data of the form.

$$m(t) = \begin{cases} m_1 & for\ bit\text{'1'} \\ m_2 & for\ bit\ \text{'0'} \end{cases} \quad (1.10)$$

The transmitted signal within a bit interval [0, Tb] can be written as

$$s(t) = A\cos[\phi(t)], \quad (1.11)$$

where

$$\phi(t) = \begin{cases} 2\pi f_1 t & for\ bit\text{'1'} \\ 2\pi f_2 t & for\ bit\ \text{'0'}. \end{cases} \quad (1.12)$$

$$f_i = f_c + k_f m_i, i = 1, 2.$$

k_f is the frequency modulation index. Suppose the phase ϕ(t) in the bit interval [0, Tb] is 2πf1t and the phase ϕ(t) in the next interval is 2πf2t. At t = Tb, ϕ(Tb−) = 2πf1Tb and ϕ(Tb+) = 2πf2Tb. This could cause phase discontinuity at the bit boundaries, which is undesirable in some applications. One possible way of avoiding phase discontinuities is to choose the frequencies such that the phase accumulated over a bit interval is an integral multiple of 2π,

$$f_c + k_f m_1 = \frac{n}{T_b}, \text{ n is an integer, (1.13)}$$

$$f_c + k_f m_1 = \frac{l}{T_b}, \text{ l is an integer. (1.14)}$$

Under these conditions, the phase would be continuous throughout and such a scheme is known as continuous phase frequency-shift keying (CPFSK). Note that the ASK signal has a constant frequency and the amplitude is varying, whereas FSK is a constant-amplitude signal but the instantaneous frequency is changing with time. [24]

II.6. Direct Modulation

The laser drive current can be modulated by a message signal, as shown in Fig. (II.6). 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. Directly modulated lasers (DMLs) have some major drawbacks.

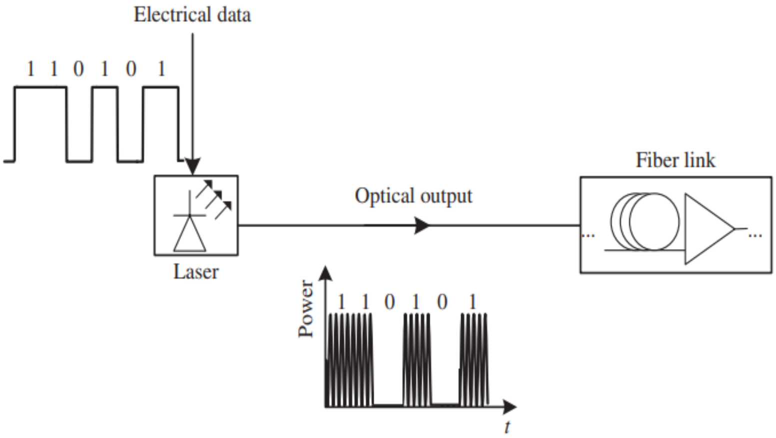


Figure (II.6): Direct modulation of a laser.

First, the instantaneous frequency of the laser output changes with time. This frequency chirping is caused by the refractive index changes of the active layer due to the carrier density modulation. The interaction of the positive chirp of the laser with the anomalous dispersion of the transmission fiber leads to pulse broadening, and sets a limit on the maximum achievable transmission distance. However, the interaction of the laser chirp with the normal dispersion of the fiber leads to pulse compression initially. In fact, the error-free transmission distance can be increased using positively chirped lasers and normal dispersion transmission fibers [18].

However, the pulses broaden eventually (even in normal dispersion fibers) and the laser chirp leads to transmission penalties for long-haul applications. 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. [21]

II.7. External Modulators

Fig. (II.7) shows the schematic of a transmitter using external modulators. Widely used external modulators are: (i) the phase modulator, (ii) the Mach–Zehnder (MZ) interferometer modulator, and (iii) the electro-absorption (EA) modulator.

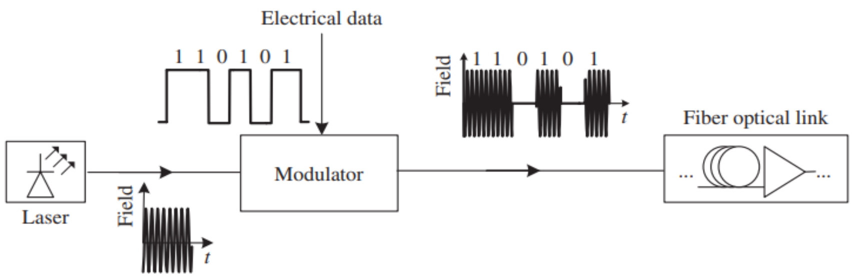


Figure (II.7): A transmitter using an external modulator.

II.8. Phase Modulation

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 [25], [26]. This effect is known as the Pockels effect or linear electro-optic effect. [25], [26]

II.9. Electro-absorption Modulator

Electro absorption 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 fc < E_{g_0}/h, where E_{g_0} is the band gap in the absence of the applied electric field. Let the driving voltage V(t) vary from 0 to V0 volts, as shown in Fig. (II.8). When V(t) = 0, the photon energy is less than the band gap and the optical carrier is not absorbed. When V(t) = V0, 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. Fig. 8.2 shows the typical dependence of the absorption coefficient on the wavelength. Suppose the carrier wavelength is $\lambda 0$. Let $\alpha 0$ and $\alpha 1$ be the absorption coefficients at V(t) = 0 and V(t) = V0, respectively. If L is the length of the modulator, the optical power exiting the modulator is

$$P_{out} = \begin{cases} p_{max} = p_0 \exp(-\alpha_0 L) & when\ V(t) = 0 \\ \rho_{min} = p_0 \exp(-\alpha_1 L) & when\ V(t) = V0 \end{cases} \quad (1.15)$$

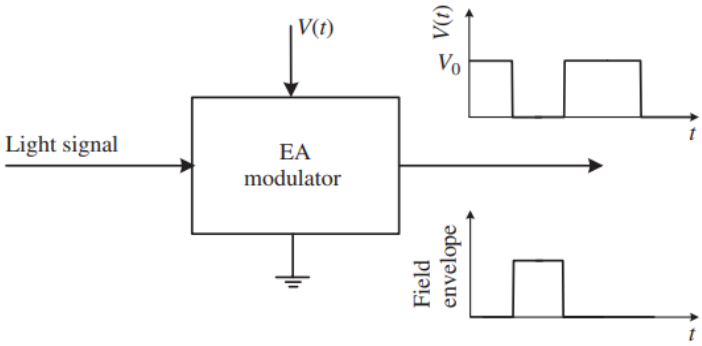


Figure (II.8): Amplitude modulation using an EAM.

where P0 is the input power; the extinction ratio is

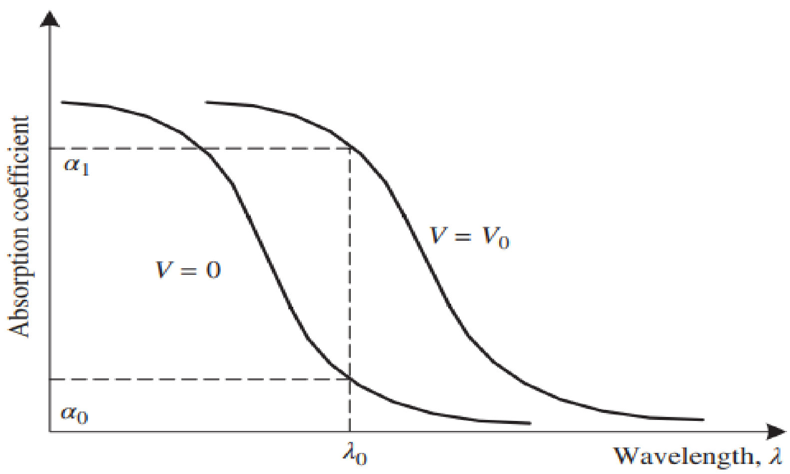


Figure (II.9): Typical dependence of absorption coefficient on wavelength.

$$\delta = \frac{\mathrm{p}_{\max}}{\rho_{\min}} = \frac{\exp(-\alpha_0 L)}{\exp(-\alpha_1 L)}. \qquad (1.16)$$

To obtain the optimum performance, a high extinction ratio is desirable. To achieve this, typically InP-based semiconductors are used for 1300-nm or 1550-nm applications. The absorption coefficient can be changed significantly by applying a relatively lower driving voltage. Therefore, the EAMs are very effective and the size could be quite small. The length of EAMs is typically 200 mm, whereas that of electro-optic modulators is a few centimeters. EAMs can easily be integrated with the laser diode, since both are based on similar semiconductor materials. The drawbacks of EAMs are as follows. (i) They have residual chirps similar to directly modulated lasers. The interaction of the chirp and fiber dispersion could lead to enhanced pulse broadening. (ii) The extinction ratio is typically ≤ 10 dB, which could lead to a power penalty [27].

II.10. Conclusion

In this chapter, we delved into a detailed study of electro-optic modulation and electro-absorption modulation, as well as understanding the basic operation principle of optical modulators accompanied by digital modulation schemes such as ASK, PSK, and FSK, in addition to external modulators, in preparation for simulation in Chapter Three.

CHAPTRE III

Simulation Results and Discussion

III.1. Introduction

The aim of this chapter is to simulate a modulator based on electro-absorption mechanism for optical communication systems. The physical process behind the modulation operation is based on the Quantum Confined Stark Effect. We use an integrated environment to simulate optical, electrical and system-level properties.

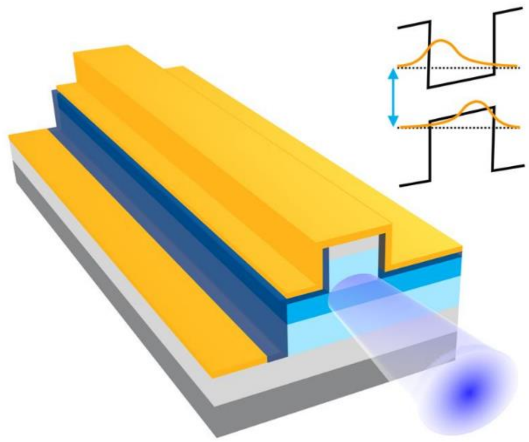


Figure (III.1): Schematic diagram of the modulator.

III.2. Simulation workflow

Quantum Confined Stark Effect (QCSE) is used in electro-absorption modulators to provide a mechanism of modulation of optical absorption by changing the applied voltage (i.e. electric field). In the absorption regime, excitons are an important effect since they can be stable in quantum wells even at higher electric fields and significantly impact the shape of the absorption spectrum. First, we use a mode solver to calculate the effective mode index and overlap with the gain region. Then, we compute the absorption coefficient and transmission as function of the applied voltage. Finaly, we calculate the time- domain modulation response. All simulations are performed using the Ansys software.

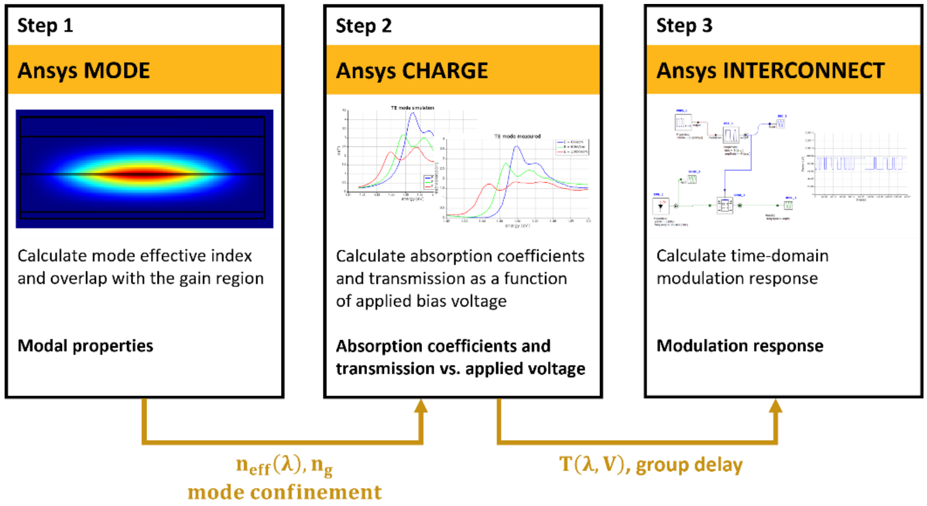


Figure (III.2): The simulation workflow.

III.3. Optical mode calculation

The first step is to calculate the optical mode profile and extract the effective and group indices of the fundamental (TE) mode as well as its confinement factor with respect to the absorption medium to be used in the next steps. These are all calculated in the vicinity of the nominal target frequency and are expected to be locally weakly frequency-dependent. Figure. 3 gives the field distribution of the fundamental mode for the wavelength 0.85 µm. Moreover, the mode effective index is found to be 3.5. The effective and group indices, as well as the confinement factor used in the subsequent steps, are stored

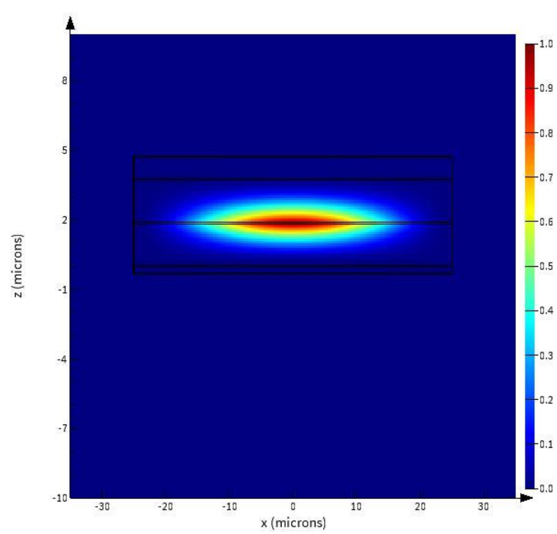


Figure (III.3): The field distribution of the fundamental mode.

III.4. Absorption Calculation

Here, we investigated the effect of applying a voltage to the absorption coefficient. The simulation will run voltages from 0V to -10V in steps of -0.5V and also -10.25V (the last one to have electric field that matches one of the measured fields). The absorption coefficients and index perturbation vs. electric field and bias for TE and TM modes are shown in the following plots.

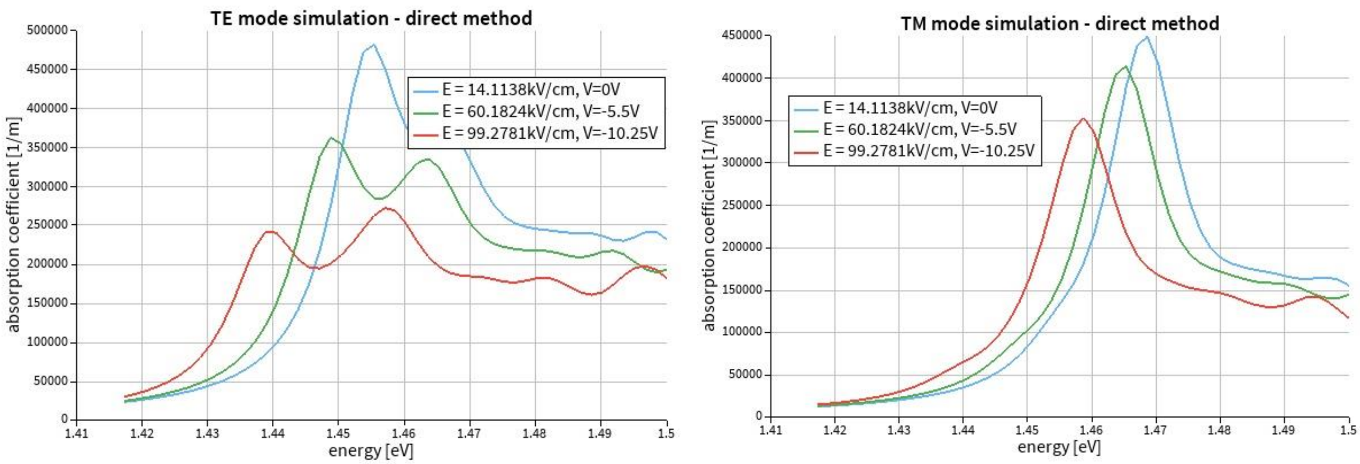


Figure (III.4): The variation of the absorption with energy.

We observe that the absorption peak for both of the TE and TM mode can be shifted when an external voltage is applied.

III.5. Communication system simulation

Here the time-variant S-parameter element is used to build a compact model for the modulator structure under study in this example. When the simulation is run the time-variant S-parameter element reads the S-parameter file and creates a digital filter to fit and interpolate the transmission transfer function. This digital filter represents a parametric macro-model for the transmission controlled by voltage.

A simple test-bench is set up to test modulator performance. Here the modulator is connected to a laser source and is biased with a PRBS stream.

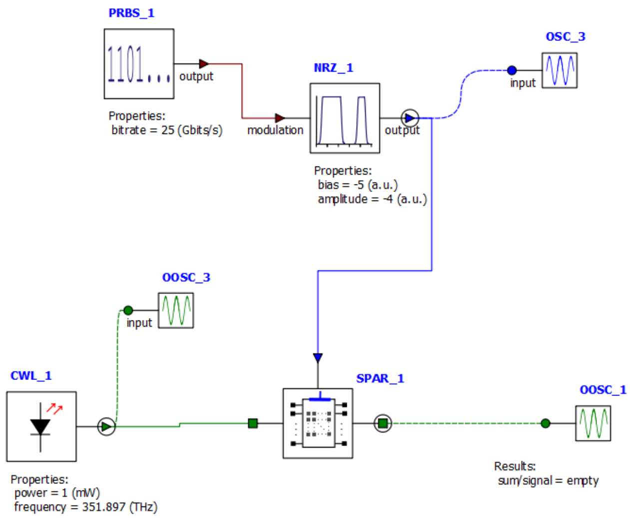
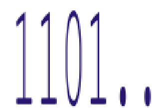


Figure (III.5): Schematic diagram of the simulated communication system.

The system is composed of:

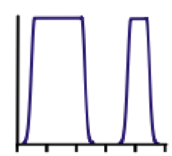
III.5.1. PRBS Generator (PRBS)

The pseudo-random bit sequence (PRBS) generator a maximum length sequence code using a random initial state.



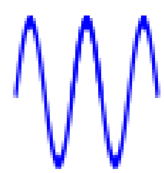
III.5.2. NRZ Pulse Generator (NRZ)

The NRZ Generator pulse generator creates a sequence of non-return to zero pulses coded by an input digital signal.

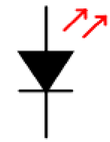


III.5.3. Oscilloscope (OSC)

Allows observation of constantly varying signals in time domain.

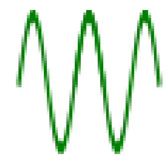


III.5.4. CW Laser (CWL)



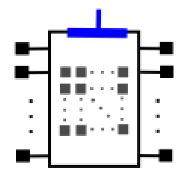
The CW laser model generates a continuous wave (CW) optical signal.

III.5.5. Optical Oscilloscope (OOSC)



Allows observation of constantly varying optical signals in time domain.

III.5.6. Optical Time Variant S-Parameter (SPAR)



Optical time variant s-parameter element, where the device also modifies and includes the signal.

The input electrical signal is given by figure 6.

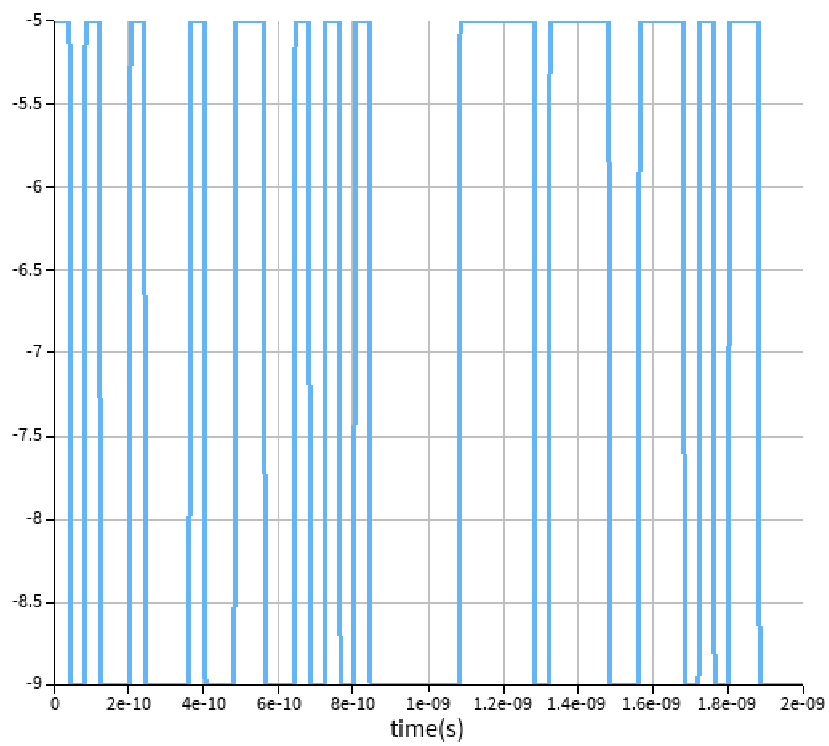


Figure (III.6): Input electrical signal.

The input optical power is given by figure 7.

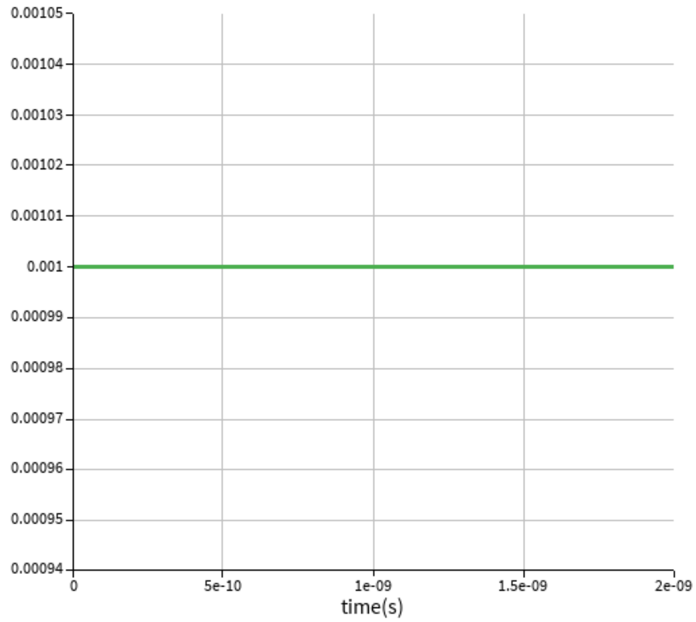


Figure (III.7): Input optical signal.

The output optical signal is given by figure 8.

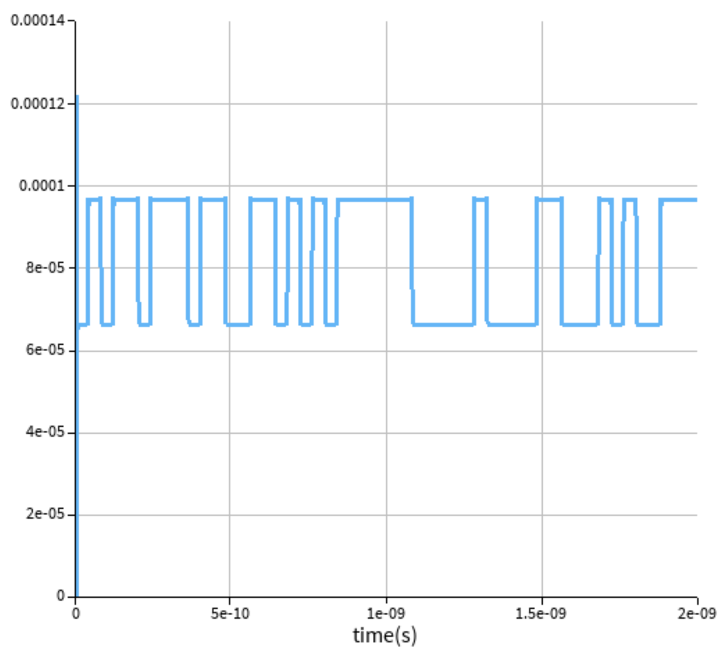


Figure (III.8): output optical signal.

III.6. Observation

We notice that when the electrical signal is given in Oscilloscope (OSC_3), as well as the optical energy is given in Optical Oscilloscope (OOCS_3), the optical exit signal is the result of the intervention of the modulator that ensured the signal.

III.7. Conclusion

In this chapter, we addressed simulating the modulator based on the electro-absorption mechanism for optical communication systems using Ansys software. First, we highlighted the modulator to observe the light field distribution, where it takes on an elliptical shape. Second, absorption calculation was studied with the effect of applying voltage on the absorption coefficient, noticing the appearance of absorption coefficients and disturbance of the index versus electric field. Finally, we have simulated the optical transmitter base on the electro-absorption modulator. It has clearly observed the possibility of modulating an optical carrier with an electrical signal.

General Conclusion

Optical communication is a technology that uses light waves to transmit data between devices and installations. It relies on the use of optical fibers that allow large amounts of data to be transmitted at high speed via optical signals transmitted in fibers rather than conventional electrical signals.

In this work, numerical study of an optical modulator based on electrical absorption is carried out using the Ansys software.

The numerical investigation of an electro-absorption based optical modulator provides valuable insights into its performance characteristics and potential applications. Through computational simulations and analysis, researchers can thoroughly understand the behavior of the modulator under different operating conditions, such as varying voltages, wavelengths, and input signals.

This study allows for improved modulator design to achieve required performance measures, such as adjustment depth, bandwidth and power consumption. In addition, it enables engineers to identify and mitigate potential challenges or constraints in the operation of the device, thereby facilitating the development of more efficient and reliable visual communication systems.

In chapter 1 we have delved into the fundamentals of optical communication systems, covering their structure, optical fibers, optical transmitters, receivers, and optical modulators.

In Chapter 2, the focus shifts to optical modulators, exploring their basic operating principles, including photoelectric modulation, line programming, pulse shaping, and digital modulation techniques.

In Chapter 3, we have conducted a series of numerical simulations of the optical modulator. The obtained results are remarkable, showcasing the effectiveness of the modulator under different conditions. We have shown that optical absorption can be tuned by applying a voltage across the waveguide. This phenomenon has been exploited to design a modulator for high-speed optical communications.

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