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Theme

Study of the performances of a PIN Mach-Zehnder modulator

In front of the jury composed of:

Mr. ..	**….**	**President**
Mr. …..	**….**	**Examiner**
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2023-2024

بسم الله الرحمن الرحيم

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Praise be to Allah, who guided us and we would not have been guided if it had not been for Allah's guidance, prayers and peace be upon our ..Master Muhammad, his family and his pure companions and after

As I finish this scientific effort, I can't help but extend our deepest thanks and gratitude to everyone who helped me accomplish this memorandum, especially our dear Professor,

Professor Madjouri Abdelkader, who did not skimp on his knowledge and experience in the field, and on the efforts he made with us to complete this memorandum and follow up our work to the end

Dedication

The trip wasn't short and it shouldn't have been, the dream wasn't close and the road was fraught with facilities, but I did it and got it

Thank God for love, thanks and gratitude, thanks to which today I am looking at a long-awaited dream that has become a reality that I am proud of

To my first example, the meaning of love and devotion to the blessing of life and the secret of existence, to whom I called the secret of my success and tenderness, a surgical balm… To whom she guided and accompanied me in all walks of my life and still does to this day.… May Allah save her and grant her forgiveness and wellness …. Mom is my paradise

To the dear one whose name I proudly bore, echoing my name high in the heavens, bearing the honor of your title with all pride, I am the daughter of this man, may Allah preserve him, I hope that Allah will extend your life to see the fruits that have come to be picked after a long

Waiting, your words will remain stars to be guided by today, tomorrow and forever… Dear dad

To my firm rib, which does not tend to those who extended their hands to me in my weakness and believed in my ability to those with whom I had a support and my first and last refuge ….. My brothers and sisters (Ramzi Malak Farah Moad)

To those with whom I had no blood relationship.. It's a fragrance of friendship.. The love of my friends (Bouchra shahla, Mbarka, Anfal, Bouthaina)

And to all my esteemed teachers who did not hesitate to extend a helping hand to me, especially the supervisor and professor (Madjouri Abdelkader)

I dedicate this achievement to you and the fruit of my success, which I have always wished for, and here I am today completing the first fruits of it thanks to the Almighty, thank God for what he has given me, and that he helps me and makes me blessed wherever I am..

Nesrat Narimane

Dedication

The trip was not short and should not have been, the dream was not close and the road was not fraught with facilities, but I did it and got it.

Thank God for love, thanks and gratitude, thanks to which today I am looking at a long-awaited dream that has become a reality that I am proud of.

To whom God is full of prestige and reverence ..To the one who taught me to give without waiting ..To whom I proudly bear his name

My dear father

To my angel in life .. To the meaning of love, to the meaning of tenderness and devotion .. To the blessing of life and the mystery of existence

My beloved mom

To whom it was said:

"We will support you with your brother".

Who were a support, support and strength for me in my course of study

Dear brothers and sisters

To those who carried the most sacred message in life, to those who paved us the path of Science and knowledge

Our best teachers who have been with me throughout my academic career

Kasmi Asma

Abstract

Abstract

This memorandum discusses the importance of optical modulators, which have a major role in processing information and converting an electrical signal into a light signal. This study aims to improve the performance of the Mach-Zehnder modulator using the PN and PIN connections, by presenting the results of numerical simulation and analysis, where we compared these connections. And its effect on the Mach-Zehnder modulator, as we saw that both the effective index and the optical loss can be modified by completely changing the voltage applied to the link.

Keys works: modulators, Mach-Zehnder modulator, Fiber optic, LiNbO3

Résumé

Ce mémorandum discute de l'importance des modulateurs optiques, qui jouent un rôle majeur dans le traitement de l'information et la conversion d'un signal électrique en signal lumineux. Cette étude vise à améliorer les performances du modulateur Mach-Zehnder utilisant les connexions PN et PIN, en présentant les caractéristiques des modulateurs optiques. résultats de simulation et d'analyse numériques, où nous avons comparé ces connexions. Et son effet sur le modulateur Mach-Zehnder, car nous avons vu que l'indice effectif et la perte optique peuvent être modifiés en changeant complètement la tension appliquée à la liaison.

mots clés: modulateurs, modulateur Mach-Zehnder, Fibre optique, LiNbO3

ملخص:

تناقش هذه المذكرة أهمية المغيرات البصرية التي لها دور كبير في معالجه المعلومات وتحويل الإشارة الكهربائية إلى إشارة ضوئية، حيث تهدف هذه الدراسة إلى تحسين أداء المغير ماخ زيندر بواسطة الوصلات PN و PIN وذلك من خلال تقديم نتائج المحاكاة العددية وتحليلها، حيث قمنا بالمقارنة بين هذه الوصلات وأثرها على المغير ماخ زيندر حيث رأينا انه يمكن تعديل كل من المؤشر الفعال والخسارة للبصرية عن طريق تغيير الجهد المطبق بشكل كامل على الوصلة

الكلمات المفتاحية: مفاتيح يعمل: المغير ، ماخ-زيندر المغير ، الألياف البصرية ، نيوبات الليثيوم

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Summary

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List of Abbreviations

LEDs	Light-Emitting Diodes
PN	Positive-Negative
LD	Laser Diode
PIN	Positive-Intrinsic-Negative
InGaAs	Indium Gallium Arsenide
SNR	Signal-to-Noise Ratio
LiNbO3	Lithium Niobate
ASK	Amplitude Shift Keying
PSK	Phase Shift Keying
PM	phase modulator
FSK	Frequency Shift Keying
DMLs	Directly Modulated Lasers
MZ	Mach–Zehnder
EA	Electro-Absorption
MZMs	Mach–Zehnder Modulators
EAM	Electro-Absorption Modulator
OOK	On Off Keying

General Introduction

General Introduction

Fiber optic communications is a means of transmitting information from one place to another by sending pulses of light through optical fibers. A main process of the communication system is the modulation which can be realized directly or externally. Furthermore, external modulation can be physically achieved through electro-absorption or electro-optic mechanism. The goal of the present work is to numerical study and analyzes the performances of an electro-optic modulator.

In the first chapter, the general structure of communication systems based on optical fibers was presented. We have saw that electrical signals should be converted before transmitted over fibers. Such operation can be successfully ensured by using optoelectronic devices called modulators.

The different techniques of digital modulation employed in optical fiber communications have been given in details. Moreover, both direct and external modulation approaches have been presented. The physical process behind optical modulation, namely electro-absorption and electro-optic has been also given.

The main results of a complete optoelectronic simulation were the subject of the last chapter. Firstly, we have considered a simple PN junction eversely biased. We have demonstrated that a voltage applied to the junction enlarges the depletion zone and changes the refractive index of the guide. Hence, such a phenomenon has been exploited to realize a modulation scheme. Furthermore, a PIN junction has been considered to form Mach–Zehnder Modulator (MZ) arm for dual arms modulator. This study was conducted through 3 softwares from the Ansys group, which are Ansys charge, Ansys mode, and Ansys Interconnect.

Chapter 1:

Fiber optic communications systems

Introduction

A typical fiber optic communication system consists of an optical transmitter, an optical fiber, and an optical receiver. An optical transmitter converts the information-carrying electronic signal into an optical signal, which is then transmitted over a long length of optical fiber. At the receiver end, an optical detector converts the optical signal back into an electronic signal so that the information is retrieved and delivered to the destination [1]. In this chapter we focus on the basics of optical communications technologies. The focus is on the main characteristics and performance features of optical fibers, transmitters and receivers.

1. Fiber-optic communication systems

Fiber-optic communication systems are lightwave 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, lightwave technology, together with microelectronics, led to the advent of the "information age" during the 1990s[2].

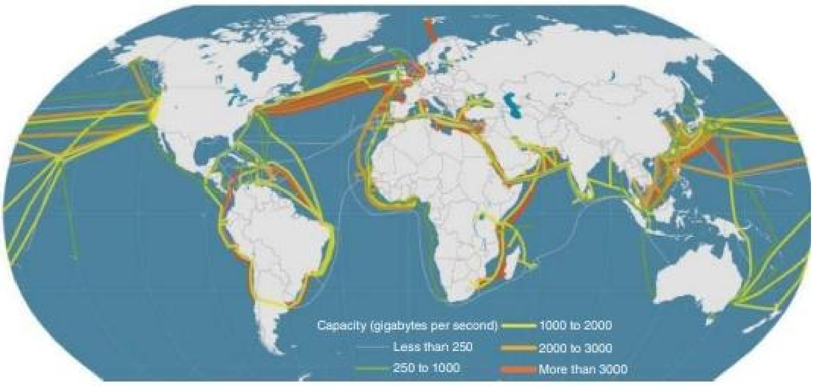

Fig.1: International undersea network of fiber-optic communication systems around 2016

2.Optical communications

The fiber-optic communication link shares similarities with other conventional communication system links. The most basic form of it consists of a transmitter, a receiver and an optical glass or silica fiber as a transmission medium. The transmitter converts any digital or analog signal into a discrete light pulse (pulse modulation) or an intensity based light signal (amplitude modulation) respectively [3]. For this a light producing diode is usually used as they emit wavelengths that are the same as the wavelength region of the attenuation for the low-loss fiber [4]. Most commonly a laser producing diode is used, as it is more efficient than a non-laser light emitting diode such as LEDs [3]. After the signal makes its trip through the optical fiber it is received by a receiver at the end where it gets amplified and demodulated to return as an electrical signal that can be interpreted by the electronic equipment and be decoded. While it is important to have fiber with high capacityit is also important to have fast optical transmitters and receivers to keep up with its speed [5].

Fig.2: Generic optical communication system

3. Optical fibers

In the late 1960s low-loss silica fiber was proposed as a medium for optical communication transmission. By the late 1970s, research and development of this medium produced silica fiber with the loss of 0.2dB/km, the lowest theoretical limit of silica fiber. This allowed for low-loss silica to outperform any other metal-based medium that existed at the time, all in a fiber that could be as thin as a human hair [3]. This breakthrough allowed for the development of systems that work with optical communication, as interest into the potential of such systems has gone up exponentially as time went on.

Fiber optics' transmitting principle depends upon the concept of total internal reflection. Where if a ray of light is going from one medium to another, and if the angle between it and the second medium is sufficiently low enough, instead of passing to the second medium, the ray of light will instead be completely reflected by it, and it remains in the first medium [6]. A fiber optic utilizes this property to its benefit as illustrated in (fig 3).

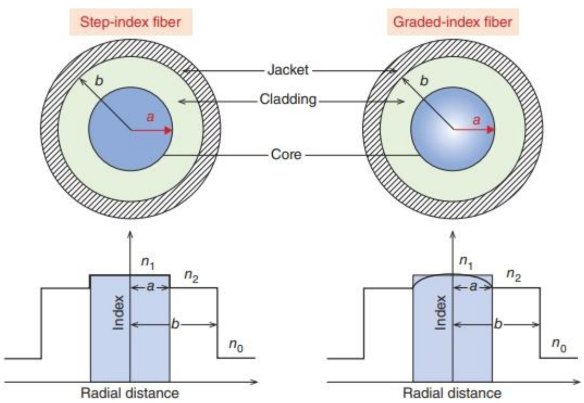

Fig.3: Total Internal Reflection in an optical fiber

3.1 Geometrical optic description

An optical fiber consists of a thin cylindrical strand of silica glass (its core) surrounded by a cladding whose refractive index is slightly lower than that of the core. Because of an abrupt index change at the core-cladding interface, such fibers are called step-index fibers. In a different type of fiber, known as the graded-index (GRIN) fiber, the refractive index decreases gradually inside the core [2].

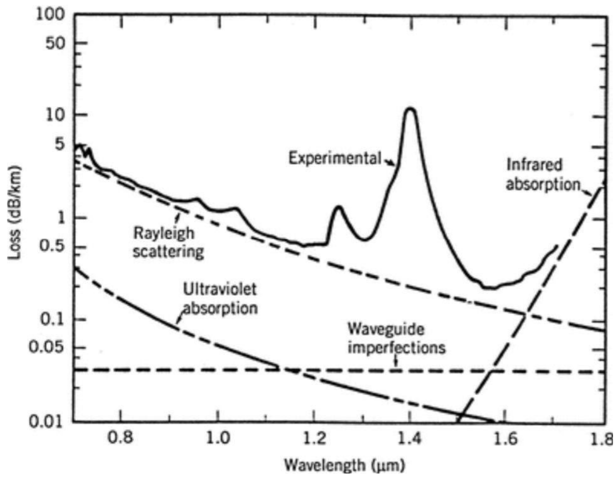

Fig.4: Cross sections and refractive-index profiles for step-index and graded-index fibers

3.2 Fiber Attenuation

Optical power attenuation of a light signal as it propagates along a fiber is an important consideration in the design of an optical communication system; the degree of attenuation plays a major role in determining the maximum transmission distance between a transmitter and a receiver or an in-line amplifier. The basic attenuation mechanisms that cause power level reductions in a fiber are absorption, scattering, and radiative losses of the optical energy. Absorption is related to the fiber material, whereas scattering is associated both with the fiber material and with structural imperfections in the optical waveguide [7].

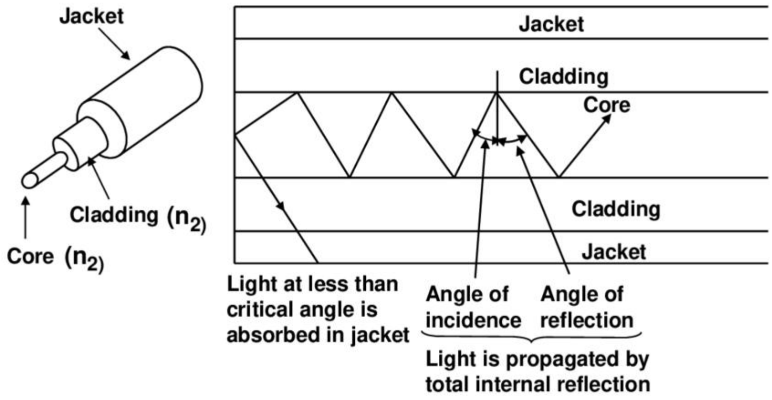

Fig.5: Loss spectrum of a single-mode fiber

3.3 Dispersion in Optical Fibers

Dispersion, also known as pulse spreading, means spreading out of an optical pulse of light energy in time as it propagates down a fiber. Dispersion occurs because of the difference in the propagation time taken by the light rays that traverse different propagation paths within the fiber. If the pulse spreading is sufficiently severe, one pulse may interfere with another, Signal dispersion in optical fibers can be broadly classified in three main categories: Chromatic or Intramodal Dispersion, Intermodal Dispersion or Mode Dispersion and Polarization Mode Dispersion [8].

4 Optical transmitters

The role of an optical transmitter is to convert the electrical signal into optical form and to launch the resulting optical signal into the optical fiber. (Fig 6) shows the block diagram of an optical transmitter. It consists of an optical source, a modulator and a channel coupler. Semiconductor lasers or light-emitting diodes are used as optical sources because of their compatibility with the optical-fiber communication channel [2].

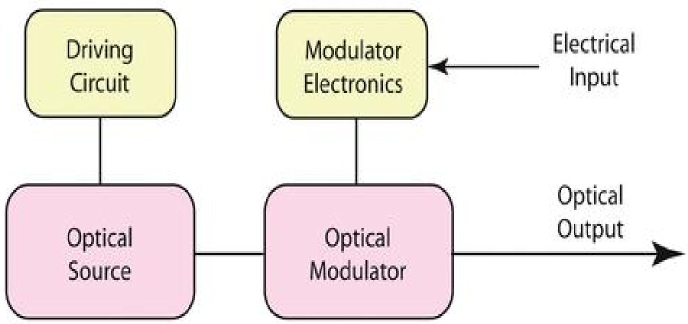

Fig.6: Components of an optical transmitter

4.1 Semiconductor Energy Bands

Semiconductor materials have conduction properties that lie somewhere between those of metals and insulators. As an example material, consider silicon (Si), which is located in the fourth column (group IV) of the periodic table of elements. A Si atom has four electrons in its outer shell, by which it makes covalent bonds with its neighboring atoms in a crystal. Such outer-shell electrons are called valence electrons [7].

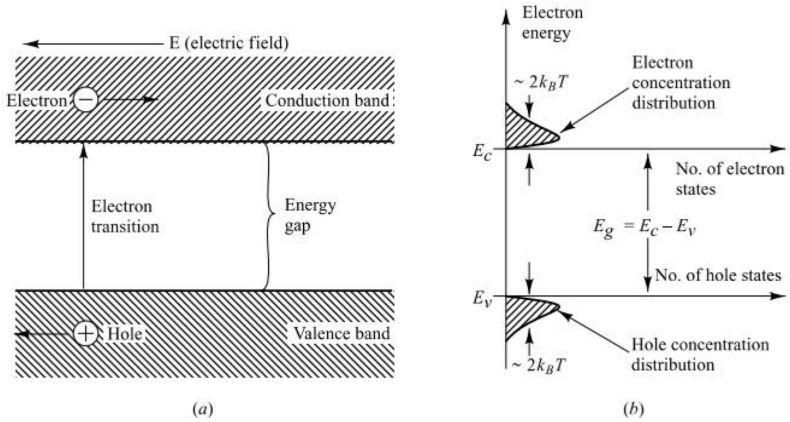

Fig.7:(a) Energy level diagrams showing the excitation of an electron from the valence band to the conduction band;(b) equal electron and hole concentrations in an intrinsic semiconductor created by the thermal excitation of electrons across the bandgap

A PN junction or diode is formed by bringing p-type and n-type materials in contact, as shown in (Fig.8).The n-side is electron-rich while the p-side has only a few electrons. So, the electrons diffuse from the n-side to the p-side. Similarly, holes diffuse from the p-side to the n-side. As the electrons and holes cross the junction, they combine. When an electron combines with a hole, it means that it becomes part of the covalent bond. As a result, a region close to the junction is depleted of electrons and holes and hence this region is called a depletion region [9].

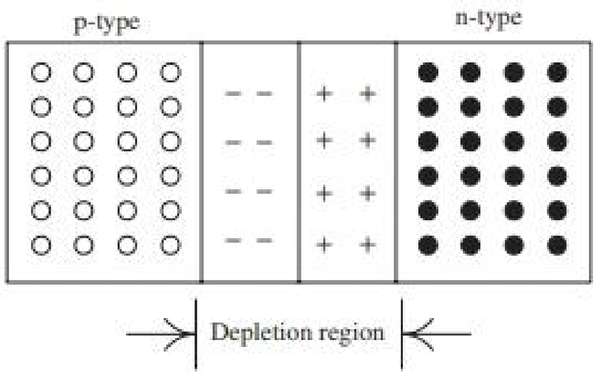

Fig.8: A PN junction or diode.

4.2 Light Emitting

Lasers come in many forms with dimensions ranging from the size of a grain of salt to one that will occupy an entire room. The lasing medium can be a gas, a liquid, an insulating crystal (solid state), or a semiconductor. For optical fiber systems the laser sources used almost exclusively are semiconductor laser diodes. They are similar to other lasers, such as the conventional solid-state and gas lasers, in that the emitted radiation has spatial and temporal coherence; that is, the output radiation is highly monochromatic and the light beam is very directional. Despite their physical and material differences, the basic principle of operation is the same for each type of laser. Laser action is the result of three key processes[7]

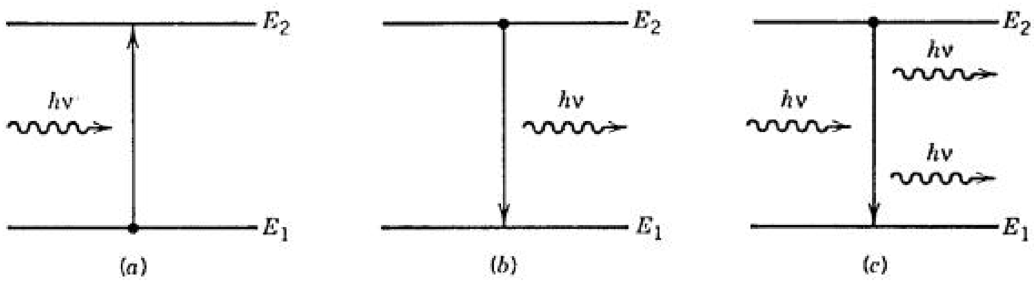

Fig.9: The Three fundamental processes occurring between the two energy states of an atom: (a) absorption; (b) spontaneous emission; and (c) stimulated emission.

4.3 Laser

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. A laser diode can be considered as an optical oscillator (or, an optical resonator) because an electromagnetic wave is formed within a cavity that provides highly coherent monochromatic light radiations at its output. This means stimulated emission process (sometimes known as lasing) with properties such as identical energy (as well as frequency), same polarization and in phase to that of incident photon. In order to achieve only stimulated emission rather than spontaneous emission or absorption, it is essential to increase the radiation density as well as the population density of the upper energy states as compared to that of the lower energy states. This condition is known as population inversion. For this to happen, it becomes quite essential that atoms having upper energy states be excited. Thus, a non-equilibrium distribution is obtained. The population inversion is made possible by employing an external energy source[8].

4.4 transmitter design

A packaged optical transmitter includes several other components such as a coupling device used to inject the modulated light into a pigtail (a short piece of fiber) and an electrical driving circuit for supplying current to the optical source and the modulator [10][11].

5 Optical receiver

An optical receiver converts the optical signal received at the output end of the optical fiber back into the original electrical signal. (Figure 10) shows the block diagram of an optical receiver. It consists of a coupler, a Photodetector, and a demodulator. The coupler focuses the received optical signal onto the Photodetector. Semiconductor photodiodes are used as Photodetectors because of their compatibility with the whole system [2]**.**

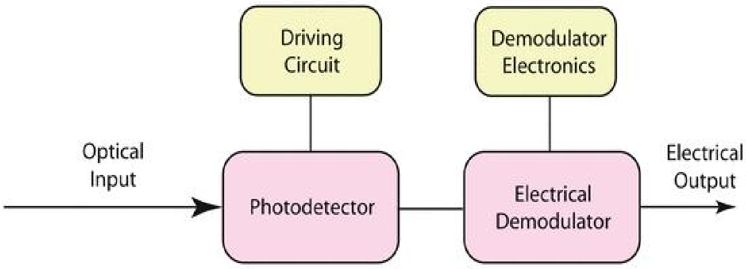

Fig.10: Components of an optical receiver

5.1 Photodetector

A semiconductor Photodetector I the basic component in an optical receiver , as shown in Fig.

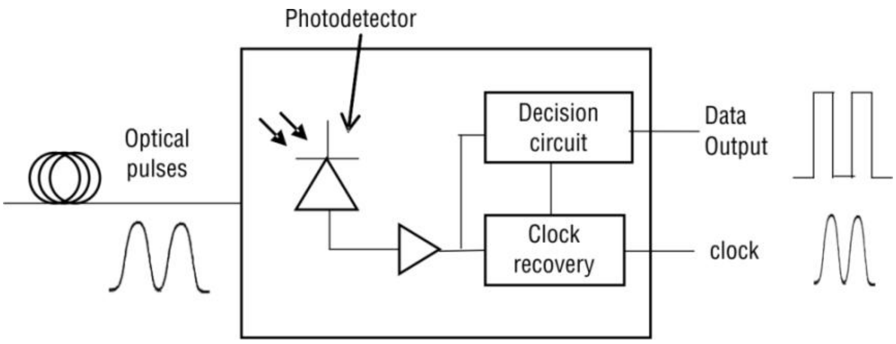

Fig.11: A Photodetector in an optical receiver

A Photodetector converts the received optical signal into its equivalent electrical signal through the photoelectric effect. Photodetectors made of semiconductor materials absorb incident photons in the form of optical pulses and produces electrons, i.e., photocurrent .It generally requires a higher degree of sensitivity at operating wavelengths, Fast response for adequate bandwidth up to a few GHz and Low noise – minimal noise due to leakage and dark currents .High quantum efficiency–large electrical response to given light energy [8].

5.2 Common Photodetectors

The physical mechanism behind the photodetection process is the absorption of photons by a semiconductor material. This section focuses on reverse-biased p–n junctions that are commonly used for making optical receivers [12].

5.2.1 p–n Photodiodes

When a p–n junction is reverse-biased, it forms a region called the depletion region, which lacks free charge carriers and creates a substantial built-in electric field that impedes the movement of electrons from the n-side to the p-side (and vice versa for holes). When light illuminates one side of this junction, typically the p-side, electron-hole pairs are generated by absorption. Due to the strong built-in electric field, these electron-hole pairs accelerate in opposite directions within the depletion region, with electrons moving towards the n-side and holes towards the p-side. This generates a current flow proportional to the incident optical power. Consequently, a reverse-biased p–n junction functions as a Photodetector, commonly referred to as a p–n photodiode [12].

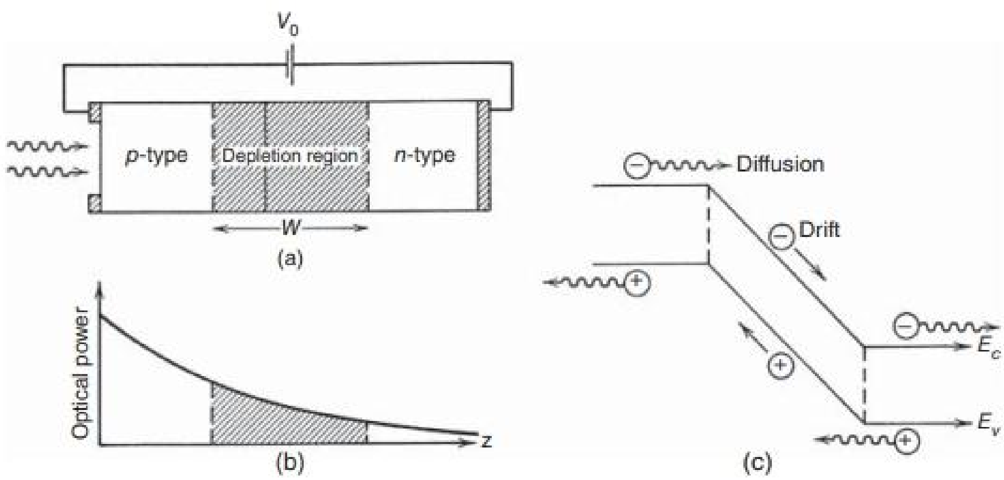

Fig.12: (a) A p–n photodiode under reverse bias; (b) variation of optical power inside the photodiode; (c) energy-band diagram showing carrier movement through drift and diffusion.

5.2.2 p–i–n Photodiodes

One straightforward method to enhance the width of the depletion region involves introducing a layer of undoped (or lightly doped) semiconductor material between the p–n junction. This intermediary layer, being nearly intrinsic in nature, gives rise to a structure known as the p–i–n photodiode. In (Figure 4.5(a)), the device configuration is depicted alongside the internal electric-field distribution during reverse-bias operation. Due to its intrinsic properties, the middle i-layer exhibits high resistance, leading to a significant voltage drop across it. Consequently, an intense electric field manifests within the i-layer. Essentially, the depletion region spans the entirety of the i-region, and its width, denoted by W, can be modulated by adjusting the thickness of the middle layer. The primary distinction from the p–n photodiode lies in the prevalence of the drift component of the photocurrent, which supersedes the diffusion component. This dominance arises because the majority of incident power gets absorbed within the i-region of a p–i–n photodiode [12].

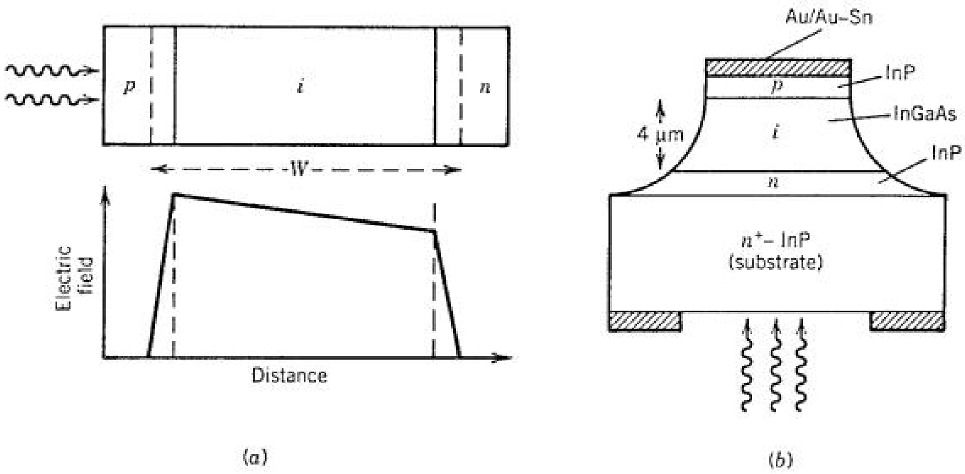

Fig.14: (a) A p–i–n photodiode together with the electric-field distribution under reverse bias; (b) design of an InGaAs p–i–n photodiode.

5.3 Receiver noise

Optical receivers convert incident optical power Pm into electric current through a photodiode (The relation $I_p = RP_{in}$) assumes that such a conversion is noise free. However, this is not the case even for a perfect receiver. Two fundamental noise mechanisms, shot noise and thermal noise, lead to fluctuations in the current even when the incident optical signal has a constant power [2].

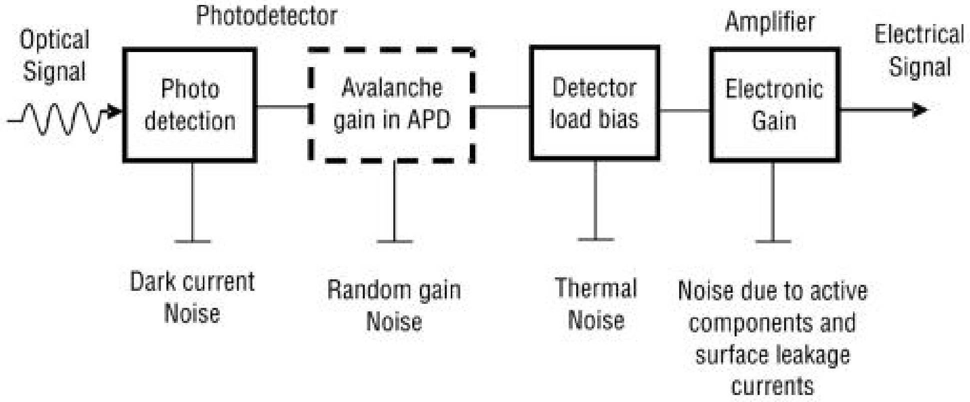

Fig.13: Optical receiver front-end showing noise types

5.3.1 Sources of photodetection noise

Major noise sources in a photodiode can be categorized as thermal noise, shot noise and dark current noise. Because of the random nature of the noises the best way to specify them is to use their statistical values such as spectral density, power and bandwidth [13].

5.3.2 SNR of an optical receiver

In an optical receiver, SNR is usually defined as the ratio of signal electrical power and noise electrical power. This is equivalent to the ratio of their mean-square currents [13].

$$SNR = \frac{\langle I^2_{s}(t)\rangle}{\langle i^2_{th}\rangle + \langle i^2_{sh}\rangle + \langle i^2_{dk}\rangle + \langle i^2_{amp}\rangle}$$

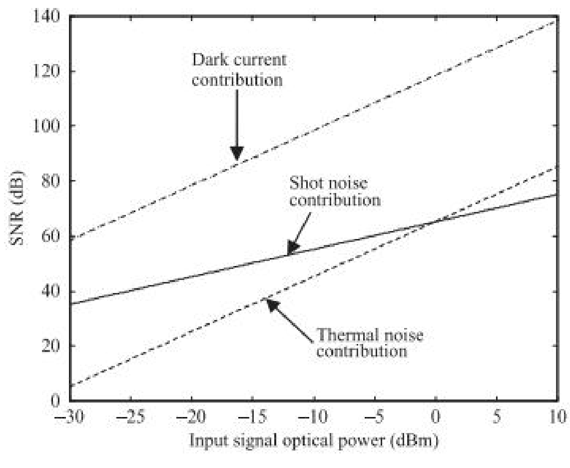

Fig.14: Decomposing SNR by its three contributing factors

6 Optical modulator

An optical modulator is a device that is used to modulate a light beam that propagates either in free space or in an optical waveguide. This device can alter different beam parameters and therefore optical modulators can be categorized as amplitude, phase, or polarization modulators. In addition, modulators can be also classified into two operational categories: electro refractive and electro-absorptive. The application of an electric field to a material can result in a change to the real and imaginary refractive indices. A change in real refractive index, Δn, with an applied electric field is known as electro-refraction, and a change in the imaginary part of refractive index, Δα, with applied electric field is known as electro-absorption. The primary electric field effects that are traditionally useful in semiconductor materials to cause either electro-absorption or electro-refraction are the Pockels effect, the Kerr effect, and the Franz-Keldysh effect. However, it has been shown that these effects are weak in pure silicon at the communications wavelengths of 1.3 μm and 1.55 μm [8,9]. Therefore alternative modulation means have to be found for silicon. One option is to use thermal modulation, as silicon exhibits a large thermo-optic coefficient, although this is too slow for the high frequencies required in modern communications Applications [14].

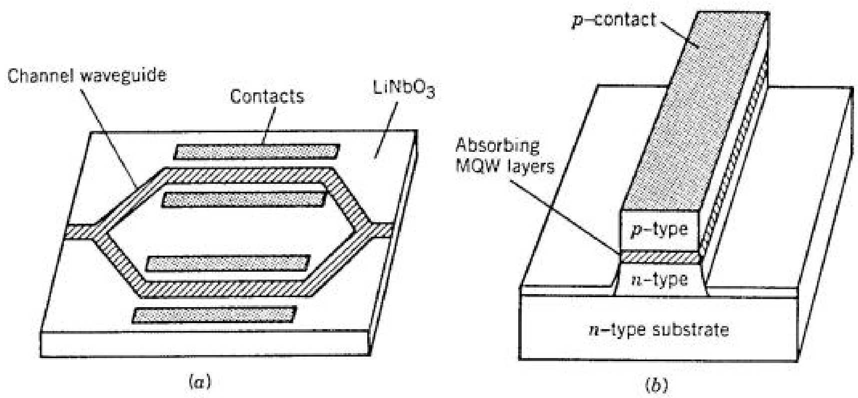

Fig.15: Two kinds of external modulators: (a) LiNbO3 modulator in the Mach–Zehnder configuration; (b) semiconductor modulator based on electro-absorption

Conclusion

In this chapter, we studied optical fiber communication in which we have discussed the characteristics of the optical fiber ,the optical transmitter, the optical receiver and also the optical modulator which has several types including the Mach-Zehnder modulator which we will study in the second chapter.

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Chapter 2:

Physical prosses for optical modulation

Introduction

Modulation is one of the ways and means to protect and ensure safe access to data. There are two types of modulators: digital modulators and optical modulators, which are used in optical communications. There are two types: direct and external modulators. Direct modulators use lasers for modification, while external modulators rely on electricity to change the properties of the material transmitting the light wave, either through absorption [1], which are called electrical absorption modulators, or through a change in the index of refraction of the material, which are called photoelectric modulators, such as Mach-Zehnder, which is the basis of our study.

1 Digital Modulation Schemes

There are many types of digital modulation techniques and also their combinations, depending upon the need. Of them all, we will discuss the prominent ones [2].

1.1 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.1(a))

$$c(t) = A\,cos(2\pi f_c t + \theta) \tag{1}$$

In Eq.(1), 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. Suppose the amplitude is proportional to the message signal m(t) [3]

$$\mathrm{A}(t) = k_a m(t) \tag{2}$$

where k_a is amplitude sensitivity. Now, the carrier is said to be amplitude modulated. The modulated signal can be written as [3]

$$\mathrm{s}(t) = k_a m(t)\,cos(2\pi f_c t + \theta) \tag{3}$$

When the message signal m(t) is a digital signal, such as shown in (Fig.1(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 A_1 is sent and to transmit bit '0', a sinusoid of amplitude A_2 is sent [3].

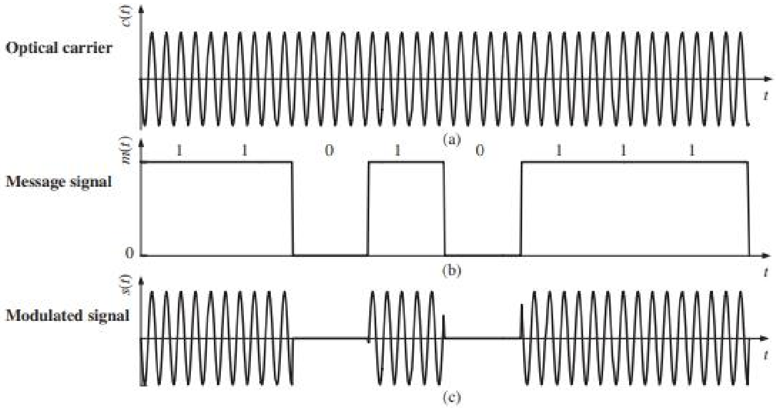
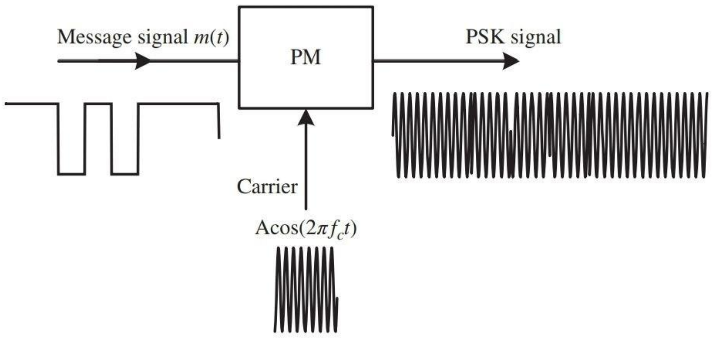


Fig.1: Modulation of the optical carrier by digital data: (a) carrier, (b) data, and (c)modulated signal

1.2 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 phase modulation. Suppose the phase is proportional to the message signal [3].



$$\theta(t) = k_p m(t) \text{ (b)} \tag{4}$$

Fig.2: Generation of a PSK signal. PM = phase modulator

1.3 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, as shown in (Fig.3(c)). Let the message signal [3].

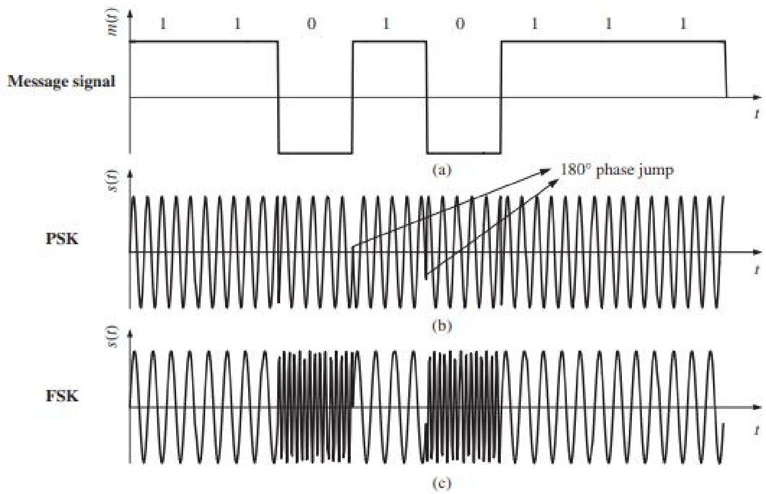


Fig.3: Phase and frequency modulation of an optical carrier. (a) Message signal, (b) Phase-shift keying, and (c) Frequency-shift keying.

2 Electro-optic modulator

Electro-optic modulators use the electro-optic effect, which is the change of the refractive index of a material in response to an applied electric field. By applying a voltage to an electro-optic crystal, such as lithium niobate, the phase of the light passing through the crystal can be controlled. This can be used to modulate the amplitude or frequency of the light, depending on the configuration of the device. Electro-optic modulators are fast, compact, and efficient, but they require high voltages and precise alignment of the optical components. Optical modulation techniques can be divided into two types: direct modulation of lasers and external modulation of lasers [4].

2.1 Direct modulation

The laser drive current can be modulated by a message signal, as shown in (Fig.4) 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 [3].

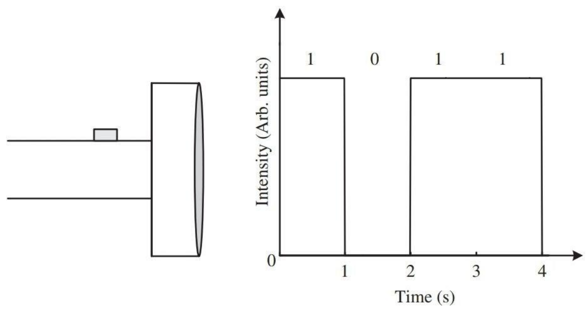


Fig.4:A simple optical modulator: the switch of a flash light.

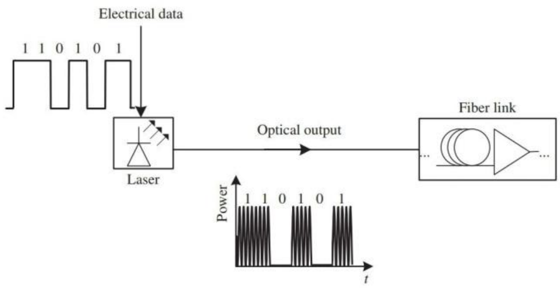


Fig.5: Direct modulation of a laser

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 [5]. 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 [3].

2.2 External modulators

(Fig.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 electro-absorption (EA) modulator [3].

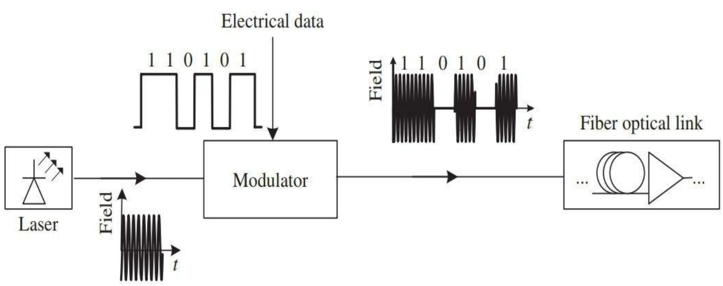


Fig.6: A transmitter using an external modulator

2.2.1 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 [6][7]. This effect is known as the Pockels effect or linear electro-optic effect. Consider the light propagation in a LiNbO3 crystal as shown in (Fig.7) Suppose E is the electric field intensity due to the applied voltage and an optical wave is propagating along the x-axis with its direction of polarization parallel to the z-axis. The dependence of the refractive index on the reflective field intensity is given by [6][7].

$$n = n_0 - \frac{1}{2} n_0^3 r_{33} E_z \qquad (5)$$

where n_0 is the refractive index in the absence of the applied electric field and r_{33} is a coefficient describing the electro-optic effect. If V is the voltage applied across the crystal and d is the thickness of the crystal, the z-component of the electric field intensity is [3].

$$E_z = V/d \qquad (6)$$

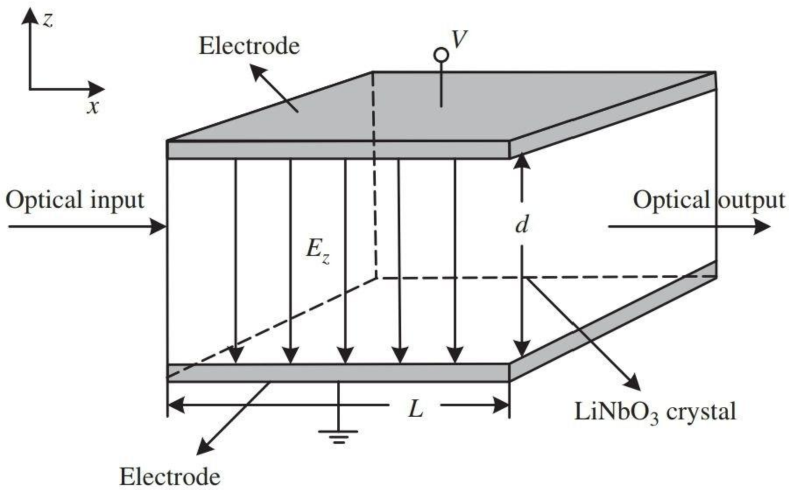


Fig.7: Phase modulation of an optical signal in a LiNbO3 crystal.

2.2.2 Dual-Drive Mach–Zehnder Modulators (MZMs)

A MZM consists of two arms, as shown in (Fig.8) Voltages V1 and V2 are applied to the upper and lower arms, respectively. The exact analysis of the field propagation in this structure requires knowledge of the transverse field distributions. Instead, we follow an approximate approach in which the guided modes of the waveguide are replaced by plane waves propagating in the direction of the x-axis. We ignore the losses in the y-branches and arms. Let the electric field of the input optical beam be [3].

$$\psi_{in} = A_0\, exp(-i2\pi f_c t) \quad (7)$$

where f_c is the frequency of the optical carrier. The first y-branch splits the input wave into two optical beams of equal power. Therefore, the electric field of the optical beam entering the upper (or lower) arm of the interferometer is [3].

$$\frac{A_0}{\sqrt{2}} exp(-i2\pi f_c t) \quad (8)$$

In (Eq.8), we have ignored a constant phase factor due to propagation in the y-branch. The factor $1/\sqrt{2}$ is introduced so that the total power is conserved. From the law of reciprocity, it follows that if the input and output of a y-branch are reversed, i.e., if the y-branch is used as a two-input/one-output device with inputs being $\psi_{in}/\sqrt{2}$, its output would be ψin, which is $1/\sqrt{2}$ times the addition of its inputs. This fact will be used later to find the output of the second y-branch. The optical beams in the upper and lower arms undergo a phase shift of ϕ1 and ϕ2, respectively, in the presence of applied voltages [3].

$$\phi_j = \frac{2\pi L}{\lambda_0}\left(n_0 - \frac{\frac{1}{2}n_0^3 r_{33} V_j(t)}{d}\right), \text{j= 1,2}$$

$$= \phi_0 - \frac{V_j \pi}{V_\pi} \quad (9)$$

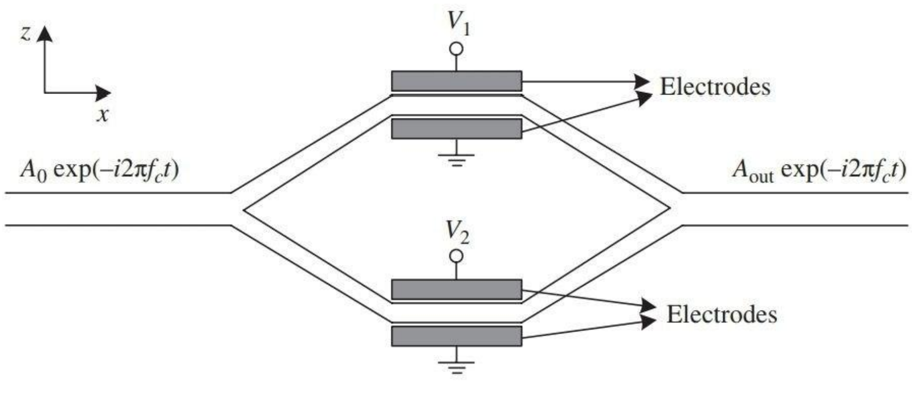


Fig.8: A dual-drive MZM.

The optical beams in the upper and lower arms are recombined via a second y-branch. The optical fields at the inputs of the second y-branch are [3].

$$\psi_j = \frac{A_0}{\sqrt{2}} exp[-(2\pi f_c t - \phi_j)], \; j = 1,2 \quad (10)$$

The output of the second y-branch is[3]

$$\psi_{out} = \frac{\psi_1+\psi_2}{\sqrt{2}} \quad (11)$$

Substituting Eqs (10) and (9) in Eq (11), we find that the output of the MZM is [8] [9]

$$\psi_{out} = \frac{A_0}{\sqrt{2}} exp(-\, i\pi f_c t)\left[\frac{exp(i\phi_1)}{\sqrt{2}} + \frac{exp(i\phi_2)}{\sqrt{2}}\right] = A_{out} exp(-\, i\pi f_c t) \quad (12)$$

2.2.3 Electro-absorption Modulator (EAM)

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 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, as shown in (Fig.9) 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. (Fig.10) shows the typical dependence of the absorption coefficient on the wavelength. Suppose the carrier wavelength is λ_0 . Let α_0 and α_1 be the absorption coefficients at V(t)=0 and V(t)= V_0 , respectively. If L is the length of the modulator, the optical power exiting the modulator is [3]

$$P_{out} = \begin{cases} P_{max} = P_0 exp(-\,\alpha_0 L) & When\, \mathrm{V(t)} = 0 \\ P_{min} = P_0 exp(-\,\alpha_1 L) & When\, \mathrm{V(t)} = V_0 \end{cases} \quad (13)$$

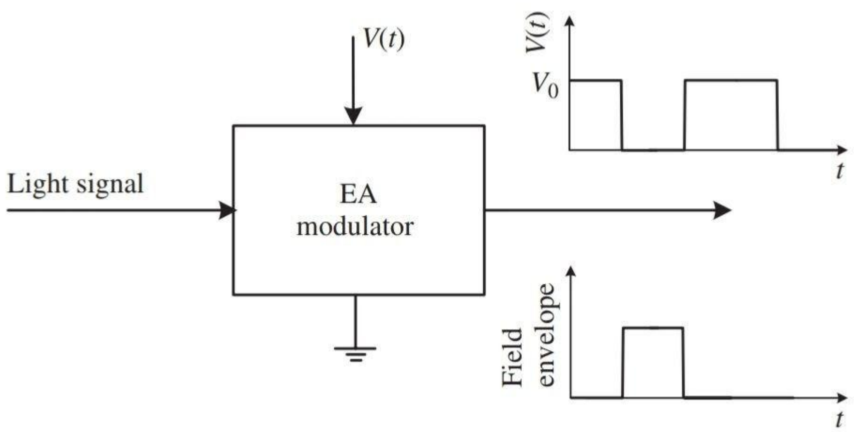


Fig.9: Amplitude modulation using an EAM

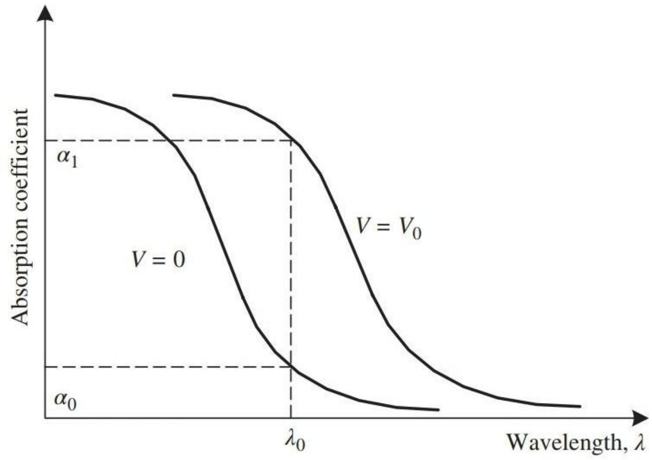


Fig.10: Typical dependence of absorption coefficient on wavelength.

where P_0 is the input power; the extinction ratio is [3]

$$\delta = \frac{P_{max}}{P_{min}} = \frac{\exp(-\alpha_0 L)}{\exp(-\alpha_1 L)} \qquad (14)$$

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. They have residual chirps similar to directly modulated lasers. The interaction of the chirp and fiber dispersion could lead to enhanced pulse broadening. The extinction ratio is typically ≤ 10 dB, which could lead to a power penalty [10].

Conclusion

We have discussed in this chapter about optical modulators and their types. We focused on external modulators that have a major role in optical communications. We have presented the two mechanisms behind the optical modulation: electro-absorption and electro-optic. In the next chapter we will provide results of numerical simulations carried out to study optical modulator based on electro-optic effect.

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Chapter 3:

Results and discussion

Introduction

Here, the numerical simulations results are reported and analyzed. In the first part, we consider studying a PN depletion phase shifter for use in photonic integrated circuits. Furthermore, we consider analyzing the performances of a PIN Mach-Zehnder (MZ) modulator. The PIN MZ creates a change in refractive index by injecting charge into a quasi-intrinsic (lightly doped) region in the waveguide. A PIN junction is formed by doping the arms of the slab adjacent to the waveguide. N-type (donor) dopants are applied to one side of the device, and p-type (acceptor) dopants to the other, giving rise the built-in potential of the junction.

1. PN depletion phase shifter

The simulation workflow is given in figure 1. In the first step, electric properties are determined by computing the spatial carrier distribution as a function of the applied voltage. Furthermore, optical properties are determined by calculating the guided mode characteristics. Finaly, a system-level simulation is performed by computing the variation of the phase shift as function of the applied voltage.

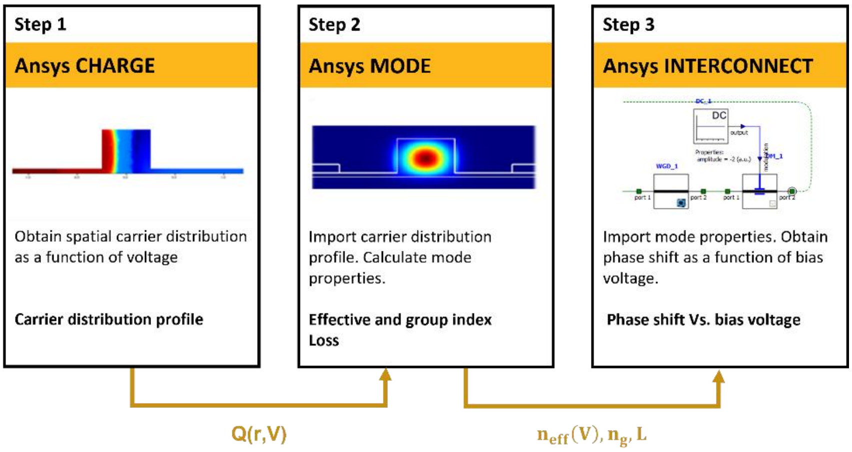

Fig 1: The simulation workflow for the PN phase shifter.

1.1 Results of electrical simulation

The figures Below illustrate the electron distribution profile in log scale at the cross-section of the phase shifter for 0V (left) and -4V (right) bias voltage applied to the device. It can be seen from the figures that with no bias voltage applied, the charge distribution at the cross-section of the waveguide is symmetric. By applying a reverse bias that is strong enough, the electrons are partially pushed out of the waveguide (to the left) as a result of the widening of the depletion region across the PN junction causing a rather dramatic change in charge distribution across the waveguide.

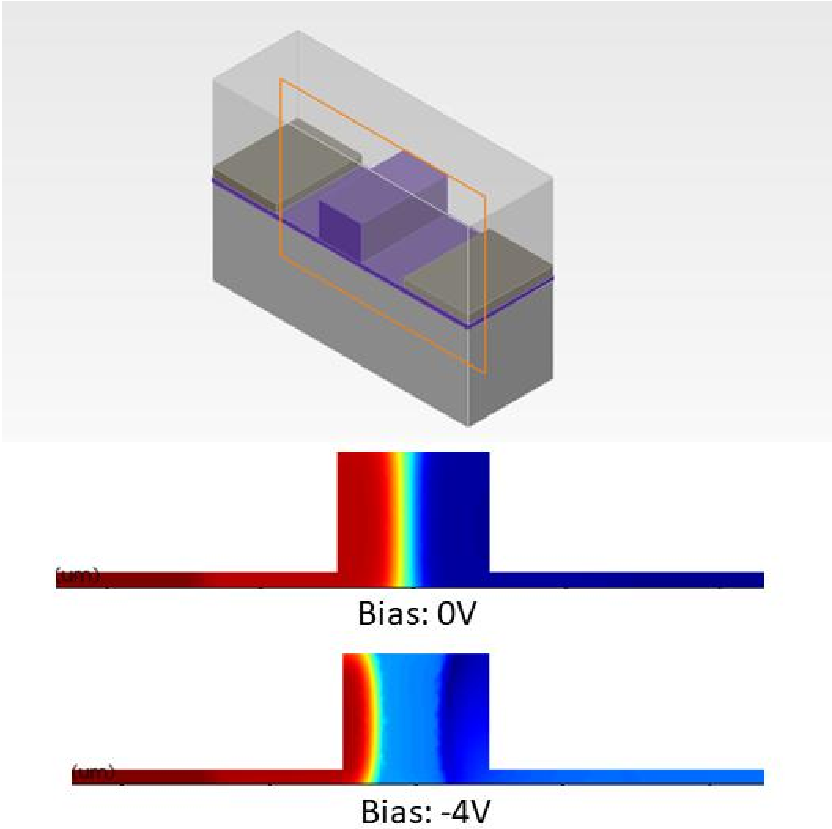

Fig 2: Schematic view and electron distribution profile at the cross-section.

This change in charge distribution and depletion region width will change the junction capacitance as depicted in the C-V plot of the device. As expected, the contribution of electrons and holes to the junction capacitance is very similar and is reduced as a higher reverse bias voltage is applied due to the widening of the depletion region. The amount of capacitance will affect the operation speed (bandwidth) of the phase shifter and thus can be used in its circuit model to consider this effect.

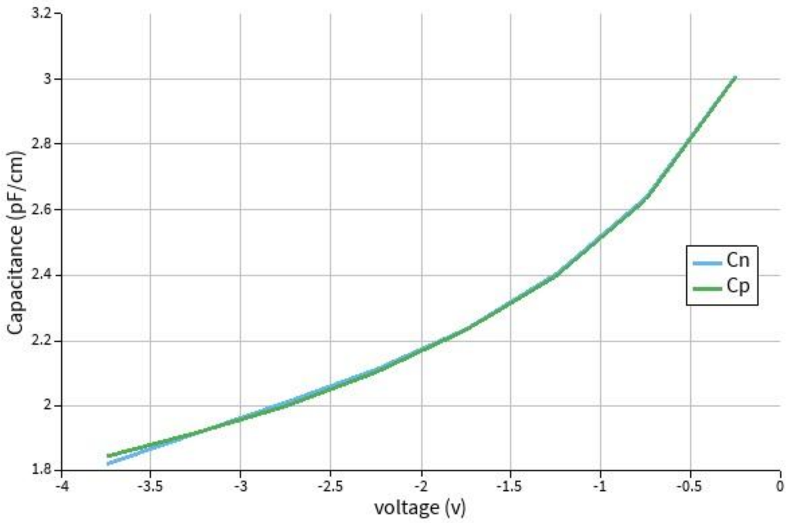

Fig 3: Variation of the junction capacitance with the applied voltage.

1.2 Results of optical simulation

The finite difference method is used to compute the guided modes and its propagation properties along with the impact of the applied voltage. Figure 4 gives the field distribution of the TE fundamental mode at 1.55 µm. Moreover, figure 5show the change in real part of effective index (left) and the loss (right) of the phase shifter as a function of the applied voltage. The results show that a larger reverse bias results in a higher effective index perturbation and lower loss. This is expected since the depletion of free carriers from the junction (waveguide) as a result of reverse bias application should reduce the amount of light absorption along the waveguide. A higher index perturbation will result in lowering the required length of the phase shifter to achieve a π phase shift thanks to the extra phase shift provided by this perturbation.

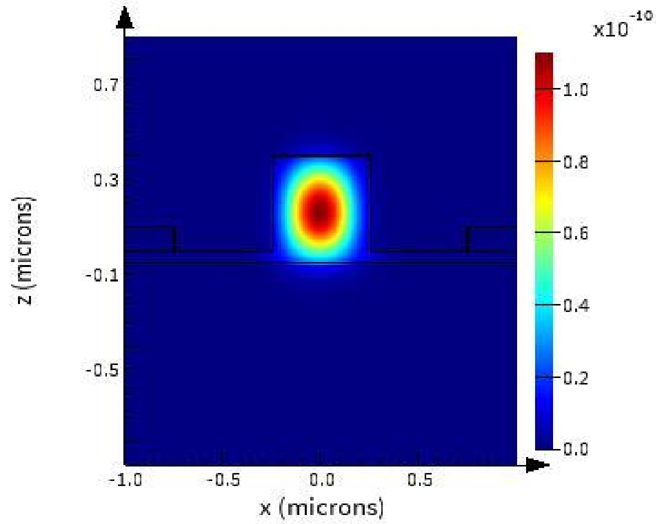

Fig 4: Field profile of the fundamental mode computed at 1.55 µm

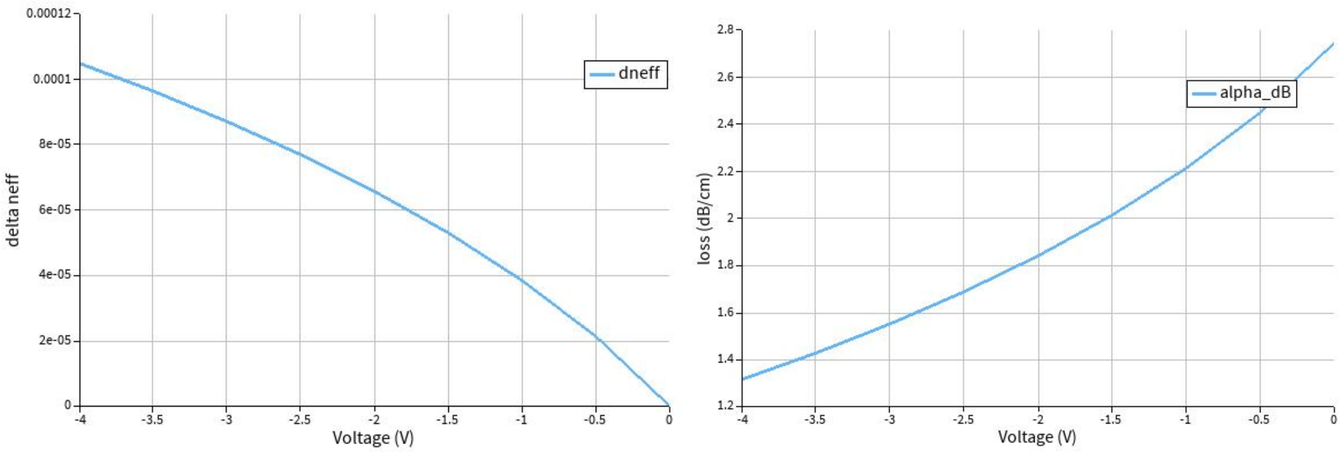

Fig 5: Variation of the mode effective index (left) and propagation loss (right) with the applied voltage.

1.3 Results of circuit simulation

The PN junction is considered as a modulator, where the phase of the optical signal is changed when an external voltage is applied. Figure 6 depicts the scheme of the system to be simulated.

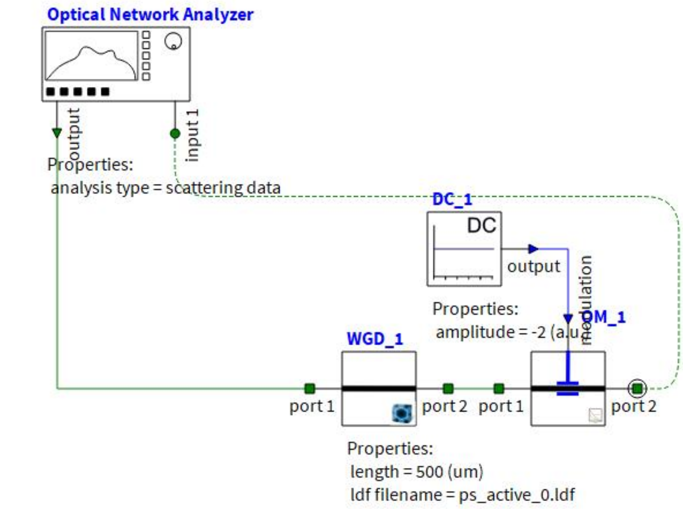

Fig 6: Simulation layout for analyzing the variation of the phase with the applied voltage.

The obtained phase results as a function of bias voltage are shown in the figure below. The shift in phase as the bias voltage varies is obvious from the plot. Here, the results show that for a length of 500 µm, the phase shift is about 0.2 rad at 4 volts bias voltage.

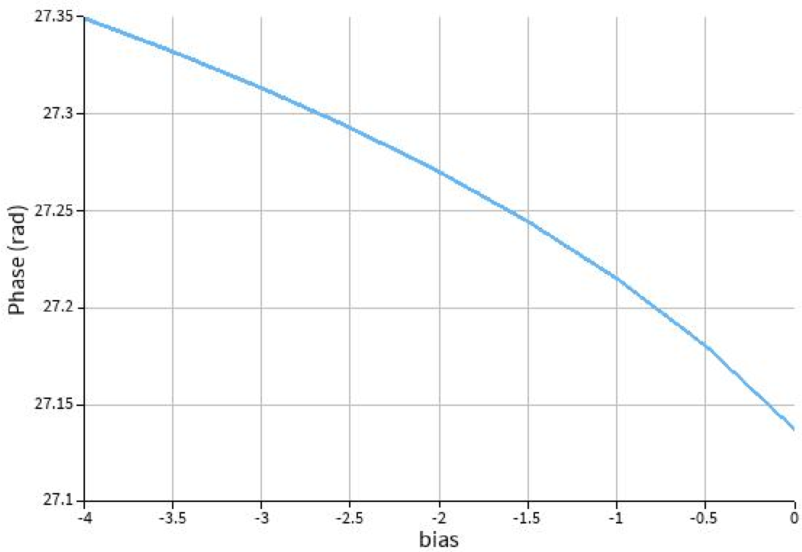

Fig 7: Variation of the phase with applied voltage.

2. PIN Mach-Zehnder modulator

A PIN junction is formed by doping the arms of the slab adjacent to the waveguide. N-type (donor) dopants are applied to one side of the device, and p-type (acceptor) dopants to the other, giving rise the built-in potential of the junction. The doping profile of the structure is given by figure 8. Strongly doped implants are formed beneath the contacts (x < -3.6 µm and x > 3.6 µm) to form an ohmic contact interface.

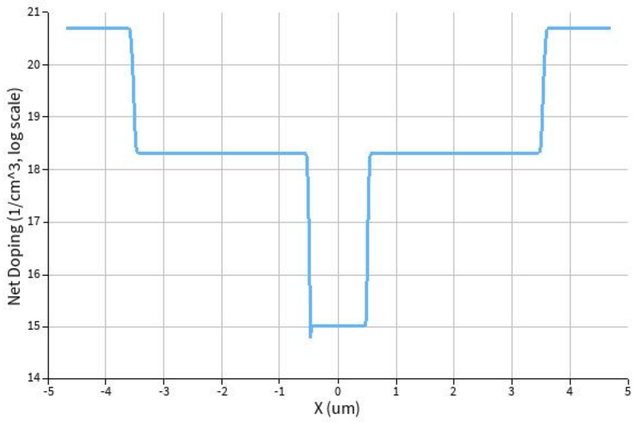

Fig 8: Doping profile of the PIN modulator.

We use a finite difference method to calculate the optical mode at different voltages. The first figure shows the change in effective index of the optical mode with respect to applied bias and the second figure plots the propagation loss [dB/cm] in the waveguide due to material absorption as a function of bias voltage. In addition, the modulation response is calculated by assuming a modulation length of 700 micron for demonstration purpose.

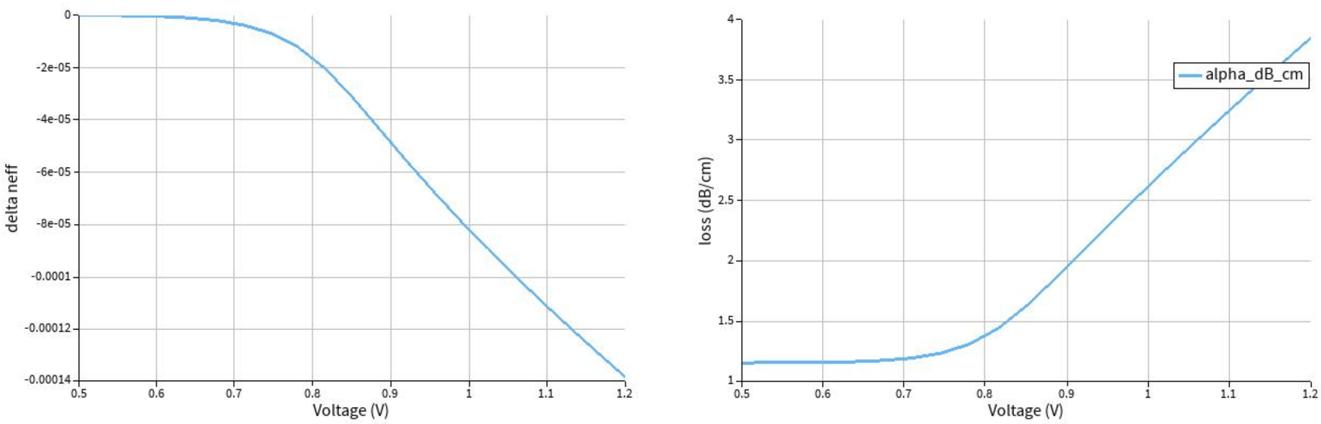

Fig 9: Variation of the effective index (left) and optical loss (right) with applied voltage.

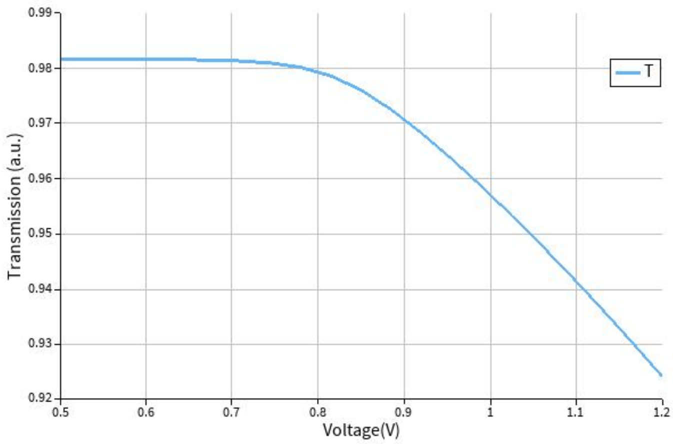

Fig 10: Variation of the optical transmission coefficient with applied voltage.

Conclusion

The aim of this chapter is to provide the results of simulation of the PN phase shifter and a PIN modulator. For the first case a complete optoelectronic study has been carried out and we have seen that both the effective index and optical loss can be modulated by varying a voltage eversely applied to the junction. Furthermore, the PIN phase shifter exhibits the same characteristics. Accordingly, both the structures can be used for MZ modulator for optical communications.

General Conclusion

General Conclusion

In light of the rapid development in the field of communications, our perspective is moving towards adopting optical communication technologies that rely on the use of light as a means of transmitting data quickly and with high efficiency. Optical communication is an important step towards providing secure and fast information transfer without distraction or loss.

To ensure the safety and security of transmitting information, we need to develop systems and methods to protect this information, and here comes the role of modulators that include electrical information in the optical signal. Inverters are divided into two types: direct and external. Direct modulators rely mainly on lasers to process information, while external modulators rely on electricity to process information.

Among the external modulators, an optical absorption modulator is used, which absorbs electrons resulting in a change in the properties of the conducting material, allowing the waveform to be changed and controlled. There are also modulators that rely on electricity, such as the Mach-Zehnder modulator, which converts the electrical signal into a light signal and modifies the characteristics of the light signal, such as phase or intensity.

We have studied a numerical simulation of a Mach-Zehnder modulator using PN and PIN connections, using ANSYS programs, which aim to improve the device's performance in optical communications by analyzing and improving its response to electrical signals. The results we obtained through this study are that the loss of light in the PIN is more than in the PN. This happens with the application of an electrical voltage

due to the presence of the insulating region that reduces the interaction of free charges with light, and the bandwidth is wider, but the modulation efficiency is lower than that of PN. However, the control accuracy and stability compensate for this.

Through this analysis, researchers and engineers can choose the most appropriate technology for their specific applications and achieve optimal performance of the Mach Zehnder variator

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