SIMULATION OF PHOTODETECTORS PIN AND APD FUNCTIONALITY IN AN OPTICAL COMMUNICATION SYSTEM

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SIMULATION OF PHOTODETECTORS PIN AND APD FUNCTIONALITY IN AN OPTICAL COMMUNICATION SYSTEM

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requirements for the award of the degree of
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In the name of ALLAH the Most Beneficial and the most Merciful
Specially dedicated to my beloved Parents, Brothers and Sisters.

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ABSTRACT

Much interest has recently been expressed in investigating the basic PIN (a diode with a wide, lightly doped between a p-type semiconductor and an n-type semiconductor region). And the more complex, expensive (about 4x the cost of the PIN) and voltage-hungry APD receiver(a highly sensitive semiconductor device that utilizes the photoelectric effect to convert light to electricity. It supplies a built-in first stage of gain through avalanche multiplication.) performances, mainly due to the on-going and high-pressured commercial demands for cost-cutting in systems incorporating these ultra-fast receivers. APD photodetectors have been shown as the better candidate for long haul communications, due to their internal gain availability. In the PIN photodiode, thermal noise plays the dominant role in the performance of the receiver. In the APD, both the thermal and shot noise is significant. In this report, a performance comparison of the conventional PIN photodiode with the Avalanche Photodiode (APD) in an optical communication system is presented. The effects of bandwidth, gain, extinction ratio, shot noise and thermal noise are compared and studied in detail. It was shown that the Q factor produced by each detector is heavily affected by the thermal noise in the PIN device, and by both the thermal and shot noise in the APD. It was also found that the APDs gain plays a significant role, and the shot noise has to be carefully dealt with. Additionally, the relationship of receiver sensitivity with thermal and shot noise was investigated and compared.

ABSTRAK

Terkini, terdapat minat yang menggunung terhadap kajian tentang PIN asas dan persembahan yang lebih kompleks, mahal (kira-kira 4x kos PIN) dan voltan-lapar penerima APD, terutamanya disebabkan oleh permintaan komersial berterusan untuk mengurangkan kos dalam sistem yang menggabungkan penerima ultra-cepat. Fotopengesan APD telah ditunjukkan sebagai calon yang terbaik untuk komunikasi jarak jauh, disebabkan oleh kebolehsediaan gandaan dalamannya. Di dalam fotodiod PIN, hingar terma memainkan peranan yang dominan dalam prestasi penerima. Di dalam APD, kedua-dua hingar terma dan ditembak adalah penting. Dalam laporan ini, perbandingan prestasi diantara fotodiod PIN konvensional dan fotodiod Avalanche (APD) dalam sistem komunikasi optik dibentangkan. Kesan lebar jalur, gandaan, nisbah pupus, bunyi tembakan dan hingar terma dibandingkan dan dikaji dengan teliti. Ia telah menunjukkan bahawa faktor Q yang dihasilkan oleh setiap pengesan dipengaruhi oleh hingar terma dalam peranti PIN, dan oleh kedua-dua hingar terma dan ditembak di dalam APD. Ia juga didapati bahawa gandaan APD memainkan peranan yang penting, dan hingar ditembak perlu diuruskan dengan berhati-hati. Selain itu, hubungan sensitiviti penerima dengan hingar terma dan ditembak telah disiasat dan dibandingkan.

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Q – Quality Factor

BER – Bit Error Rate

SNR – Signal Noise Ratio

CW – Continuous Wave

RZ – Return-to-Zero

NRZ – Non Return-to-Zero

CD – Chromatic Dispersion

OSNR – Optical Signal Noise Ratio

PD – Photodetector

APD – Avalanche Photodetector

F – Excess Noise Factor

M – Multiplication Gain

BW – Bandwidth

PRBS – Pseudo-Random-Bit-Sequence

ISI – Inter Symbol Interference

ER – Extinction Ratio

EDFAs – Erbium Doped Fiber Amplifiers

ROSAs – Receiver Optical Sub-Assembly

TOSAs – Transmit Optical Sub-Assembly

dB – Decibel

PDF – Probability Distribution Function

Hz – Hertz

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CHAPTER 1

INTRODUCTION

1.1 Introduction

For over 20 years, since the invention of the laser and the development of low-loss optical fiber, fiber systems have become the dominant backbone of the information-carrying infrastructure around the world, due to their high capacity, high speed, low cost, and high security. There are three essential parts in an optic communication system: a transmitter, a transmission medium, and a receiver. A laser is the core of a transmitter, with its output beam modulated by an input electric signal and then coupled into an optical fiber, which serves as the transmission medium to carry the signal to the receiving end. A photodetector serves as the heart of an optical receiver and converts the optical signal back to an electrical signal.

1.2 General System Descriptions

Typically, for long-haul communications, the optical fiber communication on system shown in Fig 1-1 is used [1]. The basic components of such an optical communication systems are the transmitter, the medium of transmission and the photoreceiver. There is also an optical encoder, through which the electrical information signal is converted to an optical Signal by modulating the optical emission from the optical transmitter. This optical transmitter is usually a light emitting diode or a laser diode together with a relevant modulating and driving circuits. After that, the optical signal is transmitted through a medium that provides suitable propagating conditions for the carrier signals. This transmission medium is usually an optical fiber with optical amplifiers and repeaters depending on its length. Finally, at the photoreceiver, the optical signal is converted back into an electrical signal.

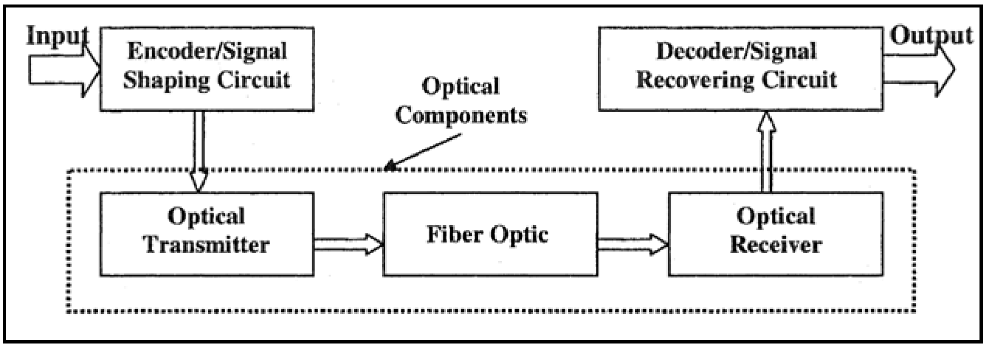

Figure 1.1: Schematic representation of an optical fiber communication system.

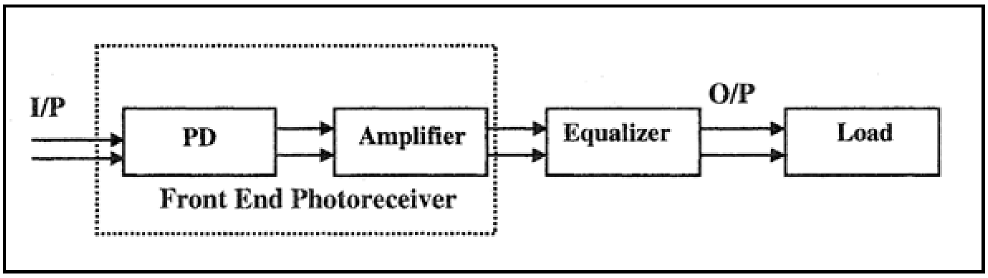

Figure 1.2: Schematic representation of the photoreciever of the optical communication system.

The photoreceiver contains a photodetector and pre-amplifier with relevant biasing and demodulating circuits [1]. A schematic of the photoreceiver is shown in Fig, 1-2.

The primary advantages of optical telecommunication systems are their high bandwidth due to high frequency of the optical carriers (100 GHz), low signal attenuation and low dispersion, which are achieved by a choosing of a suitable laser wavelength and optical fiber. Optical signals are immune to a crosstalk and hence several communication links can be supported by a signal fiber. They are also immune to the interference from inductive coupling and they offer more secure communications.

Conventional fiber is made of silica with a core having higher refractive index than its cladding. These changes in the refractive index result in a total internal reflection of a propagating signal, thus allowing for the signal to propagate over a long distance. Single mode fiber may be preferred as a transmission medium over multimode fiber because it could be optimized for low dispersion and attenuation for a certain wavelength. A dominant mechanism of attenuation in the signal mode fibers is impurity scattering.

With the present level of impurity control in manufacturing of single mode fibers, today's commercial fibers are very close to the theoretical attenuation limit of 0.15dB/km at a wavelength (λ) of 1.55μm. Zero dispersion in the commercial fibers can be achieved at 1.3μm. This means that the shape of the signal at this wavelength does not change as it propagates through the fiber. Depending on the system requirement, either 1.3μm or 1.55μm is used as a carrier wavelength.

1.3 Basic Principles

Optical fiber communication systems can utilize both analog and digital modes of modulation. Analog optical fiber communication systems are usually limited to short distance and low bandwidth applications such as cable TV. As in the case with wire line systems, analog systems are less efficient in comparison to digital systems because of their higher signal-to-noise ratio requirements. In addition, high linearity that is required for analog signal recovery circuits is not easily achieved in semiconductor optoelectronic components. These entire additional requirements make the digital format of modulation a better choice for communication systems. Also, with the development of a superior quality digital television, merging of television, telephone and internet traffic will favor the switch to digital optical communication systems.

Optical fiber telecommunication systems are used for both short and long-haul communications. In short-haul applications, a typical separation between a source and a receiver is between 30 to 80 km, depending on the speed of transmission and the particular application. Usually, in such systems, no additional signal amplification or phase correction is required along the path. In long-haul applications, where a typical separation between the source and the receiver can be a few thousand kilometers, as in sub-marine applications, signal regeneration is necessary at approximately every 100km.

The distance between the repeaters is determined by a combination of the required bit rate, the carrier wavelength (1.3μm or 1.55μm), attenuation and dispersion in the fiber. One way to categorize optical communication systems is to consider the distance over which they operate. At one end of the spectrum are the long-haul systems, concerned with information transport across the greatest possible distances. Therefore, silica based optical fiber is a suitable transport medium over a great distance with very low propagation loss, hence achieving high capacity that occurs at operating wavelengths in the neighborhood of 1.55μm. But, when the distance traveled is less critical, other factors come into play, such as the costs associated with endpoints, networking topologies and standards and compatibility with legacy systems. High costs photodetectors and optoelectronic integrated circuits (OEICs), exclude their use in short distance applications such as local area networks, fiber to the home, and optical interconnects on print circuit boards and between boards. High volumes of low cost OEICs will be needed also for optical buses in cars and in optical storage system like CD-ROM and digital versatile disk (DVD).

If an optical signal is propagating through the fiber, it loses power due to attenuation. A relation between the input optical power P_{in}, and output optical power P_{out} from a fiber of a length L_{fiber} can be described by [2]

$$\frac{P_{out}}{P_{in}} = 10^{\frac{\alpha_{att}|L_{fiber}}{10}} \tag{1.1}$$

where α_{att} is the fiber attenuation in decibels (dB). Therefore, the Fiber link has a transmitter with an output power Pout and receiver with sensitivityP_{min} then the maximum repeater distance due to signal attenuation L_{fiber} L_{att} is [2]

$$L_{att} = \frac{10}{\alpha_{att}} log\left(\frac{P_{trans}}{P_{min}}\right) \tag{1.2}$$

The other limiting factor is chromatic dispersion as the transmitter output is never perfectly monochromatic, and the modulation may introduce additional spreading of the signal in frequently/wavelength space (chirp). Therefore, an optical modulation signal is represent by a narrow band of different wavelengths within the pulse, traveling along the fiber. Due to chromatic dispersion, different wavelengths are traveling with different group velocities, resulting in a change of the pulse shape with the traveling of the pulse along the fiber. For an optical source with root-mean-square (rms) spectral width ($\sigma\ \lambda$), the rms pulse broadening (σ) at distance L_{fiber} from source is given by

$$\sigma = \sigma_\lambda L_{fiber} D_{C'} \tag{1.3}$$

where Dc is the chromatic dispersion coefficient (ps/nm.km). The maximum bit-rate in a return-to-zero (RZ) case due to chromatic dispersion can be estimated from B=1/4σ. In this case the repeater distance L_{disp} that is limited by dispersion is given by

$$L_{disp} = \frac{1}{4BD_C\sigma'_\lambda} \tag{1.4}$$

As shown in Eq, (1-4), the BL_{disp} product is a constant that depends only on the properties of the fiber. Therefore, higher bit-rate leads to a shorter repeater distance. In this case, when the main limiting factor on ($\sigma\ \lambda$) is a finite duration of the pulse, the minimum value is given by [3]

$$\sigma = \lambda\sqrt{\frac{D_C L_{disp}}{2\pi c'}} \tag{1.5}$$

where c is the speed of light.Using Eqs. (1-3) to (1-5), we get

$$L_{disp} = \frac{\pi c}{8\lambda^2 D_C B^{2'}} \tag{1.6}$$

As shown in Eq. (1-6), B^2L_{disp}, is a constant defined by the properties of the fiber and the carrier wavelength. In this case, increasing the bit-rate leads to a sharper decrease in the repeater spacing than in the previous case that shown in Eq. (1-4).

These are only two examples of the fundamental factors attenuation and chromatic dispersion that affect the repeater spacing. In a real system, there are other factors that dispersion that affects the repeater spacing. In a real system, there are other factors that should be taken into account to calculate the optimum repeater spacing like power budget and use time analyses.

1.4 Performance Characteristics

The role of the photodetector demands that it must satisfy very stringent performance and compatibility requirements that are generally similar to the requirements for sources. The main performance criteria for good photodetectors in optical communications systems are described [1].

1.4.1 Quantum Efficiency and Responsivity

The quantum efficiency is a measure of how many electron-hole pairs are created and then collected by the contacts to the external circuit per incident photon. One of the essential requirements in high performance photodetectors is to have high quantum efficiency. As the photodetector should produce a maximum electrical signal for a given amount of optical power.

There are two kinds of quantum efficiency internal quantum efficiency and external quantum efficiency. Internal quantum efficiency is defined as the ratio of the number of photogenerated electron-hole pairs being collected by the contacts to the number of incident photons .External quantum efficiency (η) compares the collected photocurrent to the number of the incident photons, thus involving the effects of surface reflections, the absorption coefficient (α) of the material of the absorption layer, the surface recombination and the non-radiative recombination of holes and electrons before carriers are collected. Also (η) is a function of the wavelength of the incident light (λ). An alternative figure of merit that may be used is responsivity (R) that is defined as the ratio of the primary photocurrent (without internal gain) I_{opt} to the incident optical power Pi and R is related to (η) as follows

$$R = \frac{\eta e \lambda}{hc} = \frac{\eta}{1248}\lambda$$

$$R = \frac{I_{opt}}{P_i} = \frac{\eta q \lambda}{hc} \tag{1.7}$$

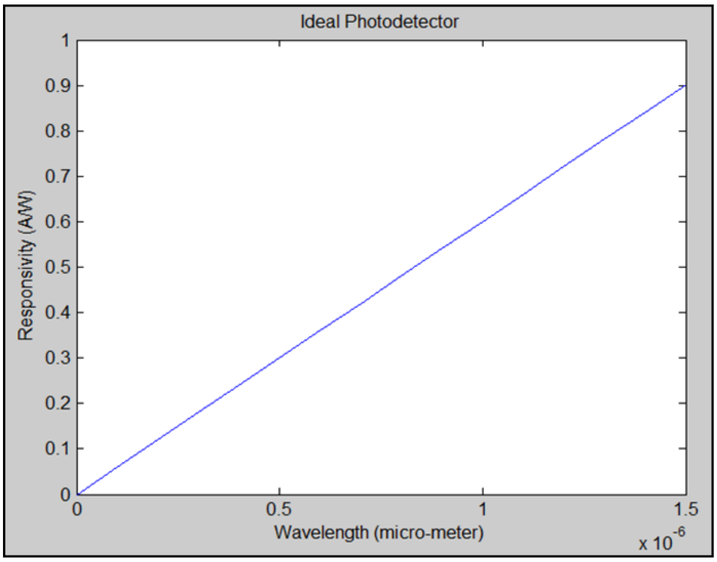

Figure 1.3: Responsivity against wavelength characteristic for ideal silicon PDs.

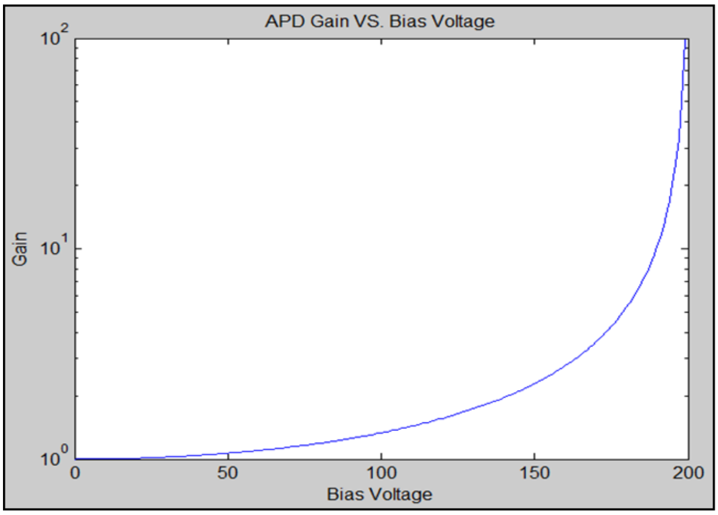

Figure 1.4: Responsivity against wavelength characteristic for ideal and typical silicon PDs [4].

1.4.2 Bandwidth

For high speed photodetector, the time delay for the conversion from optical to electrical signal should be minimal. The bandwidth, also known as the ”3-dB frequency” of a photodetector, is a measure of how fast the photodetector can respond to a series of light- pulses. It is defined as the frequency at which the power of the electrical signal is 3-dB lower than its DC power. This is a one of the critical performance characteristics for optical fiber communication system. The speed of the photodetector is mainly limited by two time constants.

The first one is the transit time that is needed by the photogenerated carriers to travel through the active Layers of the photodetector to be collected by the contacts at the ends of the device. If the bandwidth is mainly limited by this time constant, it is called the transit time limited bandwidth and a short response time is required to increase the bandwidth. The second time constant that limits the speed of the photodetector is the $R_{tot}C_d$ time constant where C_d is the photodetector junction capacitance and is the equivalent parallel resistance. The $R_{tot}C_d$ time constant depends on the dimensions of the photodetector, so it can be minimized by the reduction of the area of the photodetector that reduces its capacitance, but then it becomes difficult to collect much light resulting in low quantum efficiency. Therefore, the dimensions of the photodetector have to be optimized to solve this trade-off between the speed and the quantum efficiency of the photodetector.

1.4.3 Gain

The photodetector should be able to detect weak optical signals at a specific wavelength; this requires high internal gain, in addition to high responsivity and low internal noise. The gain of the photedetector is defined as the ratio of the number of collected election- hole pairs to the number of primary photogenerated pairs and it expresses the photodetectors sensitivity at the operating wavelength. Therefore, APD is a good choice because of its internal multiplication gain mechanism and its low multiplication noise characteristics at low biases, which means that this device has high detection selectivity.

1.4.4 Excess Noise Factor

All avalanche photodiodes generate excess noise due to the statistical nature of the avalanche process. The Excess Noise Factor is generally denoted as F. The excess noise factor is a function of the carrier ionization ratio, k, where k is usually defined as the ratio of hole to electron ionization probabilities (k<1). The excess noise factor is given by:

$$F = kM + \left(2 - \frac{1}{M}\right)(1 - k) \tag{1.8}$$

1.4.5 High Fidelity

To reproduce the received signal waveform with fidelity, for analog transmission, the response of the photodetector must be linear with respect to the incident optical signal over a wide range of inputs. Therefore, the photodetector is able to recover the received optical pulses over a wide range of optical power. In digital systems, this requirement would not be critical because the digital applications are less sensitive to the fluctuations in the optical power.

1.4.6 Wavelength Sensitivity Range

The spectral range of the pbotodetector is the range of wavelengths that the semiconductor material of the absorption layer of the photodetector is sensitive to. The spectral range of a photodetector is defined as the cutoff wavelength that is determined by the material of the absorption layer. Since the photodetector is sensitive only to the photons with the energy larger than the bandgap energy of the material of the absorption layer, there is a cutoff wavelength λ for the sensitivity of a photodetector and it is defined as

$$\lambda_c = \frac{hc}{E_g'} \tag{1.9}$$

1.4.7 Low Noise

Noise is defined as the fluctuations of the electrical signal. It is usually measured in rms value of the current or the voltage. This is one of the most important characteristics since it determines the theoretical sensitivity limit of the photodetector. Sources of the noise are in the dark current, leakage currents and shunt conductance and they must be minimized. Also, the gain mechanizing within either the photodetector or associated circuitry must be of low noise. The dark current is the generation-recombination (g-r) current without incident light, this current is consider as background noise. One of the design aims of photodetectors is to minimize this g-r current.

1.4.8 Stability of Performance Characteristics

Ideally, the performance characteristics of the photodetector should be independent of changes in ambient conditions. In other words, the photodetector must be capable of continuous stable operation over the commercial temperature range for long times and must maintain the desired performance characteristics under possibly demanding environments for a certain lifetime without significant degradation. However, the photodetectors currently have characteristics such as sensitivity, noise, internal gain and bandwidth that vary with temperature and therefore compensation for temperature effect is often necessary. Good designs, proper process development and stringent control of fabrication process help in stabilizing and improving the performance of the device.

1.4.9 Small Size

The physical site of the photodetector must be small far efficient coupling to the fiber and to allow for easy integration with the electronics. The small size of the photodetector also results in a smaller capacitance.

1.4.10 Low Bias Voltage

Ideally the photodetector should not require excessive bias voltages or Currents so as not to increase the power consumption of the photoreceiver.

An APD differs from a PIN photodiode by providing internal photo-electronic signal gain. The gain is a function of the APDs reverse voltage, VR, and will vary with applied bias.

$$M = \frac{1}{1 - \left(\frac{V_d}{V_{BR}}\right)^n} \qquad (1.10)$$

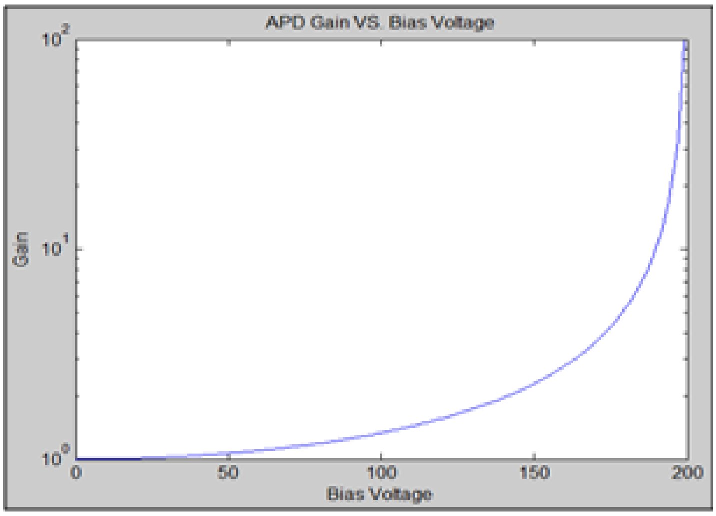

Figure 1.5: APD Gain vs. Bias Voltage

1.4.11 Low Cost and High Yield

Economic considerations are often of prime importance in any large scale communication system application. Despite the stringent control of the fabrication process, a spread in certain process parameters can still happen resulting in a percentage of the fabricated device failing to meet specification, thus increasing the manufacturing cost .Therefore, in practice, there should be always a certain process window where the change of the fabrication parameters can be tolerated and the denied performance. Characteristics can still be maintained.

1.5 Problem Statement

Most of the research has been focused on the optical to electrical conversion process. The photodetector is a key component in optical communication systems. The basic parameters used to characterize a photodetector are responsivity, quantum efficiency; rise time and bandwidth, this requirement being especially important as systems become faster. There is a need and motivation to improve the parameters.

This work gives designers a comparison overview to wisely implement the suitable PDs according to their applications based on their requirements, reliability, and price.

Such simulation for optimized communication system can help in analyzing the device under development and predict the performance for a given link distance. The simulation output helps eliminating any possible performance degradation before implementing the actual hardware.

1.6 Objective

The main objectives of the work are:

(1) To design and simulate optical communication systems incorporating such photodetectors at the signal propagation level using state of the art simulation techniques of lab like measurement instructions.

(2) To optimize photodetectors parameters available in software - such as; bandwidth, gain, dark current, thermal and shot noise, extinction ratio.

1.7 Scope of the project

The scope of this project is first of all design optimized communication system with Pin & APD photodetector. After that, simulate the design in terms of performance parameters using mostly Optisystem, and Optsim, Matlab, sigmaplot, and excel when required. Then, optimize the proposed Communication system.

1.8 Thesis Organization

The development of both digital and analog communication systems has established new requirements for APDs and PINs. The motivation for the research in this thesis is to find new approaches for performance improvement of photodetectors to deal with these challenges. After a general overview of basic theories in chapter 1, a brief review of photodetector applications in optical communication systems and a general view of the impact-ionization-engineering (IIE) of APDs in addition to the problem statement, objectives, scope of the project, and literature review are presented in chapter2.

Introduces the project methodology, global parameters, simulation tools, the design steps, introducing the software used in the simulation process and the design specifications is discussed in chapter 3. An illustration of simulated results, the comparison between PIN and APD and the advantages of the proposed design over other designs structure, discussions for each graph and the comparisons are also provided in chapter 4. Chapter 5 contains the conclusion of the project and the recommended future work.

1.9 Summary

In this chapter, an overview of the optical fiber communication system is presented. This overview concentrates mainly on the photoreceiver which is one of the critical components that affects the performance of the optical communication system. In fact, photodetectors plays the major role in the performance of the photoreceiver. Both the performance characteristics of the photodetectors and the different material that can be used for the absorption and multiplication layers of the photodetectors are discussed, showing some important features of each of them. A survey of different kinds of photodetectors is presented. This survey includes the photodetectors that do not have internal gain like PN-PDs, PIN-PDs. Photodetectors that has internal multiplication gain such as APDs, is also include in this survey. For these photodetectors, different structures, materials and sample experimental results have been presented.

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