FREE SPACE OPTICAL FRONT-END RECEIVER'S BANDWIDTH ENHANCEMENT EMPLOYING MICRO-ELECTRO-MECHANICAL SYSTEMS VARIABLE FEEDBACK CAPACITOR

ARNIDZA RAMLI

UNIVERSITI TEKNOLOGI MALAYSIA

FREE SPACE OPTICAL FRONT-END RECEIVER'S BANDWIDTH ENHANCEMENT EMPLOYING MICRO-ELECTRO MECHANICAL SYSTEMS VARIABLE FEEDBACK CAPACITOR

ARNIDZA RAMLI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

JANUARY 2010

To my beloved parents, ayah and mama,
my siblings and fiancé
for their constant warmth and support

ACKNOWLEDGEMENT

Alhamdulillah, praise to Allah S.W.T that has given me His blessing and strength to complete this thesis. In this short column, I would like to express my sincere gratitude to my supervisor, Dr. Sevia Mahdaliza Idrus, Deputy Director I, Photonics Technology Centre, Universiti Teknologi Malaysia (UTM) for her guidance, encouragement and valuable advice throughout my research work. I also would like to thank my co-supervisor, Assoc. Prof. Dr. Abu Sahmah Mohd Supa'at for his encouragement and invaluable supervision.

I would like to take this opportunity to acknowledge Mr. Tengku Nadzlin Tengku Ibrahim, Head of Microelectronics Laboratory, Universiti Tun Hussein Onn (UTHM) and technicians Mrs. Hasnah Rahmat and Mr. Ahmad Nasrull Mohamed for allowing me to use the accommodation at their lab for my simulation works.

I want to acknowledge the Ministry of Higher Education for their financial support through the Fundamental Research Grant Scheme (FRGS), Vot 78203.

Finally, I would like to thank to the members of Photonics Technology Centre for their help and support. I am also indebted to my colleagues, friends especially my fiancé, Wan Mohamad Maulana for their constant support and encouragement.

ABSTRACT

Free space optical front-end receiver usually suffers high photodetector input capacitance which limits the bandwidth of the system. This is due to the large detection area required to collect as much optical radiant power as possible to increase the system's sensitivity. In this work, the bootstrap transimpedance amplifier (BTA) is adopted as an alternative approach for free space optical front-end receiver design. This technique offers the usual advantages of the transimpedance amplifier (TIA) together with the effective capacitance reduction technique. An improved photodetector model and the both front-end structures; TIA and BTA have been simulated using harmonic balance technique offers by Microwave Office, and the results show that the design improves the system bandwidth by 6.7 times in average. However, the performance of the BTA was found limited to a certain photodetector input capacitance. In order for the front-end structure to adapt with various photodetectors capacitance, MEMS variable capacitor (varicap) is introduced as a tunable feedback element for the bootstrap loop for an optimum performance. The MEMS varicap have been designed and modeled using CoventorWare and found to be practical for circuit implementation. The implementation of MEMS varicap with the design BTA optical front-end receiver was verified using the CoventorWare ARCHITECT. The simulation of the BTA employing MEMS variable capacitor as the feedback capacitor shows the improvement in bandwidth by 1.04 times in average for various photodetector input capacitance.

ABSTRAK

Penerima bahagian depan optik ruang bebas kebiasaannya menghadapi nilai kemuatan masukan pengesan foto yang tinggi mengakibatkan pembatasan lebar jalur sistem. Ini disebabkan oleh luas pengesanan yang besar diperlukan untuk menerima sebanyak mungkin kuasa sinaran optik bagi meningkatkan kepekaan sistem. Di dalam kajian ini, penguat trans galangan butstrap (BTA) telah digunakan sebagai pendekatan alternatif bagi reka bentuk penerima bahagian depan optik ruang bebas. Teknik ini menawarkan faedah seperti yang didapati dari penguat trans galangan (TIA) beserta teknik penurunan kemuatan berkesan. Model pengesan foto dan kedua-dua struktur penerima bahagian depan; TIA dan BTA telah disimulasi menggunakan teknik imbangan harmonik oleh *Microwave Office*, dan keputusan menunjukkan reka bentuk ini telah membaiki lebar jalur sistem secara purata sebanyak 6.7 kali ganda. Walaubagaimanapun, prestasi BTA terhad terhadap kemuatan masukan pengesan foto tertentu. Untuk menjadikan struktur penerima bahagian depan sesuai untuk pelbagai kemuatan pengesan foto, pemuat boleh ubah MEMS diperkenalkan sebagai elemen suap balik boleh tala untuk gelung butstrap bagi mencapai prestasi optimum. Pemuat boleh ubah MEMS telah direkabentuk dan dimodelkan menggunakan CoventorWare dan didapati praktikal untuk pelaksanaan litar. Pelaksanaan pemuat boleh ubah MEMS bersama reka bentuk penerima bahagian depan BTA telah ditentusahkan menggunakan CoventorWare ARCHITECT. Simulasi BTA menggunakan pemuat boleh ubah MEMS sebagai pemuat suap balik menunjukkan pembaikan terhadap lebar jalur sebanyak 1.04 kali ganda secara purata untuk pelbagai kemuatan pengesan foto.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

IrDA	-	The Infrared Data Association
IR	-	Infrared
LAN	-	Local Area Networks
FSO	-	Free Space Optics
RF	-	Radio Frequency
LOS	-	Line of sight
OWC	-	Optical Wireless Communications
BER	-	Bit Error Rate
APC	-	Adaptive Power Control
TEC	-	Temperature Controller
TIA	-	Transimpedance Amplifier
BTA	-	Boorstrap Transimpedance Amplifier
MEMS	-	Micro-Electro-Mechanical Systems
Op-amp	-	Operational Amplifier
MWO	-	Microwave Office
Varicap	-	Variable capacitor
MOS	-	Metal oxide semiconductor
APD	-	Avalanche photodiode
FOV	-	Field of View
BJT	-	Bipolar junction transistor
FET	-	Field-effect transistor
VHF	-	Very high frequency
UHF	-	Ultra high frequency
FM	-	Frequency modulation
VCO	-	Voltage controlled oscillator

PLL	-	Phase locked loop
CMOS	-	Complementary metal oxide semiconductor
MOSFET	-	Metal-oxide-semiconductor field-effect-transistor
IC	-	Integrated circuit
DC	-	Direct current
BW	-	Bandwidth
MSM	-	Metal-Semiconductor-Metal
AC	-	Alternating current
NG	-	Noise Gain
MUMPs	-	Multi-User MEMS Process

LIST OF SYMBOLS

R	-	Resistance
T	-	Temperature
B	-	Bandwidth
$\overline{e_T}$	-	Thermal noise voltage
k	-	Boltzmann's constant
$\overline{i_d}^2$	-	Dark current noise
q	-	Electronic charge
I_d	-	Dark current
$\overline{i_q}$	-	Quantum noise
I_p	-	Generated photocurrent
hf	-	Energy of photon
Eg	-	Bandgap energy
λ	-	Operating wavelength
R_l	-	Load resistor
V_{bias}	-	Bias voltage
V_{out}	-	Output voltage
$A_{transimp}$	-	Transimpedance gain
i_s	-	Current source
R_f	-	Feedback resistor
A_{OL}	-	Open loop voltage gain
Z_{fb}	-	Feedback impedance
f_{3dB}	-	3dB bandwidth
C_f	-	Feedback capacitance

C_{in}	-	Input capacitance
C_μ	-	Base-collector capacitance
e_0/A_{OL}	-	Gain error signal of op-amp
C_{min}	-	Minimum capacitance
C_{max}	-	Maximum capacitance
C_v	-	Variable capacitance
ε_d	-	Dielectric constant of air
A	-	Area of the plates
d	-	Spacing between two plates
x	-	Vertical displacement at a certain bias condition
V_{pi}	-	Pull in voltage
τ_t	-	Transit time
l_d	-	Depletion region length
v_s	-	Average carrier saturation velocity
ω_t	-	Frequency response due to transit time
C	-	Parallel plate capacitor
ε	-	Permittivity of the dielectric
C_j	-	Junction capacitance
ε_0	-	Permittivity in vacuum
ε_r	-	Permittivity of the semiconductor
A_d	-	Area of the depletion region
l_d	-	Depletion region length
ω_{RC}	-	Frequency response due to RC time constant
R_s	-	Junction series resistance
ω_p	-	Pole frequency
A_0	-	DC gain
C_d	-	Photodiode capacitance
ω_0	-	Unity gain frequency
C_a	-	Amplifier input capacitance
I_{pd}	-	Output current of photodiode

R_{bulk}	-	Bulk resistance
I_s	-	Reverse saturation current
e_j	-	Junction voltage
I_l	-	Leakage current
P	-	Incident optical power
η	-	Detection efficiency
h	-	Plank's constant
v	-	Optical frequency
R	-	Responsivity
C_{jo}	-	Zero bias junction capacitance
V_j	-	Built-in voltage
m	-	Grading coefficient
V_B	-	Breakdown voltage
V_{in}	-	Differential input voltage
V^+	-	Positive terminal voltage
V^-	-	Negative terminal voltage
R_{in}	-	Input resistance
R_{out}	-	Output resistance
G	-	Gain of op-amp
f_z	-	Zero frequency
C_p	-	Parasitic capacitance
V_1	-	First bias voltage
V_2	-	Second bias voltage

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 FSO Communications Link

Over the last two decades, wireless communications have gained enormous popularity. Wireless offers flexibility, cost effectiveness and mobility which are the attractive option for many personal as well as organizational communication needs. Wireless provides extensibility options to wired counterparts that have reached cabling limits. Moreover, wireless communication is naturally suitable for mobile applications. This novel idea has led to growing interest in using optical signals in free space and has inspired related research and development. The Infrared Data Association (IrDA) was an outcome of the increased interest in the infrared option as the medium for wireless carrier. As optical wireless evolved, the IEEE 802.11 infrared (IR) standard for wireless Local Area Networks (LAN) was a result of realizing the importance of optical wireless [1].

Infrared wireless communication possesses two main advantages, the abundance of unregulated spectrum in 700nm – 1500nm region and the ease with which the IR radiation can be confined. IR wireless or Free Space Optics (FSO) offers cost-effective solution to the existing fiber-based where the system can be built on the roofs of office and houses to reduce the cost of laying the cable. It can be summarized that the advantages of FSO system are [1-3]:

- No need for trenching
- Time and labour saving (quick and efficient installation)
- Does not require radio permits and licenses
- Bandwidth equal or superior to fiber systems and much better than RF
- Unlike cable, FSO is a recoverable and non-fixed asset
- FSO does not cause electromagnetic interference with other equipment

Today, FSO has entered homes, offices, industry and health care, with applications in the field of remote control, telemetry and local communication [3]. Accordingly, the typical applications of FSO are illustrated in Figure 1.1. The growing demand of broadband applications and congestion of Radio Frequency (RF) spectrum have fueled interest in the development of the IR option [1]. The IR spectral region offers a virtually unlimited bandwidth that is unregulated worldwide. IR and visible light are close together in wavelength and they exhibit qualitatively similar behavior. Both are absorbed by dark objects, diffusely reflected by light-colored objects and directionally reflected from shiny surfaces [4]. The available commercial systems offer capacities in the range of 100 Mbps to 2.5 Gbps and demonstration systems report data rates as high as 160 Gbps. FSO systems can function over distances of several kilometers as long as there is a clear line of sight (LOS) between the source and the destination.

1.1.1 FSO versus RF Wireless Link

Conventionally, wireless networks were implemented as RF systems because of the already available RF technologies. RF systems offer a wide range of coverage and high immunity to blocking because its have the ability to penetrate most physical obstructions. However, at high frequency the coverage capability of RF systems are limited since line of sight becomes essential as the data rate increases. Furthermore,

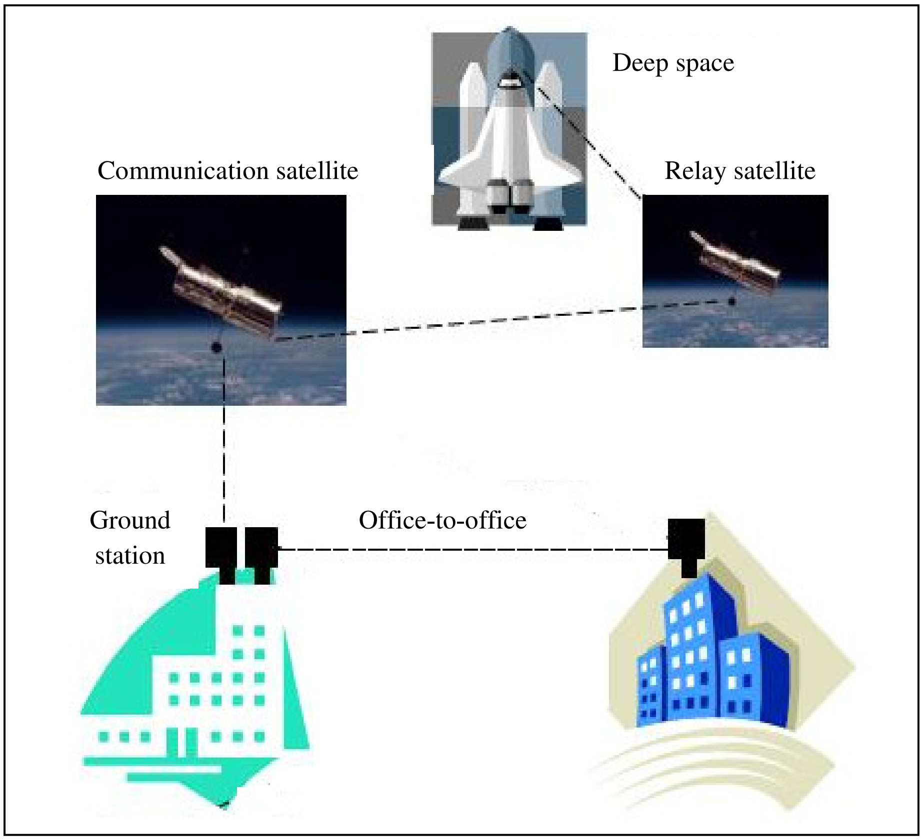

Figure 1.1 Typical applications for free space optics including office-to-office communications as well as technology for intersatellite link, satellite-to-ground station and to terrestrial.

expensive components must be used to operate RF systems at high frequencies. As a result, some RF-based wireless systems operate at low carrier frequencies to avoid loss of the major RF advantages thus limits the data rate.

The development of IR or optical wireless communications (OWC) is an option of growing demand of broadband applications and congestion of RF spectrum. Contrary to RF wireless, IR systems require no licenses, offer unregulated spectrum and provide unlimited bandwidth [1]. The difference between optical wireless and RF can be seen in the system installation which is little different from fitting a microwave satellite dish. For optical wireless, the pair of units (i.e. signal and power leads) is attached to convenient line-of-sight poles. Following alignment, transmission and reception is locked-in and users report performance at least as good as that from fiber or radio systems [2].

There are many advantages of IR over RF system. First, IR systems are manufactured using inexpensive components because of the simple technology needed for optoelectronic devices [1]. These components consume little power compared to RF systems. In addition, IR signals do not interfere with relatively nearby signals of the same nature like radio signals thus facilitate the system design and resulting in a significant cost savings. Moreover, IR signals are more immune to fading than radio signals so less power is loss to attenuation. This is because the dimensions of the receiver's photodetector are many orders of magnitude larger that the wavelength of the optical radiation and thus, the spatial fluctuations in signal strength due to multipath are averaged over the large detector area, which acts as an integrator [5].

IR systems also offer great reusability. The nature of the optical radiation is such that the transmitted signal is obstructed by opaque objects, and the radiation can have high directivity using sub-millimetre scale beam shaping elements. This combination of high directivity and spatial confinement gives optical channels an unmatched advantage in terms of security [5]. These characteristics allow the reuse of same communication equipments and wavelengths of one system in another nearby system without taking special provisions for interference from and to neighbouring rooms. Accordingly, the security measures and data encryption needed for optical wireless systems are reduced compared to those of RF systems leading to simpler design process and less overhead. These different between radio and infrared are summarized in Table 1.1.

Table 1.1: Comparison between Radio and Infrared

Property	Infrared	Radio	Implication for IR
Bandwidth regulated	No[4]	Yes[4]	Approval not required. Worldwide compatibility[4]
Passes through walls	No[4]	Yes[4]	Less coverage. More easily secured. Independent links in different rooms.[4]
Multipath Fading	No[3,4,6]	Yes[3,4,6]	Simple link design[4]
Source of Bandwidth Limitations	High Photodiode Capacitance, Multipath Dispersion[3]	Multipath Dispersion	Problematic at high data rates
Source of Dominant Noise	Ambient Background Light[3,4,6]	Interference from Other Users[3,4,6]	Limited range[4]
Security	High[3,6]	Low[3]	Facilitate system design
Input X(t) Represents	Power[3,4]	Amplitude[3,4]	Difficult to operate outdoors[4]
Path Loss	High[3,4,6]	High[3,4,6]	Limited range

1.1.2 FSO Challenges

The advantages of free space optical wireless or FSO do not come without some cost. When light is transmitted through optical fiber, transmission integrity is quite predictable except for unforeseen events such as backhoes or animal interference. However, when light is transmitted through the air, the atmosphere which is a complex and unquantifiable subject is the challenges.

1.1.2.1 Atmospheric Attenuation

Some of the atmospheric attenuations of FSO system are fog, low clouds, rain, snow, dust and various combinations of each. However, the discussion in this subtopic will be more on fog since it is typically dominated in the atmospheric attenuation [7]. Fog substantially attenuates visible radiation. The effect on FSO optical wireless radiation is entirely analogous to the attenuation and fades. Similar to the case of rain attenuation with RF wireless , fog attenuation is not a “show-stopper” for FSO because the optical link can be engineered such that, for a large fraction of the time an acceptable power will be received even in the presence of heavy fog [7,8]. FSO wireless-based communication systems can be enhanced to yield even greater availabilities.

1.1.2.2 Physical Obstruction

FSO system need to have widely spaced redundant transmitters and large receive optic resulting in the concern as interference from objects such as bird. On a typical day, an object covering 98% of the receive aperture and all but one transmitter will not cause an FSO link to drop out. Thus birds are unlikely give any impact on FSO transmission.

1.1.2.3 Scintillation

On a bright sunny day, scintillation is the most crucial factor that affects the performance of many FSO optical. The effects are typically reflected in Bit Error Rate (BER) statistics. Some optical wireless products have a unique combination of large aperture receiver, widely spaced transmitters, finely tuned receive filtering and automatic gain control characteristics. The effective way to reduce scintillation is by employing large aperture approach compared to multiple smaller apertures, which perform less averaging at lens. In addition, certain optical wireless systems also apply a clock recovery phase-lock-loop time constant that eliminate the affects of atmospheric scintillation and jitter transference.

1.1.2.4 Reliability

The reliability of FSO can be improved by employing an adaptive laser power (Adaptive Power Control or APC) scheme to dynamically adjust the laser power in response to weather conditions. In clear weather the transmit power is greatly reduced, enhancing the laser power is increased as needed to maintain the optical link, and instead as the weather clears. A Temperature Controller (TEC) that maintains the temperature of the laser transmitter diodes in the optimum region will maximize reliability and lifetime, consistent with power output allowing the FSO system to operate more efficiently and reliably at higher power levels.

1.2 Research Background

We are surrounded by on going revolution in optical communication technology whereby optical fiber communication link is the main backbone for all communication networks due to numbers of advantages. On the other hand, OWC or FSO has emerged as an alternative method on delivering data wirelessly through IR. Taking into account both the advantages and disadvantages of IR FSO, it is questionable that it will replace radio as the only medium to transmit information wirelessly. It is more likely that radio and IR will continue operating in a complementary manner, with one being preferred over the other, depending on the specific application. FSO will probably continue being favored for short-distance systems where security, low cost, and immunity to radio interference are required. Radio, on the other hand, will very likely continue being used for transmission over longer distances, in situations where high mobility is necessary or for systems operating in environments where the atmospheric conditions favor it over FSO [9].

The robust FSO systems, which establish communication links by transmitting laser beams directly through the atmosphere, have matured to the point that mass-produced models are now available (i.e. FlightLite™ 100 manufactured by Light Pointe) [10]. FSO communications refers to the transmission of modulated IR beams through the atmosphere to establish optical communications link. The engineering maturity of FSO is often underestimated, due to a misunderstanding of how long FSO systems have been under development. The truth is FSO was historically first demonstrated by Alexander Graham Bell in the late nineteenth century. His experimental device is called "photophone" which the system converted sounds into telephone signal and transmitted them through free air space to a receiver along a beam of light for a distance of some 600 feet. Although Bell's photophone never became a commercial reality, it demonstrated the basic principle of optical wireless communications [11,12]. Essentially all of the engineering of today's FSO communications systems was done over the past 40 years or so, mostly for defense applications. By addressing the principal engineering challenges of FSO, aerospace and defense activity established a strong foundation upon which today's commercial FSO systems are based [12].

In FSO communications, the power transmitted is low due to eye safety and power consumption considerations. Therefore, it is important for the detectors to receive as much radiant optical power as possible. The basic structure of an optical receiver is similar to that of a direct detection RF receiver: a low-noise preamplifier, the front-end photodetector, amplification stages, the post-amplifier, filtering and some signal processing. In direct detection optical communication systems, the optical signal incident on the photodiode is converted into an electrical current, which is then amplified and further processed before the information carried by the optical signal can be extracted as shown in Figure 1.2.

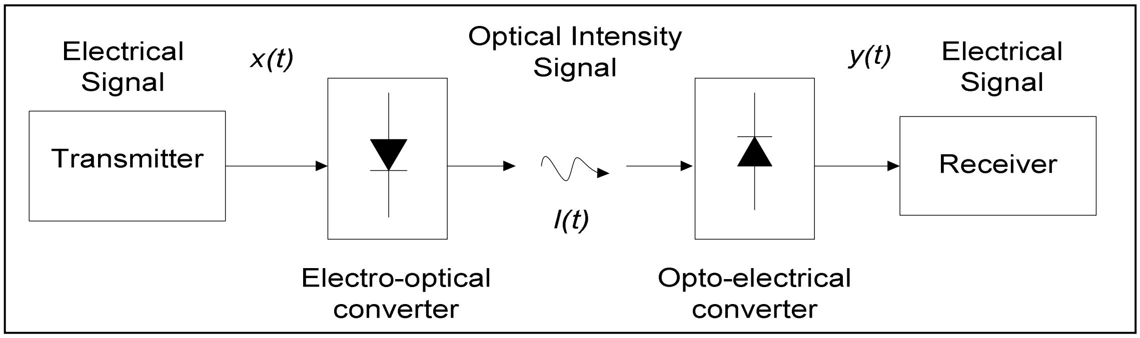

Figure 1.2 Block diagram of a direct detection channel.

The receiver performance will depend on the devices and design techniques used. Among various receiver structures the high impedance and Transimpedance Amplifier (TIA) [13] are popular for fiber-based application. High impedance approach results in high sensitivity while the transimpedance approach obviates the need for bandwidth equalization. However, the Bootstrap Transimpedance Amplifier (BTA) was found to be an attractive approach as an alternative for the both structures mentioned above.

1.3 Significance of Research in FSO Receiver Design

FSO communication offers the possibility of high data rate links among satellites and the Earth, allowing even greater flexibility in terms of network connectivity and access [14]. There is marked growth in mobile telecommunications which employs optical systems, for example by using an optical upconverter for millimeter wave radio over fiber and using a sub-carrier multiplexed optical fiber system to support mobility [1,15], as well as by other applications. To support this development, wideband optical receivers with rather different requirements, which specifically address these applications is necessary. An optical receiver should generate low noise across the band to maximize the signal to noise ratio of all the received channels and have good gain flatness across the band to preserve the channel content.

Besides that, the requirements for free space optical links are different than those for optical fiber links. The laser wavelength must be chosen for optimum atmospheric transmission, and very importantly, the photodetection scheme has to be chosen to give high sensitivity and selectivity. Typical large photodetection area of commercial detectors has capacitance around 100-300 pF [9] compared to 50pF in fiber link. This value of capacitance can affects the bandwidth of the system. Hence, techniques to reduce the effective detector capacitance are required in order to achieve a low noise and wide bandwidth design. Thus the research direction has to be directed to designing an optical front-end receiver with low noise, high gain-bandwidth product and high sensitivity and selectivity.

1.4 Problem Statement

FSO or optical wireless communications link operates in high noise environments. In addition, the performance is subjected to several atmospheric factors like environmental temperature, fog, smoke, haze and rain. A good sensitivity and a broad bandwidth receiver implement a small photodetection area where the aperture is small. However, FSO optical receiver requires a large aperture and large collection area, which possibly be achieved by using a large area photodetector and large filter. However, large area of photodetector produces high input capacitance that reduces the bandwidth. Hence, techniques to reduce the effective detector capacitance are required in order to achieve a low noise as well as wide bandwidth design.

1.5 Research Objectives

Based on the above mentioned research problem statement, the main objectives of this study are:

- To investigate the effect of photodetector input capacitance to the performance of the optical wireless front-end receiver by using mathematical analysis.
- To enhance optical front-end receiver bandwidth to perform high gain-bandwidth product by using integrated Micro-Electro-Mechanical Systems (MEMS) variable feedback capacitor with bootstrap transimpedance amplifier.

1.6 Scope of the Study

- Review, design and analyze the bootstrapping technique for bandwidth enhancement of an optical front-end receiver.
- Develop the optical-electrical conversion and operational amplifier (op-amp) model in Microwave Office (MWO) for optical front-end circuit simulation.
- Design and model the MEMS variable capacitor (varicap) to be implemented as variable feedback capacitor of the BTA by using CoventorWare simulator.
- Model and simulate the optical front-end receiver by using MWO and CoventorWare for performance characterization and validation purposes.
- Result analysis and comparison of simulation results for two different simulation environments.

1.7 Research Methodology

The study begins with the literature study and full understanding of the optical receiver design considerations where the review and analysis of the bandwidth enhancement technique especially the bootstrapping technique and the variable capacitor technology was done. Then, two optical front-end receivers; TIA and BTA were design followed by the three parallel plate MEMS variable capacitor. The system designs were then simulated in which the mathematical analysis was done based on the transfer function of the TIA and BTA to investigate the effects of the photodetetor capacitance to the bandwidth of the systems. The works then proceed for the system modeling and simulation in two different simulation environment; MWO and CoventorWare ARCHITECT. The modeling and simulation begin with the photodiode and op-amp modeling that will be implemented in the TIA and BTA systems, followed by the MEMS varicap and its integration with the BTA system. Finally, the results analysis was carried out. The methodology of this research study can be found in the flow chart below.

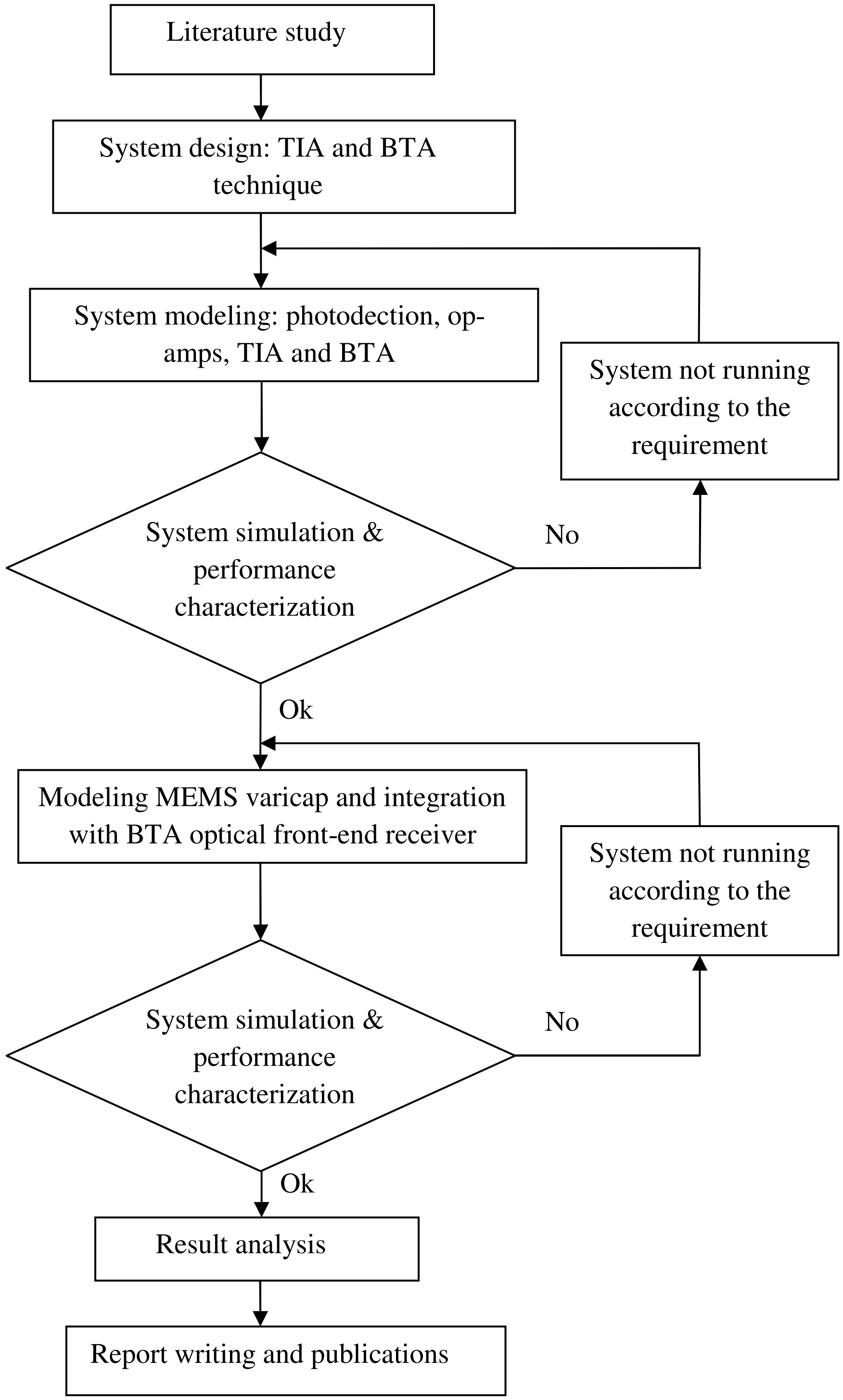

Figure 1.3 The flow chart of the research study

1.8 Thesis Outline

This thesis begins with Chapter 1 where a brief introduction of optical front-end receiver structure was described. The significance and goals for the research were presented.

Following the introductory chapter, the theory of optical wireless receiver design is presented in Chapter 2. Some considerations in the front-end design such as optical link design, factors that determine the effectiveness of the receiver and noise consideration were also described. This is followed by the discussions on two important elements in front-end receiver design; photodectetor and preamplifier structure for FSO application including the detection principle of pn junction, large window photodetector and preamplifier design's configuration. Several bootstrapping technique for front-end design from a numbers of researchers were reviewed. This chapter extends the discussion in the employment of MEMS varicap in the front-end design where several technologies and reviews from previous works were presented.

In Chapter 3, the theoretical analysis in optical front-end receiver design was realized. The main limitation in the performance of front-end receiver for FSO link was described where the effect of photodiode capacitance to the bandwidth of the system was analyzed.

The modeling and simulation of the front-end design was described in Chapter 4. The modeling includes the photodetection modeling, op-amp modeling, TIA and BTA modeling and the BTA employing MEMS varicap modeling. Two simulation environments involved were harmonic balance simulation by MWO and MEMS system-level simulation by CoventorWare. The simulations were done for validation and performance characterization.

Chapter 5 discussed the simulation results and analysis that was realized utilizing two simulation environments; harmonic balance simulation for nonlinear characteristics of the system and MEMS system-level simulation for MEMS varicap modeling and simulation. The results obtained from the TIA and BTA simulations and also the BTA employing MEMS varicap were presented.

Finally in Chapter 6, a concluding remarks, achievements and suggestion for future work are given. Modeling technique obtained through this research can be applied for future development of optical front-end receiver design.