DEVELOPMENT OF REMOTE OPTICAL LOCAL OSCILLATOR FOR RADIO OVER FIBER SYSTEM

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ABSTRACT

Radio over Fiber (RoF) is a promising technology capable of serving huge demands in the ever expanding wireless communication system. A number of studies have employed four RoF system architectures namely optical heterodyning, external modulation, optical transceiver, and up- and down-conversion for signal generation to solve the problem of system congestion. In this study, the millimeter-wave (mm-wave) frequency band has been identified in resolving the congestion problem. In particular an up-conversion RoF system architecture which uses a Remote Optical Local Oscillator (ROLO) is proposed. The optical signal, generated using a 10 GHz radio frequency (RF) signal utilises the Stimulated Brillouin Scattering (SBS) technique at the Central Station (CS). At the Base Station (BS), this signal is used to up-convert a modulated intermediate frequency (IF) signal by using a microwave mixer. The mixer is developed using a Heterojunction Bipolar Transistor (HBT) as its main active component due to its high internal gain. In addition, the mixer also functions as the frequency conversion stage. This study discovered that the proposed RoF-ROLO system is effective in reducing the dispersion effect which normally restricts the performance of mm-wave RoF system, in which the frequency conversion is done at the BS. The system was designed and simulated using the OptiSystem software for up to 40 GHz mm-wave carrier. Besides, the HBT mixer configuration has been successfully modelled and simulated using Microwave Office (MWO) software. Verification was carried through real-time measurement. The simulated conversion gain of the mixer achieved ranges between 2.11 dB to 7.97 dB for modulated IF input power ranging from -30 dBm to -10 dBm, respectively. These values were obtained by fixing the Local Oscillator (LO) power to 0 dBm. Moreover, the system has practically up-converted RF signal at 12.92 GHz. The new configuration between the SBS mm-wave signal generation with the up-conversion technique has been found to be practical by omitting the necessity of mm-wave LO at the BS; yet the frequency conversion still can be done at the BS.

ABSTRAK

Radio melalui gentian (RoF) merupakan satu teknologi utuh yang mampu memenuhi permintaan yang luas di dalam sistem komunikasi tanpa wayar yang semakin berkembang. Beberapa kajian telah menggunakan empat sistem seni bina RoF iaitu pengheterodinan optik, pemodulatan luar, penghantar-terima optik, dan penukaran-naik dan -turun untuk penjanaan isyarat bagi menyelesaikan masalah kesesakan sistem. Di dalam kajian ini, jalur frekuensi gelombang milimeter telah dikenal pasti dalam menyelesaikan masalah kesesakan frekuensi di dalam sistem tersebut. Khususnya satu penukaran-naik seni bina sistem RoF yang menggunakan pengayun optik tempatan jauh (ROLO) telah dicadangkan. Isyarat optik tersebut dijana menggunakan 10 GHz isyarat frekuensi radio (RF) menggunakan teknik serakan Brillouin terangsang (SBS) di stesen pusat (CS). Di stesen pangkalan (BS), isyarat ini digunakan untuk menaik-tukar isyarat frekuensi perantaraan (IF) termodulat dengan menggunakan pengadun gelombang mikro. Pengadun tersebut dibangunkan menggunakan transistor dwikutub heterosimpang (HBT) sebagai komponen aktif utama disebabkan oleh gandaan dalamannya yang tinggi. Di samping itu, pengadun tersebut juga berfungsi sebagai tahap penukaran frekuensi. Kajian ini mendapati bahawa sistem RoF-ROLO yang dicadangkan berkesan dalam mengurangkan kesan sebaran yang biasanya menghadkan prestasi gelombang milimeter sistem RoF, di mana penukaran frekuensi dilakukan di BS. Sistem ini telah direka dan disimulasi menggunakan perisian *OptiSystem* sehingga 40 GHz pembawa gelombang milimeter. Disamping itu, konfigurasi pengadun HBT telah berjaya dimodelkan dan disimulasi menggunakan perisian *Microwave Office* (MWO). Pengesahan telah dijalankan melalui pengukuran masa sebenar. Gandaan penukaran secara simulasi bagi pengadun tersebut dicapai antara julat 2.11 dB sehingga 7.97 dB bagi kuasa masukan IF termodulat masing-masing antara julat -30 dBm hingga -10 dBm. Nilai-nilai ini telah diperolehi dengan menetapkan kuasa pengayun tempatan (LO) kepada 0 dBm. Selain itu, sistem ini telah menukar-naik isyarat RF secara praktikal pada 12.92 GHz. Konfigurasi baru di antara penjanaan isyarat gelombang milimeter SBS dengan teknik penukaran-naik didapati sangat praktikal dengan mengabaikan keperluan LO di BS; namun penukaran frekuensi masih boleh dilakukan di BS.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2G	-	Second generation
3G	-	Third generation
4G	-	Fourth generation
AC	-	Alternating current
A/D	-	Analog to digital converter
AMP	-	Amplifier
APD	-	Avalanche photodiode
A/W	-	Ampere per watt
B-C	-	Base-Collector
B-E	-	Base-Emitter
BER	-	Bit error rate
BJT	-	Bipolar junction transistor
BS/BSs	-	Base station/s
CMOS	-	Complementary-symmetry metal oxide semiconductor
CO	-	Central office
CS	-	Central station
CW	-	Continuous wave
CNR	-	Carrier to noise ratio
dB	-	Decibel
dBm	-	Decibel-milliwatt
D/A	-	Digital to analog converter
DC	-	Direct current
DFB	-	Distributed feedback
DIPP	-	Dispersion induced power penalty
DPMZM	-	Dual parallel Mach-Zehnder modulator

DPSK	-	Double phase shift keying
DSB	-	Double sideband
DSB-SC	-	Double sideband suppressed carrier
DSF	-	Dispersion-shifted fiber
EAM/EAMs	-	Electro-absorption modulator/s
EAT	-	Electro-absorption transceiver
EDFA	-	Erbium doped fiber amplifier
EM	-	Electromagnetic
EOM	-	External optical modulator
E/O	-	Electro-optic
FET	-	Field effect transistor
GaAs	-	Gallium Arsenide
Gbps	-	Giga bit per second
GHz	-	Giga hertz
HBT	-	Heterojunction bipolar transistor
HEMT	-	High electron mobility transistor
HPT	-	Heterojunction phototransistor
IC	-	Integrated circuit
IEEE	-	Institute of electrical and electronics engineers
IF	-	Intermediate frequency
IM-DD	-	Intensity-modulation direct-detection
InGaAs	-	Indium gallium arsenide
InP	-	Indium phosphide
ISI	-	Inter symbol interference
I/V	-	Current-voltage
kHz	-	Kilo hertz
km	-	Kilometer
LD/LDs	-	Laser diode/s
LMDS	-	Local multipoint distribution service
LNA	-	Low noise amplifier
LO	-	Local oscillator
LSB/LSBs	-	Lower side band/s
Mbps	-	Mega bit per second

MHz	-	Mega hertz
mm-wave	-	Millimeter wave
MSC	-	Mobile switch center
MWO	-	Microwave office
MZM	-	Mach-Zehnder modulator
MSM-PD	-	Metal-semiconductor-metal photodiode
μm	-	Micrometer
NA	-	Not available
NBUTC-PD	-	Near-ballistic uni-travelling carrier photodiode
nH	-	Nano Henry
nm	-	Nanometer
OEM	-	Optoelectronic mixer
O/E	-	Opto-electronic
OIL-SOM	-	Optically injection-locked self-oscillating optoelectronic mixer
OM	-	Optical modulator
OSA	-	Optical spectrum analyzer
OSSB	-	Optical single sideband
PC	-	Polarization controller
PD/PDs	-	Photodiode/s
pF	-	Pico Farad
PL1/PL2	-	Pump laser 1 or 2
PPA	-	Photoparametric amplifier
PSTN	-	Public switching telephone network
RAU/RAUs	-	Remote antenna unit/s
RF	-	Radio frequency
RF_{USB}	-	Radio frequency at upper side band
RIN	-	Relative intensity noise
RN	-	Remote node
RoF	-	Radio over fiber
ROLO	-	Remote optical local oscillator
Rx	-	Receiver
SBS	-	Stimulated Brillouin scattering

SiGe	-	Silicon germanium
SMF/SMFs	-	Single mode fiber/s
SMM	-	Single-mode modulation
SNR	-	Signal to noise ratio
SOA	-	Semiconductor optical amplifier
SOA-EAM	-	Semiconductor optical amplifier-electro-absorption modulator
SOA-MZI	-	Semiconductor optical amplifier Mach-Zehnder interferometer
SSB	-	Single sideband
SSMF	-	Standard single mode fiber
Tx	-	Transmitter
UMTS	-	Universal mobile telecommunications system
USB/USBs	-	Upper side band/s
UTC-PDs	-	Uni-travelling carrier photodiodes
WDM	-	Wavelength division multiplexing
WLAN/ WLAN s	-	Wireless local area network/s
WPAN	-	Wireless personal area network
XGM	-	Cross-gain modulation

LIST OF SYMBOLS

P_{rf}	-	Detected RF power
I_{dc}	-	DC photocurrent
Z	-	MZM input impedance
V_{rf}	-	RF signal voltage
V_{π}	-	Peak voltage required to produce a peak phase shift of π radians
D	-	Chromatic dispersion of the fiber
λ	-	Wavelength
L	-	Propagation length
f	-	Propagation frequency
c	-	Speed of light
g_B	-	Brillouin gain
A_{eff}	-	Effective core area
$\Delta k_1/\Delta k_2$	-	Phase mismatch
ω_s	-	Signal frequency
ω_{smax}	-	Maximum signal frequency
E_p	-	Amplitude of pump wave
E_s	-	Amplitude of stokes wave
P_p	-	Power of the pump wave
P_s	-	Power of the scattered wave
α	-	Attenuation of the fiber
α_a	-	Attenuation of the fiber at the acoustic wave
v_a	-	Velocity of the acoustic wave
A_{RF}	-	Amplitude of RF signal
A_{LO}	-	Amplitude of LO signal

ω_{RF}	-	RF angular frequency
ω_{IF}	-	IF angular frequency
ω_{LO}	-	LO angular frequency
η	-	Quantum efficiency
R	-	Responsivity
h	-	Planck's constant
q	-	Electron charge
f_{IF}	-	Frequency of IF signal
f_{LO}	-	Frequency of LO signal
f_{RF}	-	Frequency of RF signal
α_o	-	Base transport factor
α_T	-	Common-base current gain
γ	-	Emitter efficiency
h_{fe}	-	Common-emitter current gain
i_{out}	-	Output current
i_{pd}	-	AC primary photocurrent
m	-	Light modulation index
I_{pd}	-	DC primary photocurrent
G_0/G_1	-	Fourier coefficients
v	-	Optical frequency
P_{mod}	-	Peak modulated component of the incident optical power
R_{Load}	-	Load resistor
G_{ext}	-	Extrinsic conversion gain
G_{int}	-	Intrinsic conversion gain

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION TO THE PROJECT

1.1 Research Background

Over the past decade, mobile radio infrastructures have been the principal form of communication system. Booming requirements on high channel capacity, larger service coverage, multimedia services and broadband applications entail a technology that can meet those demands in the upcoming future. The need for reliable and cost effective communications has consequently led to the use of fiber-based wireless system. Such system greatly provides superior possible bandwidths for both fiber and free-space applications. Therefore, radio over fiber (RoF) technology is the most capable solution to deal with the improved capacity and mobility. The RoF technology also able to lessen the costs of base stations (BSs) whereby most of the signals such as radio frequency (RF) generation, coding, multiplexing and modulation can be processed at the central station (CS).

RoF system is characterized by having both a fiber optic link and free-space radio path. The use of free-space radio path as the final drop to the end-users provides flexibility since the end-users do not have to be fixed in location. Such systems are important in a number of applications, including mobile communications, wireless local area networks (LANs), and wireless local loop, among others. Rapid developments in both lightwave and microwave enabling technologies have fuelled an intense effort into the research and development of these networks [1-3].

Another advantage of RoF is that it is very reliable and is a prominent key in increasing users' density and mobility in their daily life. In particular its application could be used in places such as airports, shopping malls, hotels, and office buildings. However, due to the limited availability of the RF bands, it has been expected that the millimeter wave (mm-wave) bands would be used to meet the demand for higher signal bandwidth and frequency congestion will not be a constraint in the future RoF-based optical-wireless access networks [1].

RoF technology permits a microcellular network system to be realized by using a fiber-fed distributed antenna network as shown in Fig. 1.1. The received RF signals at each base station (BS) are then being sent out over an analog optical fiber link to a CS where all the demultiplexing and signal processing are carried out. Each microcell simply consists of a linear analog optical transmitter, an amplifier as well as the smaller and low power transceiver of antenna. Therefore, the expenses on microcellular antenna site can be significantly reduced. In addition by having such a distributed antenna network, can give some advantages such as low RF power of BSs, high density allocations, frequency reuse, high quality signal, enhanced coverage plus low fiber attenuation. All the mentioned advantages make RoF an appealing technology for many dissimilar signal radio applications especially in mobile communication network.

RoF technology involves the use of optical components and techniques to allocate RF signals from the CS to the BSs. Thus, RoF makes it possible to centralize the RF signal processing function in one shared location (CS). It also offers the use of optical fiber that has a very low signal loss (about 0.22 dB/km for 1550nm and 0.4 dB/km for 1310nm wavelengths) to distribute the RF signals to the BSs [4]. As we are concern, the integration of wireless and optical networks is a potential solution for increasing capacity and mobility as well as decreasing costs in the access network.

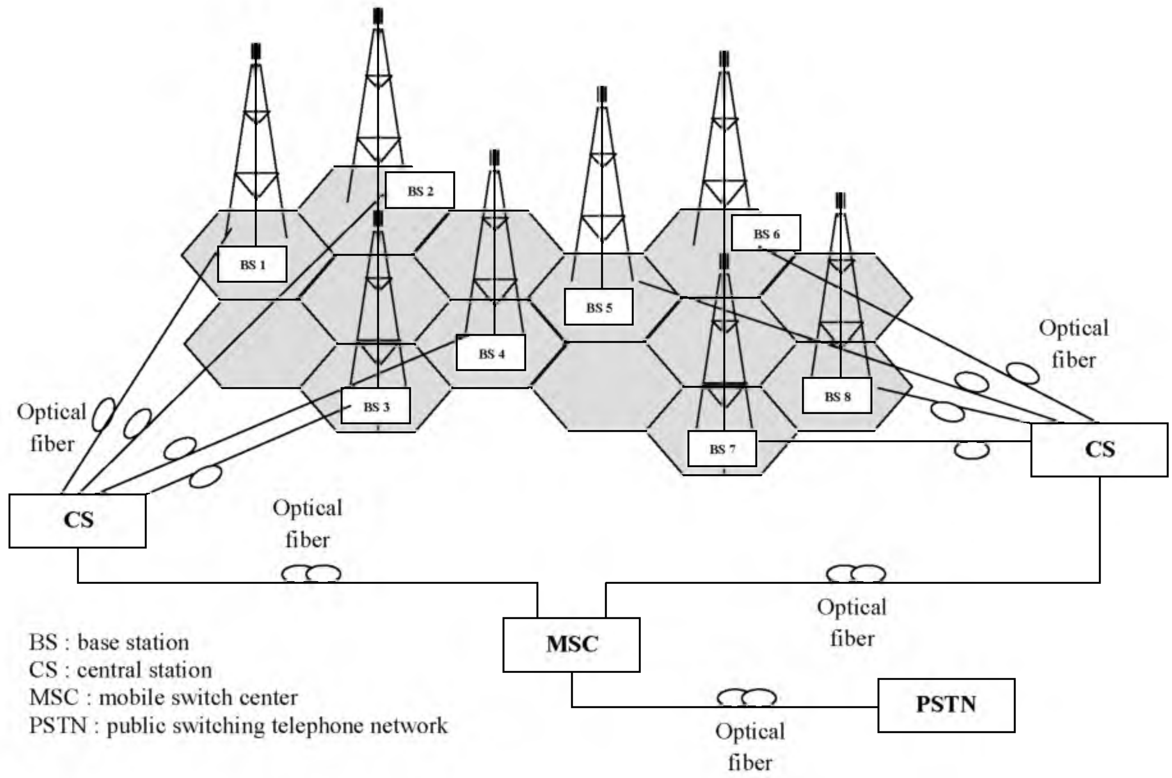

Figure 1.1 RoF technology for microcellular network system

1.2 Problem Statements

The immense growth of wireless communication system in the last decade has resulted in the significant increase in the demand for high user capacity and high data rate services. In particular a wider radio frequency spectrum is very much needed over a radio link. It is essential for radio link to employ higher frequency carriers because spectrum congestion occurs at low frequencies. Numerous research works have been conducted in mm-wave signal generation with optical mm-wave production being a vital technique in RoF system [5-6]. The use of optical fiber for signal distribution in mm-wave radio communication systems has also been widely investigated [7-9] since they provide high bandwidths and pico-cell sizes.

By using RoF, the capacity of optical networks can also be integrated with the flexibility and mobility of wireless access networks. Considering these conditions, the combination of wireless and optical networks could provide a solution for the increasing capacity and mobility as well as reducing the costs in the access network. In this study, the concept of RoF has been implemented since it is able to provide several advantages such as it can reduce the complexity at the antenna site and the radio carriers can be allocated dynamically to the different antenna sites (frequency reuse).

On the other hand, RoF link might suffer from the dispersion effect when transmission of higher frequency like mm-wave signal is involved. Even though the dispersion effect can be compensated with the use of dispersion-shifted fiber (DSF) where zero dispersion wavelengths occur, such fiber is quite expensive and could increase the cost of creating a new fiber link or replacing the existing link. In addition, due to the zero dispersion wavelength, the attenuation coefficient of the fiber is slightly increased which, might degrade the performance of the signal. Considering these issues, several techniques were proposed by number of works in avoiding or minimizing the dispersion effects.

1.3 Motivation

Motivated by the mm-wave implementation in RoF system, this study presents the development of a new configuration of RoF system architecture known as remote optical local oscillator (ROLO) system which RF signal is optically generated by using the stimulated Brillouin scattering (SBS) technique at the CS. This optical frequency carrier is transmitted through the fiber and photo-detected by *p-i-n* photodiode (PD) at the BS. While, at the BS, the RF generated signal is used to up-convert the modulated intermediate frequency (IF) signal by a microwave mixer. The new configuration of RoF-ROLO system is capable of reducing the dispersion effect that limits RoF system performance at higher frequency, in which the frequency up-conversion is done at the BS. The new integration between the all optical signal generation based on SBS technique and the frequency up-conversion seemed to be more practical by omitting the necessity of local oscillator (LO) at the BS. This study also gives detail description of the work involved in realizing the proposed system in terms of modeling, designing, fabricating and demonstrating of the system. The performance and achievement of the work are presented and explained in detail in the assigned chapters.

1.4 Research Objectives

The main objectives of this research are as follow:

- To model an optical RF signal generator utilizing SBS technique up to mm-wave frequency band at low optical carrier input power through simulation.
- To design a microwave mixer based on heterojunction bipolar transistor (HBT) as the main active component to achieve high conversion gain at up-converted frequency of 12.4 GHz.
- To develop a heterodyne RoF system architecture by integrating the optical RF generated signal model with the HBT RF mixer with optimum dispersion effect.
- To demonstrate experimentally the proposed RoF-ROLO system architecture at microwave frequency.

1.5 Scopes of Works

This research intends to concentrate on the following scopes:

1. Investigate and study the current research and technology in RoF for mm-wave band.
2. Investigate the mm-wave signal generation techniques including the optically RF signal generation utilizing SBS technique.
3. Study and understand the concept and fundamental of optical signal generation based on SBS technique, RF mixing, HBT as a mixer, and RoF-ROLO as a system.

4. Model and simulate an optical signal generation based on SBS up to mm-wave region by using OptiSystem version 10.0 as a simulation tool.
5. Study the performance of the SBS model by the changing effects of the SBS fiber loop length, optical carrier power of the continuous wave (CW) laser and different responsivity values of the *p-i-n* PD.
6. Model and develop a microwave mixer based on available HBT in Microwave Office (MWO) version 7.03 simulator.
7. Realize the RF mixer through fabrication for up-conversion frequency of 12.4 GHz with high conversion gain.
8. Model and develop a RoF-ROLO system by integrating the model of all optical signal generation based on SBS technique and the model of RF mixer in the OptiSystem environment.
9. Obtain and evaluate the performance parameters of the system by mainly studying the dispersion effect in RoF link.
10. Demonstrate the system through experimental arrangement and investigate the performance between the simulation and measurement.

1.6 Research Methodology

In order to address the research objectives, a work flow of the research is constructed and presented in Fig. 1.2. This work flow shows the development of the system and covers all the issues that have to be considered throughout this project. At the initial stage, investigation on the current research in RoF is conducted. This involves focusing on the literature on RoF system as well as all the related research works. It is important to study and comprehend the concept of generation signal based on SBS technique, the RF mixing concept, RF mixer design and specification and RoF-ROLO as a system.

This stage also covers the investigation on the architecture of RoF optical receiver and any other signal generation technique. It is necessary to differentiate the system architecture and the subsystem characteristics from the previous works. In this work, the RoF-ROLO system has been designed to meet the important characteristics which are lower input power level, high system conversion gain as well as minimizing the dispersion effect. In addition, understanding on the software to be used, which are the MWO and OptiSystem is also required. Detailed information about the software is available in Appendix A. All suitable circuit designs and architectures are clarified appropriately. Other research activities under this module are carried out at the second stage progress.

In the second stage, the modeling and designing of the main components of the system which are the optical signal generation model based on SBS technique by using OptiSystem and the HBT RF mixer model by using the MWO simulator are developed. The simulation of SBS model development is within the parameters of setting up of the performance analysis. As for the HBT mixer model development, it is significant to consider the main design characteristics such as the S-parameter and matching circuit during the simulation. The performance of the HBT mixer model is also determined. It is important that the results obtained from the simulation have to be analyzed and verified. An optimum design and operating conditions of the mixer are determined before it is fabricated. The fabricated mixer is then being tested and analyzed and integrated with the SBS model of the optical signal generation. Both subsystems development will be explained in detail in chapter 3 and 4 respectively.

Consequently, the best configuration from the simulation of both models is then integrated to become a one full system known as a RoF-ROLO system are continued in stage 3. This system is developed and simulated in OptiSystem environment. The performance of the system is investigated before it is realized through hardware implementation and demonstration. It is expected that the design is tested successfully on the system; hence the measurement results are in line with the simulation analysis. The description and specification of the equipments used for the experiment are available in Appendix B.

This stage is the most crucial because it is where all the results from both simulation and hardware implementation are analyzed thoroughly. It is important to compare both results so that an optimum design can be determined. In addition, should there be any problems or limitations on the design, it will then be rectified and further implications, suggestions and possible recommendations will be given.

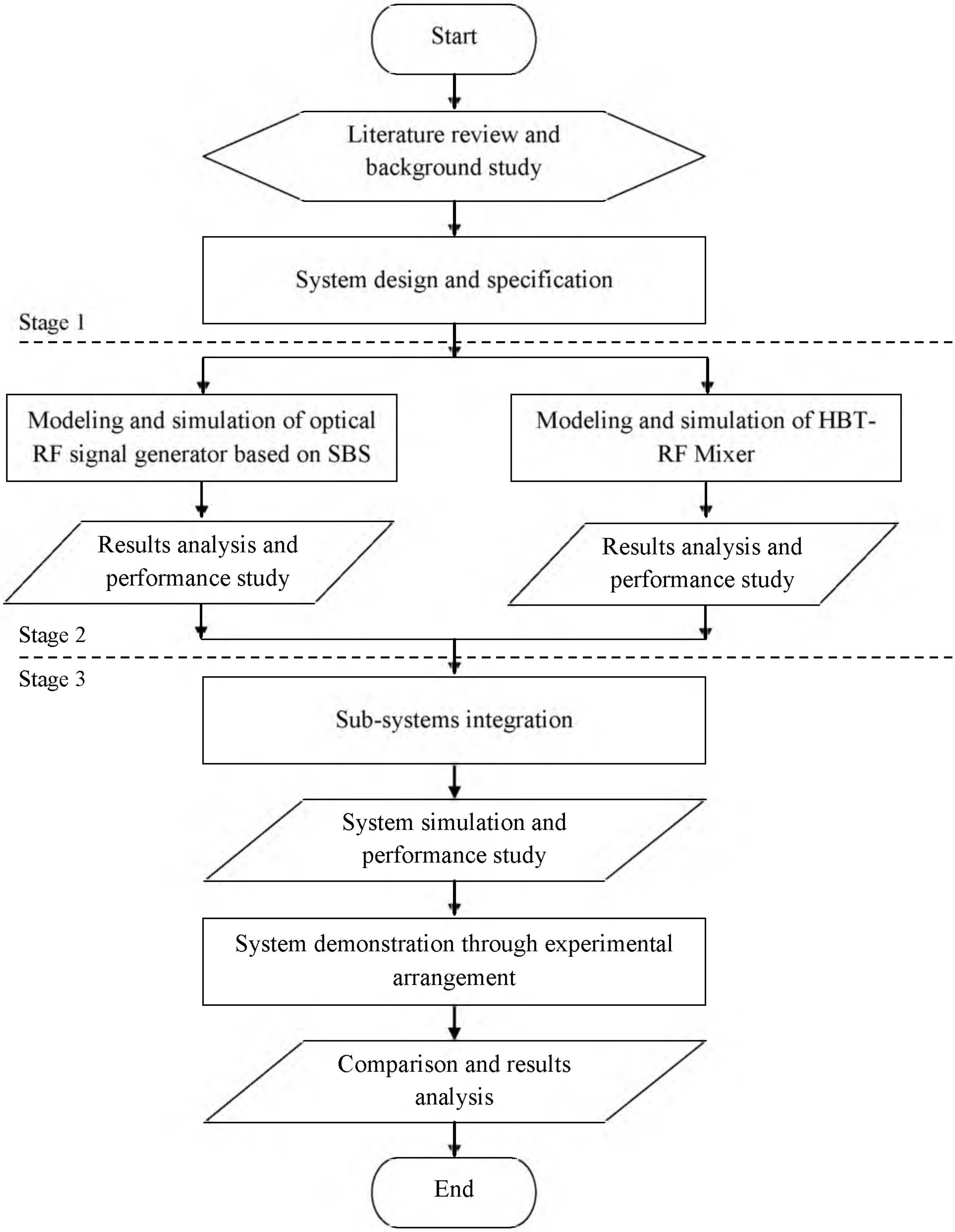

Figure 1.2 Flow chart of the research methodology

1.7 Thesis Outline

Much of this work is devoted to the study of RoF-ROLO system for radio over fiber. In Chapter 1, an overview of the research, aims, motivation, problems and reasoning of the study are discussed. The scopes of research work are also presented accordingly. Methodology of the research work that covers the matters in completing the work is thoroughly given.

Chapter 2 broadens the discussion and provides more detail background and reviews of the RoF system and technology, mm-wave signal generation techniques, carrier signal generation utilizing SBS technique, frequency conversion based on mixing technique, as well as the general idea of the proposed RoF-ROLO system is introduced.

In Chapter 3, the development of the all-optical signal generation utilizing SBS technique is discussed. This chapter begins with the presentation of the block diagram of proposed system with explanation of each sub-block followed by the flowchart of the optical signal generation based on SBS technique. Next, the SBS simulation model development in OptiSystem environment is given. The performance of the model through the changing effect of different optical fiber loop, different optical carrier power and different responsivity of *p-i-n* PD are discussed. Finally this chapter presents the experimental demonstration of the SBS configuration.

Chapter 4 firstly presents the flowchart of the RF mixer designs. The explanation covers the fundamental of RF mixing and its characteristics followed by the modeling and simulation of the mixer by using MWO as the simulation tool. The development of HBT mixer, design consideration and the simulation results are presented. The performance of the model with the effect of different input power and conversion gain study are also highlighted. The fabrication process of the mixer is explained before the experimental arrangement of the mixer is demonstrated. Later, the performance of the mixer is discussed based on the comparison between the simulation and experimentation.

In Chapter 5, the development of RoF-ROLO system is presented by integrating both SBS signal generation model and RF mixer model covered from previous chapters. This model is acting as a whole proposed system that simulated in OptiSystem environment. Results analysis based on the simulation and measurement are compared, discussed and concluded.

Finally in Chapter 6, a concluding remarks and recommendations for future prospects for this work are given. The original contributions are highlighted, and all the publications and awards related to this work are also presented.

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