DEVELOPMENT OF PLANAR MONOPOLE ANTENNA FOR UWB TECHNOLOGY: DESIGN, PERFORMANCE EVALUATION, AND CIRCUIT MODELING

ADI MAHMUD JAYA MARINDRA

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF
MASTER OF ENGINEERING IN COMPUTER ENGINEERING
INTERNATIONAL COLLEGE
KING MONGKUT'S INSTITUTE OF TECHNOLOGY LADKRABANG
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Thesis Title	Development of Planar Monopole Antenna for UWB Technology: Design, Performance Evaluation, and Circuit Modeling
Student's Name	Adi Mahmud Jaya Marindra
Student's ID	54601102
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Thesis Advisor	Dr. Sathaporn Promwong
Thesis Co-advisor	Prof. Dr. Junichi Takada

ABSTRACT

This thesis discusses three aspects on the development of planar monopole antenna for UWB technology which includes antenna design, performance evaluation, and circuit modeling. In the aspect of design, we propose an extended design procedure where the importance of radiation stability over the entire UWB bandwidth is also involved. The extended design procedure can solve the problem of radiation drops occurred on the UWB planar monopole antenna which is designed by the common procedure. In the common procedure, only return loss and radiation pattern at some frequency points are usually considered so the radiation over the entire band is unwittingly neglected. As the final design result, a novel UWB elliptical planar monopole antenna with very small size and stable radiation is presented. Since the quality of UWB antenna is very important after fabrication process, a comprehensive performance evaluation scheme for UWB planar monopole antenna is introduced. The evaluation scheme begins by doing measurement of two antennas with the same design, which is known as two-identical-antenna method. Based on the extension of Friis' transmission formula and UWB waveform transmission relative to isotropic antenna, performance parameters in frequency domain and time domain are derived. Then, the presented scheme is used to evaluate and to compare the developed UWB planar monopole antennas. As the third aspect, this thesis also presents a method for synthesizing UWB planar monopole antenna into equivalent circuit by impedance or admittance approximation. Circuit modeling is necessary to predict the overall system performance in system co-design. Since the antenna characteristic such as impedance or admittance is directly approximated to get the value of circuit components, the equivalent circuit is not only simple but also has very similar characteristic compared to the modeled UWB antenna.

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Bangkok, 25 February 2013

Adi Mahmud Jaya Marindra

TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

LIST OF TABLES

LIST OF ABBREVIATIONS

3D	Three Dimensional
ADC	Analog-to-Digital Converter
AWGN	Additive White Gaussian noise
BPSK	Binary Phase Shift Keying
BW	Bandwidth
CAD	Computer Aided Design
CEPT	Conference of European Posts and Telecommunications
CRL	Communications Research Laboratory
CST	Computer Simulation Technology
DSC	Digital Still Camera
DVC	Digital Video Camcorder
ECC	Electronic Communications Committee
EIRP	Effective Isotropic Radiated Power
EMC	Electromagnetic Compatibility
FCC	Federal Communications Commission
FDTD	Finite Difference Time Domain
FIT	Finite Integration Technique
FR4	Fibreglass-resin laminate
HDTV	High-Definition Television
HF	high frequency
Hz	Hertz
IDA	Infocom Development Authority
IEEE	Electrical and Electronics Engineers
IR	Impulse Radio
ITU	International Telecommunication Union
LCD	Liquid Crystal Display
LDC	Low Duty Cycle
LNA	Low Noise Amplifier
LOS	line-of-sight

LPDA	Log-Periodic Dipole Array
MAC	Medium Access Control
MB-OFDM	Multiband OFDM
MWS	Microwave Studio
PAM	Pulse Amplitude Modulation
PCB	Printed Circuit Board
PC	Personal Computer
PHY	Physical layer
PLL	phase locked loop
PMA	Planar Monopole Antenna
PPM	Pulse Position Modulation
PR	pseudo-random
PSD	Power Spectral Density
PVP	Personal Video Player
RF	Radio Frequency
RMS	Root Mean Square
Rx	Receiver
SMA	SubMiniature version A
SNR	Signal-to-Noise Ratio
SR	Stretch Ratio
SPICE	Simulation Program with Integrated Circuit Emphasis
Tx	Transmitter
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
UWB	Ultra Wideband
UWB-IR	UWB Impulse Radio
VCO	Voltage Control Oscillator
VSWR	Voltage Standing Wave Ratio
W	Watt
WBAN	Wireless Body Area Network

WiBro	Wireless Broadband
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network

CHAPTER I

INTRODUCTION

1.1 Background and Motivation

During the last decades, wireless communication technologies have greatly changed our life. In past years, wireless communication technologies only could be enjoyed for broadcasting services such as public radio and television. The past communication technologies were still dominated by communication over cable. As every technology is created to simplify the human lives, wireless communication technologies emerge a lot of benefits and flexibilities which are not offered by wired communication technologies. Cellular phones give us even more freedom such that we can communicate with other people at any time and in any place. Wireless Local Area Network (WLAN) technology connects computers to the internet without suffering from managing yards of unsightly and expensive cable. Billions of wireless devices are used by people in the world for various services and applications. The wireless communication technologies make our lives easier and make everything more connected.

Nowadays, the technical improvements of wireless communication technologies are still being done to increase the performance and enable a large number of new services. More interests have been put into short-range wireless communications where wireless connections and data transfers between devices in short distance are very potential to develop. The short-range wireless communication can be used for some applications such as in Wireless Personal Area Network (WPAN) and Wireless Body Area Network (WBAN) technologies. The future WPAN aims to provide reliable wireless connections between computers, portable devices, and consumer electronics within 10 meters which are usually for indoor uses. The WBAN technology aims to provide connections between wireless nodes or sensors on human body or inside human body which also usually less than 3 meters. Such indoor networks in home and on human body are unique, in that they simultaneously require high data rates (for big data transfer), very low cost (for broad consumer adoption), and very low power consumption (for embedding into battery-powered devices). They require high data rate and very low power consumption which are hardly solved by the currently existing wireless technologies.

Claude Shannons paper 1948, "A Mathematical Theory of Communication", gave us the mathematical framework by which we go about answering the question of how to build radios that can transmit digital signals at higher bit rates. Theoretically, the maximum achievable data rate or capacity for an ideal band-limited additive white Gaussian noise (AWGN) channel is related to the bandwidth and the signal-to-noise ratio (SNR) by Shannon's capacity equation [1, 2] as

$$C = B\log_2\left(1 + \frac{S}{N}\right) \tag{1.1}$$

where C denotes capacity or the maximum transmit data rate, B stands for the channel bandwidth, S is the signal power, and N is the noise power. Equation 1.1 indicates that the transmit data rate can be increased by increasing the bandwidth occupation or the transmission power. However, the transmission power cannot be readily increased because many portable devices are battery powered and the potential interference should also be avoided. Shannons law tells us that useful radios can be built which exploit large amounts of bandwidth while expending very little power. Thus, a large frequency bandwidth will be the solution to achieve high data rate.

On February 14, 2002, the Federal Communications Commission (FCC) of the United States adopted the First Report and Order that permitted the commercial operation of ultra wide-band (UWB) technology [3]. The FCC did not define a technology. They did allocate spectrum 3.1 GHz to 10.6 GHz and set rules by which the spectrum could be exploited. With its enormous bandwidth, UWB provides a promising solution to satisfy these requirements and becomes an attractive candidate for future short-range wireless communications. Since then, UWB technology has been regarded as one of the most promising wireless technologies that promises to revolutionize high data rate transmission and enables the WPAN and WBAN industries leading to new innovations and greater quality of services to the end users.

Now, the achievement of high data rate in UWB is not mainly considered anymore because other technologies, such as the new standard of Wi-Fi, can provide very high data rate competeing UWB. Furthermore, there was also a standardization problem in releasing the high-data rate UWB to the market. But still, UWB has other advantages which are potential for numerous applications. UWB impulse radio particularly offers low complexity system which also leads the UWB system to be low cost and low power consumption. High resolution time-ranging is also one of special advantages of UWB which is used for development of UWB radar and UWB equipment tracking system.

The UWB technology has experienced many significant developments. However, there are still challenges in implementing this technology live up to its full potential. One particular challenge is the UWB antenna. Among the classical broadband antenna configurations that are under consideration for use in UWB systems, a straight wire monopole features a simple structure, but its bandwidth is usually only around 10%. A vivaldi antenna is a high gain directional antenna [4, 5] and therefore it is unsuitable for indoor systems and portable devices. A biconical antenna has a big size which limits its application [6, 7]. Log periodic and spiral antennas tend to be dispersive and suffering severe ringing effect, apart from big size [8]. Despite of challenges in size, impedance bandwidth, and radiation characteristic, the performance of UWB antenna also should be assessed in special treatment due to its wideband operation and time domain transmission for UWB impulse radio. There is a growing demand for small-size and low cost UWB antennas that can satisfy the UWB requirements and provide satisfactory performance in frequency domain and time domain.

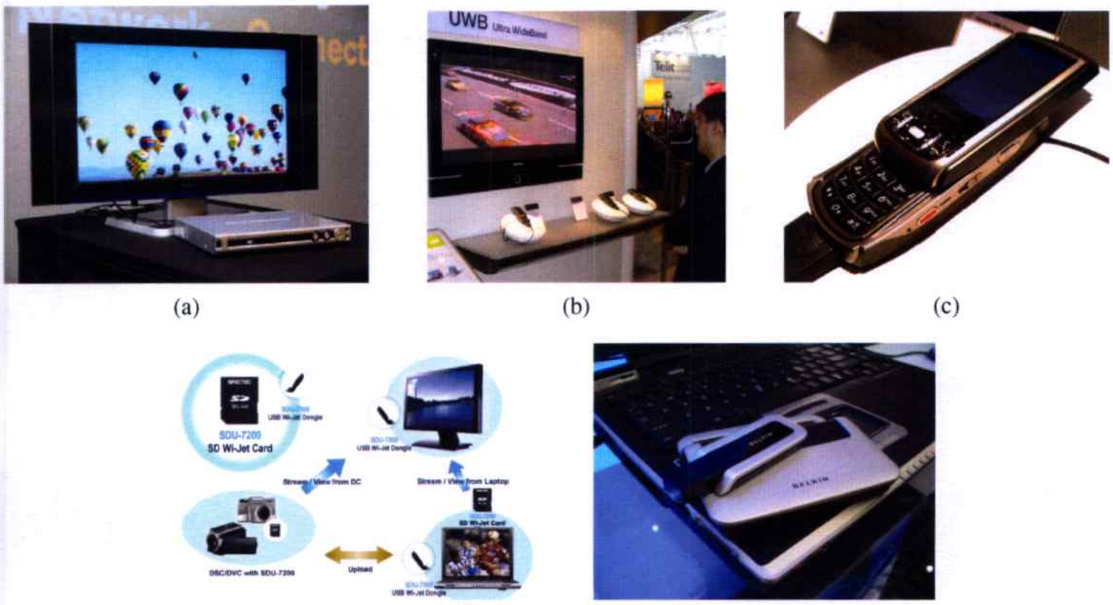
The planar monopole antenna has attracted considerable research interests due to its simple structure and UWB characteristics with omnidirectional radiation patterns [9]. However, it still needs more investigation of why this type of antenna can achieve ultra wide bandwidth and operates over the entire UWB bandwidth. Most of studies on UWB planar monopole antenna are still limited on the efforts of enhancing the impedance bandwidth by structure modifications. In reality, design of an antenna does not only influence the antenna impedance, but also the transmission performance of the antenna. Due to the unique features of UWB technology, there should be more comprehensive study and consideration in the making of planar monopole antenna until it is integrated into UWB system with achievable performance.

1.2 Review of State of The Art

UWB is one of the most exciting technologies in the wireless world today, but it has been fraught with controversy since its inception. Although the development efforts from academic and industry grow significantly, the global standardization has posed some complicated issues. This section will explain through the recent report of commercialization and standardization processes of UWB technology.

Since the approval of unlicensed UWB bandwidth in 2002, researches for UWB technology have been increasing rapidly. In the academic point of view, the continuous studies and researches in UWB technology may born numerous theories and technical innovations which will be beneficial for the future of wireless technologies. In industrial view, developing UWB technology is the way to prepare the readiness of companies in UWB marketing and commercialization. Freescale Semiconductor, WiMedia, and Samsung are several leading companies which have participated in the development of UWB technology by producing and demonstrating their UWB products under the specified standards. Their demonstrated products make us believe that UWB technology is actually just almost in our hands.

Freescale Semiconductor was the first company to produce UWB chips in the world and its XS110 solution is the only commercially available UWB chipset to date [10]. The chipset delivers more than 110 Mbps data transfer rate supporting applications such as streaming video, streaming audio, and high-rate data transfer at very low levels of power consumption. Some electronic



(a) (b) (c) (d) (e)

Figure 1.1: Some demonstrated prototype UWB products for WPAN applications: (a) Haier HDTV and media server, (b) Samsung HDTV, (c) Samsung cellphone, (d) Spectec CameraJet system, (e) Belkin's cable free USB hub

industries have demonstrated UWB products especially for WPAN applications as shown in Fig. 1.1.

At 2005 3GSM World Congress, Samsung and Freescale demonstrated the world's first UWB-enabled cellphone featuring its UWB wireless chipset [11]. Pictures, MP3 audio files or data from the phone's address book can be selected and transferred directly to the laptop at very high data rate owing to the UWB technology exploited. In June, 2005, Haier Corporation and Freescale Semiconductor announced the first commercial UWB product, i.e. a UWB-enabled liquid crystal display (LCD) digital television and digital media server [12]. The Haier television is a 37-inch, LCD High-Definition TV (HDTV). The Freescale UWB antenna, a flat planar design etched on a single metal layer of common FR4 circuit board material, is embedded inside the television and is not visible to the user. The digital media server is the size of a standard DVD player but includes personal video player (PVP) functionality, a DVD playback capability and a tuner, as well as the Freescale UWB solution to wirelessly stream media to the HDTV. The digital media server can be placed as far away as 20 meters from the actual HDTV, providing considerable freedom in home theatre configuration. The rated throughput between these two devices is up to 110 Mbps at this distance, which will allow several MPEG-2 video streams to be piped over the UWB link.

At 2006 CeBIT Expo, Samsung and Freescale also demonstrated HDTV running a video which is fed from a cellphone at 13 Mbps using UWB technology [13]. These functions underscore the changing role of the cellular phone for new applications which provide the ability for consumers to wirelessly connect their cell phone to other devices and transfer their data and files very fast. The news from Spectec CameraJet system in 2011 also support this technology. Alereon, Inc. and Spectec Computer, Inc. bring new levels of speed and connectivity to the transfer of media from mobile devices. The Spectec solution consists of the SDU-7200 Wi-Jet SD card and the SDU-7500 Wi-Jet USB dongle. Both are powered by the Alereon ECMA and ISO standard AL6000 Ultra Wideband chipset. The Spectec Wireless Camera-Jet solution is designed to allow digital still camera (DSC) and digital video camcorder (DVC) to quickly and easily connect to HDTVs, PCs, digital media adapters and mass storage devices to transfer and view pictures or stream videos without removing the media.

In CeBIT Expo, Belkin also announces its new CableFree USB (Universal Serial Bus) Hub, the first UWB-enabled product to be introduced in the U.S. market [14]. The Belkin's four-port hub enables immediate high-speed wireless connectivity for any USB device without requiring software. USB devices plug into the hub with cords, but the hub does not require a cable to connect to the computer. So it gives desktop computer users the freedom to place their USB devices where it is most convenient for the users. Laptop users also gain the freedom to roam with their laptop around the room while still maintaining access to their stationary USB devices, such as printers, scanners, hard drives, and MP3 players through wireless connections.

The efforts from industries to implement UWB technology seem going smoothly by seeing the demonstrated products for WPAN applications. However, it should be realized that frequency is a very valuable resource and should be ruled for the operation. Although in 2002 FCC has permitted UWB for commercial use, the UWB standard could not be finished easily. First, there were issues over its possible interference with other key technologies such as GPS. The FCC rule-making was a long and torturous process which finally ended in March 2003, and potential changes to these rules are still under discussion.

There was a major controversy over standardization in 2006, with proponents lining up behind two different proposals between UWB multiband-OFDM (MB-OFDM) scheme and UWB impulse radio (UWB-IR) scheme. A committee within the IEEE was formed to define UWB radio. This committee was called IEEE 802.15.3a. More than 20 proposals were submitted to the committee, and after a year these proposals were combined to the point that there were only two proposals surviving. One proposal, called MB-OFDM proposal, represented a combination of many proposals. The other proposal, Impulse Radio Direct Spread UWB, was from Freescale Semiconductor. After several years of negotiation, it became obvious to both sides that a consensus could not be reached, and both sides decided to abandon the IEEE process as a means to building an internationally recognized standard. Without meeting any agreement between two proposals, the IEEE standardization process was ended by eventually agreeing to reject both proposals.

As it goes in 2007, ECMA International, which controls the ISO formats, has accepted WiMedia as an ISO standard. Officially, the WiMedia protocol will be known as the ISO/IEC 26907, governing a distributed medium access control (MAC) sublayer and a physical layer (PHY) for wireless networks. The ECMA-369 standard was also approved as ISO/IEC 26908 and specified the MAC-PHY interface for a high rate, ultra-wideband wireless transceiver, the agency said. Specifically, the standard covers transceivers communicating data at 480 Mbps that operate in the UWB spectrum of 3.1 to 10.6 GHz. The competitor, Freescale, formed the UWB Forum and then later split off to develop its own Cable Free standard [15].

Some important standardization activities did not disband and produced their final output and the following were published: IEEE 802.15.4a UWB Low-Rate Wireless Personal Area Networks (WPANs), Standard ECMA-368 High Rate Ultra wideband PHY and MAC Standard, Standard ECMA-369 MAC-PHY Interface for ECMA-368, Standard ISO/IEC 26907:2007, Standard ISO/IEC 26908:2007.

The regulatory bodies around the world still currently continue working on the UWB regulations. Definitely, it is a big benefit if the Institute of Electrical and Electronics Engineers (IEEE) could make the global UWB standards for UWB High-Rate WPAN since the industries have been ready to produce the devices. But it was failed in reality. Nevertheless, it should be noted that the number of research on UWB antenna is not affected too much by those controversies. Due to the problems in standardization, there are some limitations of research on UWB antenna for commercialization, but not for academic and development purposes. The researches on UWB antenna aim to study the techniques to make good antenna with characteristics fit to the requirement of technology and applications. Since 1993 to 2007, research and patent on UWB antenna in the United States are greatly increasing [16]. State of the art in UWB antennas is presented in [17]. The planar monopole antenna (PMA) is on high demand to be a part of wireless devices for potential applications such as in above examples.

1.3 Objectives and Scope of Research

The objective of this thesis is to study the development of planar monopole antenna for UWB technology by using both simulation and experimental approaches. The study includes three aspects: design, performance evaluation, and circuit modeling. The analysis is based on UWB impulse radio (UWB-IR) where the antennas are developed for a UWB system which transmits and receives impulse or non-sinusoidal waveform.

The objective in the aspect of design is to implement planar monopole antennas for UWB technology with detail reports through the design guidelines or procedures from simulations to the results after fabrication. Real implementations are useful in the improvement of procedure or technique to design UWB planar monopole antenna.

In the aspect of performance evaluation, the objective is to understand the quality of the developed antennas by taking into the account of UWB waveform transmission when the antennas are considered as transmitter or receiver. This aspect is very important to verify the design of planar monopole antenna by seeing its performance as front-end device in UWB radio.

In the aspect of circuit modeling, the objective is to synthesize the equivalent circuit from a UWB antenna which would be useful for UWB system co-design. A UWB antenna must be synthesized into a circuit form before integrated in simulation with other RF circuits.

1.4 Thesis Outline

This thesis is organized in seven chapters as follows:

Chapter 2: A brief introduction to UWB technology is presented in this chapter. The history, definition, application and regulation of UWB technology are described. The fundamental of UWB radio transmission is also discussed to support the relation with the antenna operation. The unique features of UWB impulse radio scheme, Friis' transmission formula, and waveform for UWB operation are also addressed.

Chapter 3: This chapter covers the fundamental of electromagnetics, antenna theory, to the basics of UWB planar monopole antenna. Some important parameters of antenna are described. The primary requirements for a suitable UWB antenna and the challenges are discussed. Some general approaches of UWB planar monopole antenna and electromagnetic simulation tool are also introduced.

Chapter 4: In this chapter, design of planar monopole antenna for UWB technology is studied. The design procedures, design techniques and operation principle with some design examples are addressed based on the investigation from the antenna simulation to the measurement after fabrication.

Chapter 5: The performance evaluation of planar monopole antennas is studied in this chapter. The method of performance evaluation is detailed by showing several cases in evaluating and comparing UWB antennas. From simulation and measurement, antenna transmission characteristics are investigated in frequency domain. Some quantitative parameters in time domain are derived based on measurement data and UWB waveform processing to quantify the performance of UWB antennas.

Chapter 6: In this chapter, a simple circuit modeling method for UWB antenna is applied to synthesize the equivalent circuit. The methodology and the way to obtain the circuit parameters are described. As an example, the already simulated UWB antenna is used to confirm the accuracy of the circuit modeling method.

Chapter 7: This chapter summarizes the researches that have been discussed in this thesis. Contributions and suggestions for future work are also given in this chapter.

CHAPTER II

THEORY OF UWB TECHNOLOGY

2.1 Overview of UWB

2.1.1 History

UWB is not a new technology. When Hertz proved Maxwell equation in 1886, he did experiment with spark gap transmission. It was also carried by Guglielmo Marconi in 1896 for one-mile rooftop link and in 1901 for transmitting the Morse code sequences across the Atlantic ocean using spark gap radio transmitters [18–20]. The spark gap was resulting very large bandwidth radio-frequency signals. However, the benefit of a large bandwidth and the capability of implementing multi-user systems provided by electromagnetic pulses were never considered at that time. Other references declare that the physical cornerstone for understanding UWB pulse propagation was established by Sommerfeld in 1901 when he attacked the diffraction of a time-domain pulse by a perfectly conducting wedge [21]. In other words, the first wireless communication system was actually based on UWB. Owing to the technical limitations, narrowband communication was preferred to UWB.

UWB has experienced well over 40 years of technological developments. The origin of the development of UWB technology stems from work in time-domain electromagnetic begun in 1960's to fully describe the transient behavior of a certain class of microwave networks through their characteristic impulse response. Then in the past 20 years, UWB was used for radar, sensing, military communications and niche applications. A substantial change occurred in February 2002, when the FCC (2002a,b) issued a ruling that UWB could be used for data communications as well as for radar and safety applications [3].

For more comprehensive history of UWB technology, Table 2.1 shows its chronological order based on 3 eras started from 1886. There are "pioneering era" when wireless world was about to start, "subnanosecond impulses era" when new interest in UWB technology started again with more research contributions, and "standardization and commercialization era" after the great technical developments related to subnanosecond pulses [22]. Nowadays, further research developments are still carried out towards the advancement of UWB technology. For UWB physical layer, research on UWB antenna, channel propagation, efficient transceiver, circuit implementation, and other application-based researches are still considerable. Nowadays, high data rate applications of UWB seem ignored because Wi-Fi technology is continuously developed as a competitor. UWB radar and tracking applications are more considered by researchers.

Table 2.1: History of UWB technology in timeline view [22]

Pioneering Era	
1886	Hertz proves Maxwell equations, first spark gap transmission
1894	Guglielmo Marconi starts his first laboratory in Italy
1893 -1896	Righi develops spark oscillators later used by Marconi
1896	Marconi meets Sir William Preece, first UWB one-mile rooftop link in London
1898	Sir Oliver Lodge, biconical antenna
1901	12th December, Guglielmo Marconi reports first Transatlantic wireless transmission
1902	Valdemar Poulsen invented the Poulsen Arc Transmitter
1906	Lee De Forest invents the Audion, the first vacuum tube. Spark gap transmissions will be quickly replaced by continuos wave radios
Subnanosecond Impulses Era	
1939	Philip Carter, conical monopole antenna
1941	Nils E. Lindeblad, Coaxial Horn Element antenna
Late 1950's	Impulse response analysis of microwave N-ports (Lincoln Lab, Sperry, others)
1960	Henning F. Harmuth, Gerald F. Ross, Kenneth W. Robbins, Paul Van Etten started experimentation with Impulse UWB
1962	Hewlett-Packard, sampling oscilloscope commercialized; Georges Robert Pierre Marie , wideband slot antenna
1963	G. Ross - Ph.D. thesis in time-domain electromagnetics
1965	G. Ross - Sperry Research development of UWB technology (1965-1980)
1972	Kenneth W. Robbins, short pulse Coherent processing tunnel diode ultra wideband receiver replaces sampling oscilloscope, Fundamental patent for UWB single-pulse detector U.S. Patent No. 3,662,316
1973	Gerald F. Ross, US Patent 3,728,632: Transmission and reception system for generating and receiving base-band pulse duration pulse signals without distortion for short base-band communication system
1974	Morey - Fundamental patent on UWB ground penetrating radar U.S. Patent No. 3,806,795
1978	Bennett & Ross - Time-Domain Electromagnetics and Its Applications Seminal paper on UWB
1984	Ross/Fontana collaboration on UWB communications systems development (MSSI/ANRO)
1985	Henning F. Harmuth, large Current Radiator
1986	Ross/Fontana First fielded short pulse UWB Communications system
1989	U.S. Department of Defense (DoD), Ultra Wide Band term was used for the first time
1990	OSD/DARPA Assessment of Ultra-Wideband (UWB) Technology
1994	T.E.McEwan, Micropower Impulse Radar (MIR) operating at ultra low power; First UNCLASSIFIED UWB communications programs; MSSI 34 UWB development programs for Government & military
Standardization and Commercialization Era	
1998	Time Domain Corporation, Commercial Time Modulated Impulse UWB system
2000	Mark A. Barnes, UWB slot antenna
2002	February, US FCC, UWB regulation for data communication, safety and radar applications
2006	24th March, CEPT, ECC Decision of 24 March 2006 amended 6 July 2007 on the harmonised conditions for devices using UWB technology in bands below 10.6 GHz
2006	1st December, CEPT ECC Decision of 1 December 2006 on the harmonise conditions for devices using Ultra-Wideband (UWB) technology with Low Duty Cycle (LDC) in the frequency band 3.4 - 4.8 GHz
2007	31 August, IEEE 802.15.4a - 2007 IEEE Standard for Information Technology - Telecommunications and information exchange between system - Local and metropolitan area networks - specific requirement part 15.4: wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications for Low-Rate Wireless Personal Area Networks (WPANs)

2.1.2 Definition

In February 2002, the FCC issued the FCC UWB rulings that provided the first radiation limitations for UWB and also permitted the technology commercialization. The final report of the FCC First Report and Order (Federal Communications Commission, 2002a,b) was publicly available during April 2002. The document introduced four different categories for allowed UWB applications, and set the radiation masks for them. The proposed definition by FCC for UWB transmission is: any signal, which has a fractional bandwidth B_f larger than 0.20, or which occupies a bandwidth (BW) greater than 500 MHz, i.e.,

$$\begin{aligned} B_\mathrm{f} &\geq 0.2 \quad \text{or} \\ BW &\geq 500\ \text{MHz} \end{aligned} \tag{2.1}$$

The fractional bandwidth is defined as the ratio of signal bandwidth to the center frequency and is given by

$$B_\mathrm{f} = \frac{BW}{f_\mathrm{C}} = \frac{(f_\mathrm{H} - f_\mathrm{L})}{(f_\mathrm{H} + f_\mathrm{L})/2} \tag{2.2}$$

where f_H and f_L are the highest and the lowest frequency of the signal spectrum at the -10 dB emission point, respectively. The f_C is the center of frequency of the signal spectrum.

As shown in Fig. 2.1 the conventional radio transmission systems (i.e. narrowband as well as wideband systems) have small fractional bandwidths when compared to the UWB signals. As an example, consider the UMTS mobile communication system which operates around 2 GHz with a bandwidth of 5 MHz. This system is often called wideband, however according to Eq. 2.1, the fractional bandwidth is 0.0025, which is much smaller than 0.2 [22].

Intentional UWB radiators must be designed to guarantee that the 20 dB bandwidth of the emission is contained within the UWB frequency band. The minimum bandwidth measured at points 10 dB below the peak emission level is 500 MHz. This definition can be simply understood by seeing the bandwidth constraint shown in Fig. 2.2. The permissible emission levels for UWB signals in the UWB band are set at -41.3 dBm/MHz or under the FCC part 15 noise level. It is called power spectral density (PSD). The PSD of UWB systems is generally considered to be extremely low, especially for communication applications. The power spectral density (PSD) is defined as

$$\text{PSD} = \frac{P_\mathrm{t}}{BW} \tag{2.3}$$

where P_t is the transmitted power in Watts (W), BW is the bandwidth of the signal in Hertz (Hz), and the unit of PSD is Watt/Hertz (W/Hz) or dB/Hertz in logarithmic scale. For UWB systems, the energy is spread out over a very large bandwidth (hence the name ultra wideband) and, in general, is of a very low power spectral density.

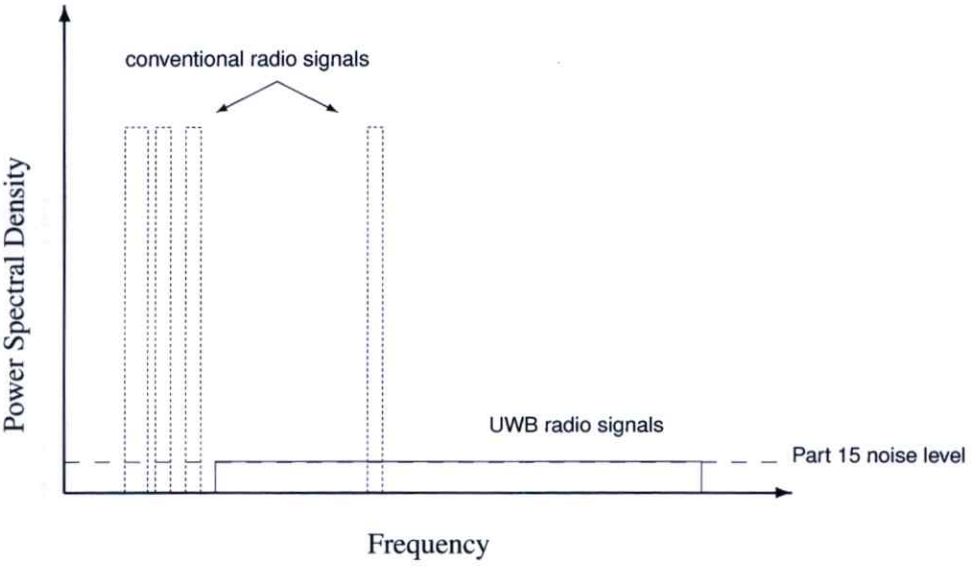


Figure 2.1: The spectrum of the UWB radio signals versus conventional radio signals

The transmitted power for UWB is the lowest one compared to the other narrowband communication systems such as radio, WLAN, and cellular. The level PSD ruled by FCC, -41.3 dBm/MHz, is 75 nW/MHz which means that the maximum transmitted power for 7.5 GHz bandwidth should be 0.5625 mW. In WLAN with the transmitted power 1 W and spread out over 20 MHz, the PSD is 0.05 W/MHz. One of the benefits of low-power spectral density is a low probability of detection, which is of particular interest for military applications: for example, covert communications and radar. This is also a concern for wireless consumer applications, where the security of data for corporations and individuals using current wireless systems is considered to be insufficient [24]. Hence, the definition of UWB is very related to the term of fractional bandwidth, bandwidth, and power spectral density. Compared to the other conventional wireless technology, UWB is recognized by its high fractional bandwidth, extremely wide bandwidth, and low PSD.

2.1.3 Regulation

Any technology has its own properties and constrains placed on it by physics as well as by regulations. Government regulators define the way that technologies operate so as to make coexistence more harmonious and also to ensure public safety. Since UWB systems operate over a very wide frequency spectrum which will overlap with the existing wireless systems, it is natural that regulation is an important issue.

The international regulations for UWB technology is still not available now and it will be mainly dependent on the findings and recommendations from the International Telecommunication Union (ITU). Currently, United States, with the FCC approval, is the only country to have a complete ruling for UWB devices. Other regulatory bodies around the world have also been

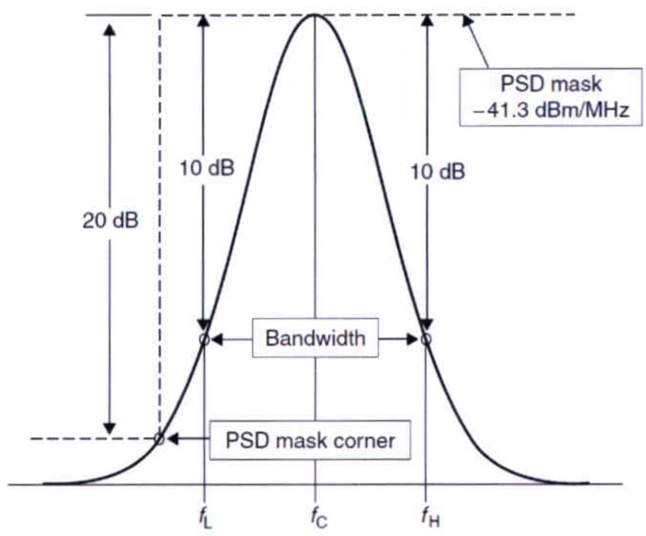


Figure 2.2: Bandwidth constraint of UWB [23]

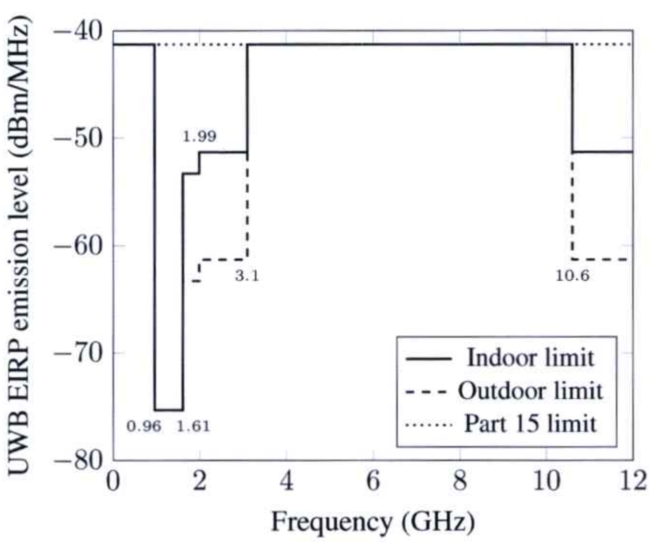


Figure 2.3: FCC spectral mask for indoor and outdoor UWB systems

trying to build regulations for UWB.

2.1.3.1 FCC's Regulation

In the USA, the regulatory agency The Federal Communications Commission (FCC) launched its first works on UWB radio technology as early as 1998. The FCC approved the deployment of UWB on an unlicensed basis in the 3.1 to 10.6 GHz band subject to a modified version of Part 15.209 rules. The essence of the rulings is that power spectral density (PSD) of the modulated UWB signal must satisfy the spectral masks specified by spectrum-regulating agencies. The FCC has assigned the Effective Isotropic Radiated Power (EIRP) allowed for each frequency band. The spectral mask for indoor applications specified by the FCC in the United States is shown in Fig. 2.3 and Table 2.2.

Table 2.2: FCC spectral mask for indoor and outdoor UWB systems

Frequency	Indoor EIRP dBm/MHz	Outdoor EIRP dBm/MHz
960 MHz-1.61 GHz	-75.3	-75.3
1.61 GHz-1.99 GHz	-53.3	-63.3
1.99 GHz-3.1 GHz	-51.3	-61.3
3.1 GHz-10.6 GHz	-41.3	-41.3
Above 10.6 GHz	-51.3	-51.3

2.1.3.2 Other Regulations

The regulatory bodies outside United States are also actively conducting studies to reach a decision on the UWB regulations now. They are, of course, heavily influenced by the FCC's decision, but will not necessarily fully adopt the FCC's regulations.

In Europe, the Electronic Communications Committee (ECC) of the Conference of European Posts and Telecommunications (CEPT) completed the draft report on the protection requirement of radio communication systems from UWB applications [25]. In contrast to the FCC's single emission mask level over the entire UWB band, this report proposed two sub-bands with the low band ranging from 3.1 GHz to 4.8 GHz and the high band from 6 GHz to 8.5 GHz, respectively. The emission limit in the high band is -41.3 dBm/MHz. It should be noted that such a power limitation does not make it possible to carry out reliable communication systems for a distance of about one meter.

In order to encourage a fast emergence of UWB systems in Europe, the ECC currently considers the possibility of using mitigation techniques to ensure the compatibility of UWB systems with the other radio services in the 3.1 GHz to 4.8 GHz band. Among these mitigation mechanisms, we can find the detection and avoidance (DAA) systems which allow us to avoid bands already used by other systems and the use of low duty cycle (LDC). Thus, in order to ensure co-existence with other systems that may reside in the low band, the ECC's proposal includes the requirement of Detect and Avoid (DAA) which is an interference mitigation technique [26]. The emission level within the frequency range from 3.1 GHz to 4.2 GHz is -41.3 dBm/MHz if the DAA protection mechanism is available. Otherwise, it should be lower than -70 dBm/MHz. Within the frequency range from 4.2 GHz to 4.8 GHz, there is no limitation until 2010 and the mask level is -41.3 dBm/MHz. The UWB spectral mask regulated by ECC is shown in Fig. 2.4 and Table 2.3.

In Asia, the regulation of UWB is particularly well advanced in Japan, Singapore, and Korea [27]. The spectral mask of UWB regulation in Asia is presented in Fig. 2.5. In Japan, from September 2002, the Information and Technology Communication Sub-Council working group presented its first investigations on UWB technology at the ministry for telecommunications, in

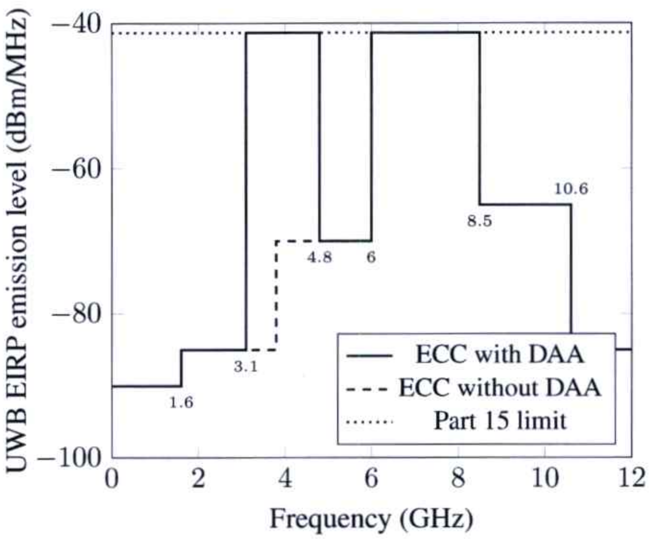


Figure 2.4: ECC spectral mask for UWB systems

Table 2.3: ECC spectral mask for UWB systems

Frequency	With DAA EIRP dBm/MHz	Without DAA EIRP dBm/MHz
Below 1.61 GHz	-90	-90
1.6 GHz-3.1 GHz	-85	-85
3.1 GHz-3.8 GHz	-41.3	-85
3.8 GHz-4.8 GHz	-41.3	-70
4.8 GHz-6 GHz	-70	-70
6 GHz-8.5 GHz	-41.3	-41.3
8.5 GHz-10.6 GHz	-65	-65
Above 10.6 GHz	-85	-85

order to prepare the regulation of UWB. Moreover, the Communications Research Laboratory (CRL) is developing a project with many industrial partners in order to design marketable UWB systems. However, the emission mask proposed by their ministry of internal affairs and communications, MIC, remains more restricted than the American mask. A preliminary proposal presented in August 2005 suggests a limitation of UWB emissions to the 7.25-10.25 GHz frequency bands with a power spectral density of -41.3 dBm/MHz. The Japanese UWB radiation mask for indoor devices has two bands; from 3.4 to 4.8 GHz and from 7.25 to 10.25 GHz. The latest announcement of Japans UWB regulation was limited to the approval of indoor usage, so outdoor usage will also be discussed. Japanese authorities also plan to set up a working group to discuss regulations on the 24 GHz band for use in automotive radars.

At the beginning of 2003, the Singaporean regulatory agency named Infocom Development Authority (IDA) created a UWB research area, called UWB Friendly Zone, which makes it possible to deploy tests and demonstrators in Singapore with experiments using an emission power of about 10 dB above the FCC limit and a band spreading from 2 GHz to 10 GHz. With that, the IDA

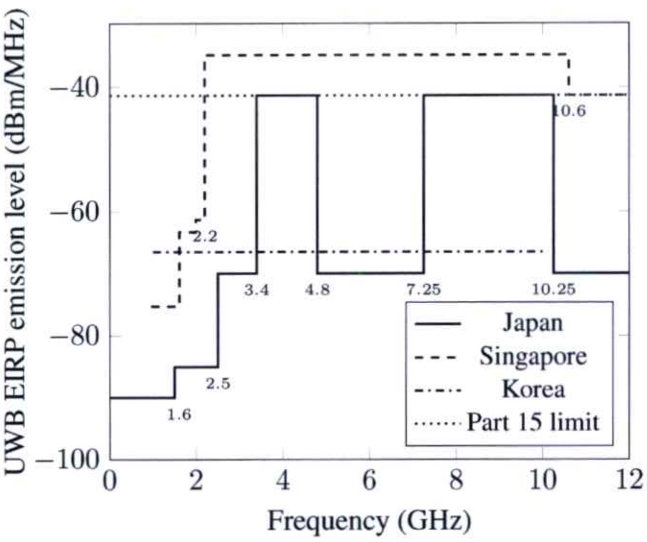


Figure 2.5: Regulation of spectral mask for UWB systems in Asia

tries to give an significant advance in Singapore to new telecommunication technologies, in order to remain scientifically and economically competitive. To conclude, it should be specified that the greatest constraint of regulation comes from management of the interference. The problems of UWB regulation do not come from the effect of only one UWB system, but from the aggregation of hundreds of devices using this technology, creating a sum of signals which can possibly interfere with other systems, like the navigation or safety systems. So, the UWB scientific community currently works to test and define systems which remain inoffensive, even when using several co-localized equipment [28].

Korea is working on the regulation of UWB radio through its Reform Frequency Regulation for Unlicensed Stations. From the Korean proposal, it is expected that the emission levels in the satellite digital multimedia band and WiBro (Wireless Broadband) operating in the 2.3 GHz, be more restrictive. For the frequency range of 1 GHz to 10 GHz, the Korean emission level is 66.5 dBm/MHz, which is about 25 dB lower than the FCC limit.

The UWB regulation is summarized in Table 2.4. In the end, there is no best approach that works for all countries, but governments, regulators, and industry need to find the right balance that best benefits the public. From a UWB industry perspective, it is beneficial to find a common framework so that the same technology can be used for different countries with only minor modifications [29].

2.1.4 Key Benefits

The unique advantages of UWB systems are numerous. First of all, it introduces unlicensed usage of an extremely wideband spectrum, as mentioned in the previous subsections. The underlay usage of spectrum greatly increases spectral efficiency and opens new doors for wireless

Table 2.4: Summary of UWB regulation

Region	Frequency Bands	Additional Requirements
United States	3.1 GHz to 10.6 GHz	-41.3 dBm/MHz
European Union	3.1 to 4.8 GHz	-41.3 dBm/MHz with either protection mechanism: Using DAA with transmit level reduced to -70 dBm/MHz in presence of other services that require protection Restricting duty cycle to a maximum of 5% over 1 second and 0.5% over 1 hour
	4.2 to 4.8 GHz	No limitation until 2010
	6 to 8.5 GHz	-41.3 dBm/MHz
Japan	3.4 to 4.8 GHz	-41.3 dBm/MHz with DAA, transmit level reduced to -70 dBm/MHz in presence of other services that require protection
	7.25 to 10.25 GHz	-41.3 dBm/MHz
Singapore	2.2 to 10.6 GHz	-35 dBm/MHz
Korea	1 to 10 GHz	-66.5 dBm/MHz

applications. The introduction of cognitive features along with opportunistic spectrum usage will further enhance current UWB applications. UWB technology is likely to provide high data rates. The data rate can be easily traded-off for extension in range by designing appropriate adaptive transceivers. Similarly, data rate and range can be traded-off for power, especially for low data rate and short range applications.

UWB has a number of key benefits that make it attractive for consumer communications applications [30]. In particular, the main benefits of UWB systems are described as follows.

UWB systems have potentially low complexity and low cost

The low complexity and low cost of UWB systems arises from the essentially baseband nature of the signal transmission. Unlike conventional radio systems, the UWB transmitter produces a very short time domain pulse, which is able to propagate without the need for an additional RF (radio frequency) mixing stage. The RF mixing stage takes a baseband signal and injects a carrier frequency or translates the signal to a frequency which has desirable propagation characteristics. The very wideband nature of the UWB signal means it spans frequencies commonly used as carrier frequencies. The signal will propagate well without the need for additional up-conversion and amplification. The reverse process of down-conversion is also not required in the UWB receiver. Again, this means the omission of a local oscillator in the receiver, and the removal of associated complex delay and phase tracking loops. The UWB technology allows the use of impulse generated in baseband and directly transmitted on the radio channel without modulation. This possibility of transmission without carrier may simplify the architecture of the radio systems. Indeed, it is possible to design UWB transmitter-receivers without any synthesizer using a phase locked loop (PLL), any voltage control oscillator (VCO) or any mixer.

UWB systems have noise-like signal

Due to the low energy density and the pseudo-random (PR) characteristics of the transmitted signal, the UWB signal is noise-like, which makes unintended detection quite difficult. Whilst there is some debate in the literature, it appears that the low power, noise-like, UWB transmissions do not cause significant interference to existing radio systems. The interference phenomenon between impulse radio and existing radio systems is one of the most important topics in current UWB research.

UWB systems are resistant to severe multipath and jamming

In usual propagation channels, narrowband systems suffer from fading related to the multipath which combine in a destructive way. In the case of impulse signals, the transmitted waveforms can have a great bandwidth, so the multipath presenting delays lower than one nanosecond can be resolved and added in a constructive way. This recombination causes some complications on the system implementation, as it leads to the design of a receiver with a great number of diversity branches. UWB systems offer a great processing gain. Thus, the interference UWB systems may have on other systems is reduced, thanks to the low level of the power spectral density authorized by the FCC. On the contrary, the interference caused by narrowband systems on UWB systems is a priori minimized by the bandwidth covered by the impulse signals.

UWB systems have very good time domain resolution

Because of their great bandwidth, UWB signals have a high temporal resolution, typically about one nanosecond. A first implication of this property is related to the localization and tracking application: knowing the delay of a signal with a precision of about 0.1 to 1 ns, it is possible to obtain information on the position of the transmitter with an accuracy of 3 to 30 cm.

UWB systems have low power spectral density

This characteristic is not intrinsic to UWB signals as they were defined, but it is imposed by the radio spectrum regulation authorities. Indeed, as UWB signals present a wide spread spectrum, the occupied frequency band necessarily covers the frequencies already allocated to existing radio systems. To allow a peaceful coexistence of UWB with existing narrowband radio technologies, the FCC has limited the power spectral density of UWB signals to -41.3 dBm/MHz, which corresponds to the power spectral density limit of authorized non-intentional radio transmissions. This low power spectral density improves the safety of UWB radio communications, since it becomes more difficult to detect the transmitted signals. Another consequence of this characteristic concerns the propagation distance which is thus limited to about 10 meters. So, the applications considered for UWB systems are short range and high data rate, and are particularly adapted to the development of ad-hoc networks.

UWB systems provide protected and secured communications

UWB signals are signals that are by nature difficult to detect. Indeed, they are spread over a broadband and transmitted with a low power spectral density close to the noise floor level of traditional radio communication receivers. These characteristics enable secured transmissions with a weak probability of detection and a weak probability of interception.

Good obstacle penetration properties

UWB signals offer good capabilities of penetration in the walls and the obstacles, in particular for the low frequencies part of the spectrum. This makes it possible to have a good precision in terms of localization and tracking. The American company Time Domain, Inc., pioneer in the topic of UWB for communication, has developed a broad activity around radar systems of vision through walls.

2.1.5 Applications

For a few years, the world of telecommunications has faced an increasing demand for wireless numerical applications, in the industrial environment as well as from the general public. This increasing need for wireless connectivity leads to the development of many standards for wireless and short range communication systems. As mentioned earlier in the previous subsection, UWB offers some unique and distinctive properties that make it attractive for various applications. Its huge bandwidth and low PSD emerge several benefits which are not provided by other wireless technologies. As UWB has low PSD, it is more considered for short range wireless application with distance below 10 meters. Some possible applications are illustrated in Fig. 2.6 and described below.

Wireless Personal Area Network (WPAN) for office and home networking

UWB has the potential for very high data rates using very low power at very limited range, which will lead to the applications well suited for WPAN. The peripheral connectivity through cableless connections to applications like storage, I/O devices and wireless USB will improve the ease and value of using Personal Computers (PCs) and laptops. High data rate transmissions between computers and consumer electronics like digital cameras, video

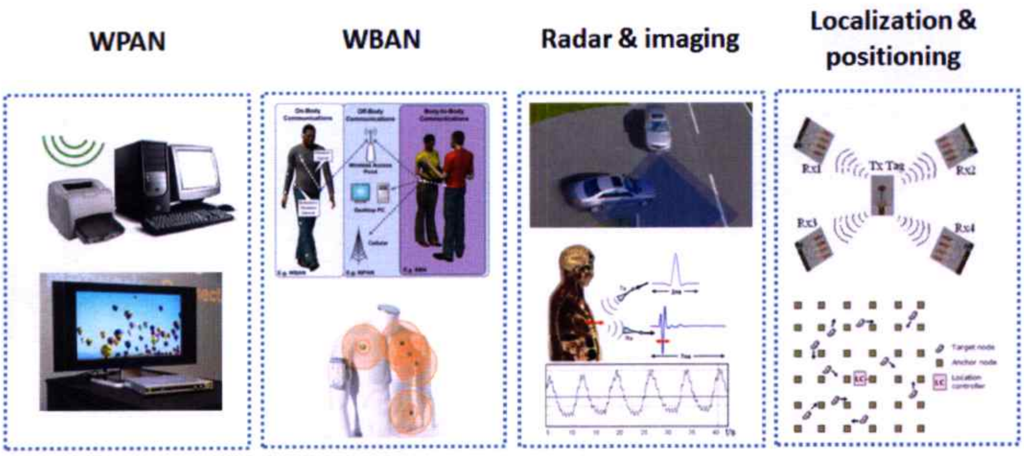


Figure 2.6: Illustration of some UWB applications

cameras, MP3 players, televisions, personal video recorders, automobiles and DVD players will provide new experience in home and personal entertainment [31].

Wireless Body Area Network (WBAN)

WBANs are another example of how our life could be influenced by UWB. Probably the most promising application in this context is medical body area networks. Due to the proposed energy efficient operation of UWB, battery driven handheld equipment is feasible, making it perfectly suitable for medical supervision. Moreover, UWB signals are inherently robust against jamming, offering a high degree of reliability, which will be necessary to provide accurate patient health information and reliable transmission of data in a highly obstructed radio environment. The possibility to process and transmit a large amount of data and transfer vital information using UWB wireless body area networks would enable tele-medicine to be the solution for future medical treatment of certain conditions. In addition, the ability to have controlled power levels would provide flawless connectivity between body-distributed networks. UWB also offers good penetrating properties that could be applied to imaging in medical applications; with the UWB body sensors this application could be easily reconfigured to adapt to the specific tasks and would enable high data rate connectivity to external processing networks (e.g. servers and large workstations) [32].

Radar and imaging

UWB radars can be used in automobile traffic control systems to prevent collisions while driving and parking; they can also be used in security systems as signaling sensors, which provide detection of unsanctioned intrusion into the guarded area. This type of radar can be applied in a rescue service to detect people buried under building obstructions or snow slips; if a person is motionless, the detection can be performed using a person's heart and thorax beats. UWB radars are useful in hospitals and at home where they can provide remote measuring of heart and respiratory beats and other parameters of the patient's vital activity. UWB radar can measure distances up to an object with high accuracy; for example, monitoring of the levels of liquid (water, oil, liquid gas) in tank for a long time [33].

Localization and positioning

UWB is an excellent signaling choice for high accuracy localization and positioning in short to medium distances due to its high time resolution and inexpensive circuitry. It is also considered to be the unique signaling choice for short-range, low-data rate communications such as in wireless sensor networks (WSNs) [34].

2.2 Fundamental of UWB Radio Transmission

2.2.1 UWB Radio Transmission Model

UWB systems have historically been based on impulse radio concepts. Impulse radio scheme refers to the generation of a series of very short duration pulses of the order of hundreds of picoseconds. Each pulse has a very wide spectrum, which must adhere to the spectral mask requirements. Any given pulse will have very low energy because of the very low power levels permitted for typical UWB transmission. Therefore, many pulses will typically be combined to carry the information for one bit. Other radio transmission concept for UWB is multiband OFDM (MB-OFDM) which will be neglected in this discussion because this scheme works by sinusoidal wave transmission like in narrowband systems. Hence, this thesis concerns more on UWB impulse radio (UWB-IR) as UWB technology originally made for.

The UWB impulse radio concept corresponds to the emission of impulses of very short duration (around 100 ps to 1 ns). Typically, this type of impulses occupies a very broad spectrum (about 1 to several GHz). It is thus a mono-band approach. If narrowband systems use sinusoidal wave to represent the information bits, UWB-IR systems use very short impulse waveform to represent the bits. Modulation schemes are necessary for both systems to distinguish between 0 and 1 in the transmitted binary informations. The ideal waveform for UWB is the rectangular passband waveform with rectangular shape of spectrum. Root raised cosine waveform, gaussian waveform, hermite waveform, legandre waveform, and prolate spheroidal waveform are some typical examples of UWB waveform [22,24]. The concept of pulse transmission in UWB radio is illustrated in Fig. 2.7.

There are three popular modulation schemes in UWB radio transmission: pulse amplitude modulation (PAM), pulse position modulation (PPM), and binary phase shift keying (BPSK). The PAM scheme encodes information based on the amplitude of the pulses. The transmitted pulse $v_{\mathrm{PAM}}(t)$ can be represented as

$$v_{\mathrm{PAM}}(t) = x_i \cdot w_{\mathrm{t}}(t) \tag{2.4}$$

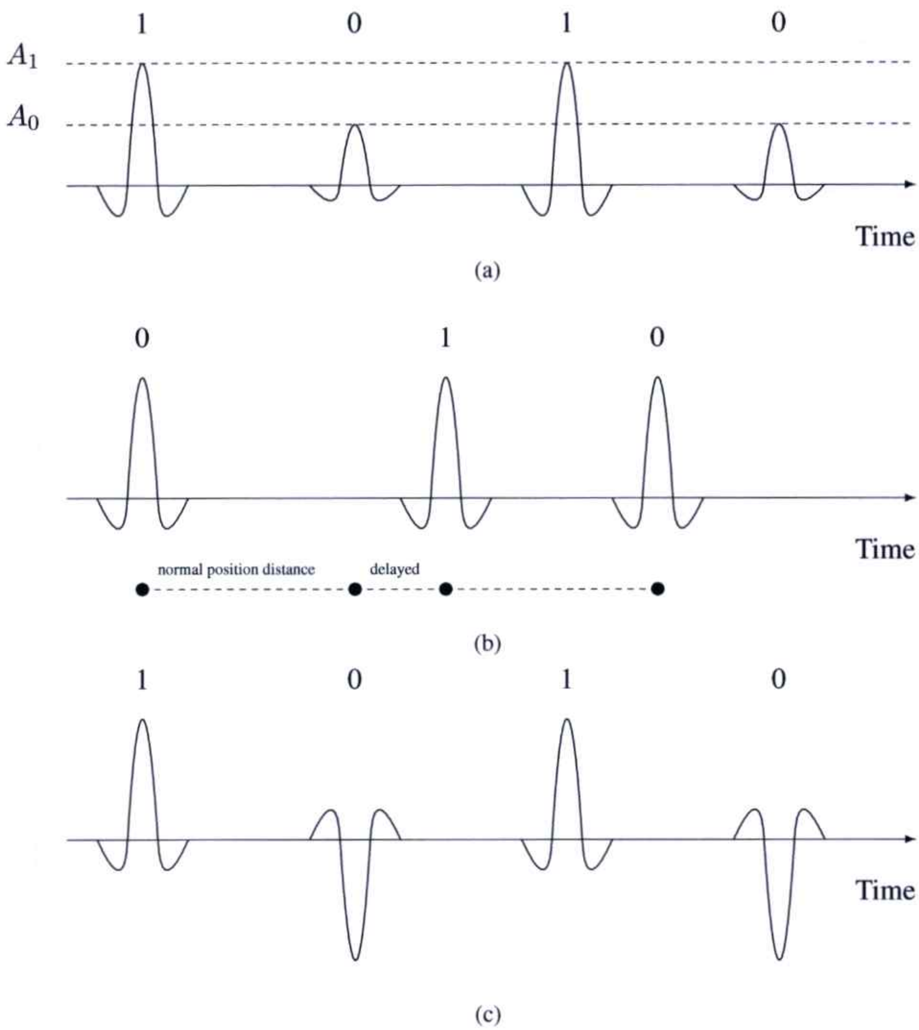


Figure 2.7: Illustration of pulses to represent the information bits in UWB-IR: (a) using pulse amplitude modulation (PAM), (b) using pulse position modulation (PPM), (c) using binary phase shift keying (BPSK)

where $w_t(t)$ is the UWB waveform, i is the bit value, i.e. '1' or '0', and

$$x_i = \begin{cases} A_1, & i=1 \\ A_0, & i=0 \end{cases} \tag{2.5}$$

In PPM, the bit to be transmitted determines the position of the UWB pulse. The transmitted pulse $v_{\text{PPM}}(t)$ can be represented as

$$v_{\text{PPM}}(t) = w_t(t)(t - a \cdot x_i) \tag{2.6}$$

where $w_t(t)$ is the UWB waveform, a is the delay time to change pulse position from the normal

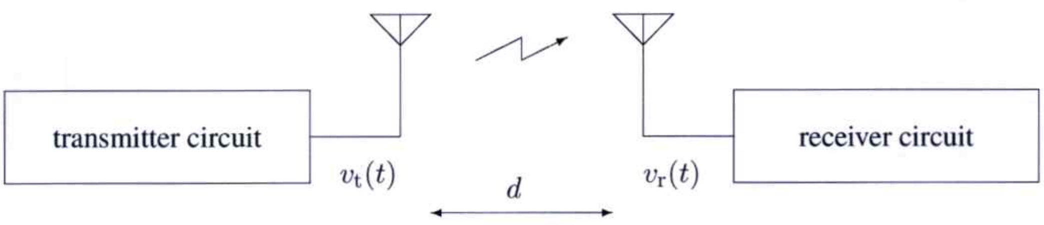


Figure 2.8: UWB radio transmission model

position, i is the bit value, i.e. '1' or '0', and

$$x_i = \begin{cases} 1, & i=1 \\ 0, & i=0 \end{cases} \tag{2.7}$$

In BPSK modulation, the bit to be transmitted determines the phase of the UWB pulse. The transmitted pulse $v_{\mathrm{BPSK}}(t)$ can be represented as

$$v_{\mathrm{BPSK}}(t) = w_t(t)e^{-\mathrm{j}(x_i \cdot \pi)} \tag{2.8}$$

where $w_t(t)$ is the UWB waveform, a is the delay time to change pulse position from the normal position, i is the bit value, i.e. '1' or '0', and

$$x_i = \begin{cases} 1, & i=1 \\ 0, & i=0 \end{cases} \tag{2.9}$$

For any kind of waveform and modulation used in the transmission, the role of antennas as the front-end of the transceiver is to radiate the UWB pulse $v_t(t)$ excited by waveform generator and to receive $v_r(t)$. A very simple model of UWB radio transmission is depicted in Fig. 2.8. The transmitter circuit may contain input waveform generator and data source driver. The receiver circuit may contain low noise amplifier (LNA), correlator, pulse detector, and analog-to-digital converter (ADC).

2.2.2 Extension of Friis Transmission Formula for UWB Impulse Radio

In UWB radio channel, the transmitter and the receiver antennas must work with broad-spectrum pulses instead of sinusoidal wave like in narrowband radio channel. The analysis of UWB transmission is definitely different with narrowband transmission. In narrowband line-of-sight (LOS) channel, the Friis' transmission formula has been commonly used to evaluate the link budget of the channel. As a channel of wireless communication always contains antennas at both transmitter and receiver, this formula is also useful for antenna analysis such as to obtain antenna gain. The Friis' transmission gain for narrowband LOS channel is defined as

$$\begin{aligned} G_{\text{Friis}}(f) &= \frac{P_{\text{r}}(f)}{P_{\text{t}}(f)} \\ &= G_{\text{f}}(f,d)G_{\text{t}}(f,\Omega_{\text{t}})G_{\text{r}}(f,\Omega_{\text{t}}) \end{aligned} \tag{2.10}$$

where f is the operating frequency, d is the separation distance between transmitter and receiver antennas, $P_{\text{t}}(f)$ and $P_{\text{r}}(f)$ respectively are the input power given to the transmitter antenna and the output power from the receiver antenna. $G_{\text{t}}(f,\Omega_{\text{t}})$ and $G_{\text{r}}(f,\Omega_{\text{r}})$ respectively are effective gain of transmitter and receiver antennas towards Ω_{t} and Ω_{t} direction. $G_{\text{f}}(f,d)$ is the free-space propagation gain which is defined as

$$G_{\text{f}}(f,d) = \left(\frac{c}{4\pi f d}\right)^2 \tag{2.11}$$

where c is the velocity of light. The frequency dependency of propagation comes from the frequency dependency of the constant gain receiving antenna aperture area $A_e = \left(\frac{c}{4\pi f}\right)^2$.

The Friis' transmission formula for narrowband systems in Eq. (2.10) then should be extended to satisfy and applicable for UWB systems [35]. In UWB systems, the link budget should be formulated in the term of frequency transfer function that takes into the account the transmission of waveform in a channel including antennas. The free space transfer function $H_{\text{f}}(f,d)$ can be written as

$$H_{\text{f}}(f,d) = \frac{c}{4\pi f d} e^{-\text{j}2\pi f d/c} \tag{2.12}$$

Free space channel transfer function $H_{\text{c}}(f)$ including the antennas is then named as the extension of Friis' transmission formula for UWB systems and can be written as

$$H_{\text{e-Friis}}(f) = H_{\text{f}}(f,d)\mathbf{H}_{\text{t}}(f,\Omega_{\text{t}}) \cdot \mathbf{H}_{\text{r}}(f,\Omega_{\text{t}}) \tag{2.13}$$

where $\mathbf{H}_{\text{t}}(f,\Omega_{\text{t}})$ and $\mathbf{H}_{\text{r}}(f,\Omega_{\text{t}})$ are respectively the complex transfer function vectors of the transmitter antenna and the receiver antenna towards the $\Omega_{\text{t}} = (\hat{\theta}_{\text{t}},\hat{\phi}_{\text{t}})$ or $\Omega_{\text{r}} = (\hat{\theta}_{\text{r}},\hat{\phi}_{\text{r}})$ direction. $\hat{\theta}_{\text{t}},\hat{\phi}_{\text{t}}$ and $\hat{\theta}_{\text{r}},\hat{\phi}_{\text{r}}$ represent the polarization of antennas toward elevation and azimuth angle which are defined with respect to the local polar coordinate of the antennas.

With $H_{\text{e-Friis}}(f)$ as the transfer function of the UWB channel and $v_{\text{t}}(t)$ as the transmitted UWB waveform, hence the received waveform can be obtained by applying the inverse of Fourier transform as

$$v_{\mathrm{r}}(t) = \int_{-\infty}^{\infty} V_{\mathrm{t}}(f) H_{\mathrm{e-Friis}}(f) e^{\mathrm{j}2\pi f t} \mathrm{d}f \tag{2.14}$$

Once the $H_{\mathrm{e-Friis}}(f)$ known from UWB channel measurement, the UWB radio transmission can be analyzed based on the transmitted waveform and the received waveform. The extension of Friis' transmission formula has been proven more accurate for UWB systems than using the original one [36, 37].

2.3 Summary

In this chapter, the overview of UWB technology and the fundamental of UWB radio transmission are discussed. Development of UWB has lasted through a very long history with rapid progression in recent years. The most significant moment was after FCC approved the unlicensed UWB frequency at 3.1 GHz to 10.6 GHz in United States, followed by other similar regulations for particular areas. The available regulations supported by numerous benefits and potential applications make UWB becomes a very promising technology for wireless communications. The unique radio feature is also one of the interesting points of UWB. UWB technology is basically conceptualized to operate with pulse transmission which is very different from narrowband radio. In order to analyze the UWB radio transmission, the extension of Friis' transmission formula should be applied instead of the original one.

CHAPTER III

ANTENNA THEORY

3.1 Basics of Antenna

The major content of this thesis is about development of antenna for UWB technology. Before getting further to the research work, it is necessary to get familiar with basic of electromagnetism and antenna theory in this chapter.

3.1.1 Electromagnetism and Maxwell Equation

Electromagnetism is the science that describes the macroscopic interactions between electric charges, which may be either stationary or moving. The best way to understand electromagnetism is by knowing Maxwell Equation proposed by James Clerk Maxwell (1831-1879) which implicitly explains the creation of electromagnetic waves. Electromagnetic waves cover the whole frequency spectrum which actually infinite. The wave velocity, v, is linked to the frequency f and wavelength λ by equation

$$v = \frac{\lambda}{f} \tag{3.1}$$

Two examples of electromagnetic waves are radio waves and optical waves. We cannot see radio waves, but we can see light as optical waves which the wavelengths are visible by human eyes. It is well-known that the speed of light (an electromagnetic wave) is about 3×10^8 m/s. For wireless communication technologies, radio waves are employed to send the information.

Maxwell Equation describe the interrelationship between electric fields, magnetic fields, electric charge, and electric current. Mathematically, the set of Maxwell Equation can be expressed in the following differential form.

$$\begin{aligned} \nabla \times E &= -\tfrac{\partial B}{\partial t} \\ \nabla \times H &= J + \tfrac{\partial D}{\partial t} \\ \nabla \cdot D &= \rho \\ \nabla \cdot B &= 0 \end{aligned} \tag{3.2}$$

where E is electric field (V/m), B is magnetic flux density (Tesla), H is magnetic field (A/m), J is current density (A/m^2), D is electric flux density (C/m^2), ρ is charge density, t is time (s), $\nabla = \frac{\partial}{\partial x}\hat{x} + \frac{\partial}{\partial y}\hat{y} + \frac{\partial}{\partial z}\hat{z}$ is a 3-dimensional vector operator, $\nabla\times$ is curl operator, and $\nabla\cdot$ is divergence operator.

Alhough Maxwell himself was not the originator of the individual equations, he derived them again independently, and he was the person who grouped those equations into a coherent set. The first equation is originally from Michael Faraday named Faraday's Law of Induction. $\nabla \times E = -\frac{\partial B}{\partial t}$ simply means that the induced electromotive force is proportional to the rate of change of the magnetic flux through a coil. Moving a conductor through a magnetic field produces electric field. It is obvious from this equation that a time-varying magnetic field ($\mu\frac{\partial H}{\partial t}$) will generate an electric field, but if the magnetic field is not time-varying, there is no electric field generated. μ is magnetic permeability of a material.

The second equation is from the modified Ampere's Circuital Law $\nabla \times H = J + \frac{\partial D}{\partial t}$. This equation means that a magnetic field appears during the charge or discharge of a capacitor. With this concept and Faradays law, Maxwell was able to derive the wave equations, and by showing that the predicted wave velocity was the same as the measured velocity of light, Maxwell asserted that light waves are electromagnetic waves. This equation shows that both the current density (J) and time-varying electric field ($\varepsilon\frac{\partial E}{\partial t}$) can generate a magnetic field where ε is magnetic permeability of a material.

The third equation is from Gauss's Law for Electric Fields $\nabla \cdot D = \rho$. This equation simply means that it is not possible for electric fields to form a closed loop. Since $D = \varepsilon E$, it is also clear that charges can generate electric fields. static or dynamic charges in a given volume are responsible for a diverging electric field. That implies that there must be a distinct source and sink for the electric field since a field cannot possibly (linearly) diverge and start and end in the same location.

The fourth equation is from Gauss's Law for Magnetic Fields $\nabla \cdot B = 0$. This equation means that the magnetic field lines are closed loops or the integral of B over a closed surface is zero. There is no physical medium which makes a magnetic field diverge.

A wave is hence generated where the electric field stimulates the magnetic field and vice versa. The set of Maxwell Equation explains that electromagnetic wave which contains electric field and magnetic field can be generated by currents and charges. With further derivation, Maxwell Equation can be used to obtain wave equation which will not be detailed in this chapter. By knowing the concept of this Maxwell Equation, it is easier to get better understanding of antenna radiation as well as radio waves. The Maxwell Equation implies the basic of electromagnetism and how the radio waves can be transmitted and received by antennas.

3.1.2 Antenna Definition

The first well-known satisfactory antenna experiment was conducted by the German physicist Heinrich Rudolf Hertz (1857-1894). The SI (International Standard) frequency unit, the Hertz, is named after him. The original intention of his experiment was to demonstrate the existence of

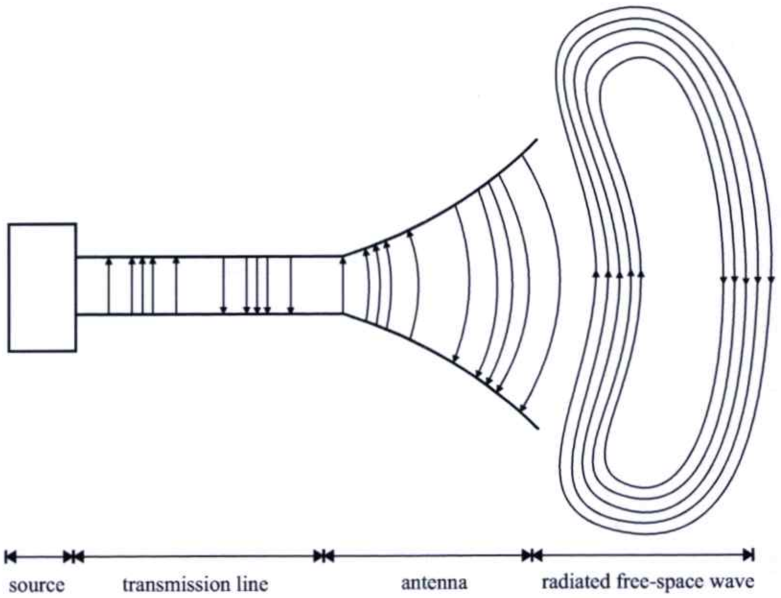


Figure 3.1: Antenna as a transition device

electromagnetic radiation.

The IEEE Standard Definitions of Terms for Antennas (IEEE Std 1451983) defines an antenna as "a means for radiating or receiving radio waves" [38]. In a book entitled "Antennas" by John D. Kraus, a radio antenna may be defined as the structure associated with the region of transition between a guided wave and a free-space wave, or vice versa [39]. In other words, a transmit antenna is a device that takes the signals from a transmission line, converts them into electromagnetic waves and then broadcasts them into free space, as shown in Fig. 3.1. While operating in receive mode, the antenna collects the incident electromagnetic waves and converts them back into signals.

Fig. 3.2 illustrates a typical radio communication system. The source information is normally modulated and amplified in the transmitter and then passed on to the transmit antenna via a transmission line. The antenna radiates the information in the form of an electromagnetic wave in an efficient and desired manner to the destination, where the information is picked up by the receive antenna and passed on to the receiver via another transmission line. The signal is demodulated and the original message is then recovered at the receiver.

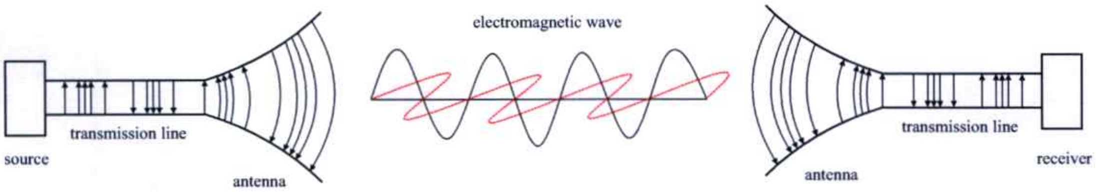


Figure 3.2: A typical radio communication system

An antenna is normally made of metal, but other materials such as copper, aluminum, or dielectric materials, etc may also be used. For wireless communication systems, the antenna is one of the most critical components. Making antenna design is an interesting and difficult subject. More recently, one of the main challenges for antennas has been on how to make them broadband and small enough in size for wireless mobile communications systems. A good design of the antenna can relax system requirements and improve overall system performance. The subject of antennas is about how to design a suitable device which will be well matched with its feed line and radiate/receive the radio waves in an efficient and desired manner.

3.1.3 Antenna Important Parameters

There are some parameters which are important for describing the characteristics of an antenna. For instance, those parameters can be used to denote the antenna bandwidth. The bandwidth of an antenna is defined as the range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard. The bandwidth can be considered to be the range of frequencies, on either side of a center frequency (usually the resonance frequency for a dipole), where the antenna characteristics are within an acceptable value of those at the center frequency. For broadband antennas, the bandwidth is usually expressed as the ratio of the upper-to-lower frequencies of acceptable operation. For example, a 10:1 bandwidth indicates that the upper frequency is 10 times greater than the lower. For narrowband antennas, the bandwidth is expressed as a percentage of the frequency difference (upper minus lower) over the center frequency of the bandwidth. For example, a 5% bandwidth indicates that the frequency difference of acceptable operation is 5% of the center frequency of the bandwidth [38].

Since antenna is a transition device linking the transmission line and the radio waves, the antenna parameters can be divided into two points of view: circuit point of view and field point of view. The antenna parameters from the circuit point of view are related to its impedance such as input impedance and reflection coefficient. The antenna parameters from the field point of view are radiation pattern, gain, directivity, and etc. In this subsection, some antenna important parameters in both points of view are described.

3.1.3.1 Antenna Input Impedance

Antenna input impedance (Z_{a}) is defined as the impedance presented by an antenna at its terminals or the ratio of the voltage to current at its terminals. Mathematically, the input impedance is

$$Z_{\mathrm{a}} = \frac{V_{\mathrm{in}}}{I_{\mathrm{in}}} = R_{\mathrm{a}} + \mathrm{j}X_{\mathrm{a}} \tag{3.3}$$

where V_{in} and I_{in} are the input voltage and current at the antenna input, respectively. Since the input impedance is complex, then it can be represented as $R_{\mathrm{a}} + \mathrm{j}X_{\mathrm{a}}$.

If the antenna is directly connected to a source of impedance Z_s, for a matched load the following condition should be met

$$Z_\mathrm{s} = Z_\mathrm{a}^* = R_\mathrm{a} - \mathrm{j}X_\mathrm{a} \tag{3.4}$$

which implies that the input impedance of an antenna should be matched with the source impedance. In reality, the antenna is normally connected to a short transmission line with a standard characteristic impedance of 50 Ω when the system is intended to act as both transmitter and receiver, or 75 Ω when the system is intended to act only as a transmitter or only as a receiver. Thus, the desired antenna input impedance is 50 Ω or 75 Ω.

3.1.3.2 Reflection Coefficient, Return Loss, and VSWR

Impedance matching is extremely important. Impedance matching is the practice of making the output impedance of a source equal to the input impedance of the load in order to maximize the power transfer and minimize the power reflection from the load. Since the antenna is just a load to a transmission line from the circuit point of view, the reflection coefficient, return loss and voltage standing wave ratio (VSWR) can be used to judge how well a load is matched with the transmission line. All these three parameters are interlinked and actually represent the same performance of an antenna which is impedance matching. Since the impedance mismatch causes reflection of signal/power, all these three parameters can be defined as a measure of how much signal/power is reflected back from the antenna terminal. The specific representations are as follows:

Reflection coefficient

Reflection coefficient (Γ) is a measure of signal reflection in a complex form which can be calculated from the impedance mismatch between the antenna impedance and the input terminal impedance.

$$\Gamma = \frac{Z_\mathrm{a} - Z_0}{Z_\mathrm{a} + Z_0} \tag{3.5}$$

where Z_a is the antenna impedance and Z_0 is the input terminal impedance.

Return loss

Return loss (L_RT) is the reflection coefficient which is expressed in logarithmic form (dB scale). It is easier to see the impedance matching by this parameter. The lower return loss means good impedance matching.

$$L_\mathrm{RT} = 20\log(|\Gamma|) = 20\log\left|\frac{Z_\mathrm{a} - Z_0}{Z_\mathrm{a} + Z_0}\right| \tag{3.6}$$

Table 3.1: Near-field and far-field condition

	$D << \lambda$	$D \approx \lambda$	$D >> \lambda$
Reactive near-field	$r < \lambda/2\pi$	$r < \lambda/2\pi$	$r < \lambda/2\pi$
Radiating near-field	$\lambda/2\pi < r < 3\lambda$	$\lambda/2\pi < r < 3\lambda$ and $2D^2/\lambda$	$\lambda/2\pi < r \leq 2D^2/\lambda$
Far-field	$r > 3\lambda$	$r > 3\lambda$ and $2D^2/\lambda$	$r > 2D^2/\lambda$

[1] D is the biggest dimension of the antenna
[2] λ is the wavelength which the antenna is operated on
[3] r is the radius of the near-field or far-field region

VSWR

The VSWR is defined as the ratio of the magnitude of of the maximum voltage on the line to the minimum voltage on the line. VSWR represents the impedance matching by a ratio between 1 and infinity. If the VSWR is equal to 1, it means that the antenna has a perfect impedance matching where there is no reflected power. The higher VSWR means the worse impedance matching. Mathematically, VSWR can be written as

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \tag{3.7}$$

The impedance mismatch, which denoted by higher return loss and VSWR, can cause a damage to the circuit connected with the antenna because the power that should be radiated precisely reflected at the antenna terminal. The commonly required specification of an antenna is $L_{\mathrm{RT}} <$ -10 dB or $VSWR < 2$. For mobile phone antennas, it is also common to specify $L_{\mathrm{RT}} <$ -6 dB or $VSWR < 3$. From the circuit point of view, the antenna bandwidth is defined as the frequency range where $L_{\mathrm{RT}} <$ -10 dB or $VSWR < 2$ (depends on the requirement).

3.1.3.3 Radiation Pattern

The radiation pattern of an antenna is a plot of the radiated field/power as a function of the angle at a fixed distance, which should be large enough to be considered far field. The far-field condition of an antenna can be seen in Table 3.1. Radiation pattern of an antenna can be obtained by measurement using standard gain horn antenna or using two-antenna method. [38].

Antenna has three-dimensional (3D) radiation pattern in reality. The 3D pattern is an excellent illustration of the radiated field distribution as a function of angle θ and ϕ in space. Unfortunately, it is difficult and also very time-consuming to measure the 3D pattern of an antenna in practice, but not in electromagnetic simulation. Most antennas have certain symmetrical features, thus, the most important patterns are the radiation patterns in the two main planes: the E-plane and the H-plane. The E-plane is the plane that the electric field *E* lies on, while the H-plane is the plane that the magnetic field *H* is on. For the ideal current element case, the electric field is E_θ

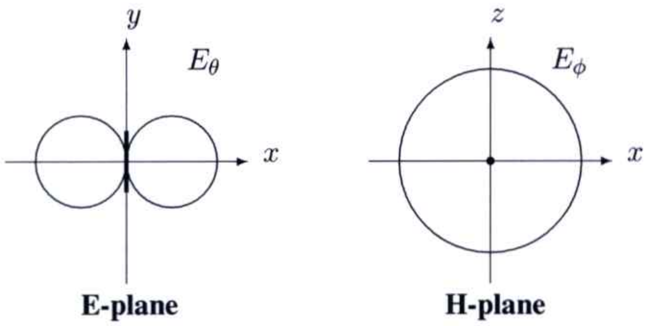


Figure 3.3: E-plane and H-plane patterns of an electrically short current element (antenna)

and the magnetic field is H_ϕ, thus the E-plane pattern is the field E_θ measured as a function of θ when the angle ϕ and the distance are fixed, while the H-plane pattern is the field E_θ measured as a function of ϕ when the angle θ and the distance are fixed. The E-plane (at $\phi = 0$) and H-plane (at $\theta = \pi/2$) patterns of the short current element are shown in Fig. 3.3.

The H-plane pattern is actually a measure of the electric field, not the magnetic field. When the patterns are plotted on a linear scale, the field pattern and power pattern may look very different. However, when the patterns are plotted on a logarithmic scale (dB plot), both the normalized field and power patterns are the same. Thus, in practice, the patterns are often plotted in dB scale, which also makes it easy to see details of the field or power over a large dynamic range.

There are three common radiation patterns that are used to describe an antenna's radiation property:

Isotropic pattern

A hypothetical lossless antenna having equal radiation in all directions. It is only applicable for an ideal antenna and is often taken as a reference for expressing the directive properties of actual antennas.

Directional pattern

An antenna having the property of radiating or receiving electromagnetic waves more effectively in some directions than in others. This is usually applicable to an antenna where its maximum directivity is significantly greater than that of a half- wave dipole.

Omnidirectional pattern

An antenna having an essentially non-directional pattern in a given plane and a directional pattern in any orthogonal plane.

3.1.3.4 Antenna Directivity and Gain

Directivity is a measure of the concentration of radiated power in a particular direction. It is defined as the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. The average radiation intensity is equal to the total radiated power divided by 4π. If the direction is not specified, the direction of maximum radiation is implied. Mathematically, the directivity (dimensionless) can be written as

$$D = \frac{U(\theta,\phi)}{U(\theta,\phi)_{\mathrm{av}}} = \frac{4\pi U(\theta,\phi)}{P_{\mathrm{rad}}} \tag{3.8}$$

where $U(\theta,\phi)$ is the radiation intensity in Watt/unit solid angle for a specified direction, $U(\theta,\phi)_{\mathrm{av}}$ is the average of radiation intensity in Watt/unit solid angle, P_{rad} is the total radiated power in Watt.

Antenna gain G is closely related to the directivity, but it takes into account the radiation efficiency μ_{e} of the antenna as well as its directional properties, as given by

$$G = \frac{P_{\mathrm{rad}}}{P_{\mathrm{in}}} D = \mu_{\mathrm{e}} D \tag{3.9}$$

where P_{in} is the input power accepted by the antenna.

Directivity is more suitable for showing characteristic of a directional antenna. As an antenna can be directional or omnidirectional, gain is more commonly used to perform the characteristic of an antenna. There are several methods of measuring the gain of an antenna, comparison with standard gain horn, two-antenna measurement, and three-antenna measurement [40]. It should be noted that all explanation above is more concerned on narrowband antenna. The considerations for UWB antenna will be discussed in the next section.

3.1.4 Antenna Network Scattering (S) Parameters

Once antenna is designed and constructed, it is essential to validate the design with measurements. A measurement is conducted based on the parameters that want to be observed. For analysis of parameters in circuit point of view, one-port measurement is needed to measure the reflected power from the antenna. When the reflected power is known, then parameters in circuit point of view can be derived. For field problem analysis, two-port measurement is necessary to measure how the antennas transmit and receive the signal/power. Single port measurement yields reflection coefficients while two-port measurement yields transmission coefficients. These concepts can be generalized for network analysis. In antenna measurement, this term and concept is absolutely used. The relations between network scattering parameters and antenna important parameters are necessary to be known. That is why it is also introduced in this chapter.

A two-port network problem can be illustrated by Fig. 3.4, where a_1 and a_2 are the input whilst b_1 and b_2 are the output at Port 1 and Port 2, respectively. This network is characterized by scattering parameters, or S-parameters.

Figure 3.4: A two-port network

$$[S] = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \tag{3.10}$$

By linking the input to the output, then

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \tag{3.11}$$

Thus, we have:

S_{11} = Port 1 reflection coefficient = b_1/a_1;

S_{12} = Port 2 to Port 1 transmission coefficient or gain = b_1/a_2;

S_{21} = Port 1 to Port 2 transmission coefficient or gain = b_2/a_1;

S_{22} = Port 2 reflection coefficient = b_2/a_2.

S-parameters are actually reflection and transmission coefficients for a network of N ports. In this case, N = 2. These parameters were originally introduced in optics, where optical waves were scattered by objects. The concepts were later extended to radio waves and RF engineering, but the term S-parameters has remained unchanged.

From Fig. 3.5, it can be clearly seen that a transmitting-receiving antenna system in the space can be considered a two-port network. The transmission and reflection can be characterized using S-parameters. S_{11} and S_{22} are the reflection coefficients of Antenna 1 and Antenna 2, respectively. They indicate how well the antenna feed line is matched with the antenna. So, it is known that reflection coefficient is actually S_{11} which the return loss and VSWR also can be derived from. There is no difference in meaning but the different symbols only stand for different terms; term of antenna characteristics and term of antenna network scattering. S_{21} and S_{12} are the transmission coefficients from one antenna to another. They are determined by the characteristics of both antennas (such as radiation patterns and matching) and the separation between them.

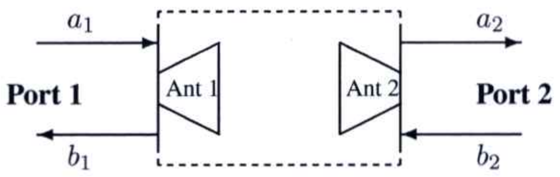


Figure 3.5: The equivalent two-port network with an antenna system

3.2 UWB Antenna

3.2.1 Requirements for UWB Antenna

The major difference in the transmission of UWB pulses is the antenna. Unlike the narrowband sinusoidal regime, the radiation of large bandwidth, non-sinusoidal waveforms is an active field of research in the antenna sector. As is the case in conventional wireless communication systems, an antenna also plays a crucial role in UWB systems. In UWB technology, the role of antennas is to operate with large bandwidth UWB waveform, not a continuous sinusoidal wave like in narrowband technologies.

The FCC's UWB bandwidth spans from 3.1 to 10.6 GHz. This huge bandwidth poses challenges on the antennas for a UWB system. Ideally, the antennas characteristics should be stable in this frequency range. The UWB antennas for wireless communications applications should have omnidirectional radiation pattern. They should radiate the pulse with minimal distortion and minimal late-time ringing. They should also be integrated with the generator on a chip. UWB antennas should be mounted on a dielectric substrate which will also serve as a protective mechanical shield and radiate through it. UWB antenna for wireless communications should be an integral part of the system and not a stand-alone element. This is an important issue in the successful implementation of UWB technology for wireless communication applications.

Based on the role and challenges of UWB antenna, there are main requirements for UWB antenna that can be summarized as follows.

Small size, low cost, and easy integration

Considering the practical applications of UWB antenna, UWB antennas should be small, low cost, and easily integrated with the transceiver circuits. UWB technology is used for short-range wireless communication where the antenna is usually embedded in portable devices. It is also highly desirable that the antenna feature low profile and compatibility for integration with printed circuit board (PCB). Hence, these requirements are very important for design consideration.

Wider impedance matching (requirement for return loss or VSWR)

As previously explained in antenna important parameters, impedance matching is a primary requirement for an antenna to decrease the reflected power at the antenna terminal. The impedance matching is also a key for an antenna whether the antenna can radiate for the operated frequency or not. For narrowband antenna, impedance matching is required only for a narrow frequency spectrum which is relatively not too difficult. However, in UWB technology, an antenna needs wider impedance matching according to the operated frequency range. What distinguishes a UWB antenna from other antennas is its ultra wide frequency bandwidth. So, the antenna must be matched at 50 Ω for wider frequency band. For a UWB antenna operated for the FCC band, its return loss must be lower than -10 dB at the range of 3.1 GHz to 10.6 GHz. If VSWR is used as the matching indicator, the VSWR of the antenna must be less than 2 at that band.

Stable radiation pattern

For a narrowband antenna, the radiation of the antenna can be determined by only show its radiation pattern for a single frequency at the H-plane and E-plane. For UWB antenna, radiation pattern at a particular frequency is definitely not enough. The pattern should be investigated at some frequency points inside the desired band. If the antenna is developed for FCC band, the radiation pattern can be investigated for 3 frequency points or more; at 3.1 GHz, at 6.85 GHz, and at 10.6 GHz for instance. The radiation characteristic of an antenna is always naturally different for different frequency points. For UWB antenna, it is necessary to make the radiation of the antenna becomes stable at the the entire band. With the stable patterns, every frequency component of a waveform would be treated (transmitted and received) with similar levels of radiation. Directional or omnidirectional radiation properties are needed depending on the practical application. Omnidirectional patterns are normally desirable in mobile and hand-held systems. For radar systems and other directional systems where high gain is desired, directional radiation characteristics are preferred.

Stable frequency response in the UWB band

To ensure the transmission performance of UWB antenna, the magnitude and the phase of frequency response of UWB antennas should be stable along the desired band. The magnitude (can be represented as antenna gain or antenna transfer function) should be flat, and the phase (can be represented as group delay) should be constant.

Good characteristics in time domain

A UWB antenna is required to achieve good time domain characteristics. For the narrow band case, it is approximated that an antenna has same performance over the entire bandwidth and the basic parameters, such as gain and return loss, have little variation across the operational band. In contrast, UWB systems often employ extremely short pulses for data transmission. In other words, enormous bandwidth has been occupied. Thus the antenna can't be treated as a "spot filter" anymore but a "band-pass filter". In this case, the antenna imposes more significant impacts on the input signal. As a result, a good time domain performance, i.e. minimum pulse distortion in the received waveform, is a primary concern of a suitable UWB antenna because the signal is the carrier of useful information. Therefore, it is indispensable and important to study the antenna's characteristics in time domain.

A good design of UWB antenna also should be optimal for the performance of overall system. For example, the antenna should be designed such that the overall device (antenna and RF front end) complies with the mandatory power emission mask given by the FCC or other regulatory bodies.

3.2.2 Classic UWB Antennas

The term broadband antennas has been applied in the past, but has usually described antennas which radiation and input impedance characteristics were acceptable over a frequency range of 2 or 3:1 before the 1950s. At that time, the bandwidth of the radiation pattern has been the limiting factor since antennas have been developed with an input-impedance that stays relatively constant with a change in frequency. But in the 1950s, a breakthrough in antenna evolution was made which extended the bandwidth to as great as 40:1 or more [41].

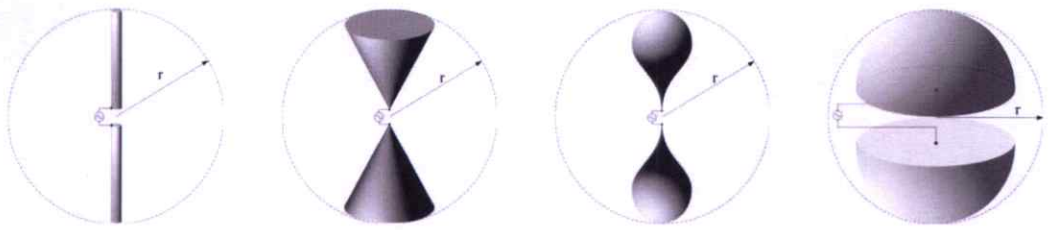
Biconical antenna, helical antenna, Yagi-Uda antenna, equiangular spiral antenna, log-periodic dipole array (LPDA) antenna are some popular broadband antennas made in the past. Among those antennas, only biconical antenna, spiral antenna and log-periodic antenna were considered for UWB antenna. General polarization of helical antenna is elliptical, hence the applications are limited. This type of an antenna is only useful in ultra high frequency (UHF) communication networks where considerable amount of fading may exist. Yagi-Uda antenna is relatively too big in structure and also practically used for UHF [38]. Biconical, equiangular spiral, and LPDA antenna structures are shown in Fig. 3.6 [42].

Biconical antenna is basically a modification from dipole antenna. Since the dipole antenna has relatively narrow bandwidth, its modifications lead antenna to achieve broader bandwidth. Four dipole configurations are shown in Fig. 3.7. One simple configuration that can be used to achieve broadband characteristics is the biconical antenna formed by placing two cones of infinite extent together. The tapered dipole and the hemispherical dipole also can be used to make broadband or UWB antennas, but the shape of biconical is the simplest one.

In spite of dipole configurations, there are monopole configurations that also can be used to make UWB antennas. For every monopole configuration shown in Fig. 3.8, the pole is positioned over a ground plane which makes the antenna to have directional radiation. The common

(a) (b) (c)

Figure 3.6: Classic UWB antennas: (a) Biconical antenna, (b) Equiangular spiral antenna, (c) LPDA antenna



(a) (b) (c) (d)

Figure 3.7: Dipole configurations: (a) Common Dipole, (b) Biconical Dipole, (c) Tapered Dipole, (d) Hemispherical Dipole

monopole has relatively narrow bandwidth, but its modifications can achieve broader bandwidth. Biconical antenna is more popular as a classic UWB antenna than monopole conical (usually named as discone antenna) because it has omnidirectional pattern which is more applicable in practice. Shapes of biconical antenna and other dipole or monopole antenna configurations are frequently adopted for later UWB antennas such as bow-tie antenna [43], diamond antenna [44], etc.

Equiangular spiral antenna and LPDA antenna are the types of frequency independent antenna. There are two principles for achieving frequency independent characteristics. The first one, "angles" principle, where the impedance and pattern properties of an antenna will be frequency independent if the antenna shape is specified only in terms of angles. For LPDA antenna, its entire shape is not solely specified by angles; it is also dependent on the length from the origin to any point on the structure. But LPDA antenna can still exhibit frequency independent characteristics. Even though the shape of the biconical antenna can be completely specified by angles, the current on its structure does not diminish with distance away from the input terminals, and its pattern does not have a limiting form with frequency. Thus the biconical structure cannot be truncated to form a frequency independent antenna. The second principle accounting for frequency independent characteristics is self-complementarity. If an antenna is its own complement, frequency independent impedance behavior is achieved. The spiral antenna is an example of antenna that

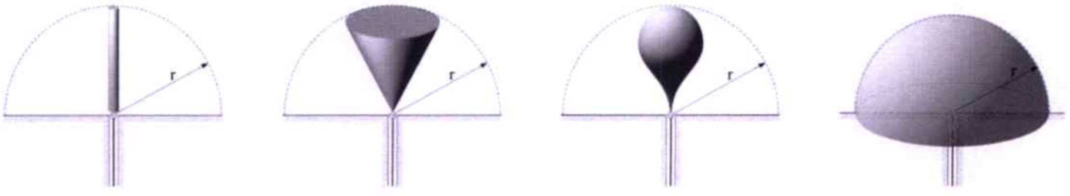


Figure 3.8: Monopole configurations: (a) Common Monopole, (b) Conical Monopole, (c) Tapered Monopole, (d) Hemispherical Monopole

uses self-complementary principle.

Although the classic UWB antennas (biconical, spiral, and LPDA) can operate over an extremely wide frequency range, they still have some limitations. The configuration needs to be infinite in principle, but is usually truncated in size in practice. This requirement makes them quite large in terms of wavelength. Frequency independent antennas, especially LPDA, tend to be dispersive because they radiate different frequency components from different parts of the antenna, i.e. the smaller-scale part contributes higher frequencies while the large-scale part accounts for lower frequencies. Consequently, the received signal suffers from severe ringing effects and distortions. Due to this drawback, frequency independent antennas can be used only when waveform dispersion may be tolerated.

3.2.3 UWB Planar Monopole Antenna

UWB antennas have been around for many decades and are used extensively. In the past, the classic UWB antennas satisfied the requirements for commercial UWB systems. However, the UWB technology has gained more and more popularity and become a good candidate for short-distance high-speed wireless communication. Furthermore, UWB antennas need different requirements, i.e. small size, due to its applications such as portable electronics and mobile communications. Therefore, the classic UWB antennas with the big size are not suitable. To satisfy different requirements such as size, gain and radiation patterns, many innovations of UWB antenna are proposed [45].

One of the great innovations on UWB antenna is planar monopole antenna. The planar monopole antenna can be viewed as the evolution of classic UWB antennas, especially from biconical antenna as shown in Fig. 3.9 [46]. The simplification of biconical antenna emerges plate monopole antenna, and then developed into the planar monopole structure by replacing an electrically large conducting plate acting as a ground plane as shown in Fig. 3.9 (e). Hence, the planar monopole antenna contains two radiating components which are a pole and a finite ground plane placed in parallel to the pole. These two components can be separated by a dielectric substrate. In practice, the planar monopole antenna is made by printing the copper on a printed

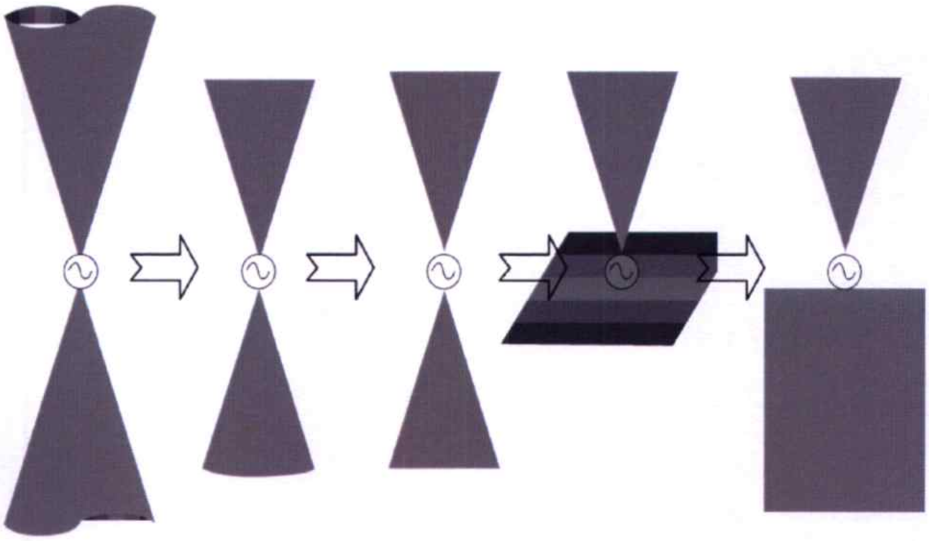


Figure 3.9: The evolution of classic antenna to planar monopole antenna, (a) Infinite biconical antenna, (b) Finite biconical antenna, (c) Bow-tie antenna, (d) Plate monopole antenna, (e) Planar monopole antenna

circuit board (PCB) into the desired antenna shape.

In other point of view, UWB planar monopole antenna can be viewed as the evolution of planar antennas such as patch antenna and microstrip patch antenna as shown in Fig. 3.10 [47]. Planar antennas have been popularly used as directional narrowband antennas. Ideally, a planar antenna consists of patch and infinite ground plane etched on a dielectric substrate or PCB. There are many types of the patch shape in the planar antennas such as rectangular, triangular, circular, or elliptical. The ground plane is cut to limit the size of the antenna. The planar antenna with feeding strip (usually called microstrip feed) is more preferable since such this feeding method is easier in fabrication.

In general, all antennas comprising planar or curved surface radiators or their variations and at least one feed are termed "planar antennas" [46]. By looking at the Fig. 3.10 (b), the radiating patch on the dielectric substrate is also can be considered as a pole. Since there is only one patch fed by microstrip, it can be called "monopole". Hence, the microstrip patch antenna is one of planar monopole antenna. The term "planar monopole antenna" is used to generalize the feeding structure. In other cases, coplanar wave guide (CPW) method also can be used as the feeding structure where the ground plane is placed beside the feeding strip or on the same side with the patch. Although using different feeding structure, the antenna still can be named as planar monopole antenna since it has "a pole" and "planar".

Planar monopole antennas have numerous advantages, including:

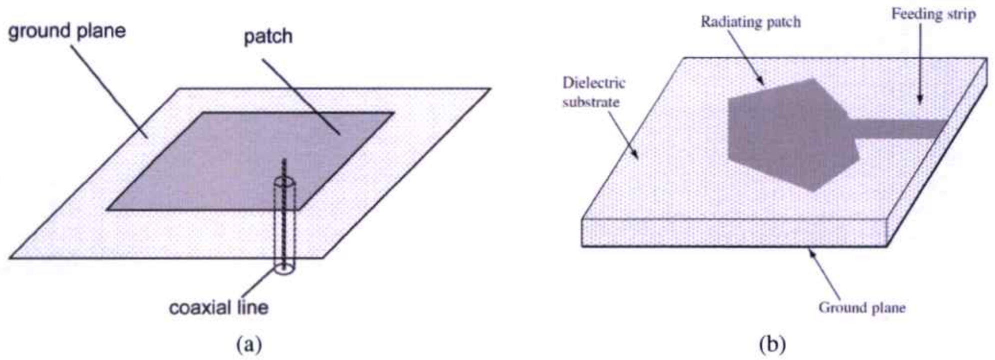


Figure 3.10: Planar antennas: (a) Patch antenna with coaxial feed, (b) Patch antenna with microstrip feed

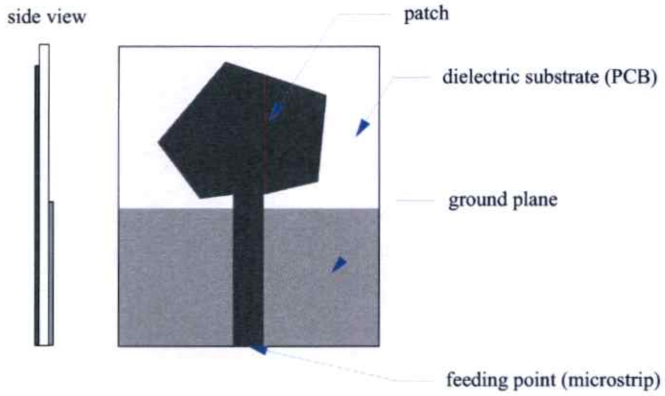


Figure 3.11: The typical structure of UWB planar monopole antenna

- light weight and small size
- easy fabrication or manufacturing using printed circuit technology
- easily integrated with electronic components
- relatively low cost, especially for mass production
- possibility of printing on curved surfaces to make conformal antennas
- easily integrated into arrays

Conventionally, planar monopole antennas were made for narrowband technology with directional radiation pattern. The directional radiation is resulted from the big ground plane radiating to the patch. For UWB technology, omnidirectional radiation is more suitable for most practical applications. Ideally, the ground plane should be infinite as for a monopole antenna. But, in reality, a small ground plane is desirable [40]. By cutting or truncating the ground plane to a particular size, omnidirectional radiation pattern can be achieved. The typical structure of UWB planar monopole antenna is illustrated in Fig. 3.11.

Table 3.2: Broadband techniques for planar monopole antenna

Approach	**Techniques**
Lower the Q	Select the radiator shape
	Thicken the substrate
	Lower the dielectric constant
	Increase the losses
Use impedance matching	Insert a matching network
	Add tuning elements
	Use slotting and notching patches
Introduce multiple resonances	Use parasitic (stacked or co-planar) elements
	Use slotting patches, insert impedance networks
	Use an aperture, proximity coupling

3.2.3.1 Broadband Techniques for Planar Monopole Antenna

To increase the bandwidth of microstrip patch antenna such as planar monopole antenna, there are several broadband techniques introduced in [47]. The techniques are summarized in Table. 3.2.

It is known that the factors affecting the bandwidth of a microstrip patch antenna are primarily the shape of the radiator, the feeding scheme, the substrate and the arrangements of radiating and parasitic elements. Essentially, the broad bandwidth of a microstrip patch antenna can be attributed to its low Q value and simultaneously well-excited multiple resonances. Lowering the Q by reducing the energy around the radiator or increasing losses broadens the bandwidth at its resonance. The quality factor (Q) is inversely proportional to the impedance bandwidth of an antenna. If the impedance matching of the antenna is denoted by voltage standing wave ratio (VSWR), the Q can be written as

$$Q = \frac{VSWR - 1}{BW\sqrt{VSWR}} \tag{3.12}$$

where BW is the bandwidth of the antenna. Alternatively, by inserting a broadband impedance network between the antenna and the feeder, good matching over a broad frequency range can be attained. If two or more adjacent modes are well excited simultaneously, the bandwidth can be twice or more than that for the single resonance.

For UWB planar monopole antenna, broadening bandwidth of the antenna might need more efforts. Some broadband techniques may be combined to enhance the impedance matching so that the bandwidth of a planar monopole antenna covers the UWB band. Shape modifications of antenna components are feasible to broaden the bandwidth of planar monopole antenna according to the approach of lowering the Q. Some examples of pole modification for planar monopole antennas are depicted in Fig. 3.12.

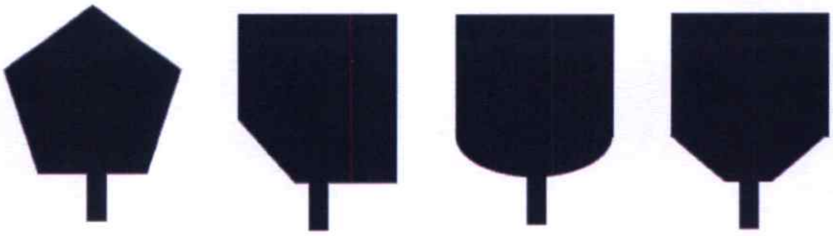


Figure 3.12: Examples of pole modifications to broaden the bandwidth of planar monopole antennas

3.2.3.2 Analysis of Microstrip Feeding for UWB Planar Monopole Antenna

The already mentioned broadband techniques implies that the design of UWB panar monopole antenna is actually much concerned on broadening the bandwidth of basic planar monopole antenna by some modifications on antenna elements. UWB planar monopole antenna design is not much tied to any mathematical calculation of the antenna dimensions, but it is more flexible.

There are existing mathematical formulas to design the basic planar monopole antenna for narrowband technology, such as the rectangular planar monopole antenna [40]. The size of the elements of the rectangular planar monopole antenna can be calculated to meet the resonance frequency. However, UWB antennas can be supposed as antennas which have no resonance or precisely have resonances at broad range of frequency. Therefore, not all of the mathematical approaches of narrowband planar monopole antenna are applicable for UWB planar monopole antenna.

Although the structure of UWB planar monopole antenna is modified from the basic planar monopole antenna, the feeding structure is still the same, microstrip feeding. Analysis of the feed is important to ensure the input terminal impedance is matched at 50 Ω or 75 Ω (*additional note: from industrial standard, the input impedance must be 50 Ω if the antenna is intended to act as both transmitter and receiver, and must be 75 Ω if the antenna is intended to act as only transmitter or receiver*). There are two methods of analysis of microstrip feeding. The first method is called transmission line method, and the second one is cavity method [38]. The cavity model is more accurate but more difficult than the transmission line model. The transmission line model is simple and sufficient for consideration of input impedance of planar monopole antenna with microstrip feeding. The transmission line model for a microstrip line is presented in Fig. 3.13.

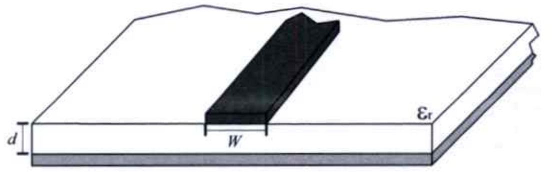


Figure 3.13: Microstrip feeding for UWB planar monopole antenna

From the literature [48], The antenna input impedance Z_0 can be calculated as

$$Z_0 = \begin{cases} \dfrac{60}{\sqrt{\epsilon_e}} \ln\left(\dfrac{8d}{W} + \dfrac{W}{4d}\right) & \text{for}\, W/d \leq 1 \\ \dfrac{120\pi}{\sqrt{\epsilon_e}\left[W/d + 1.393 + 0.667\ln\left(W/d + 1.444\right)\right]} & \text{for}\, W/d \geq 1 \end{cases} \tag{3.13}$$

where the effective dielectric constant of a micro-strip line ϵ_e is given approximately by

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2\sqrt{1 + 12d/W}} \tag{3.14}$$

W is the width of the feed, d is the dielectric thickness. By these equations, the W of a UWB planar monopole antenna can be determined when the Z_0 is given.

3.3 Antenna Design and Simulation Using CST Microwave Studio®

A large number of electromagnetic modeling software packages have been developed and are available on the market. Some are more successful technically and commercially than others. Some have become industrial standard design and analysis software.

Computer simulation technology (CST) Microwave Studio is a fully featured software package for electromagnetic analysis and design in the high frequency range. It is a specialized tool for the fast and accurate 3D electromagnetic simulation of high frequency problems. Along with a broad application range, CST Microwave Studio offers considerable product-to-market advantages: shorter development cycles; virtual prototyping before physical trials; optimization instead of experimentation. It simplifies the process of inputting the structure by providing a powerful solid modeling front end. CST Microwave Studio enables the fast and accurate analysis of high frequency (HF) devices such as antennas, filters, couplers, planar and multi-layer structures and electromagnetic compatibility (EMC) effects. Exceptionally user friendly, CST MWS quickly gives an insight into the EM behavior of high frequency designs [49].

Using CST Microwave Studio, an antenna can be designed in 3D with suitable components like in reality. By connecting ports to the antenna design, the antenna network parameters such as S_{11} or S_{21} can be obtained. Various antenna parameters including antenna radiation pattern also can be simulated. The workspace of CST Microwave Studio is shown in Fig. 3.14.

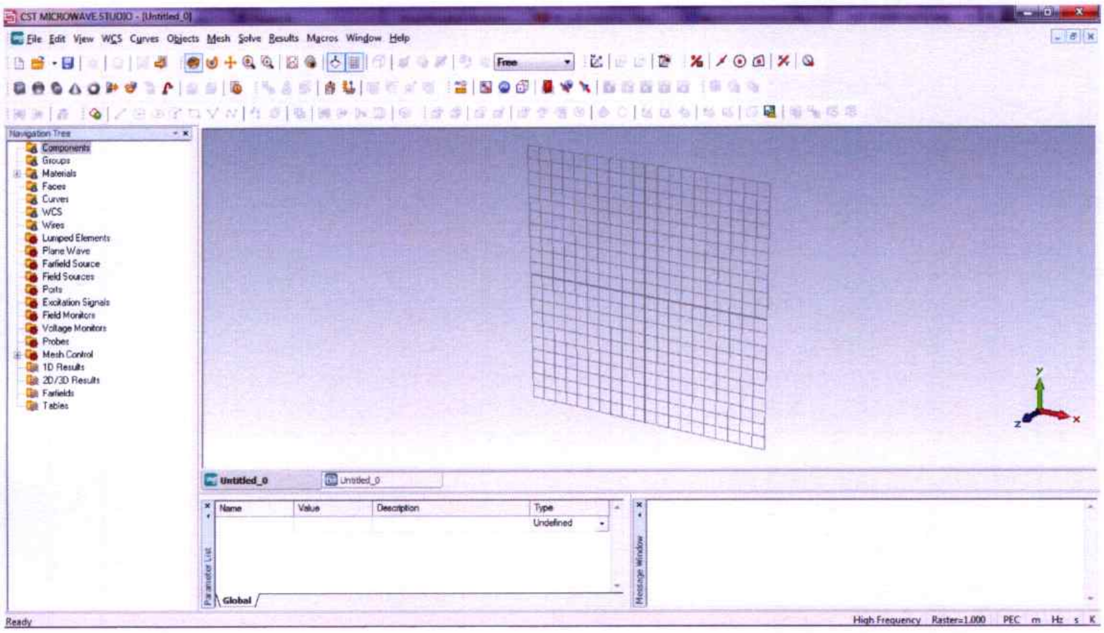


Figure 3.14: Workspace of CST Microwave Studio

CST Microwave Studio has powerful simulation performance and user-friendly interface. It uses FIT (Finite Integration Technique) and FDTD (Finite Difference Time Domain) as the numerical analysis [50]. It has four different simulation techniques (transient solver, frequency domain solver, eigen-mode solver, modal analysis solver) which best fit their particular applications. The most flexible tool is the transient solver, which can obtain the entire broadband frequency behavior of the simulated device from only one calculation run. For UWB antenna design, transient solver is more suitable as it is intended for investigating broadband frequency behavior. This solver is also very efficient for most kinds of high frequency applications such as connectors, transmission lines, filters, antennas and many more.

3.4 Summary

This chapter describes the theory of antenna from its basics, such as definition and important parameters, to the explanation of UWB planar monopole antenna. There are special requirements and challenges for UWB antenna which must be solved by UWB antenna designers. The huge bandwidth of UWB systems poses unique research challenges which have to be dexterously addressed. Furthermore, size of antenna is also an important matter for UWB technology. Some classic UWB antennas such as biconical antenna, spiral antenna, and LPDA antenna are not suitable for practical applications because of their big sizes. Planar monopole antenna becomes a promising antenna for UWB technology with many benefits and advantages. Basics of broadband techniques and analysis of planar monopole antenna are also addressed in this chapter. Design and simulation for development of UWB planar monopole antenna can be done by electromagnetic simulation software such as CST Microwave Studio.

CHAPTER IV

DESIGN OF UWB PLANAR MONOPOLE ANTENNA

In this chapter, two studies on UWB planar monopole antenna design are reported with an emphasis on the understanding of the design guidelines and their characteristics. The developed antennas are UWB planar monopole antennas with elliptical pole. The antenna characteristics are investigated from simulations and verified with measurements to obtain some insights for designing this type of antenna.

4.1 Specific Literature Review and Problem Statement

In the previous sections, some delineations of UWB planar monopole antenna have been explained in general views. There are actually plenty number of research in the topic of UWB planar monopole antenna design. Some studies prove that elliptical shape for the pole provides better design flexibility and better performance compared to the circular or the other shapes [51–53]. A UWB elliptical planar monopole antenna with extremely wide impedance bandwidth (47:1) is developed in [54], but the size of the antenna is about 120 mm which is too big. Some UWB elliptical planar monopole antennas studied in [55] concern on the effect of ground plane size to the return loss and efficiency. The larger ground plane provides higher radiation efficiency. A design from [56] performs the utilization of slots for band rejection at WLAN band by studying the effects of slots length to the VSWR of the antenna.

Other literatures [57–64] also develop UWB elliptical planar monopole antennas by showing their designs which satisfy the FCC's UWB bandwidth. The used criterion to be satisfied is either return loss or VSWR. Most of their successful antennas have size about 40 x 40 mm. In [59, 60], small or miniaturized designs with overall antenna size about 30 x 30 mm are developed, but the measured return losses are failed to comply FCC's UWB bandwidth especially at the lower cut-off frequency. Some other literatures propose techniques by meandering the feed line [61] or by modifying the ground plane [62, 63] for lowering the return loss of their antennas.

All of the investigated literatures tend to limit their design consideration on the impedance characteristic of their antennas, i.e. return loss or VSWR. Broaden the impedance matching for UWB antenna is not an easy task indeed. However, it should be realized that the radiation characteristic of UWB antennas much determine the transmission performance of the antenna. Investigating radiation pattern at particular frequency points whose power values are normalized cannot present the radiation characteristic over the UWB frequency range. When the design consideration focused on return loss of the antenna, the radiation might drop at higher frequencies [64, 65].

There should be more considerations in designing this type of antenna. Not only to satisfy the requirement of impedance bandwidth but also about mechanism and approach to make the characteristics and performances better. Therefore, design of UWB planar monopole antenna still needs to be studied in more detail to have better UWB planar monopole antenna.

4.2 Design Methodology

The main processes in the design of UWB planar monopole antenna are "specifying material" , "calculating width of microstrip feed", "parametric study & optimization ", and "checking characteristics". Basics of them will be introduced below.

Specify material

A material must be chosen before making an antenna. Since the antennas made in this thesis are "planar", therefore the choices of material are limited to the materials in the form of PCB. A double-sided PCB contains two thin copper layers separated by planar dielectric substrate between them. The most common dielectric substrate of PCB is Fibreglass-resin laminate (FR4), with the dielectric constant (ϵ_r) of approximately 4.3. Some other dielectric substrates of PCB which can be found in markets are Roger, Teflon, Duroid, and etc. The thickness of PCB is normally 1.6 mm or 0.8 mm.

Calculate width of microstrip feed

Analysis of microstrip feeding for PMA has been explained in Chapter 3. In microstrip feeding, if the properties of the material (dielectric constant and thickness) are known, the remaining parameter influencing the input terminal impedance is the width of the microstrip feed. After it is calculated, it can be verified by simulation in CST Microwave Studio whether the desired input impedance is achieved or not.

Parametric Study & Optimization

Parametric study is carried out to provide physical insight into antennas. It shows that the characteristic of the antenna, especially impedance matching, is mainly affected by geometrical and electrical parameters, such as the dimensions related to the pole, feeding strip, ground plane as well as the dielectric constant of the substrate. Parametric study is simply done by assigning initial dimensions for all parameters and then manually adjusting the dimension of one parameter while the others are fixed. For every adjustment, the characteristic of impedance matching (return loss or VSWR) of the antenna is recorded. By this way, the effects of changing dimension of each parameter can be known and the suitable dimensions of all parameters can be approximated to get the desired antenna characteristic. The approximated dimension is sometimes in a range which should be optimized. Optimization is the complementary process to help antenna designers obtaining the best dimension for each parameter. So, parametric study & optimization is a unity of important process in an antenna design. The flowchart of parametric study & optimization is presented in Fig. 4.1. Process of parametric study & optimization is facilitated by CST Microwave Studio as shown in Fig. 4.2.

Check the antenna characteristics As the finalization of the design, the antenna characteristics must be checked to satisfy the design goal. For UWB planar monopole antenna, the main requirements that should be satisfied are to get the antenna bandwidth covering the desired UWB band and to get omnidirectional radiation pattern.

In this chapter, the design methodology will be divided into two procedures which are described as follows.

4.2.1 Common Procedure

From the previous studies, the most obvious thing is that UWB antenna designers use parametric study (see Fig. 4.1) to achieve UWB bandwidth for their antennas. The common targets are: return loss <-10 dB over the UWB bandwidth and omnidirectional radiation pattern. The return loss is investigated to show that the antenna impedance satisfies over the UWB bandwidth. The radiation is usually checked by simulation and measurement in 3 frequency points, 3.1 GHz, 6.85 GHz, and 10.6 Ghz. The flowchart of UWB planar monopole antenna design with common procedure is shown in Fig. 4.3.

4.2.2 Extended Procedure

One of the main processes in UWB planar monopole antenna design is checking the antenna characteristics. In common procedure used by most antenna designers, the checked characteristics are limited to return loss and radiation patterns. The radiation patterns are usually just shown at particular frequency points, therefore the stability of radiation over the entire UWB band is usually unobserved. For UWB antennas, transmission characteristics are influenced by the stability/flatness of radiation over the entire UWB band. When the radiation of a UWB antenna is flat or constant over the desired range, the transmission characteristic of the antenna would be good. Nevertheless, it is also time-consuming to see radiation pattern at more frequency points orfor the entire UWB bandwidth.

There are two ways to check the transmission characteristic or the radiation stability of UWB antennas. The first way is by putting a probe at a specific location or antenna orientation. The probe is used to record the electric field at the specified location during the transient analysis. The electric field radiated by UWB antenna will be recorded over the determined frequency range. The second way is by copying and transforming the antenna shape to a certain distance and then assigns a new port for the second antenna which is identical to the designed antenna. This way

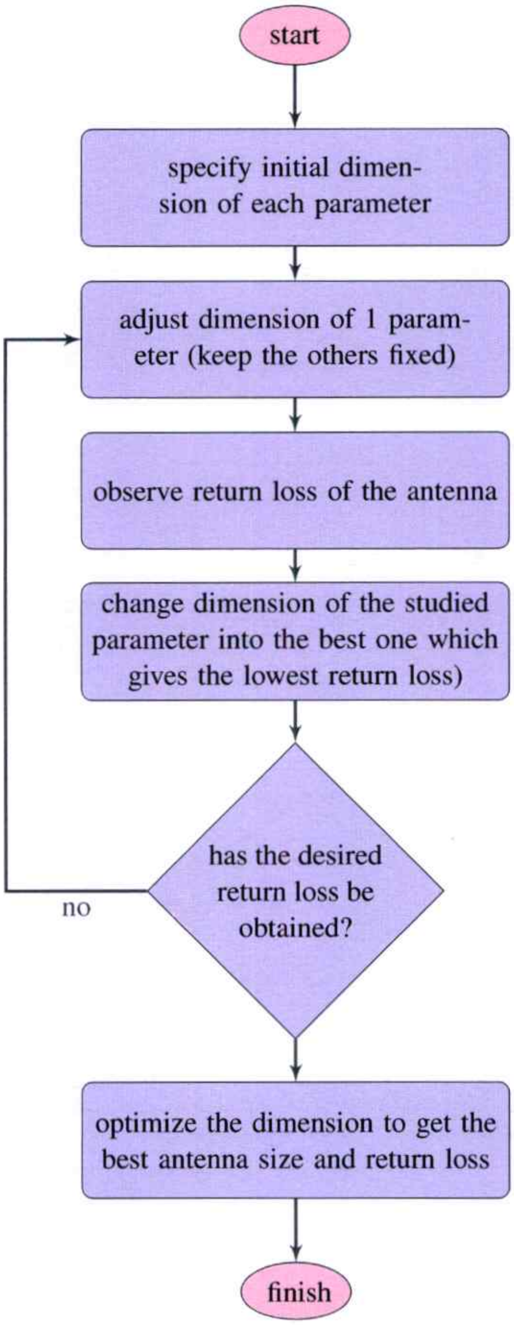
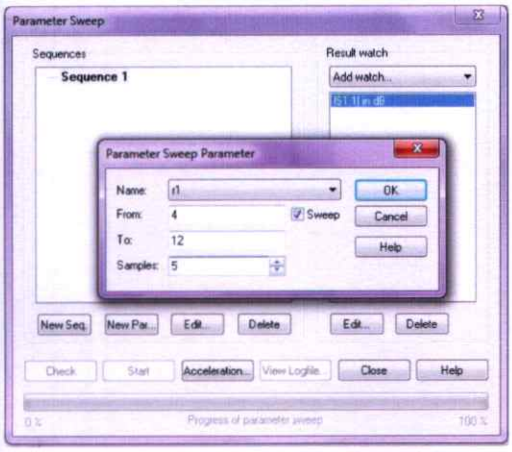
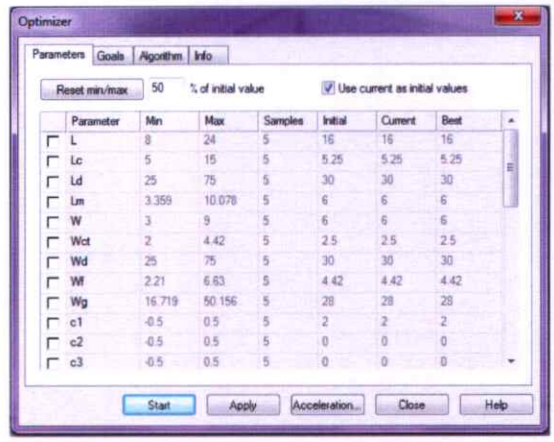


Figure 4.1: Flowchart of parametric study & optimization



(a)



(b)

Figure 4.2: Facility of parametric study & optimization in CST Microwave Studio: (a) Solve –Transient solver –Parameter sweep, (b) Solve –Transient solver –Optimizer

is similar to measurement by two-identical-antenna method, but done in simulation. By this way the transmission magnitude between both antenna ports or the S_{21} parameter can be observed. It denotes the transmission characteristic of the UWB antenna for the desired frequency range.

The extended procedure of UWB planar antenna design is to add more antenna characteristic parameter to be checked in the design flow which is the antenna transmission characteristic which can be seen by the radiated electric field or by simulation of two-identical-antenna transmission. The design flowchart of UWB planar monopole antenna with extended procedure is presented in Fig. 4.4.

4.3 Fabrication Technique

Once the design processes finished in simulation, the UWB planar monopole antenna needs to be fabricated using the specified material. This section briefly describes the fabrication technique for UWB planar monopole antenna.

An advantage of planar monopole antenna is easy fabrication or manufacturing using printed circuit technology. The fabrication technique is similar as making PCB for electronic circuits. The popular technique for PCB printing is named etching. Etching is the easiest and most cost effective for PCB printing. Etching is the process of chemically removing the unwanted copper from a plated board. The way is to put a mask or resist on the portions of the copper that we want to remain after the etch. These portions that remain on the board are the traces that carry electrical current between devices. The detail process can be seen in [66].

After the PCB is etched according to the shape of the design, the PCB needs to be connected to a SMA connector. SubMiniature version A (SMA) connector is coaxial RF connectors as the minimal connector interface for coaxial cable with a screw type coupling mechanism. A high

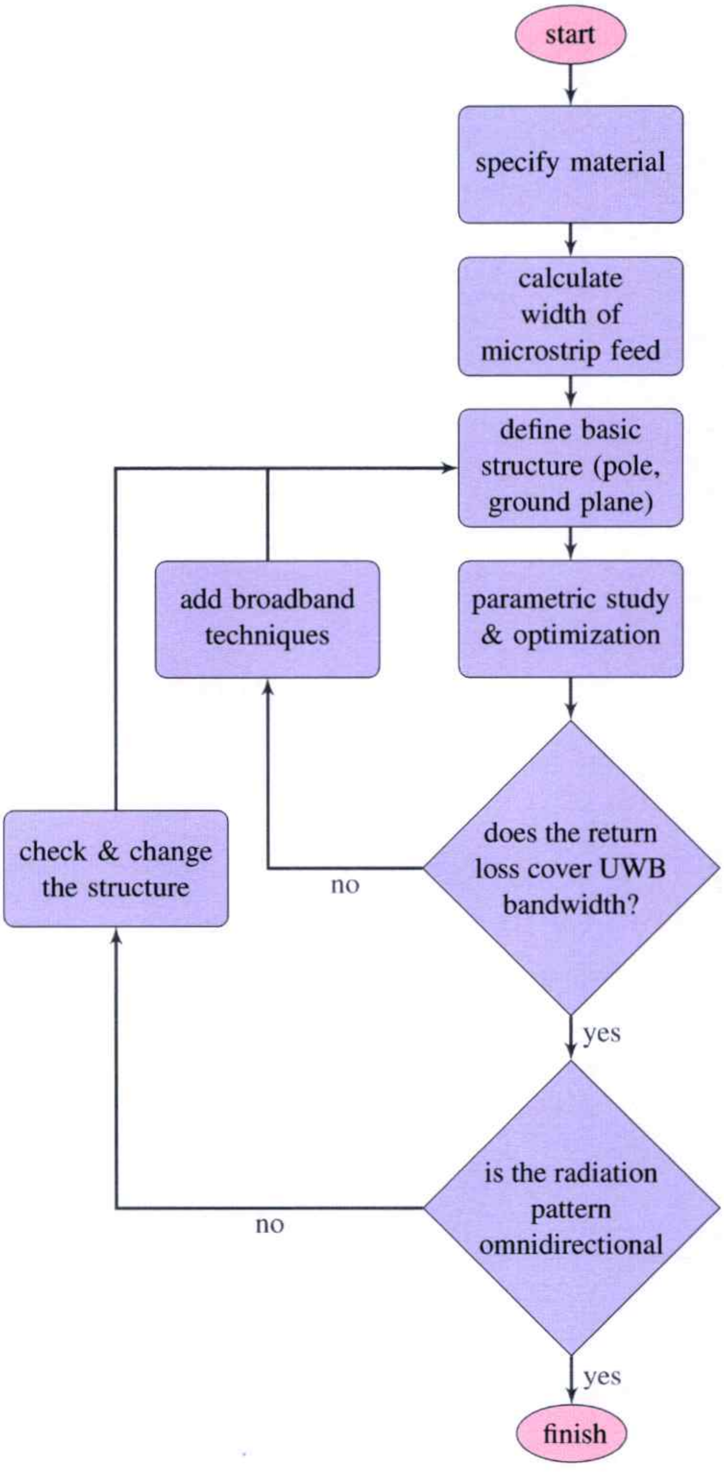


Figure 4.3: Design flowchart of UWB planar monopole antenna with common procedure

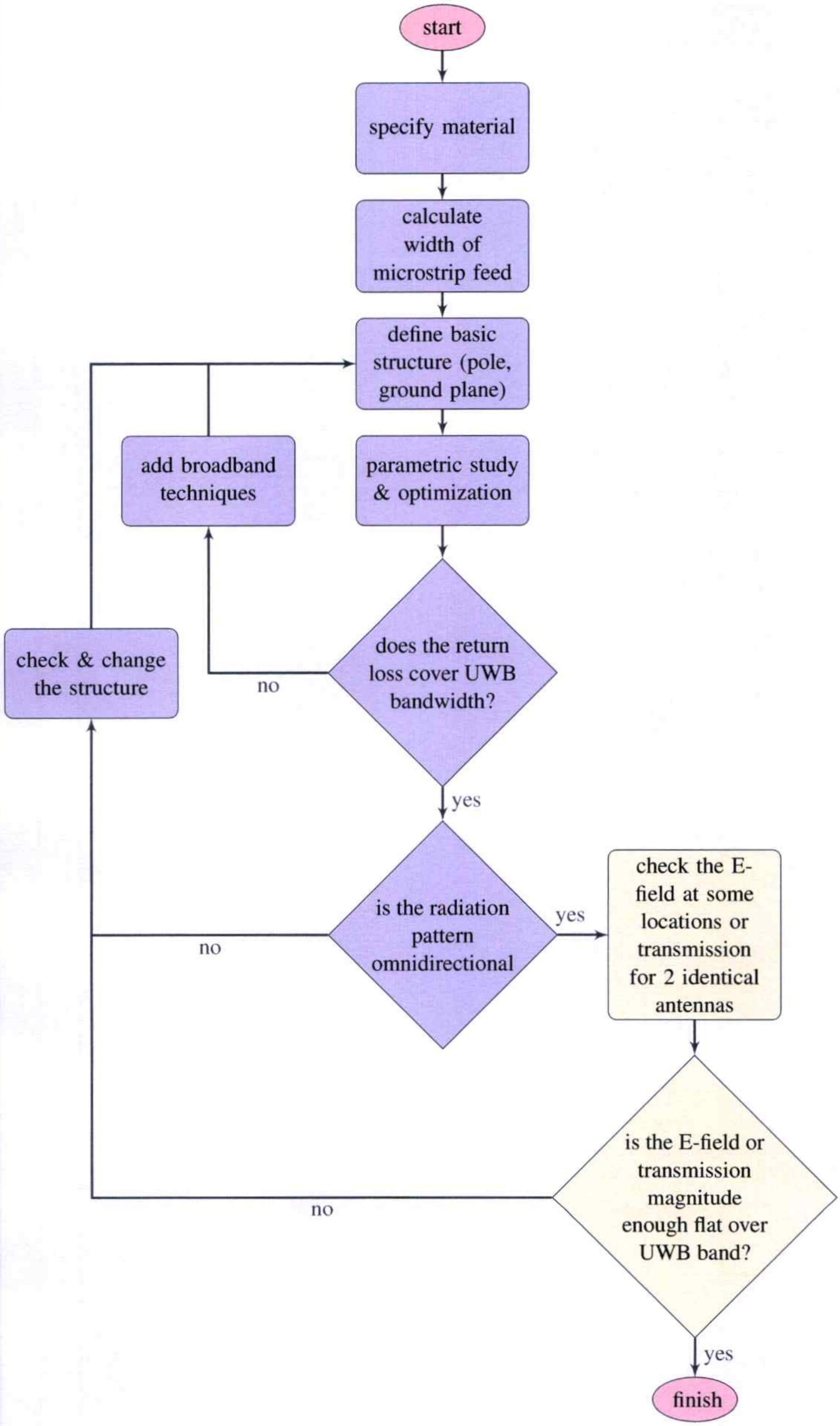


Figure 4.4: Design flowchart of UWB planar monopole antenna with extended procedure

quality SMA connector can perform through 18 GHz. Connection between the antenna and SMA connector also has important role which affects antenna characteristic in measurement. Especially for microstrip antenna, ground plane of the antenna should be well connected to SMA connector ground [67]. In this matter, soldering technique and the quality of soldering material become crucial consideration in the fabrication process. Except the tools and materials for PCB etching, the tools needed for antenna fabrication are listed below:

- solder
- solder sucker
- high quality tin (usually with silver alloys)
- vise
- cutter

Since the antenna is very simple, there are only two materials needed for antenna fabrication as listed below:

- The etched PCB
- SMA connector female 50 Ω

4.4 Design Processes and Results

In these UWB planar monopole antenna designs, there are some predetermined parameters including bandwidth, input impedance, and material which are specified below.

Bandwidth	3.1 GHz to 10.6 GHz
Input impedance	50 Ω
Material	Teflon PCB
	dielectric constant (ϵ_r) = 2.5
	thickness (d) = 1.6 mm

The bandwidth is specified according to the FCC's UWB band. The Teflon substrate is chosen because it is low cost and it has good performance for high frequency purposes. The thickness of 1.6 mm is chosen because the thicker dielectric material gives lower quality factor (Q). As explained in Chapter 3, the low Q could broaden the antenna bandwidth. Therefore, the efforts to increase the antenna bandwidth would be easier.

With the dielectric constant (ϵ_r) = 2.5 and thickness (d) = 1.6 mm, the width of the feed can be solved using Eq. 3.13 as

$$\epsilon_e = \frac{2.5+1}{2} + \frac{2.5-1}{2\sqrt{1+12(1.6)/W}} \tag{4.1}$$

$$50 = \begin{cases} \dfrac{60}{\sqrt{\epsilon_e}} \ln\left(\dfrac{8(1.6)}{W} + \dfrac{W}{4(1.6)}\right) & \text{for}\, W/(1.6) \leq 1 \\ \dfrac{120\pi}{\sqrt{\epsilon_e}\left[W/(1.6) + 1.393 + 0.667\ln\left(W/(1.6) + 1.444\right)\right]} & \text{for}\, W/(1.6) \geq 1 \end{cases} \quad (4.2)$$

In the calculations above, the only remaining variable is the width of the feed (W). By using iterative calculation in a computation program, there is no solution for $W/(1.6) \leq 1$. For $W/(1.6) \geq 1$, the obtained W is 4.444 mm. To confirm this calculation, a microstrip line is modeled in CST Microwave Studio. From simulation, the input impedance with 4.444 mm line is not resulting exactly 50 Ω. Then, the width of feed is optimized to 4.42 mm so that the input impedance becomes 50 Ω.

For antenna simulation using CST Microwave Studio, the higher specification of a computer and more multi-threading features will reduce the simulation time. In this thesis, the computer specification used for simulation is as follows.

Processor	Intel® Core™i5 2.90 GHz (4 cores)
Memory	4 GB
Harddisk drive	320 GB

In this section, two design processes and results of UWB elliptical PMA are reported. From now on, the term planar monopole antenna will be abbreviated as PMA.

4.4.1 A Common UWB Elliptical PMA Designed with the Common Procedure

For simulation, the UWB elliptical PMA designed with the common procedure is modeled in CST Microwave Studio as shown in Fig. 4.5. Because this antenna is designed with the common procedure, then this antenna is named as "common UWB elliptical PMA".

4.4.1.1 Antenna Geometry and Prototype

The geometry and prototype of the common UWB Elliptical PMA is depicted in Fig. 4.6. The overall size is quite small, about 4 x 4 cm. Elliptical shape is chosen due to its flexibility and ability to provide wide impedance bandwidth. By using only two parameters (two diameters of ellipse), the curvature of the antenna is easily changed. Detail dimensions of the antenna were determined based on empirical parametric study assisted by optimization in CST Microwave Studio. The optimized dimensions of the antenna are listed in Table 4.1.

4.4.1.2 Parametric study

Size of elliptical pole

Based on the geometry of the antenna in Fig. 4.6 (a), there are two parameters (**a** and **b**) which specify the size of the elliptical pole. The effects of both a and b to the return loss of

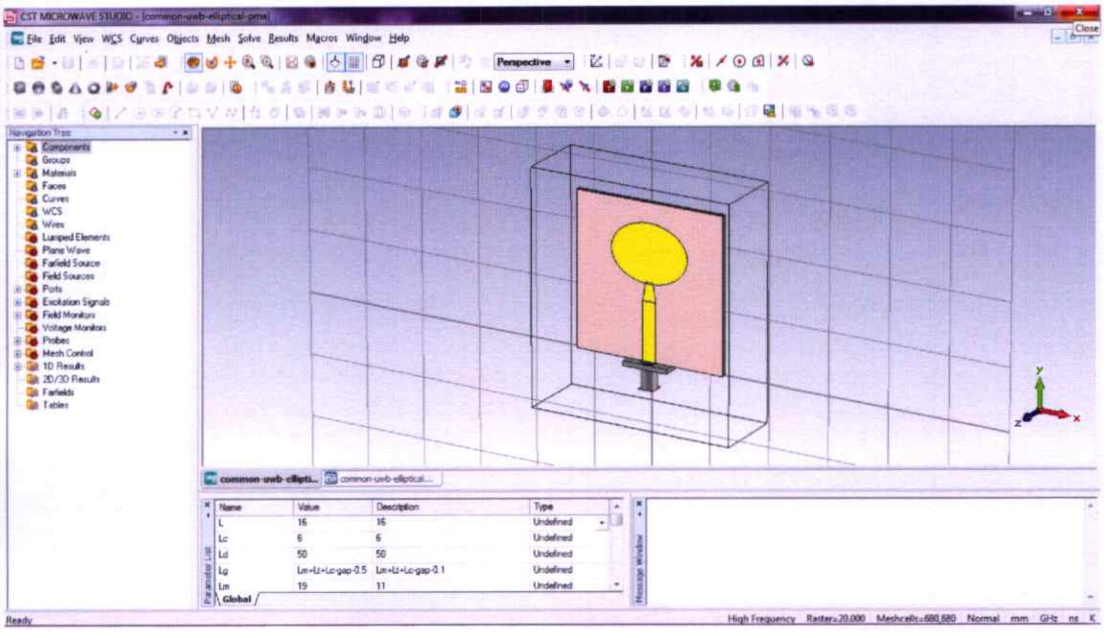


Figure 4.5: 3D model of the common UWB elliptical PMA in CST Microwave Studio

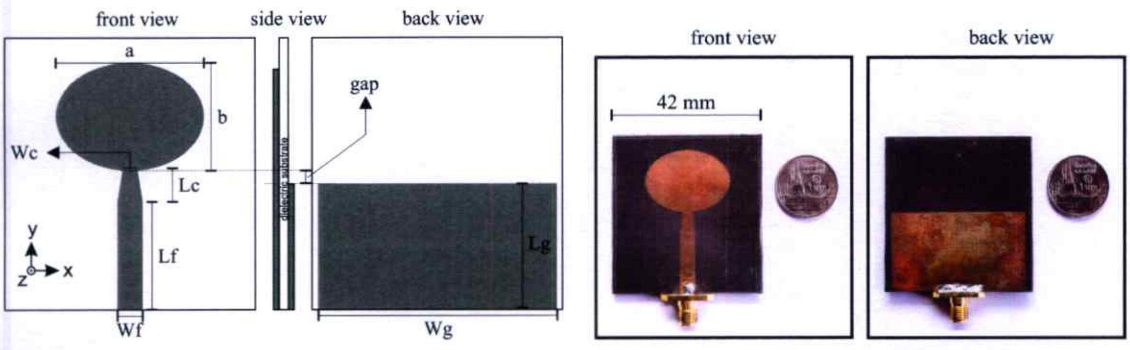


Figure 4.6: The common UWB elliptical PMA: (a) Geometry, (b) Prototype

the antenna are presented in Fig. 4.7. Adjusting **a** to smaller or bigger dimensions than the normal one will cause impedance mismatch (high return loss) at a certain frequency range, especially 4 GHz to 8 GHz. Adjusting **b** affects the cut-off at lower frequencies. Therefore, the size of elliptical pole must be well adjusted to a proper dimensions providing low return loss over the desired UWB band. In this case, the proper dimensions of **a** and **b** are 26 mm and 19 mm, respectively.

Size of ground plane

Ground plane is also a crucial consideration for the antenna. Adjustments of **Wg** and **Lg** with their effects to the return loss is presented in Fig. 4.8. The ground plane of the antenna was made to be large enough in consideration of efficiency and lower cut-off frequency. Smaller **Wg** would shift the lower cut-off frequency. However, the wider **Wg** much increases the overall size of the antenna. The **Lg** should be made such that the upper part of

Table 4.1: Dimensions of the common UWB elliptical PMA (in mm)

Wf	Wc	Wg	Lf	Lc	Lg	a	b	gap
4.42	2.5	42	19	6	24.3	26	19	0.2

the ground plane close to the lower part of the elliptical pole separated by dielectric. Hence, the desired return loss can be obtained as in Fig. 4.8 (b).

Tapered feed line

Tapered feed line is a change of the feed on the planar monopole antenna by angular approach which is classically used to make UWB antenna such as biconical, spiral, and LPDA. Based on Fig. 4.9 (a), it is obvious that the tapered feed line is very useful to enhance impedance matching or to lower the return loss at higher frequencies. When the feed is not tapered or too much tapered, the return loss at higher frequencies will be higher than -10 dB. The top of tapered feed which is represented by parameter of **Wc** must be well-adjusted to get the desired return loss. For this antenna, it is obtained that the suitable dimension of **Wc** is 2.5 mm and **Lc** is 6 mm. In angular approach, feed line should be tapered about 20° (from 0° when not tapered).

4.4.1.3 Simulation vs Measurement

For verification, the results of return loss and radiation pattern from simulation must be compared with those from measurement. The measurement was done by using Vector Network Analyzer (VNA) Hawlett Packard 8510C. The measured return loss is obtained by taking the data of S_{11} from one-port measurement. The measured radiation pattern is obtained by doing two-identical-antenna measurement inside an anechoic chamber and taking data of S_{21} at three frequency points, 3.1 GHz, 6.85 GHz, and 10.6 GHz. The data of S_{21} are then processed to find the power radiation of an antenna and then normalized to get the pattern variations over 360° angles.

The return losses of the common UWB elliptical PMA from simulation and measurement are plotted and shown in Fig. 4.10. The measurement result shows that the return loss of the antenna is lower than -10 dB from 2.88 GHz and able to satisfy the FCC's UWB band. The return losses from simulation and measurement show very good agreement. Some differences between simulation and measurement might be due to either inaccuracies in modeling or fabrication.

The radiation patterns of the common UWB elliptical PMA are presented in Fig. 4.11. The radiation patterns from measurement agree very well with those from simulation. Overall, it is clear that the radiation pattern of the antenna is omnidirectional on the H-plane at every frequency

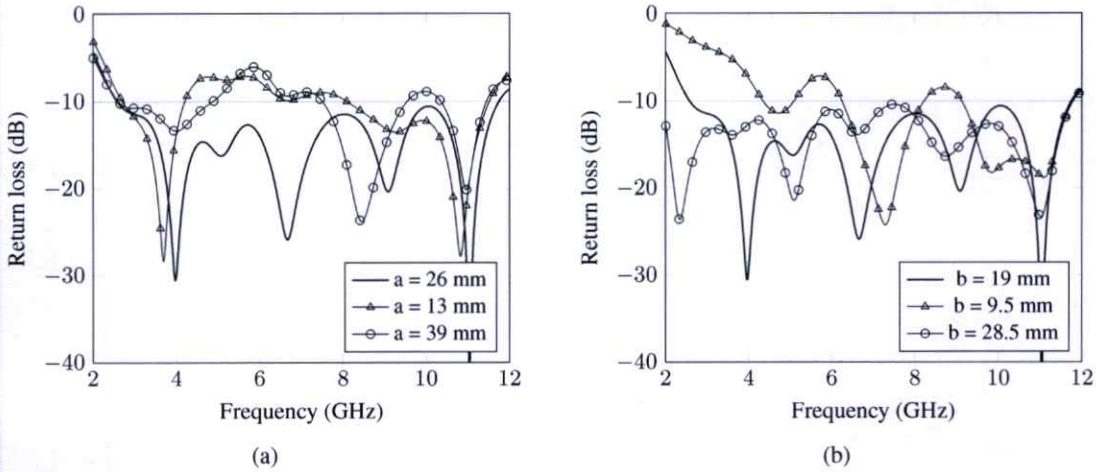


Figure 4.7: Effects of the size of elliptical pole to return loss of the common UWB elliptical PMA: (a) Adjustments of **a** (b) Adjustments of **b**

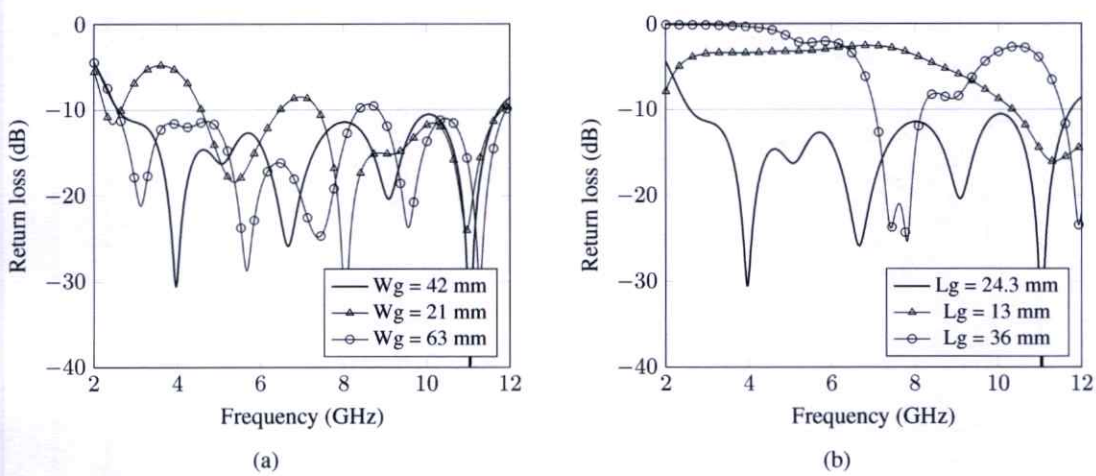


Figure 4.8: Effects of the size of ground plane to return loss of the common UWB elliptical PMA: (a) Adjustments of **Wg** (b) Adjustments of **Lg**

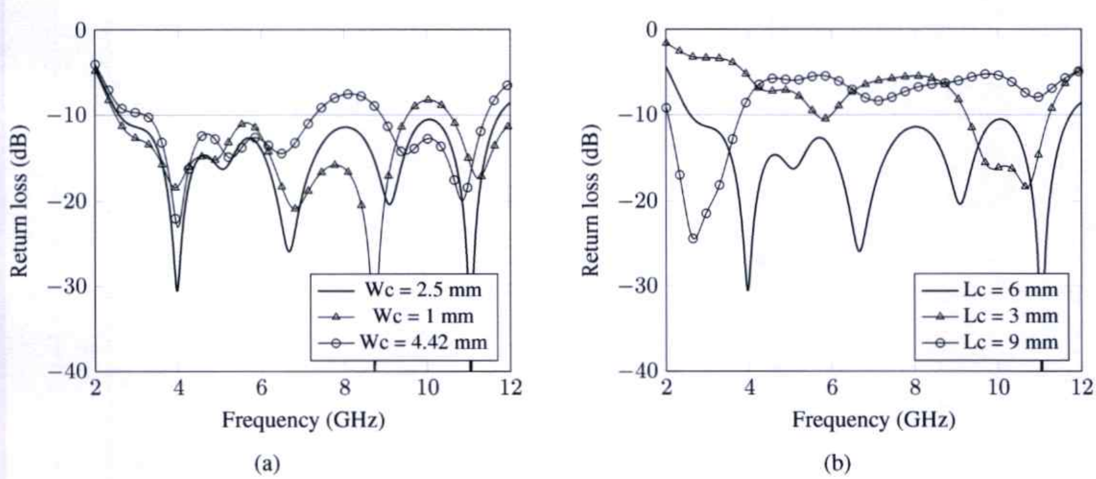


Figure 4.9: Effects of the tapered feed line to return loss of the common UWB elliptical PMA: (a) Adjustments of **Wc** (b) Adjustments of **Lc**

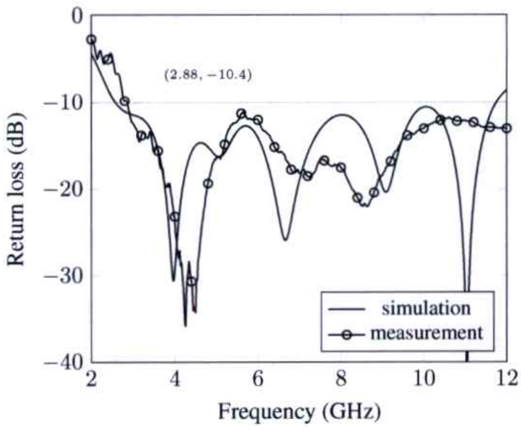


Figure 4.10: Return loss of the common UWB elliptical PMA

point. On the H-plane, variation of the radiation is generally not more than 10 dB. For the E-plane, variation of the radiation is high, more than 20 dB, and is particularly low at the bottom of the antenna. Hence, the radiation pattern of the antenna is omnidirectional on the H-plane.

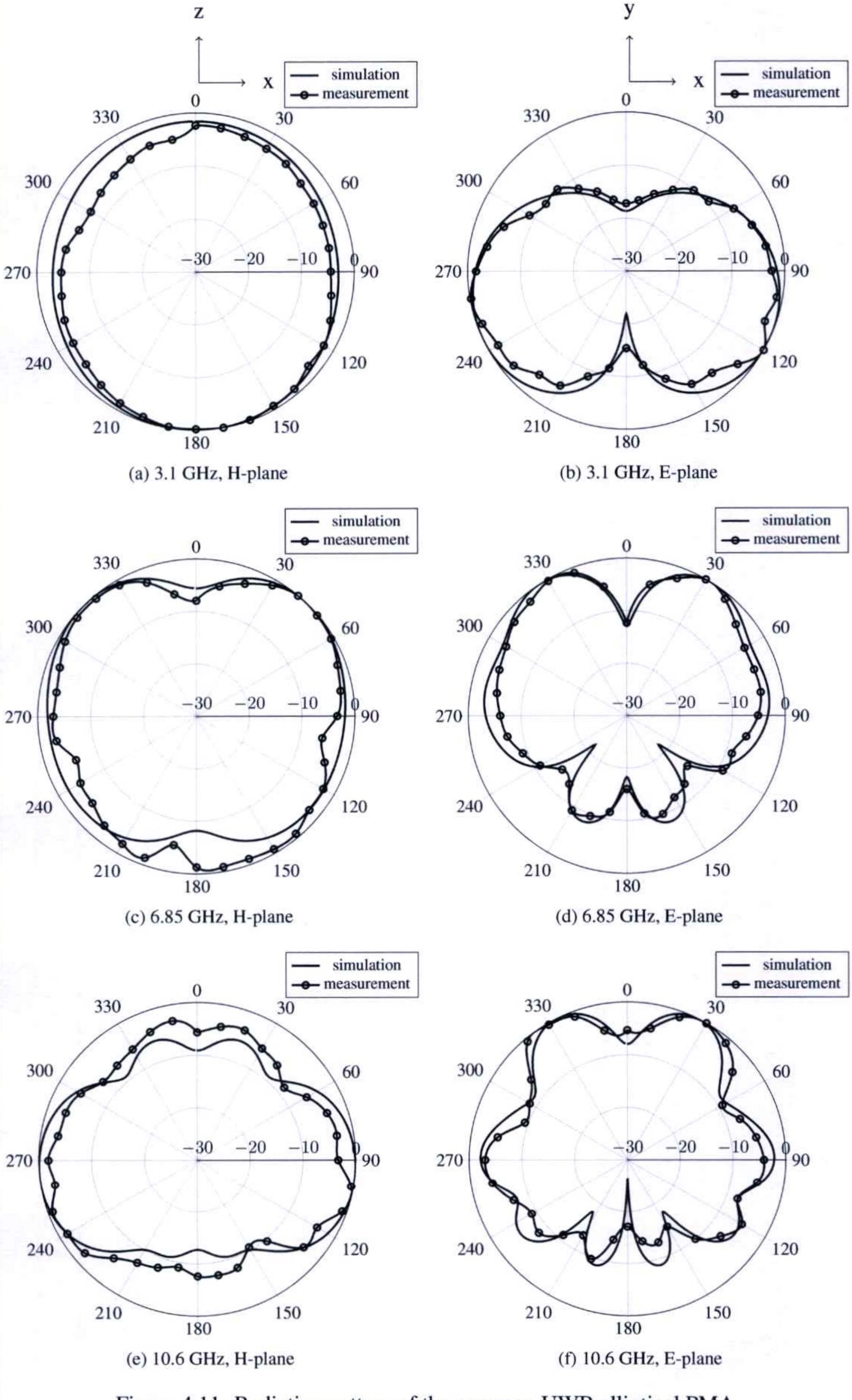
4.4.1.4 Analysis of Surface Current Distribution

In order to analyze the design of the common UWB elliptical PMA, the surface current distributions at some frequency samples are presented in Fig. 4.12. One of the characteristics of broadband antennas is the current distribution must be insensitive to the frequency. For this antenna, the current distribution looks similar for every frequency sample. Hence, this antenna has broadband characteristic which satisfies UWB bandwidth.

It is obvious that for all frequency samples, the current is stronger on the feed line and the joint part of feed line to the elliptical pole. The current is concentrated at the edges of the structure. It becomes the reason why changing the size of elliptical pole, changing the size of ground plane, and tapering the feed line can influence the return loss significantly. As the frequency increases, the current goes stronger at the upper edge of elliptical pole and also the upper edge of ground plane. The middle area of elliptical pole and the middle area of ground plane are not very influential.

4.4.2 A Novel UWB Elliptical PMA Designed with the Extended Procedure

One of the greatest challenges in UWB antenna design is to miniaturize the antenna but maintain broad impedance bandwidth and high radiation efficiency. The common UWB planar monopole antenna is quite small, but making the smaller one is still possible. Moreover, although the common UWB planar monopole antenna satisfies the UWB requirement for impedance bandwidth and radiation pattern, the radiated field is not flat over the entire UWB band. To check the flatness of its radiation over the UWB band, some probes are placed in the simulation to obtain the electric field at some locations as shown in Fig 4.13.



(a) 3.1 GHz, H-plane

(b) 3.1 GHz, E-plane

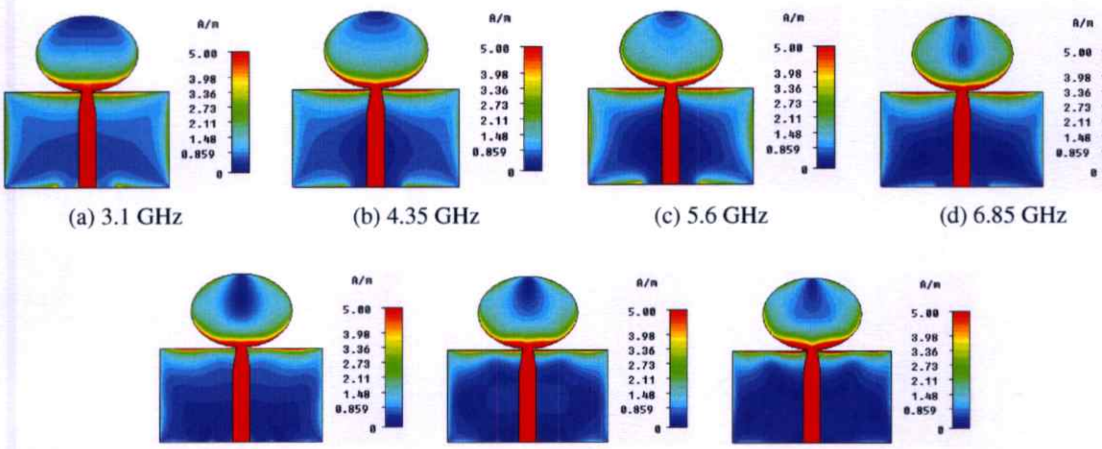
(c) 6.85 GHz, H-plane

(d) 6.85 GHz, E-plane

(e) 10.6 GHz, H-plane

(f) 10.6 GHz, E-plane

Figure 4.11: Radiation pattern of the common UWB elliptical PMA



(a) 3.1 GHz (b) 4.35 GHz (c) 5.6 GHz (d) 6.85 GHz

(e) 8.1 GHz (f) 9.35 GHz (g) 10.6 GHz

Figure 4.12: Surface current distributions of the common UWB elliptical PMA

Table 4.2: Dimensions of the novel UWB elliptical PMA (in mm)

Wf	Wc	Wgb	Wgt	Lf	Lc	Lg	a	b	a'	b'	s
4.42	2.5	28	20	6	5	11	14	17	8	8	4

The probes are placed at 1 meter from the antenna. The electric field radiated by the common UWB elliptical PMA can be seen in Fig. 4.14. The radiated electric field on H-plane $(0°, 900°, 180°)$ suffer from significant drops at higher frequencies. These might affect the transmission performance of the antenna which will be detailed in Chapter 5. Using the extended design procedure, issue of size and issue of radiation flatness over UWB bandwidth are going to be resolved.

The UWB elliptical PMA designed with the extended procedure is modeled in CST Microwave Studio as shown in Fig. 4.15. Since this antenna is addressed to improve the common one with new ideas and techniques, then this antenna is named as "novel UWB elliptical PMA".

4.4.2.1 Antenna Geometry

This novel UWB elliptical PMA is actually an improvement of the common UWB elliptical PMA related to its size and its radiation characteristic. The geometry and the prototype of the antenna are presented in Fig. 4.16. The dimensions of the antenna are listed in Table 4.2.

4.4.2.2 Parametric study

Size of elliptical pole (without the circular slot and notches)

In the beginning of design process of the novel UWB elliptical PMA, a circular slot and two notches have not been applied on the elliptical pole. Since the antenna is intended to be small, it is more challenging to get a good return loss covering the UWB band. The effects

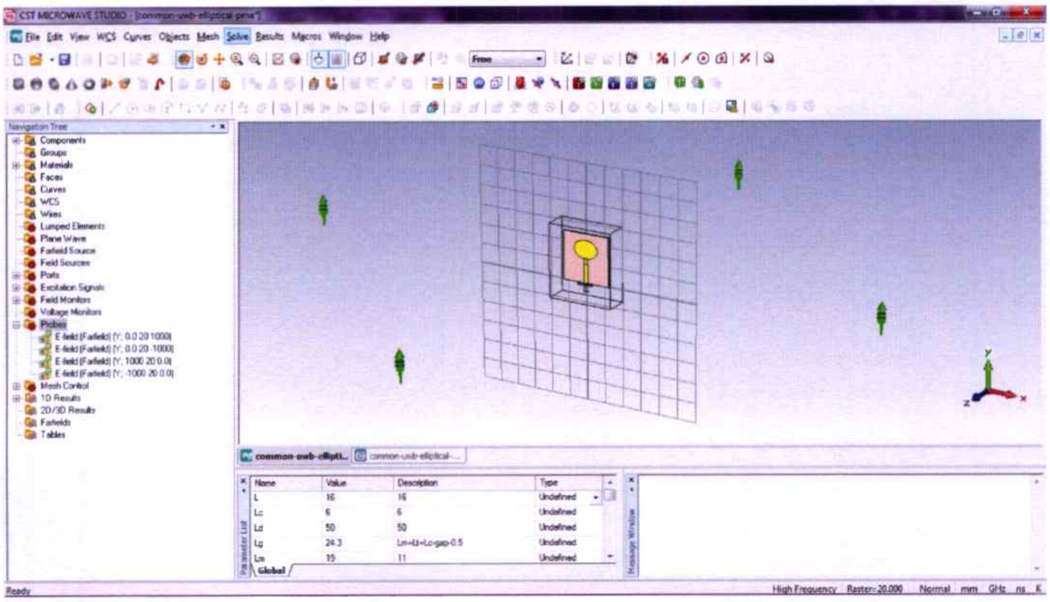


Figure 4.13: Placing E-field probes for the common UWB elliptical PMA in CST Microwave Studio

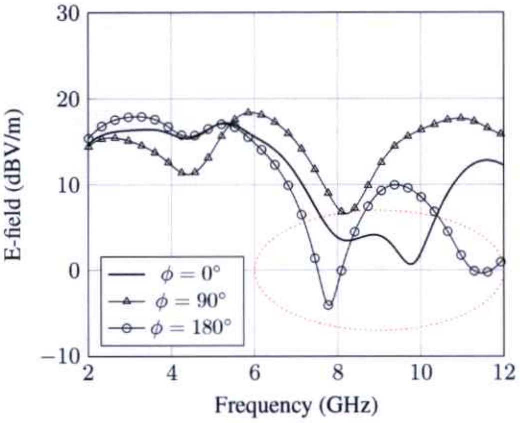


Figure 4.14: The radiated electric field by the common UWB elliptical PMA at some specified locations

of size of the elliptical pole are presented in Fig. 4.17. From Fig. 4.17 (a), the better return loss is obtained with the wider elliptical pole (width of the elliptical pole is representated by **a**). Nevertheless, other approach should be applied to maintain the overall size of the antenna, not by increasing the size of the antenna parts. The chosen dimension of **a** is 14 mm with a little impedance mismatch (high return loss) around 8 GHz. As shown in Fig. 4.17 (b), the **b** is set to be 17 mm resulting the lower frequency cut-off located around 3 GHz.

Circular slot and notches

In addition of reducing the size and copper area of the antenna, a circular slot and two notches are used to overcome the impedance mismatch (high return loss) around 8 GHz.

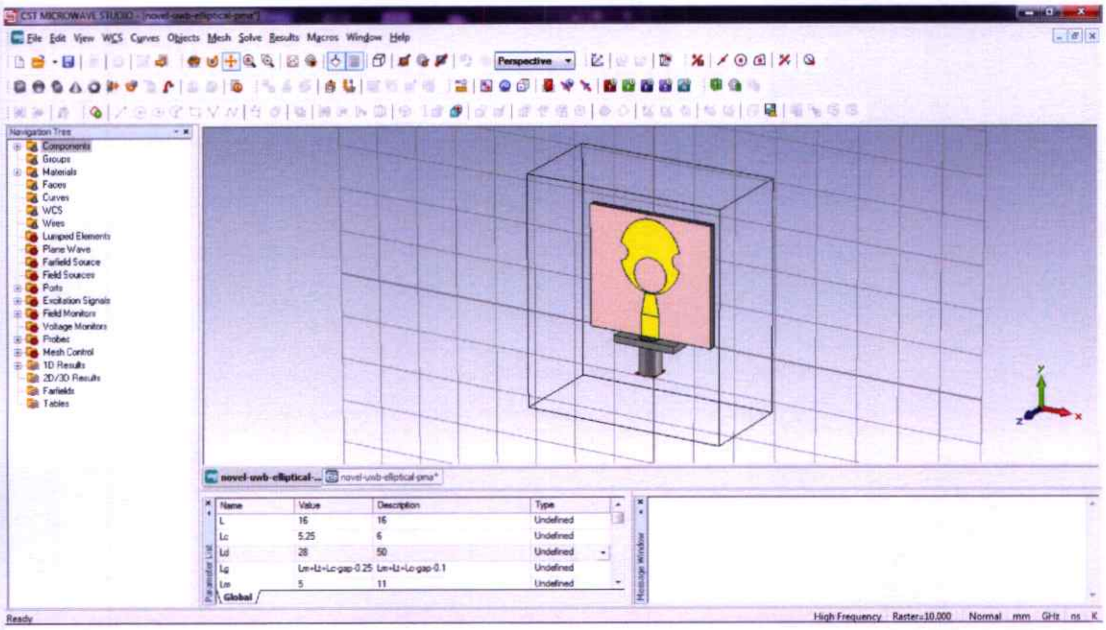
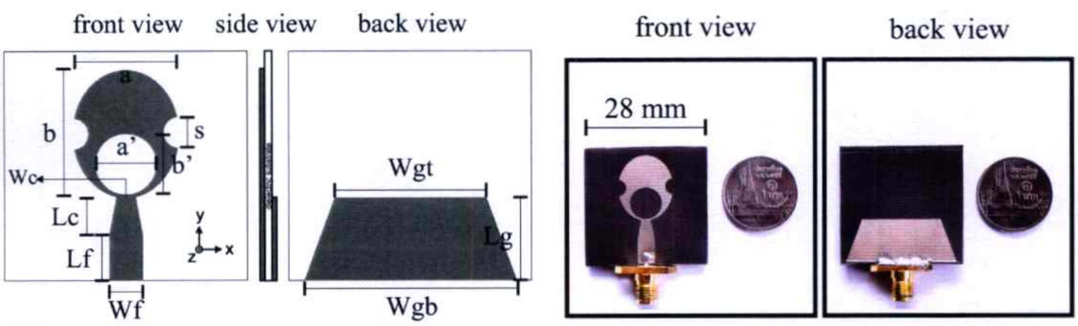


Figure 4.15: 3D model of the novel UWB elliptical PMA in CST Microwave Studio



(a) (b)

Figure 4.16: The novel UWB elliptical PMA: (a) Geometry, (b) Prototype

Fig. 4.18 proves how effective these techniques to enhance impedance matching of the antenna.

Trapezoidal ground plane

Two adjusted parameters for the trapezoidal ground plane on the novel UWB elliptical PMA are **Wgt** and **Wgb**. The effects of adjustment to the return loss are shown in Fig. 4.19. It is obvious that the suitable dimension of **Wgt** is 20 mm, while the smaller or bigger dimension results impedance mismatch (high return loss) at particular frequencies as shown in 4.19 (a). There are two possible dimensions for **Wgb**, 28 mm or 20 mm, as in Fig. 4.19. However, a trapezoidal shape with **Wgb** of 28 mm is chosen because it can improve the radiated electric field to be more flat at some antenna orientations, particularly at $\phi = 90°$. The electric field are checked by placing probes as shown in Fig. 4.20. The improvement of flatness radiation for **Wgb** into 28 mm can be observed in Fig. 4.21.

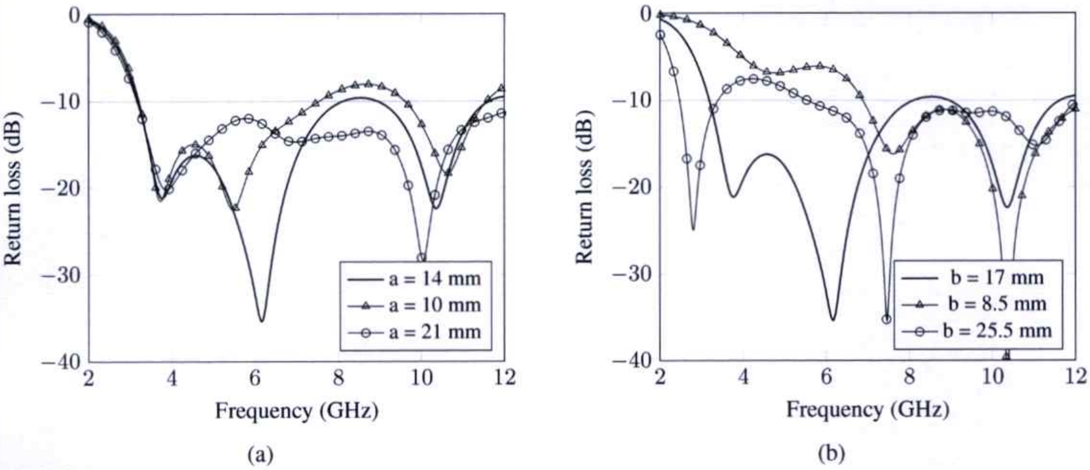


Figure 4.17: Effects of size of the elliptical pole to return loss of the novel UWB elliptical PMA: (a) Adjustments of **a** (b) Adjustments of **b**

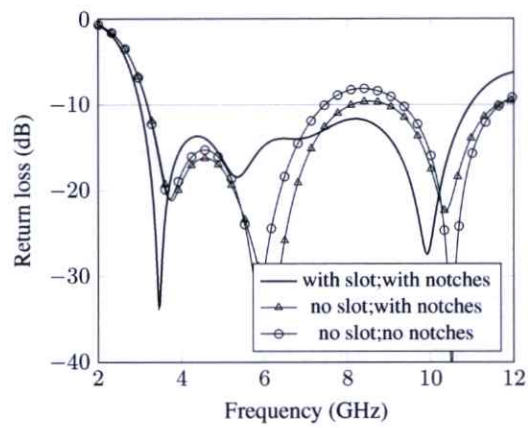


Figure 4.18: Effects of the slot and notches to return loss of the novel UWB elliptical PMA

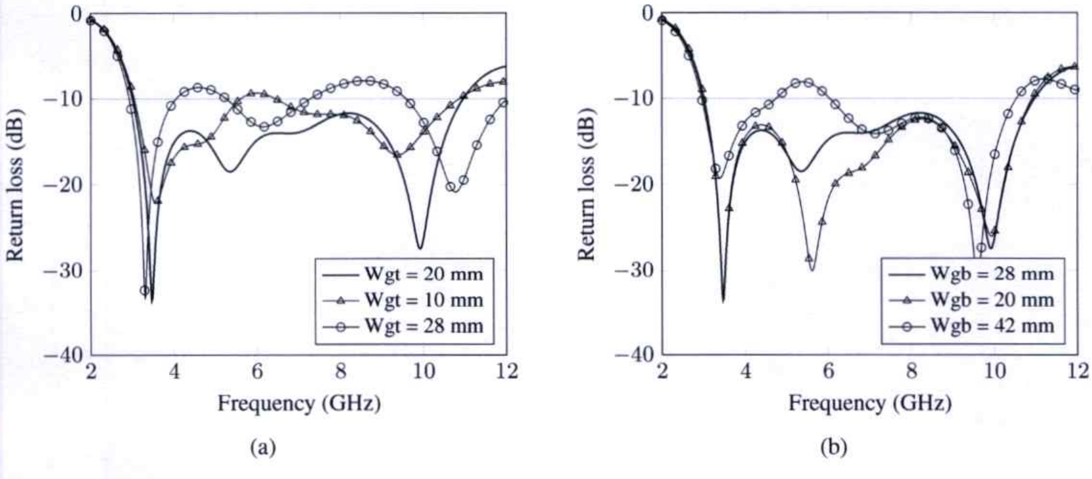


Figure 4.19: Effects of the trapezoidal ground plane to return loss of the novel UWB elliptical PMA: (a) Adjustment of **Wgt** (b) Adjustment of **Wgb**

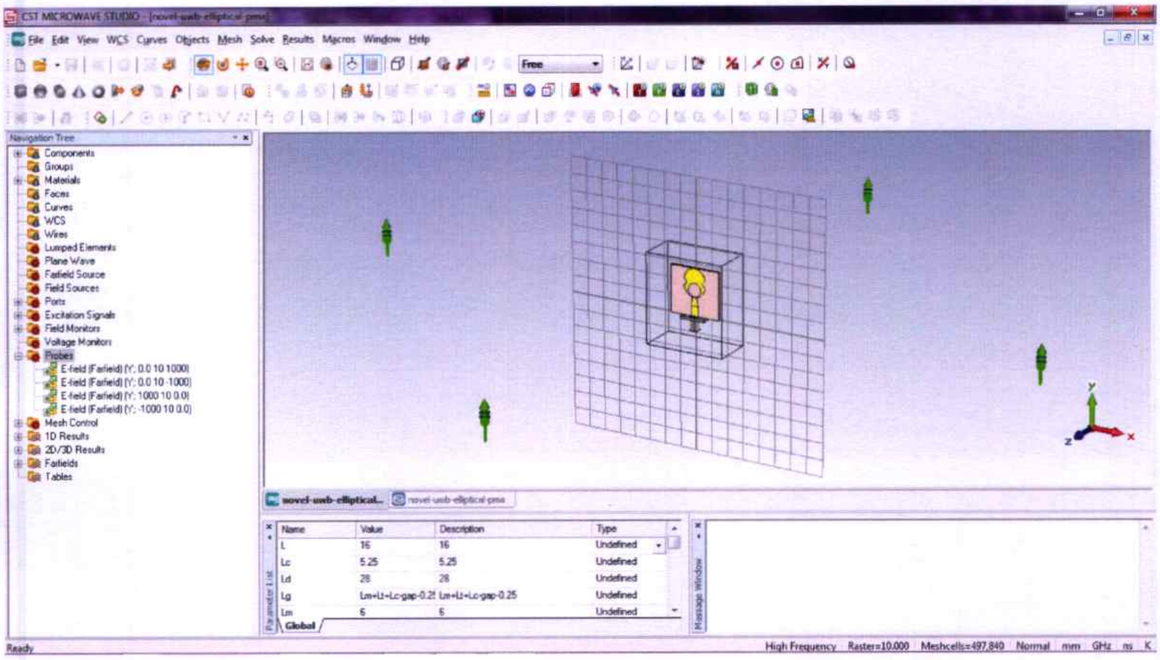


Figure 4.20: Placing E-field probes for the novel UWB elliptical PMA in CST Microwave Studio

The role of the extended procedure in the design of UWB elliptical PMA is to make a stable radiation over the desired UWB band. It is more obvious when the radiated electric field in Fig. 4.21 is compared to the radiated electric field in Fig. 4.14. By using the extended procedure in the design, the radiated electric field can be improved in the simulation. The further impacts to the antenna performance can be clearly seen later in Chapter 5.

4.4.2.3 Simulation vs Measurement

The return losses of the novel UWB elliptical PMA from simulation and measurement are presented in Fig. 4.22. The measurement result shows that the return loss of the antenna is lower than -10 dB from 3.02 GHz to 11.36 GHz and definitely able to satisfy the FCC's UWB band. The return losses from simulation and measurement show very good agreement, especially at lower frequencies. At higher frequencies such as from 5 GHz to 10 GHz, the differences between simulation and measurement results are more obvious. This discrepancy is still acceptable because both return losses are still under -10 dB with similar dips and similar cut-offs at the lower and the higher frequencies.

The radiation patterns of the novel UWB elliptical PMA are presented in Fig. 4.23. The radiation patterns from measurement agree very well with those from simulation. Overall, it is clear that the radiation pattern of the antenna is omnidirectional on the H-plane at every frequency point. On the H-plane, variation of the radiation is generally not more than 10 dB. For the E-plane, variation of the radiation is high, 10 dB to 20 dB. Hence, the radiation pattern of the antenna is omnidirectional on the H-plane.

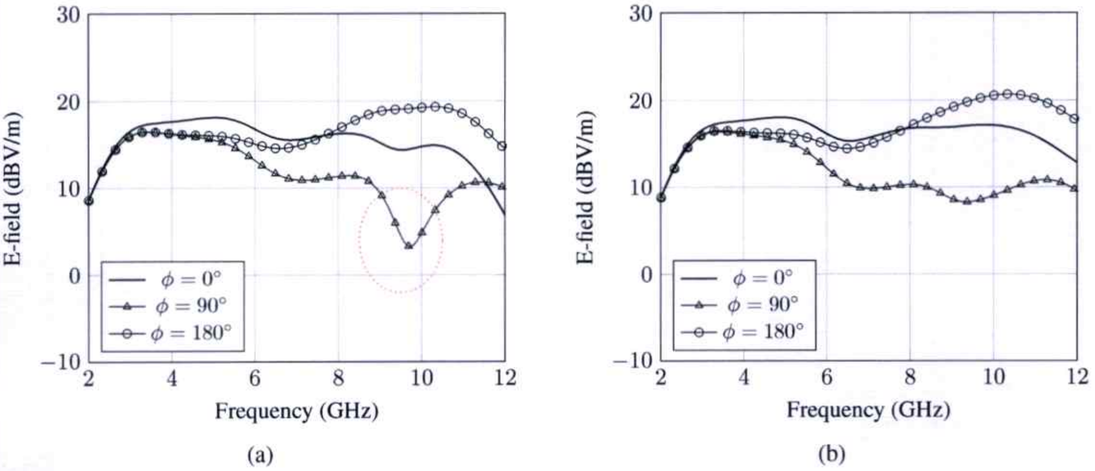


Figure 4.21: The radiated electric field by the novel UWB elliptical PMA at some specified locations: (a) With **Wgb** = 20 (not trapezoid), (b) With **Wgb** = 28 (trapezoid)

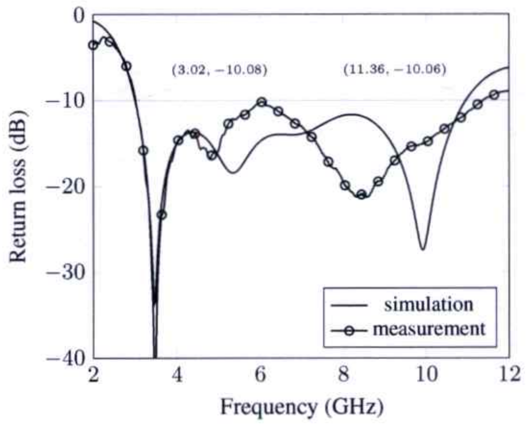
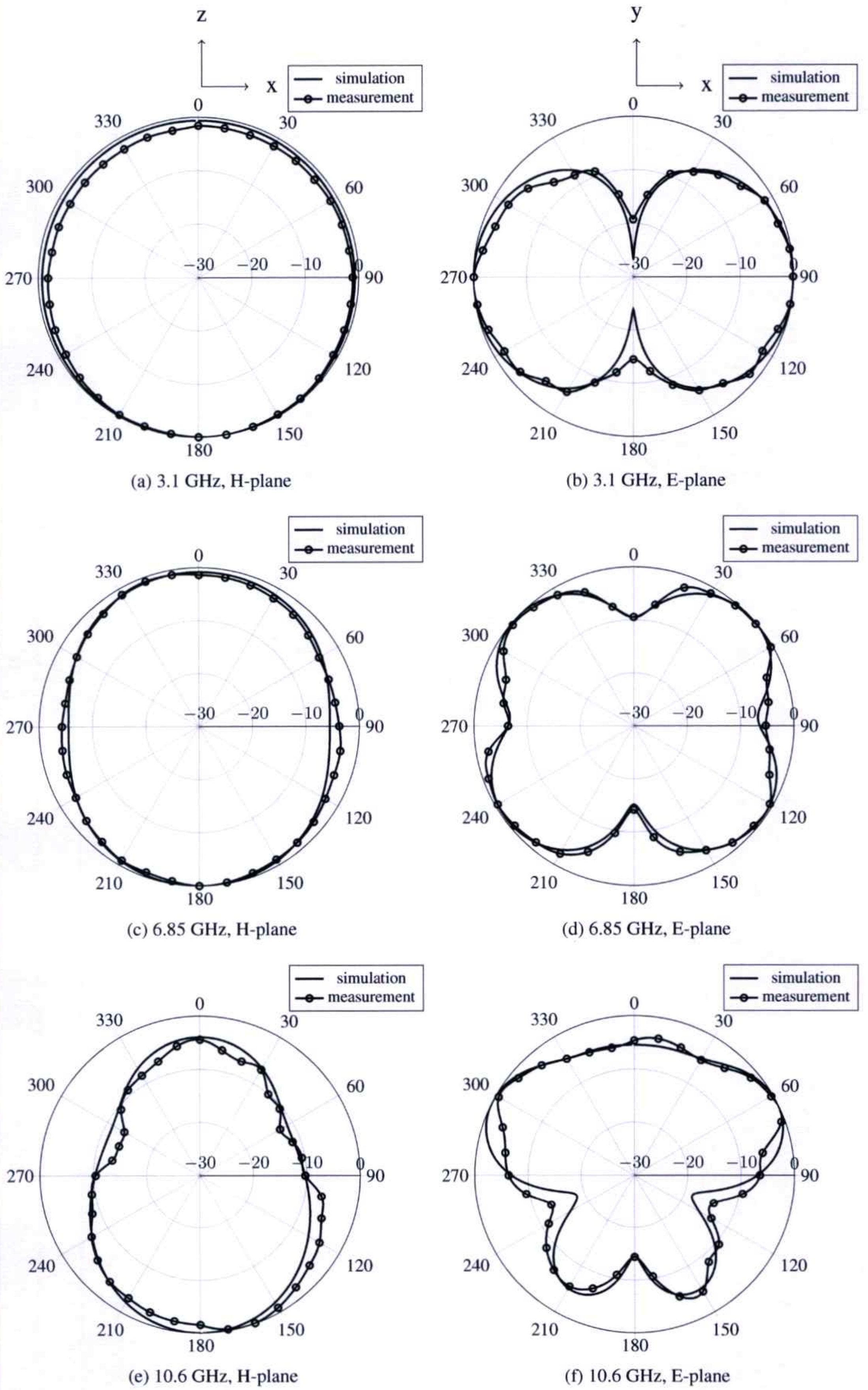


Figure 4.22: Return loss of the novel UWB elliptical PMA

4.4.2.4 Analysis of Surface Current Distribution

The surface current distributions of the novel UWB elliptical PMA are presented in Fig. 4.24. The current is dominantly distributed on the feed line, the joint part of feed line to the elliptical pole (around the circular slot), edge and the middle part of ground plane. The surface current distributions without slot and notches are presented in Fig. 4.25. Circular slot and notches can suppress the current distribution to be stronger at the lower part of elliptical pole and at the notches, especially for high frequencies. It leads the antenna to have better mutual coupling between the pole and the ground plane so that the return loss becomes lower at higher frequencies.

The surface current distributions with non-trapezoid ground plane are presented in Fig. 4.26. The current distributions at higher frequencies (9.35 GHz and 10.6 GHz) using square ground plane and trapezoid ground plane must be noticed and compared. See Fig. 4.24(f)(g) and Fig. 4.26(f)(g). With square ground plane, there is no strong current distributions at the side edges of the ground plane. That is why the trapezoid ground plane can avoid the radiation drops at those



(a) 3.1 GHz, H-plane

(b) 3.1 GHz, E-plane

(c) 6.85 GHz, H-plane

(d) 6.85 GHz, E-plane

(e) 10.6 GHz, H-plane

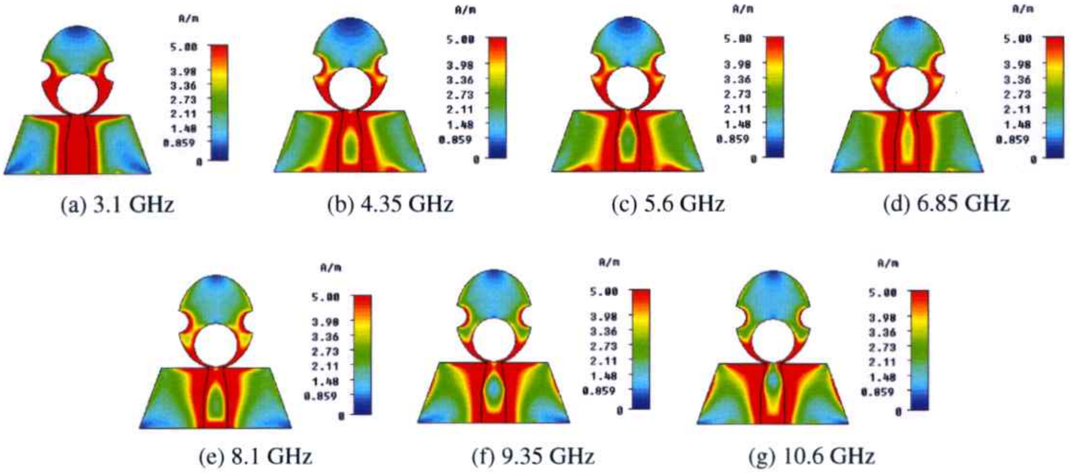
(f) 10.6 GHz, E-plane

Figure 4.23: Radiation pattern of the novel UWB elliptical PMA

frequencies according to Fig. 4.21.

4.5 Concluding Remarks

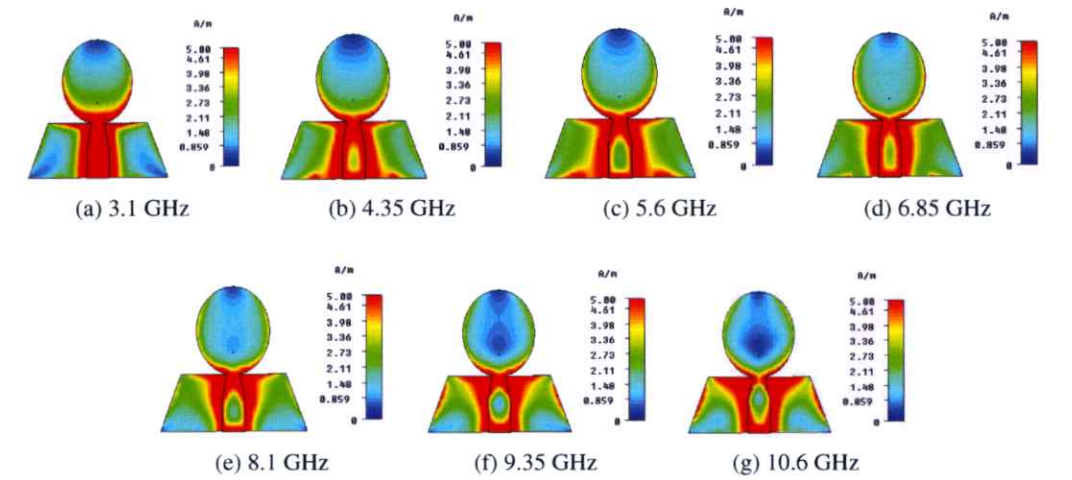
This chapter discusses steps and some important matters in the design of UWB planar monopole antenna. The CST Microwave Studio is used to perform the design simulations. Two designs of UWB planar monopole antenna are reported. The first study is a design by using common procedure where the observed antenna characteristics are only return loss and radiation pattern. A common UWB elliptical PMA with microstrip feed is designed and fabricated. The second design is a design by using the extended procedure where the flatness of radiation over the desired UWB band is also involved. A novel UWB elliptical PMA is proposed with smaller size and with more flat radiation compared to the common one. By these two design studies, the design processes using parametric study and some techniques to enhance impedance matching are demonstrated. The informations from parametric study and impedance matching techniques studied in this chapter are very useful for UWB antenna designers. For instance, a tapered feed line, adding slot or notches, trapezoidal ground plane are very useful to enhance the impedance matching or to stabilize the radiation. To verify the simulation, measurement results are presented. Both return losses of the developed antennas can cover the FCC's UWB bandwidth. The radiation patterns of both antennas are omnidirectional on H-plane. The results from measurement agree very well with those from simulation. Some little discrepancies between the simulation and measurement results are found, but they are still acceptable.



(a) 3.1 GHz (b) 4.35 GHz (c) 5.6 GHz (d) 6.85 GHz

(e) 8.1 GHz (f) 9.35 GHz (g) 10.6 GHz

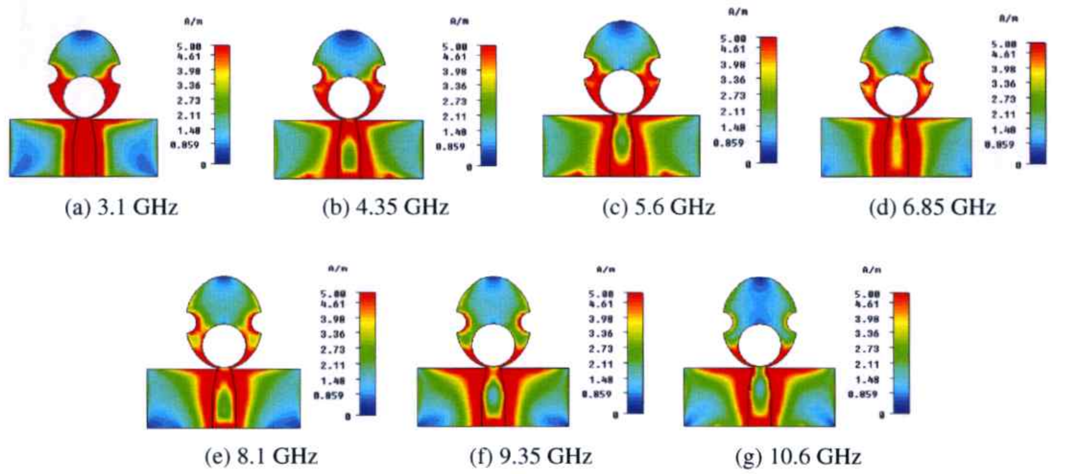
Figure 4.24: Surface current distributions of the novel UWB elliptical PMA



(a) 3.1 GHz (b) 4.35 GHz (c) 5.6 GHz (d) 6.85 GHz

(e) 8.1 GHz (f) 9.35 GHz (g) 10.6 GHz

Figure 4.25: Surface current distributions of the novel UWB elliptical PMA without slot and notches



(a) 3.1 GHz (b) 4.35 GHz (c) 5.6 GHz (d) 6.85 GHz

(e) 8.1 GHz (f) 9.35 GHz (g) 10.6 GHz

Figure 4.26: Surface current distributions of the novel UWB elliptical PMA with non-trapezoid (square) ground plane

CHAPTER V

PERFORMANCE EVALUATION OF UWB PLANAR MONOPOLE ANTENNA

In Chapter 4, UWB elliptical planar monopole antennas have been designed with investigations on their return losses and radiation patterns. Those characteristics are sufficient to satisfy the basic requirements of antenna, because with good impedance matching and desired radiation pattern an antenna has been able to radiate electromagnetic waves for a specified frequency band. A UWB elliptical PMA with an extended design procedure also has been developed to get better radiation characteristic over the desired UWB bandwidth.

For narrowband antennas, after investigating return loss and radiation pattern, the antenna performance is usually denoted by a single value of gain to represent how strong the antenna can radiate or transmit sinusoidal wave at the resonance frequency. However, UWB antennas are operated for extremely wide bandwidth where the radiation characteristic of the antenna changes by different frequency. The antenna characteristics should be flat over the desired UWB band. Moreover, UWB antennas also need to be considered for time domain operation (see Chapter 2). Therefore, the performance of the antenna should be evaluated further. In this Chapter, a comprehensive performance evaluation of UWB planar monopole antenna will be performed.

5.1 Specific Literature Review and Problem Statement

In UWB systems, the antennas act as front-end devices for impulse transmission, not sinusoidal wave like in narrowband systems. Owing to this unique feature of UWB radio system, UWB antennas should be considered as a system, not single unit in the design [68].

Studies on UWB planar monopole antenna design are rarely followed by performance evaluation. Some published works [69–73] consider evaluating the performance of their UWB antennas. In [69, 70], the UWB antenna is evaluated by doing two-identical-antenna method measurement in frequency domain to show channel transfer function (S_{21}) and group delay in frequency domain, and then doing another measurement in time domain to show the impulse responses without any quantitative parameters. Channel transfer function and group delay are also used in [71], but the impulse responses are easily derived from the frequency domain data by using inverse Fourier transform. A quantitative parameter, i.e. fidelity factor, is used to evaluate the time domain performance of UWB antennas in [72, 73]. Fidelity factor is also discussed in some literatures about "UWB radio" or "UWB antennas" [74–78]. Other quantitative parameters, pulse stretch ratio, introduced in [79, 80], and time domain gain, introduced in [81]. Those parameters are all important and have their own concerns. For every UWB antenna design, it is necessary to evaluate the performance comprehensively so that the whole antenna characteristics can be exhibited.

Thus, there are several kinds of parameter discussed in separated literatures for performance evaluation of UWB antennas. All the mentioned literatures generally derive the parameters without reference. A reference such as isotropic antenna can be used so that the evaluated performances known as relative to isotropic performance.

5.2 Methodology of Performance Evaluation

Performance evaluation of UWB planar monopole antenna is actually carried out by characterizing the antenna system. It is started by doing measurement using two-identical-antenna method so that the antenna transmission behavior in a link can be characterized over the UWB band. When the evaluated antennas are printed antennas, it is easy to convince that the antennas are physically identical and having the same characteristics.

After measurement, data processing is performed in computational software such as Matlab. The data processing is aimed to compute the parameters for performance evaluation. For performance evaluation in time domain, simulation of waveform transmission should be done in the data processing. When measurement provides data in frequency domain, inverse Fourier transform becomes the primary key for time domain simulation.

5.2.1 Measurement Setup Using Two-Identical-Antenna Method

UWB radio channel transfer function using two identical UWB antennas was measured as S_{21} in an anechoic chamber using vector network analyzer (VNA) Hawlett Packard (HP) 8510C series. The measurement setup is illustrated in Fig. 5.1, and the real condition is shown in Fig. 5.2. The VNA was operated in the response measurement mode where Port 1 as the transmitter and Port 2 as the receiver. In the measurement, two identical antennas were used as transmitter and receiver antennas. Both of them were rotated on horizontal direction (H-plane) to obtain the channel transfer function at every antenna orientation. The orientation was started at 0° which means that the positive z axis of both antennas are pointed each other. A new S_{21} measurement was done every 10° of rotation. The orientation angle is changed with $\hat{\phi}_{\mathrm{r}} = -\hat{\phi}_{\mathrm{t}}$ where unit vectors $\hat{\phi}_{\mathrm{r}}$ and $\hat{\phi}_{\mathrm{t}}$ express the azimuth angle of the transmitter and receiver antenna and are defined with respect to the local polar coordinate of the antenna. For complete measurement properties, the measurement setup parameters are detailed in Table 5.1. The measurement is only limited to the H-plane of the antennas, but more planes or spherical measurement for more complete evaluation is possible [74].

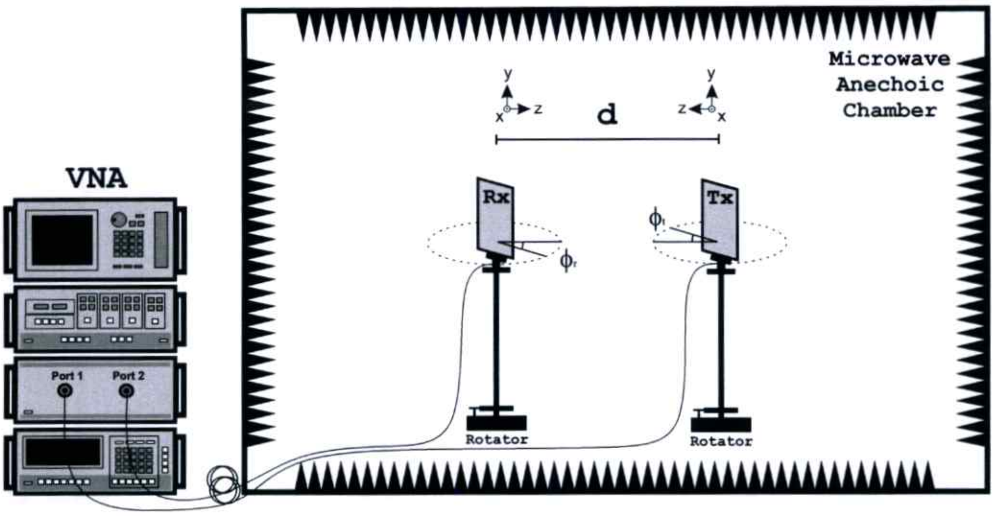


Figure 5.1: Measurement setup in anechoic chamber

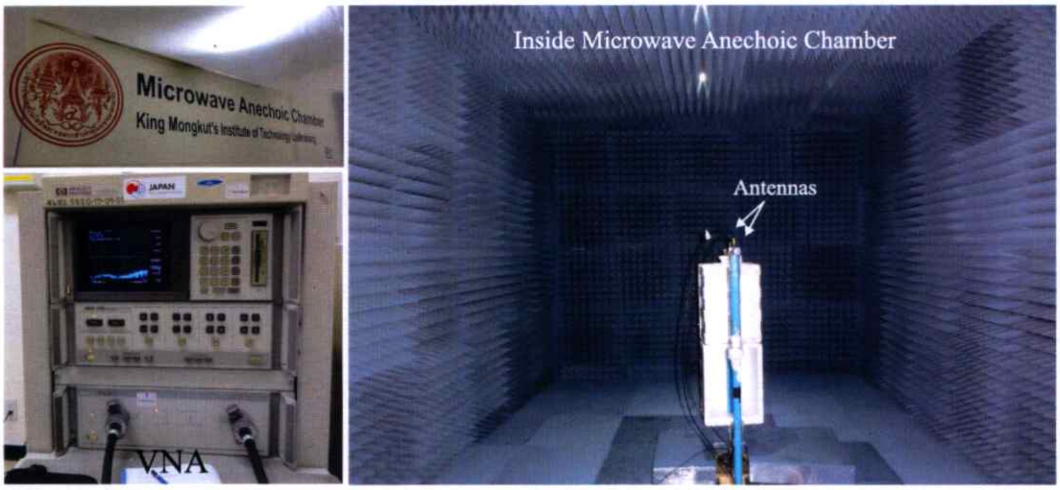


Figure 5.2: Real measurement condition

5.2.2 Derivation of Parameters for Performance Evaluation

5.2.2.1 Parameters in Frequency Domain

There are two parameters in frequency domain that can be used for performance evaluation of UWB planar monopole antenna. Both parameters are described below.

Antenna Transfer Function

Antenna transfer function can be obtained from a channel transfer function. Channel transfer function, or the transfer function of an "antenna system", is a vital parameter to obtain the impulse response affected by channel including the antennas. It can be defined as the ratio between the voltage received at the Rx-antenna terminal and the voltage at the input of the Tx-antenna. The channel transfer function $H(f)$ can be directly obtained from mea-

Table 5.1: Measurement setup parameters

Measurement Parameter	Value
Frequency range	3 GHz to 11 GHz
Number of frequency points	801
Dynamic range	80 dB
Tx & Rx antenna height	1.2 m
Distance Tx to Rx (d)	1 m, line of sight (LOS)
Rx rotation range	$0° - 350°$
Rx rotation step	$10°$
Rx rotation cut	H-plane (azimuth)

surement as S_{21}. The antenna transfer function which also can be supposed as antenna gain can be written as

$$\mathbf{H}_{\mathrm{t}}(f, \theta_{\mathrm{t}}, \varphi_{\mathrm{t}}) = \mathbf{H}_{\mathrm{r}}(f, \theta_{\mathrm{t}}, \varphi_{\mathrm{t}}) = \sqrt{\frac{H(f)}{H_{\mathrm{f}}(f, d)}} \tag{5.1}$$

For more detail, this parameter refers to the discussion of extension of Friis transmission formula for UWB Impulse Radio in Chapter 2. To minimize the signal distortion due to antenna, the antenna transfer function is required to have flat magnitude over the operating band [82].

System Group Delay

The average of the group delay is equal to the time needed for a signal (at a given frequency) to travel from one antenna terminal to the other. Group delay is used to evaluate the phase response of transfer function because it also can be defined as the rate of change of total phase shift. Mathematically, group delay can be written as a negative derivative of the phase response $\angle H(f)$ with respect to frequency.

$$\tau = -\frac{\mathrm{d}[\angle H(\omega)]}{\mathrm{d}\omega} = -\frac{1}{2\pi}\frac{\mathrm{d}[\angle H(f)]}{\mathrm{d}f} \tag{5.2}$$

In a UWB system, constant group delay is required which implies the phase changes linearly with the frequency. When the group delay is not constant, the pulse waveform will be spread out in the time domain [83].

5.2.2.2 Parameters in Time Domain

For investigating time domain transmission behavior of the UWB antenna, let choose a rectangular passband waveform [84] as the transmitted UWB signal model which is given by

$$v_{\mathrm{t}}(t) = \frac{A}{f_{\mathrm{b}}}[f_{\mathrm{H}}\mathrm{sinc}(2f_{\mathrm{H}}t) - f_{\mathrm{L}}\mathrm{sinc}(2f_{\mathrm{L}}t)] \tag{5.3}$$

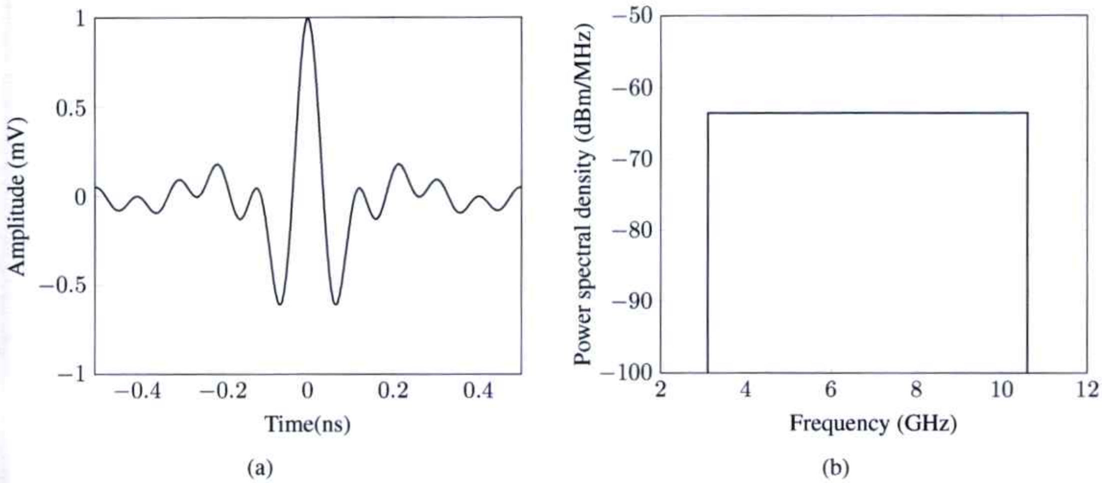


Figure 5.3: The transmitted waveform model: (a) Rectangular passband waveform in time domain (b) The spectrum of rectangular passband waveform in frequency domain

and its spectrum

$$V_t(f) = \begin{cases} \frac{A}{2f_b} & \||f| - f_c| \leq \frac{f_b}{2} \\ 0 & \||f| - f_c| > \frac{f_b}{2} \end{cases} \tag{5.4}$$

where A is the maximum amplitude, f_b is the occupied bandwidth, f_c is the center frequency, $f_L = f_c - f_b/2$ and $f_H = f_c + f_b/2$ are the lower limit and the higher limit of frequencies. For the waveform occupying the entire UWB bandwidth, f_L = 3.1 GHz and f_H = 10.6 GHz. So, the transmitted UWB signal model for this band is shown in Fig. 5.3.

After having the channel transfer function from measurement and determining the transmitted waveform, the receiver antenna output waveform $v_r(t)$ is given by

$$v_r(t) = \int_{-\infty}^{\infty} V_t(f)H(f)e^{j2\pi ft}\mathrm{d}f \tag{5.5}$$

In case of using isotropic antennas on both sides, the receiver output waveform v_{r-iso} can be written as

$$v_{r-iso} = \int_{-\infty}^{\infty} V_t(f)H_f(f)e^{j2\pi ft}\mathrm{d}f \tag{5.6}$$

where $V_t(f)$ is the spectral density of the transmitted waveform. From v_{r-iso} and $v_r(t)$, three performance parameters based on the waveform transmission using the examined UWB antenna compared to the waveform transmission using isotropic antenna are derived below.

Waveform Correlation

The waveform correlation is a measure of similarity between two waveforms as a function of a time-lag applied to one of them [73–78]. Since UWB antennas cause distortion in the waveform transmission, the correlation between the received waveform using the examined UWB antennas and the received waveform using isotropic antennas can be used to denote the antenna performance. It ranges between 0 and 1, when the waveform correlation is equal to 1, it means that the transmission performance of the examined UWB antenna is totally the same like isotropic antenna. Evaluation by correlating the transmitted waveform and the received waveform using the examined UWB antennas [75] will include the propagation or distance decays whereas it must be excluded for antenna characterization. The waveform correlation (C) should be formulated by comparing the received waveform using the examined antenna and the received waveform using isotropic antennas. Hence,

$$C = \frac{\max \left| \int_{-\infty}^{\infty} v_{\mathrm{r}}^{*}(t).v_{\mathrm{r-iso}}(t+\tau)dt \right|}{\sqrt{\int_{-\infty}^{\infty} |v_{\mathrm{r}}(t)|^2 \, dt. \int_{-\infty}^{\infty} |v_{\mathrm{r-iso}}(t)|^2 \, dt}} \tag{5.7}$$

Waveform Width Stretch Ratio

Waveform width stretch ratio (SR) indicates how much the antenna causes energy spreading or width stretching to the waveform [79, 80]. If the width of the waveform is increasing, longer inter-pulse gaps is necessary resulting lower transmission rate. The higher SR means the worse performance of the antenna. The derivation of SR is based on comparing energy distribution between two waveforms. Although $v_{\mathrm{t}}(t)$, $v_{\mathrm{r}}(t)$, and $v_{\mathrm{r-iso}}(t)$ has non-zero energy for all time t, but most of the energy is usually distributed around the maximum amplitude. Hence, the waveform width can be defined as the waveform period containing a certain part of the total energy. For every waveform $v(t)$, the normalized cumulative energy function can be written as

$$\mathrm{E_v}(t) = \frac{\int_{-\infty}^{t} |v(t)|^2}{\int_{-\infty}^{\infty} |v(t)|^2} \tag{5.8}$$

which apparently has energy value between 0 and 1. Then, the waveform width for p energy portion of waveform v is defined by

$$\mathrm{W}(v) = \mathrm{E_v^{-1}}\left(1 - \frac{1-p}{2}\right) - \mathrm{E_v^{-1}}\left(\frac{1-p}{2}\right) \tag{5.9}$$

For instance, the p can be determined as 0.9 to compare the waveform width stretching based on 0.9 of the total waveform energy. In the similar case with waveform correlation, the comparison should be done between the received signal using the examined antennas and the received signal in assumption using ideal isotropic frequency independent antennas. Then, the SR is obtained by

$$\mathrm{SR} = \frac{\mathrm{W}\left(v_{\mathrm{r}}\right)}{\mathrm{W}\left(v_{\mathrm{r-iso}}\right)} \tag{5.10}$$

Waveform Relative Gain

Waveform relative gain can be defined as the time domain gain and derived based on how the examined UWB antenna affects the maximum amplitude of the received waveform compared to the maximum amplitude of the received waveform using isotropic antenna [35, 76, 81]. The waveform relative gain is written as

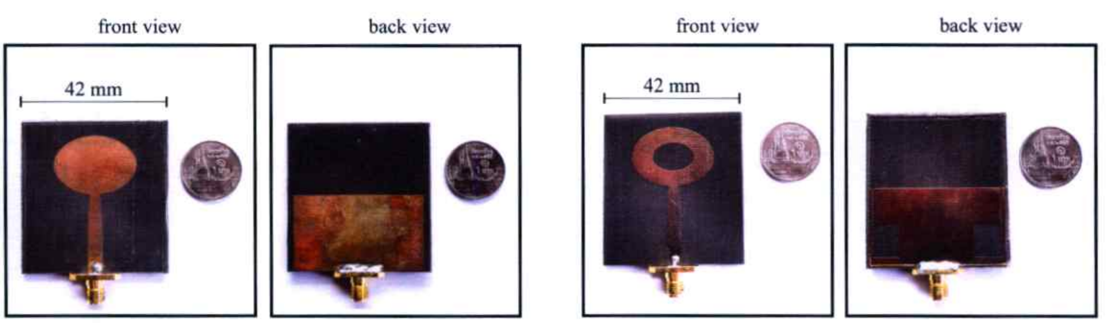
$$G_{\mathrm{w}} = \frac{\max |v_{\mathrm{r}}(t)|}{\max |v_{\mathrm{r-iso}}(t)|} \tag{5.11}$$

5.3 Case 1: Impacts of Reducing Ground Plane Effects on UWB PMA Performance

Since there are numerous possible designs of UWB PMA, the proposed methodology of performance evaluation above can be used for comparing two or more UWB PMAs. In this section, two UWB elliptical printed monopole antennas are compared. The first antenna is a common UWB elliptical PMA and the second one is a slots-added UWB elliptical PMA. Both antennas have similar design and impedance characteristic. The slots-added elliptical PMA is intended for minimizing the ground plane effects and the employed area which is claimed in the references [85, 86] that the added slots have very little effects to the antenna characteristics. Both of the UWB antennas will be evaluated together to distinguish their performances.

5.3.1 The Compared Antennas

The compared antennas are depicted in Fig. 5.4. The differences between these antennas are only at the added slots on the elliptical pole and on the ground plane. Reducing ground plane effects is a technique for minimizing the domination of ground plane to the antenna characteristics. The used techniques are usually adding particular slots or cutting particular parts of the antenna [85, 86]. Reducing ground plane effects is successful when the changes on the antenna only slightly affect the antenna characteristics, especially the impedance characteristic, i.e. return loss, and the radiation pattern.



(a) (b)

Figure 5.4: The evaluated antennas: (a) Common UWB elliptical PMA, (b) Slots-added UWB elliptical PMA for reducing ground plane effects

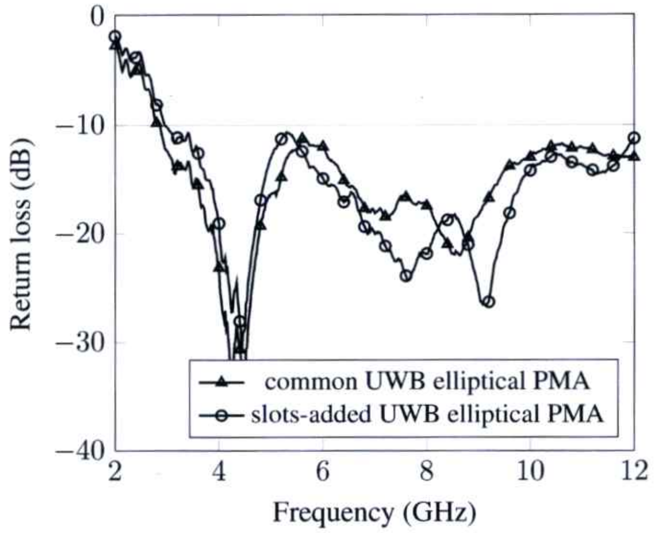


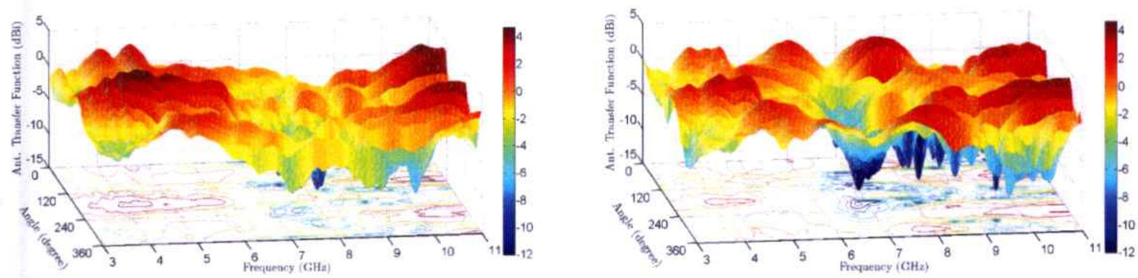
Figure 5.5: Return loss of the evaluated UWB elliptical PMAs

The return losses of both antennas are shown in Fig. 5.5. It is obvious that although there are some changes to the antenna designs, the return losses of both antennas are still similar. It denotes that the effort of reducing ground plane effects is successful. With this similar impedance characteristic, it is difficult to know which antenna is better for UWB signal transmission. Therefore, the antennas should be compared by evaluating their performances.

5.3.2 Results

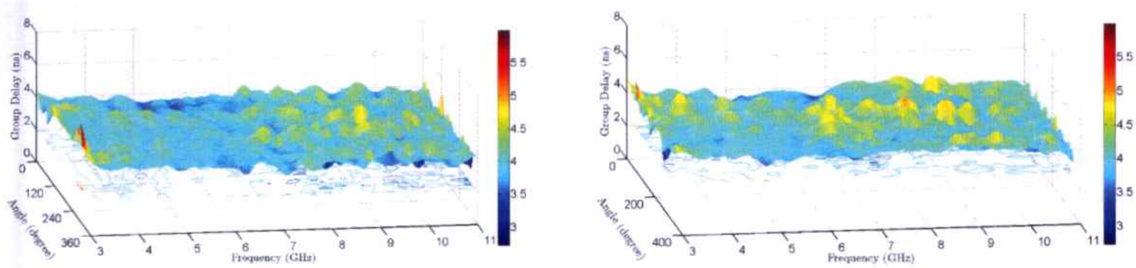
The results of performance evaluation are presented by parameters in frequency domain and time domain. Antenna transfer function and group delay are used to see the performance of UWB antennas in frequency domain. Flatness of the antenna transfer function and constancy of the group delay are the indicators of the evaluation. Fig. 5.6 shows the antenna transfer function of the common UWB elliptical PMA and the slots-added UWB elliptical PMA for their H-planes. The antenna transfer functions are not very flat with some dips occurred at particular frequencies. The transfer function of the slots-added UWB elliptical PMA looks more fluctuating than the common UWB elliptical PMA. Fig. 5.7 (a) and (b) show that the group delays of both antennas are constant, just with some ripples particularly at higher frequencies.

For clearer comparison, antenna transfer functions and group delays for some specific ϕ angles are provided in Fig. 5.8. At 0°, the antenna transfer function using the common elliptical PMA has more drops at higher frequencies. In the other words, the transfer function of the slot-added elliptical PMA is relatively more flat than the common elliptical PMA. Nevertheless, different antenna orientations give different antenna transfer functions. For the 90° and 180° angles, flatness of the transfer functions look difficult to be just subjectively assessed. For those angles, the group delays look constant. Consequently, the parameters in frequency domain are



(a) (b)

Figure 5.6: Antenna transfer function: (a) Common UWB elliptical PMA, (b) Slots-added UWB elliptical PMA for reducing ground plane effects



(a) (b)

Figure 5.7: System group delay: (a) Common UWB elliptical PMA, (b) Slots-added UWB elliptical PMA for reducing ground plane effects

still insufficient to distinguish the two evaluated UWB antennas. For more comprehensive evaluation, parameters in time domain are necessary to ensure how the UWB antenna behaves for transmission of UWB waveform.

The received waveform will be dissimilar since the transmitted waveform has been distorted and spreaded out because of unflat transfer function or inconstant group delay. For illustrations of the waveform transmission in the antenna systems, Fig. 5.9 (a) and (b) depicts the transmitted waveform, the normalized received waveform using isotropic antennas, and the received waveform using the examined antennas. The received waveform using the examined antennas looks distorted and delayed about 4 ns according to values of the group delay. The waveform correlation, the waveform width stretch ratio, and the waveform relative gain are derived by quantitative comparisons between the normalized received waveform using isotropic antennas and the received waveform using the examined antennas as explained in the previous section.

Fig. 5.10 implies that the waveform correlation of both antennas is more than 0.7 for every angle. The common UWB elliptical PMA has waveform correlations about 0.8, with maximum correlation of 0.84 at $\phi = 180°$. For comparison of both antennas, the common UWB elliptical PMA tends to have higher waveform correlation than the slots-added UWB elliptical PMA at most angles. The slots-added UWB elliptical PMA has higher waveform correlation only at $\phi = 0°$

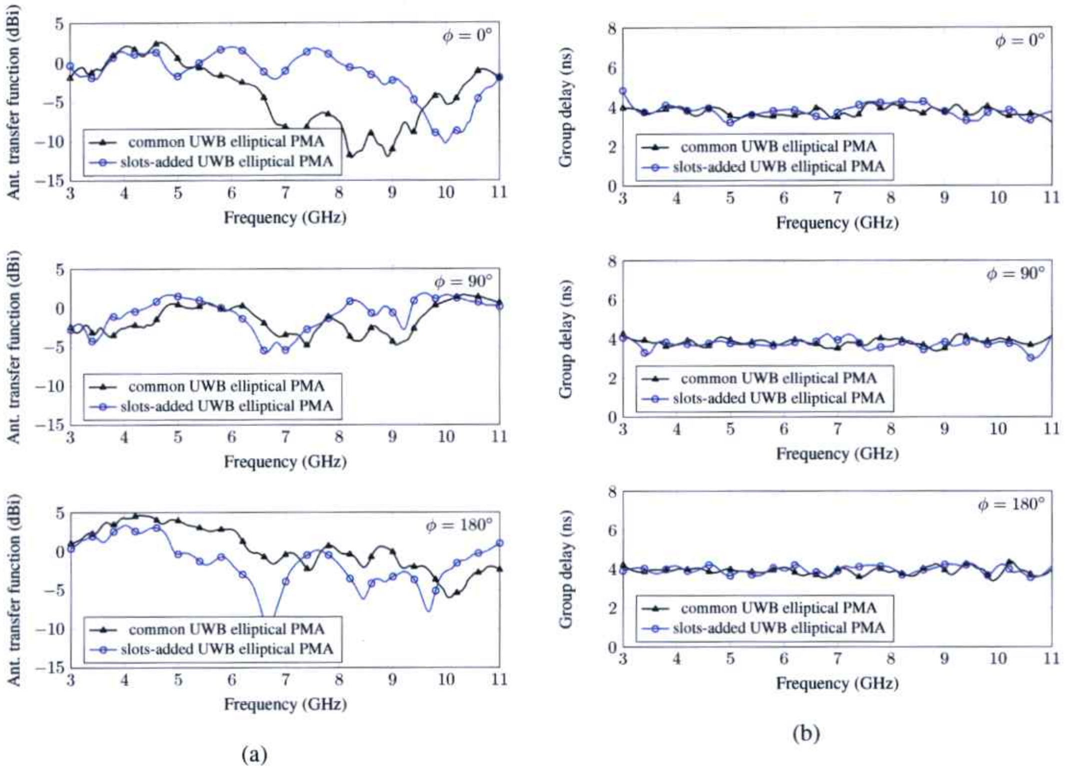


Figure 5.8: Comparison of frequency domain parameters at some specific angles (0°,90°,180°): (a) Antenna transfer function (b) System group delay

while it has more flat transfer function as seen in Fig. 5.8 (a). Although the differences between the waveform correlations are not too significant but it is enough to say that the common elliptical PMA has better performance in the term of waveform correlation.

Fig. 5.11 shows the antenna performance by the parameter of waveform width stretch ratio (SR). By this parameter, the lower value means the better antenna performance. The SRs are quantified by applying p=0.9, or 90% energy of waveforms. At $\phi = 0°$, the slots-added UWB elliptical PMA has better (lower) waveform width stretch ratio. The common UWB elliptical PMA has the best (minimum) SR of 1.1 at $300^{c}irc$ and the worst (maximum) SR of 3.08 at $\phi = 0°$ and $\phi = 180°$.

The result of waveform relative gain is shown by Fig. 5.12. The value of waveform relative gain is not so high, about 0.6 at every angle. From the figure, the common UWB elliptical PMA has slightly higher waveform relative gain at all angles. A clear difference can be seen on the ground plane side of the antennas ($\phi = 180°$). At the ground plane area, the common elliptical PMA has much higher waveform relative gain than the slots-added UWB elliptical PMA, which is approximately 1.2. So, normally the common UWB elliptical PMA has higher gain at the ground plane side when the size of ground plane is big enough. Adding slots on the UWB elliptical PMA reduces the waveform relative gain at this area.

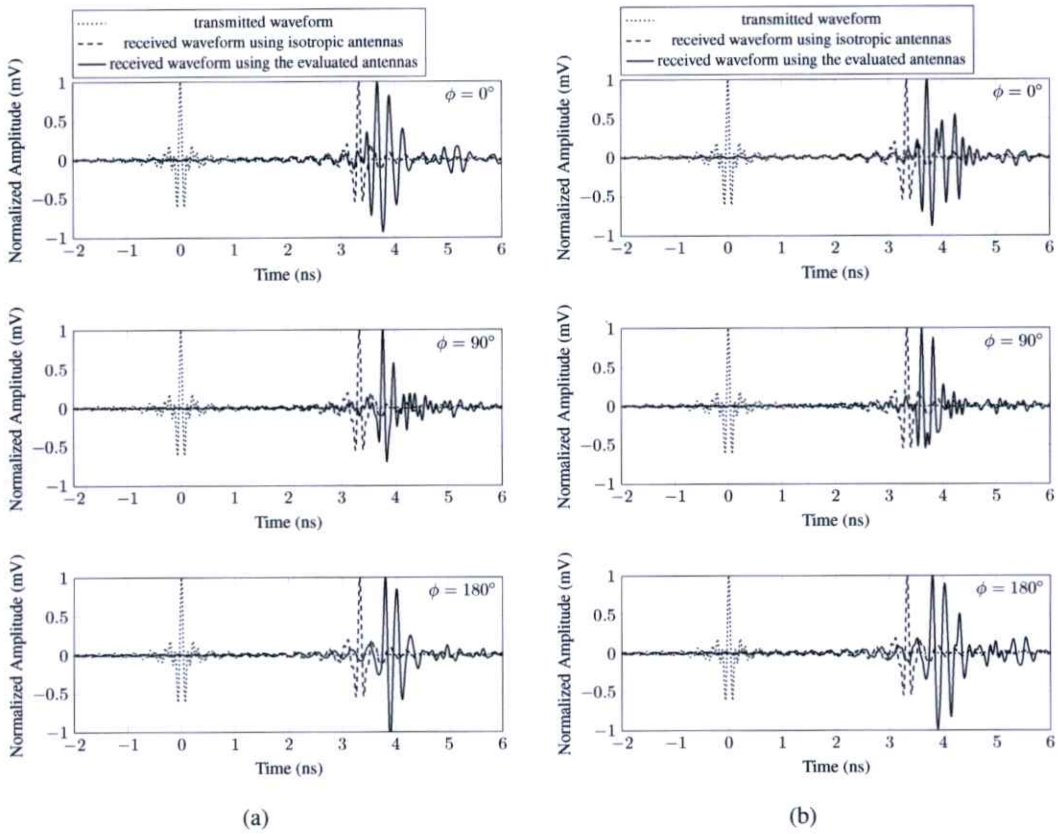


Figure 5.9: Illustration of impulse response (waveform transmission) at some specific angles: (a) The common UWB elliptical PMA system (b) The slots-added UWB elliptical PMA system

Overall, the common elliptical PMA has better performance related to its waveform transmission behavior, particularly waveform correlation. In this case, adding slots as a technique to reduce the ground plane effect precisely degrades the waveform transmission performance. The impacts of the antenna modification can be more evidently seen by this methodology of performance evaluation. Furthermore, the quantitative evaluation in time domain is very useful to distinguish the performance of the two UWB antennas which has similar designs.

5.4 Case 2: Performance Evaluation of the Novel UWB Elliptical PMA

The novel UWB elliptical antenna proposed in the previous chapter will be evaluated. Since there are some improvements for the flatness of radiation at particular direction, the performance of this antenna should be very good or just better than the common UWB elliptical PMA.

5.4.1 The Evaluated Antenna

The evaluated antenna is the novel UWB elliptical PMA as depicted in Fig. 5.13.

5.4.2 Results

Fig. 5.6 shows the antenna transfer function of the novel UWB elliptical PMA for its H-plane. The antenna transfer function doesn't have significant dips or drops like the previous

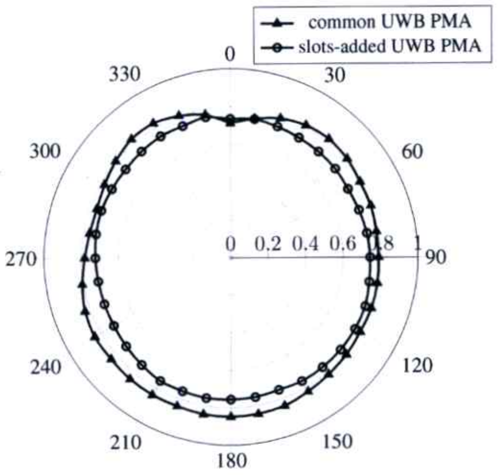


Figure 5.10: Waveform correlation of the common UWB elliptical PMA and the slots-added UWB elliptical PMA

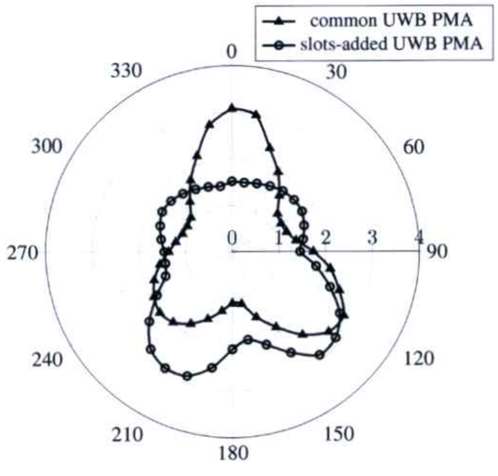


Figure 5.11: Waveform width stretch ratio (SR) of the common UWB elliptical PMA and the slots-added UWB elliptical PMA

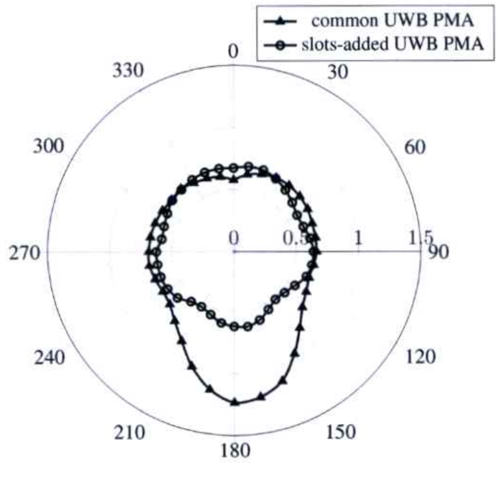


Figure 5.12: Waveform relative gain of the common UWB elliptical PMA and the slots-added UWB elliptical PMA

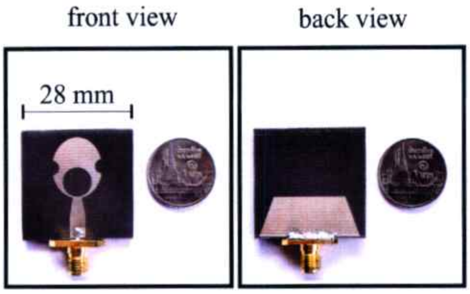


Figure 5.13: The evaluated antenna

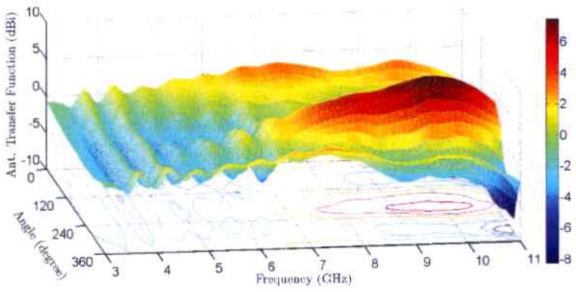


Figure 5.14: Antenna transfer function of the novel UWB elliptical PMA

case of performance evaluation. The transfer functions on ground plane area (around $180°$) look increasing at higher frequencies. So, the transfer function of the novel UWB elliptical PMA is good because there is no dips but also imperfectly flat especially for $\phi = 180°$). Fig. 5.7 shows that the group delays of the antenna is constant, only with some ripples particularly at lower frequencies.

For clearer views, antenna transfer functions and group delays for some specific ϕ angles are provided in Fig. 5.8. The antenna transfer functions for $\phi = 0°$ and $\phi = 90°$ looks relatively flat or stable over UWB bandwidth. The antenna transfer function for $\phi = 180°$ has no significant dips but looks increasing. Isotropic antenna would give a flat antenna transfer function at 0 dBi. In the Fig. 5.8 (b), the system group delays are constant, especially at higher frequencies. At lower frequencies, they are a bit wavy. It might be due the antenna size which is very small then

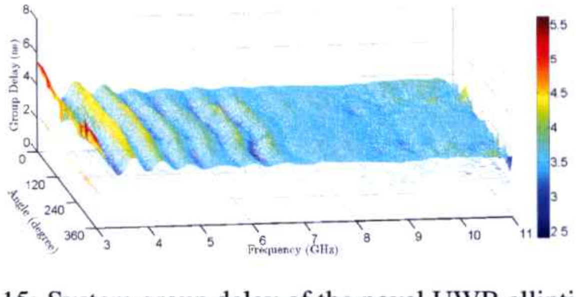


Figure 5.15: System group delay of the novel UWB elliptical PMA

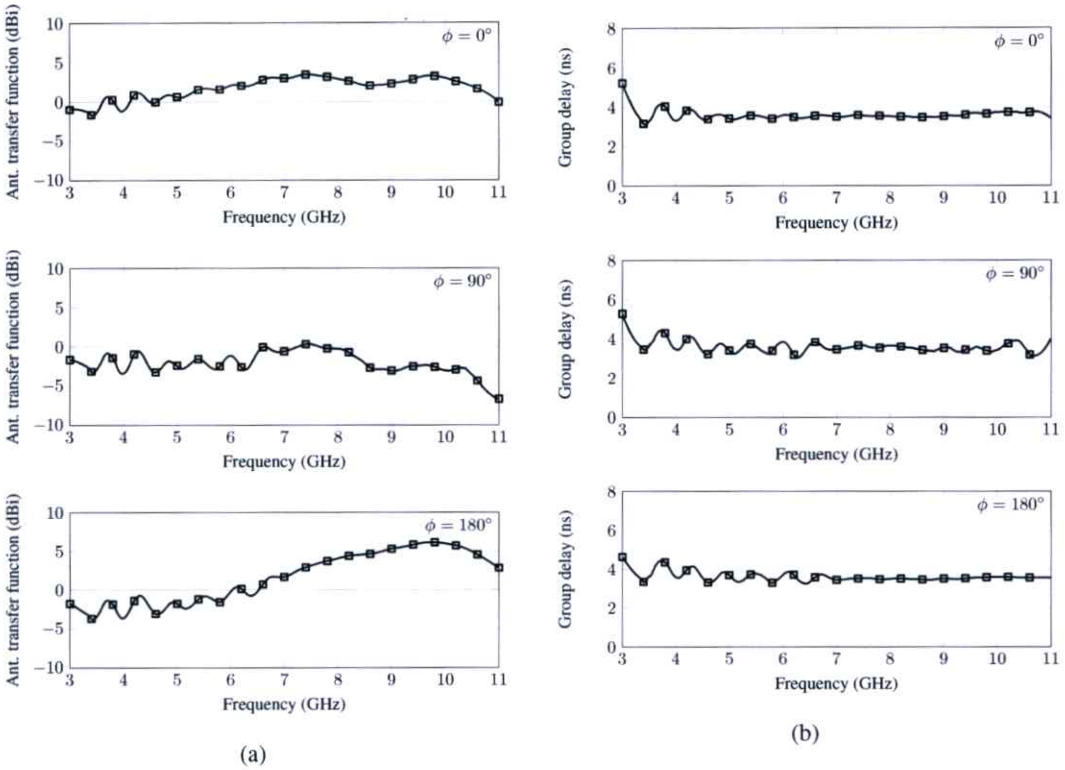


Figure 5.16: Frequency domain parameters at some specific angles (0°,90°,180°): (a) Antenna transfer function (b) System group delay

the performance at lower frequencies still more fluctuates.

The impulse responses for some specific angles are presented in Fig. 5.9. Generally, the waveforms are received at 3.5 ns after transmitted. It is apparent that the energy of received waveform for $\phi = 90^\circ$ are spread to 6 ns. Moreover, the received waveform for $\phi = 180^\circ$ looks much distorted. The performance is more easily assessed by waveform correlation, waveform width stretch ratio, and waveform relative gain.

From Fig. 5.18, the planar monopole antenna characterized in this paper has excellent waveform correlation, about 0.9 for most angles. The maximum waveform correlation is 0.91 for $\phi = 20^\circ$ and $\phi = 20^\circ$. But on the antenna ground plane side, the waveform correlations are only about 0.7. Correspond to the antenna transfer function at the angle of 180° (Fig. 5.14), the lower value of waveform correlation can happen due to the increasing transfer function at higher frequencies so that the received waveform would be more distorted. But generally, the novel UWB elliptical PMA has very good performance in the term of waveform correlation.

Waveform width stretch ratio (SR) provides other different view of the antenna performance. $p = 0.9$ or 90% energy portion is used for quantification of this performance parameter. From Fig. 5.19, the width stretch ratio is about 1 for antenna front side ($\phi = 0^\circ$) and ground plane side ($\phi = 0^\circ$) which means excellent performance. The SR tends to have worse (higher) values

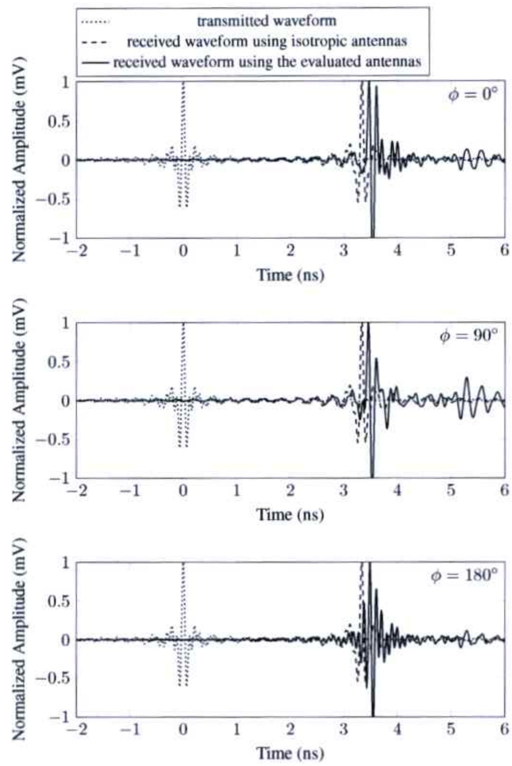


Figure 5.17: Illustration of impulse response (waveform transmission) at some specific angles

when the antenna pointed around 90° and 270°. But it can be confirmed with Fig. 5.17 where the received waveform energy for $\phi = 90°$ spread longer in time domain. Since the waveform width stretch ratio are less than 5 for all antenna orientations, the performance can be justified as very good. If the 90% energy of the transmitted waveform is delivered in about 0.4 ns, then the spreading caused by the antenna is only 0.4×5 = 2 nanoseconds. Because the waveform is symmetrical in time domain, the waveform can be transmitted well in every $\frac{2\text{ns}}{2}$ = 1 nanosecond (inter-pulse gap), which is very fast.

In Fig. 5.20, the waveform relative gain due to the antenna is about 1.4 for the antenna front

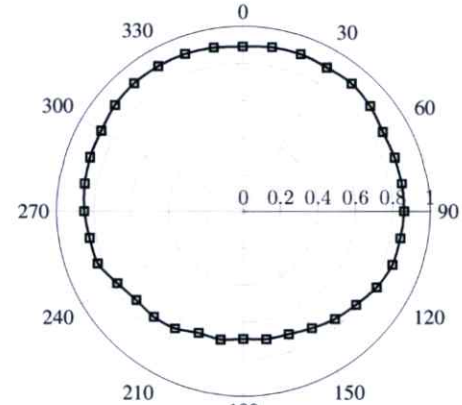


Figure 5.18: Waveform correlation of the novel UWB elliptical PMA

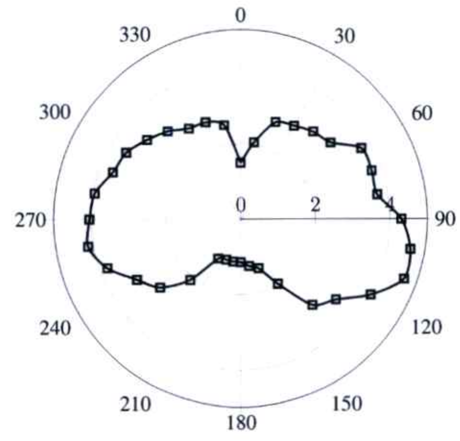


Figure 5.19: Waveform width stretch ratio (SR) of the novel UWB elliptical PMA

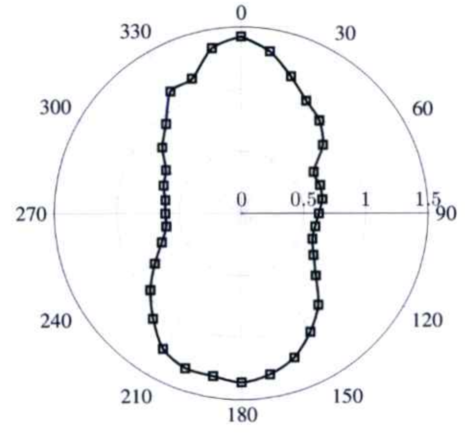


Figure 5.20: Waveform relative gain of the novel UWB elliptical PMA

and back side. The highest value is 1.42 and the lowest one is 0.6. It is very surprising to see that although this UWB antenna is small (smaller than the common UWB elliptical PMA), but it has high waveform relative gain. This happens because the E-fields are optimized in simulation to be flat and high over the entire UWB bandwidth. Therefore, this antenna has good waveform relative gain and even better compared to the common UWB elliptical PMA which has bigger size.

Overall, the novel UWB elliptical planar monopole antenna with its small size has very good performances, especially at the antenna front side. Of course, further improvements are still much necessary. It is not easy to get good performance at all antenna orientations (although only orientations on H-plane) due to the natural changes of radiation vs frequency causing unflat antenna transfer functions at some orientations.

5.5 Concluding Remarks

In this chapter, a comprehensive performance evaluation scheme for UWB planar monopole antenna is performed. Antenna transfer function and system group delay are used for frequency domain evaluation by seeing the flatness and constancy of them. Waveform correlation, waveform width stretch ratio, and waveform relative gain are used for time domain evaluation with their own concerns. Waveform correlation concerns on the waveform distortion due to antenna which is very important for UWB pulse detection. Waveform width stretch ratio concerns on the waveform energy spreading due to antenna for knowing the inter-pulse gap that can be applied in UWB transmission. Waveform relative gain concerns on how the antenna amplifies the transmitted waveform for dealing with attenuation by the channel.

It is not an easy task to make an excellent UWB antenna with good performance for all parameters and and all angles of orientation. Slight modifications on UWB elliptical PMA cause changes on the performance of the UWB antenna, although their impedance characteristics are similar. The slots-added UWB elliptical PMA which is modified from the common UWB elliptical PMA to reduce the ground plane effects is such an example. The performance evaluation scheme in this chapter is very useful to characterize and to choose the suitable antenna for a UWB system. The novel UWB elliptical PMA made in the previous chapter is also evaluated. There are quite significant improvements in this antenna through the efforts of making a flat radiation over UWB band in the design process. The antenna transfer functions tend to be more flat, and the waveform correlation is about 0.9. Moreover, the antenna radiation is more concentrated on its H-plane so the waveform relative gain is even higher than the bigger antenna like the common UWB elliptical PMA.

CHAPTER VI

CIRCUIT MODELING OF UWB PLANAR MONOPOLE ANTENNA

Different approach of UWB compared to the existing narrowband technologies imposes new design challenges for UWB system designers. One of the challenges is to model an equivalent circuit of UWB antenna so that the antenna can be included in co-simulation with transmitter/receiver circuits. By including the antenna in the system, the overal system performance can be predicted [87]. Moreover, effects of RF components to the other components also can be known. And aside for UWB system design, modeling an equivalent circuit for UWB antenna would have some other advantages. For example, it can provide useful insights into UWB antenna geometry and design [88].

In this chapter, a simple method for synthesizing equivalent circuit of UWB antenna is presented. SPICE-compatible equivalent circuit is preferly adopted since it has been popularly used for simulation of circuit/system behavior [89]. As a numerical example, equivalent circuit of a compact UWB elliptical planar monopole antenna is synthesized. Two kinds of equivalent circuit model are proposed based on vector approximation of the antenna frequency domain parameters. First model is derived by approximation of the antenna impedance, and the second one is derived by its admittance. The value of components in the circuits is obtained by the residues and poles from the approximated functions of impedace or admittance vector.

6.1 Specific Literature Review and Problem Statement

Since UWB technology has extremely wide frequency band, it is not easy to contrive a circuit model complying appropriate broadband characteristics. Equivalent circuit model of UWB antenna based on patch cavity model was introduced by [90]. Another one based on parallel plate transmission line model is done in [91, 92]. However, the frequency domain characteristic of the synthesized circuits are still not accurately fit the antenna characteristic performed by electromagnetic simulation. A method using narrowband model with perturbation gives a very simple equivalent circuit but the results are not accurate [93]. Physical circuit augmentation was proposed in [94]. The result has good accuracy, but the synthesized circuit looks the way too complicated.

The narrowband approaches for planar monopole antennas with microstrip feeding, such as transmission line model and cavity model, are not accurate enough to synthesize circuit model of UWB antennas. Also, the wider bandwidth relatively needs more circuit elements to achieve accuracy of modeling. Therefore, an efficient circuit modeling method with simple circuit model and good accuracy is needed in the development of UWB planar monopole antenna.

6.2 Methodology of Modeling

6.2.1 Vector Approximation

Frequency domain response of a UWB antenna can be represented either by impedance or admittance in the form of complex vector. The vector then can be approximated using vector fitting technique as a rational function which is formed by residues and poles [95]. Supposing a complex vector of $F(s)$ is a frequency domain response of a UWB antenna, the rational fit approximation of the vector can be written as

$$F(s) = \sum_{k=1}^{N} \frac{\mathrm{res}_k}{s - p_k} + d + s \times e \tag{6.1}$$

where res_k and p_k are the k-th complex residues and complex poles, respectively. $s = j\omega$ is complex angular frequency, d is constant term, and e is proportional term of $F(s)$.

The impedance/admittance vector can be approximated to rational function by finding poles and residues for some certain numbers of order. To find poles, starting pole a_m should be defined. Multiply F_s with an unknown function $\delta(s)$, where $\delta(s)$ has the same poles as the approximation of $\delta(s)F_s$.

$$\begin{bmatrix} \delta(s) \\ \delta(s)F(s) \end{bmatrix} \approx \begin{bmatrix} 1 + \sum_{m=1}^{M} \frac{\tilde{c}_m}{s - a_m} \\ d + s \times e + \sum_{m=1}^{M} \frac{c_m}{s - a_m} \end{bmatrix} \tag{6.2}$$

By multiplying the first row of the equation above with $F(s)$, the following relation is obtained.

$$\left(d + s \times e + \sum_{m=1}^{M} \frac{c_m}{s - a_m} \right) \approx \left(1 + \sum_{m=1}^{M} \frac{\tilde{c}_m}{s - a_m} \right) F(s) \tag{6.3}$$

or it can simply expressed as

$$(\delta F)_{\mathrm{fit}}(s) \approx \delta_{\mathrm{fit}}(s) F(s) \tag{6.4}$$

Eq. 6.4 is linear in its unknown d, e, c_m, $\tilde{c}_m$. Hence, the problem of Eq. 6.4 is a linear solvable equation $Ax = b$ for each frequency samplings. The unknown d, e, c_m, $\tilde{c}_m$ are in the solution of vector x which can be solved by least square. Now, the residues for rational function can be obtained. The complete results are obtained by solving F(s) in Eq. 6.1 with the zeros of $\delta(s)$ as new poles a_m.

6.2.2 SPICE-Compatible Equivalent Circuit

SPICE (Simulation Program with Integrated Circuit Emphasis) is a general-purpose analog electronic circuit standard simulator. It is a powerful program that is used in integrated circuit and board-level design to check the integrity of circuit designs and to predict circuit behavior. Simulating the circuit with SPICE is the industry-standard way to verify circuit operation at the transistor level before committing to manufacturing an integrated circuit. SPICE inspired and served as a basis for many other circuit simulation programs, in academia, in industry, and in commercial products. A compatibility with SPICE means that the circuit is able to be simulated in SPICE programs and is usually only composed by low level components such as resistor, capacitor, inductor, transistor, diode, op-amp, and etc.

Since the data of frequency domain responses such impedance or admittance are in complex numbers, then the obtained residues and poles would be some pairs of complex number and its conjugate [89]. Therefore, the frequency domain response $F(s)$ is

$$\begin{aligned} F(s) &= \frac{\mathrm{res}_1}{s-p_1} + \frac{\mathrm{res}_2}{s-p_2} \\ &= \frac{(\mathrm{res}_1 + \mathrm{res}_2)\, s - (\mathrm{res}_1 p_2 + \mathrm{res}_2 p_1)}{s^2 - (p_1+p_2)\, s + p_1 p_2} \\ &= \frac{as}{s^2+sc+d} + \frac{b}{s^2+sc+d} \end{aligned} \tag{6.5}$$

The model of SPICE-compatible equivalent circuit should be associated with the form of $F(s)$ so that the value of circuit components can be found using the obtained residues and poles. There are two possible models for SPICE-compatible equivalent circuit, using impedance or admittance approximation. The models will be elaborated by each subsection below.

6.2.2.1 Impedance Model

A lumped RLC circuit which can be considered as a suitable model with complex pole pairs is shown in Fig. 6.1. The equivalent impedance of the circuit can be derived as

$$\begin{aligned} Z(s) &= \frac{V(s)}{I(s)} \\ &= \frac{(sL+G_1)\left(\frac{\frac{1}{sC}G_2}{\frac{1}{sC}+G_2}\right)}{(sL+G_1)+\left(\frac{\frac{1}{sC}G_2}{\frac{1}{sC}+G_2}\right)} \\ &= \frac{sL+\frac{1}{G_1}}{s^2LC+sLG_2+\frac{sC}{G_1}+\frac{G_2}{G_1}+1} \\ &= \frac{\left(s\frac{1}{C}+\frac{1}{LG_1C}\right)}{\left(s^2+\left(\frac{G_2}{C}+\frac{1}{LG_1}\right)s+\left(\frac{G_2}{LG_1C}+\frac{1}{LC}\right)\right)} \end{aligned} \tag{6.6}$$

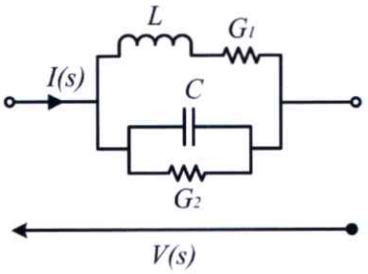


Figure 6.1: Lumped circuit for impedance model

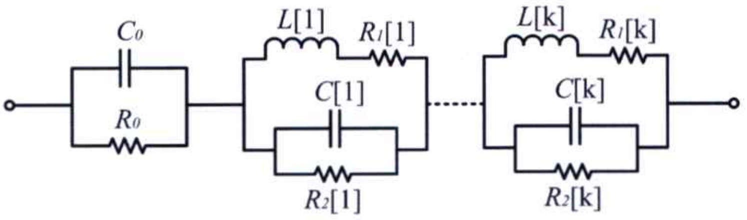


Figure 6.2: Equivalent circuit model for impedance approximaation

By corresponding the equivalent impedance with Eq. 6.5, the following relation can be established.

$$
\begin{aligned}
\mathrm{res}_1 + \mathrm{res}_2 &= \frac{1}{C} \\
-(p_1 + p_2) &= \frac{G_2}{C} + \frac{1}{LG_1} \\
p_1 p_2 &= \frac{G_2}{LG_1C} + \frac{1}{LC} \\
-(\mathrm{res}_1 p_2 + \mathrm{res}_2 p_1) &= \frac{1}{LG_1C}
\end{aligned}
\tag{6.7}
$$

Set of equations above provides a solution for value of components in the equivalent circuit model.

$$
\begin{aligned}
C &= \frac{1}{(\mathrm{res}_1 + \mathrm{res}_2)} \\
G_2 &= \frac{1}{(\mathrm{res}_1 + \mathrm{res}_2)} \times \left[-(p_1 + p_2) + \frac{(\mathrm{res}_1 p_2 + \mathrm{res}_2 p_1)}{(\mathrm{res}_1 + \mathrm{res}_2)} \right] \\
L &= \frac{(\mathrm{res}_1 + \mathrm{res}_2)}{p_1 p_2 + \left[-(p_1 + p_2) + \frac{(\mathrm{res}_1 p_2 + \mathrm{res}_2 p_1)}{(\mathrm{res}_1 + \mathrm{res}_2)} \right] \times \frac{(\mathrm{res}_1 + \mathrm{res}_2)}{(\mathrm{res}_1 p_2 + \mathrm{res}_2 p_1)}} \\
G_1 &= -\frac{1}{L} \times \frac{(\mathrm{res}_1 + \mathrm{res}_2)}{(\mathrm{res}_1 p_2 + \mathrm{res}_2 p_1)}
\end{aligned}
\tag{6.8}
$$

The conductances G_1 and G_2 then can be converted to resistance with $R_1 = \frac{1}{G_1}$ and $R_2 = \frac{1}{G_2}$, respectively. Hence, the equivalent circuit model for impedance approximation can be represented as in Fig. 6.2 for k-order. The R_0 and C_0 are determined based on the constant term d and the proportional term e, where $R_0 = \frac{1}{d}$ and $C_0 = e$.

6.2.2.2 Admittance Model

Similar way also can be done for poles and residues obtained from admittance approximation. The suitable RLC circuit for admittance model is shown in Fig. 6.3. The equivalent admittance of the circuit can be derived as

$$\begin{aligned} Y(s) &= \frac{I(s)}{V(s)} \\ &= \frac{1}{(sL+R)+\frac{\frac{1}{sC}R_2}{\frac{1}{sC}+R_2}} \\ &= \frac{1+sCR_2}{s^2LCR_2+s(R_1CR_2+L)+R_1+R_2} \\ &= \frac{\left(s\frac{1}{L}+\frac{1}{LCR_2}\right)}{\left(s^2+\left(\frac{R_1}{L}+\frac{1}{CR_2}\right)s+\left(\frac{R_1}{LCR_2}+\frac{1}{LC}\right)\right)} \end{aligned} \tag{6.9}$$

And then the following relation can be established

$$\begin{aligned} \text{res}_1+\text{res}_2 &= \frac{1}{L} \\ -(p_1+p_2) &= \frac{R_1}{L}+\frac{1}{CR_2} \\ p_1p_2 &= \frac{R_1}{LCR_2}+\frac{1}{LC} \\ -(\text{res}_1p_2+\text{res}_2p_1) &= \frac{1}{LCR_2} \end{aligned} \tag{6.10}$$

Solution for value of components in this equivalent circuit model is given as

$$\begin{aligned} L &= \frac{1}{(\text{res}_1+\text{res}_2)} \\ R_1 &= \frac{1}{(\text{res}_1+\text{res}_2)}\times\left[-(p_1+p_2)+\frac{(\text{res}_1p_2+\text{res}_2p_1)}{(\text{res}_1+\text{res}_2)}\right] \\ C &= \frac{(\text{res}_1+\text{res}_2)}{p_1p_2+\left[-(p_1+p_2)+\frac{(\text{res}_1p_2+\text{res}_2p_1)}{(\text{res}_1+\text{res}_2)}\right]\times\frac{(\text{res}_1+\text{res}_2)}{(\text{res}_1p_2+\text{res}_2p_1)}} \\ R_2 &= -\frac{1}{C}\times\frac{(\text{res}_1+\text{res}_2)}{(\text{res}_1p_2+\text{res}_2p_1)} \end{aligned} \tag{6.11}$$

After getting the value of the components, the equivalent circuit model for admittance approximation can be represented as in Fig. 6.4 for k-order. The R_0 and C_0 are also determined based on the constant term d and the proportional term e, where $R_0 = \frac{1}{d}$ and $C_0 = e$.

6.3 The Modeled UWB Antenna

The UWB antenna modeled in this chapter is the common elliptical PMA which has been designed in Chapter 4 as dipicted in Fig. 6.5. The return loss and other characteristics of this

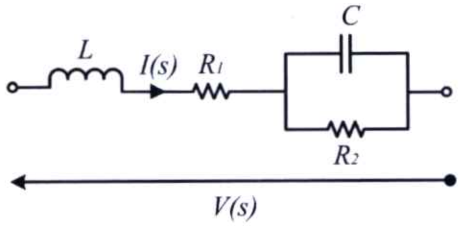


Figure 6.3: Lumped circuit for admittance model

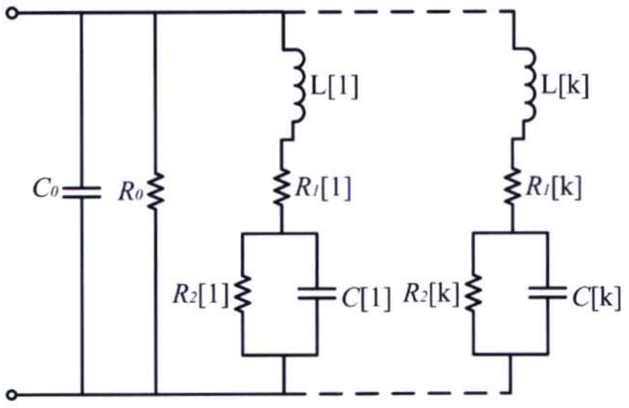


Figure 6.4: Equivalent circuit model for admittance approximation

antenna also can be seen in Chapter 4. As the approximated vectors, impedance and admittance of the modeled UWB antenna are presented in Fig. 6.6 and Fig. 6.7, respectively. Representations of them are limited to 3 GHz to 11 GHz considering the used bandwidth of UWB. For specific comparison, the value of impedance and admittance are taken from simulation in CST Microwave Studio which uses finite difference time domain (FDTD) analysis. Indeed, vectors of impedance and admittance from measurement also can be used as reference for this equivalent circuit modeling.

6.4 Results

Results of impedance approximation including residues, poles, and the circuit parameters are summarized on Table 6.1. Then, the synthesized equivalent circuit can be arranged as shown

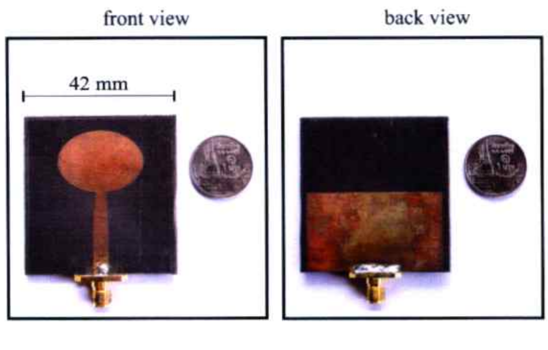


Figure 6.5: The modeled UWB antenna

Table 6.1: Impedance approximation results and equivalent circuit parameters

Order	Impedance Approximation				Circuit Parameters					
	Residues	Poles	d	e	L(e-22)	R_1(e10)	C(e-12)	R_2(e-11)	R_0	C_0
1	-1.7757e11+1.4424e11i	-5.5423e9+6.6916e10i	40.944	0	3.4198	-5.9901	-2.8159	2.0485	0.024424	0
2	2.1326e11+7.4158e+010i	-3.5854e9+6.1318e10i			22.635	1.7737	2.3445	-4.0148		
3	2.0283e11+3.9254e10i	-3.6695e9+5.2168e10i			113.04	64.264	2.4651	-7.2646		
4	1.1504e11-2.3496e9i	-2.722e9+3.9457e10i			-1479.4	-352.79	4.3463	-5.219		
5	5.4328e10-7.3519e10i	-2.3038e9+1.6697e10i			19.794	-2.4898	9.2033	4.9283		
6	6.3109e10+1.4542e10i	-2.5784e9+2.4777e10i			385.36	313.11	7.9228	-1.2066		

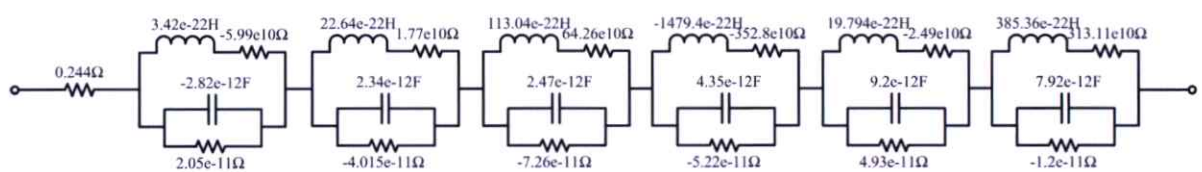
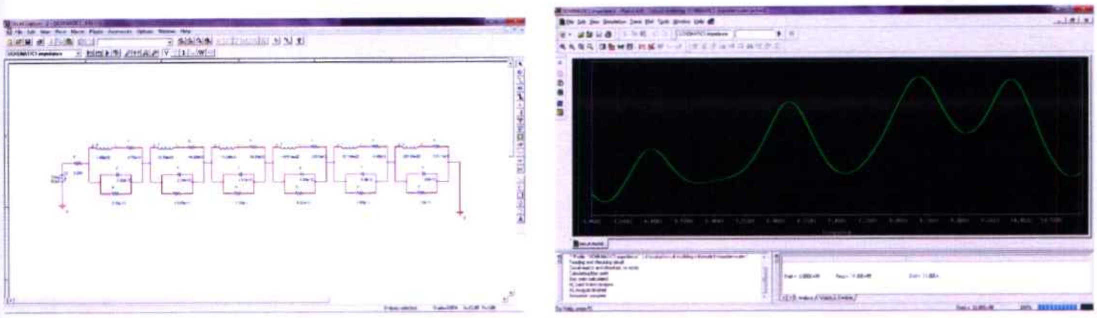
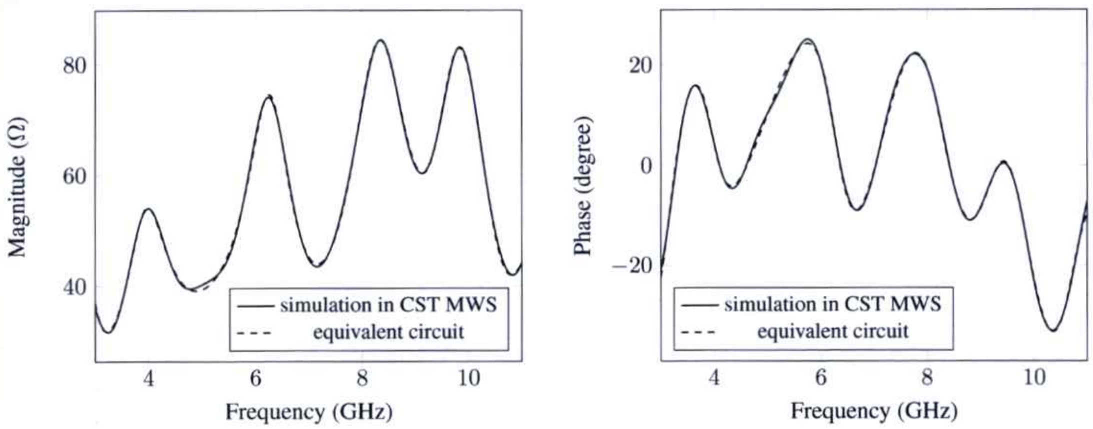


Figure 6.8: Equivalent circuit of the UWB antenna by impedance approximation



(a) (b)

Figure 6.9: Simulation of equivalent circuits by impedance approximation: (a) Modeling in OrCAD Capture, (b) Result in OrCAD PSpice



(a) (b)

Figure 6.10: Impedance approximation errors between CST MWS simulation and equivalent circuit: (a) Magnitude (b) Phase

A similar way is also acquired from equivalent circuit modeling based on admittance approximation but with different circuit connections. The residues, poles, and circuit parameters are listed in Table 6.2. The equivalent circuit is obtained by parallel connections of the lumped circuit as seen in Fig. 6.11 because the $\frac{1}{Y_{\text{equivalent}}} = \frac{1}{Y_1} + \frac{1}{Y_2} + \frac{1}{Y_3} + ... + \frac{1}{Y_k}$ for k numbers of order. The circuit is then simulated in SPICE program as shown in Fig. 6.12. The result in Fig. 6.13 also shows that the frequency response of the equivalent circuit agrees accurately with the real admittance. One weakness of this method is the presence of negative values of the components which is feasible in theory and simulation but more complicated realization in practice.

Table 6.2: Admittance approximation results and equivalent circuit parameters

Order	Admittance Approximation				Circuit Parameters					
	Residues	Poles	d	e	L(e-9)	R_1	C(e-23)	R_2(e11)	R_0	C_0
1	1.7682e7+1.6311e7i	-2.4751e9+6.7099e10i	0.022595	0	28.277	1820.2	26.146	-64.369	44.258	0
2	1.8459e7-1.8252e7i	-3.1641e9+5.8531e10i			27.087	-1481.9	29.945	54.71		
3	9.6472e7-2.3143e8i	-6.7571e9+4.6151e10i			5.1828	-538.78	8.189	1.0395		
4	-2.7966e8+4.4972e7i	-7.1739e9+4.0339e10i			-1.7879	-1.2283	-10655	-6870		
5	3.8804e7+3.3713e7i	-2.4358e9+1.9711e10i			12.885	252.05	348.02	-19.561		
6	-6.2319e7+6.0749e7i	-4.7237e9+2.5604e10i			-8.0233	162.36	166.48	20.236		

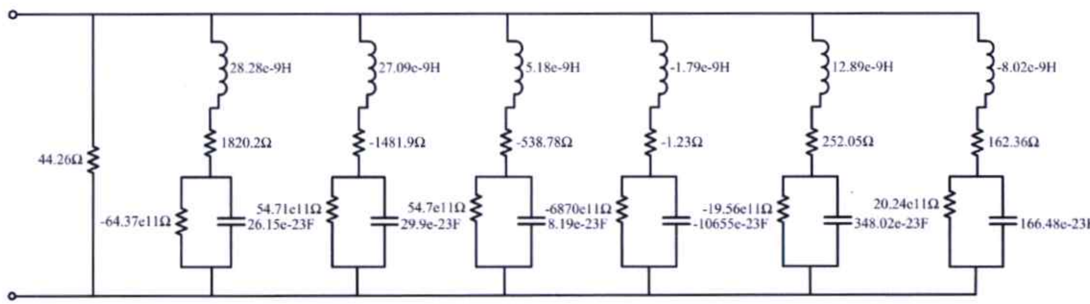
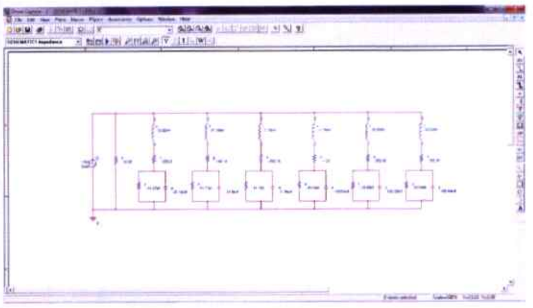
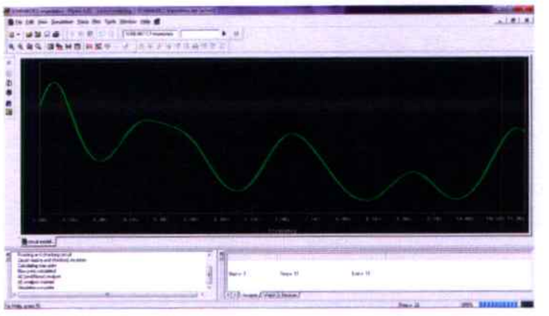


Figure 6.11: Equivalent circuit of the UWB antenna by admittance approximation



(a)



(b)

Figure 6.12: Simulation of equivalent circuits by admittance approximation: (a) Modeling in OrCAD Capture, (b) Result in OrCAD PSpice

From all results, both impedance and admittance approximation methods have been proven very accurate for equivalent circuit modeling of the UWB antenna. The synthesized equivalent circuits provide similar frequency response (impedance/admittance) compared with the real antenna frequency response. The error is extremely low. The accuracy is influenced by the number of order as shown in Fig. 6.14. The normalized RMS error [96] shows that increasing the number of order will yield a perfect fitting of frequency response. Consequently, higher number of order will also increase the complexity of the circuit. In our case, circuits with 6 numbers of orders are considered to be accurate enough to maintain the equivalent circuit in lower complexity. Trade-off between accuracy and complexity of the equivalent circuit should be considered very well. In Fig. 6.14, it is apparent that the impedance approximation model offers slightly better accuracy than the admittance model. Nevertheless, basically both methods can be chosen based on the requirements and purposes.

6.5 Concluding Remarks

This chapter presents a simple approach for synthesizing equivalent circuit of UWB antenna. The circuit is obtained by corresponding SPICE-compatible equivalent circuit with rational fit approximation of frequency domain response such impedance or admittance. By this method, two different kinds of equivalent circuit structure with similar responses can be extracted. The results show that the impedance/admittance of the equivalent circuit agrees very accurately with the approximated one from other electromagnetic software. Although this method has a weakness by having negative values for some circuit components, but it is still feasible in theory and circuit simulation.

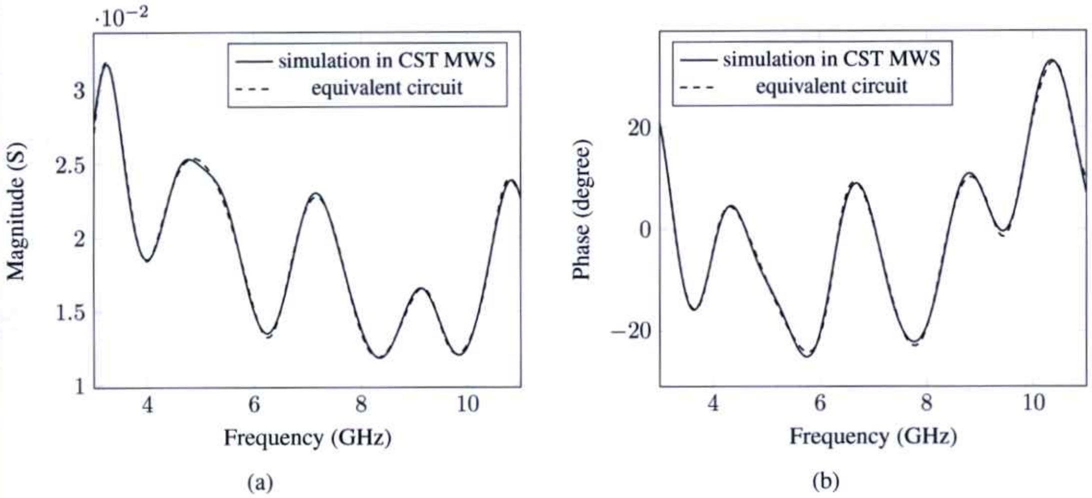


Figure 6.13: Admittance approximation errors between CST MWS simulation and equivalent circuit: (a) Magnitude (b) Phase

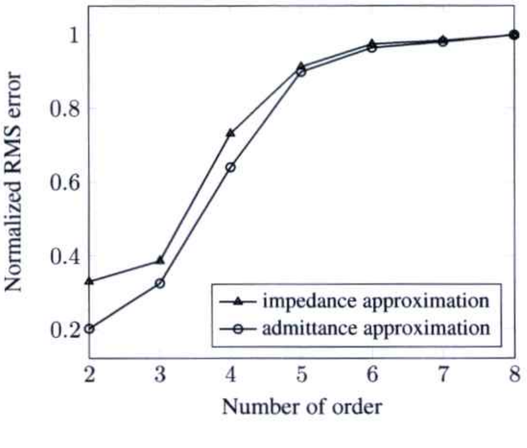


Figure 6.14: Normalized RMS error for impedance approximation and admittance approximation, 1=perfect ; 1-∞= more errors

CHAPTER VII

CONCLUSION

7.1 Thesis Summary

UWB technology will be a solution for the future short range wireless communications due to its huge bandwidth and low power spectral density which lead this technology to achieve high data rate and very low power consumption. One of the major challenges of this technology is the antenna, where most approaches for narrowband antennas are insufficient for UWB. Research in planar monopole antenna is booming until now because this kind of antenna provides huge bandwidth and omnidirectional radiation pattern which are necessary for UWB technology. In this thesis, the development of UWB planar monopole antenna is discussed in 3 important aspects: design, performance evaluation, and circuit modeling.

In the design of UWB planar monopole antenna, size and characteristics are two matters that should be noticed. The UWB antenna must have small size to be fit with most applications. The common design methodology used by most antenna designers is solely focused on the impedance characteristic, i.e. return loss, and radiation patterns at particular frequencies. In addition of those parameters, the radiation characteristic of UWB antennas also should be observed over the entire UWB bandwidth. Since the antenna radiation changes by frequency, the stability or flatness of antenna radiation becomes important. Extending the design procedure is a way offered in this thesis. In simulation using CST Microwave Studio, the antenna radiation characteristic over UWB band can be known by placing E-field probes at specific antenna orientations. Two designs of UWB planar monopole antenna with elliptical pole are performed, one with common procedure and another with the extended procedure. Both designs successfully comply UWB impedance bandwidth and have omnidirectional radiation patterns. The novel UWB elliptical PMA designed with the extended procedure has smaller size and more flat radiation while the common one suffers from drops of radiation at some frequencies. Some design techniques for UWB elliptical PMA are also discovered in this thesis. The techniques such as tapered feed line, adding slots, changing the ground plane shape are very useful to enhance the impedance matching or to improve the stability of radiation over UWB bandwidth. The presented method, design techniques, and analysis of current distribution can give guidelines and useful insights to design planar monopole antenna for UWB technology.

In the aspect of performance evaluation, UWB antennas pose more challenges because UWB technology operates on very wide bandwidth and might uses impulse-based radio transmission. To evaluate the performance of UWB planar monopole antenna, two-identical antenna measurement must be done as the first step of evaluation because UWB antennas should be considered as a system. By characterizing the antenna system, performances of the antenna can be evaluated by deriving several performance parameters. Two parameters in frequency domain are antenna transfer function and system group delay. Three parameters in time domain are waveform correlation, waveform width stretch ratio, and waveform relative gain. Those parameters are very useful to understand the performance of UWB planar monopole antenna either to evaluate or to compare some UWB antennas. The methodology of performance evaluation is then used for investigating two cases. The first case is an investigation of the impacts of reducing ground plane effects on UWB elliptical PMA performance. Reducing ground plane effects is a technique to minimize the domination of ground plane on PMA by discarding some useless parts such as by adding slots. Although after reducing ground plane effects the designs and impedance characteristics are similar, but the performance of the UWB elliptical PMA are changes. So, two UWB elliptical PMAs are compared in this case. The impacts of reducing ground plane effects can be understood by evaluating both antennas and the performance tends degraded. By the same method and parameters, the novel UWB elliptical PMA is also evaluated. The results prove that the design effort to make its radiation more flat is successful, shown by its flat transfer function for some orientations. The overall performance of the novel UWB antenna is good although not for all orientations. The waveform correlation is about 0.9. The waveform relative gain is also high, obviously higher than the common UWB elliptical PMA which is precisely bigger in size. Although the developed UWB planar monopole antennas in this thesis are still far from perfectness, the presented methods of design and performance evaluation can be the keys of improvement of UWB planar monopole antenna.

For integration of antenna into UWB system, it is necessary to model UWB antenna as a circuit. As the third aspect of development, this thesis presents a simple method of circuit modeling by applying rational fit approximation to the vectors of antenna impedance or admittance. Some suitable lumped circuit models containing resistance, inductance, and capacitance can be corresponded to the obtained poles and residues from the approximated vectors. So, once the poles and residues are obtained, the values of the circuit components are known. Then, the equivalent circuit of the UWB antenna can be built according to the desired number of order. By using the common UWB elliptical PMA as the modeled UWB antenna, the presented method is proved to be very accurate.

7.2 Contribution

The major contributions of this thesis are detailed below.

1. **Design procedures and techniques**

   This thesis elaborates the common design procedure and also appoints the new extended design procedure which is emphasized on the importance of flat radiation of UWB planar monopole antenna over the desired UWB bandwidth. This matter has not been noticed by previous researches. Furthermore, the used design techniques in the developed antennas provides useful insights to design UWB planar monopole antenna, mainly about dimensions of each part, how to apply tapered feed line, how to apply slots, and etc. The developed UWB elliptical PMAs can be used as examples for later improvements.

2. **Comprehensive method for performance evaluation**

   Performance of UWB antenna can be seen by many views. Other researches generally limit their evaluation on a few parameters without considering the others. The used standards of evaluation are usually different. This thesis presents a comprehensive method to evaluate the performance of UWB planar monopole antennas. The extension of Friis' transmission formula which is more suitable for UWB is applied. Rectangular passband waveform with ideal spectrum is used. This comprehensive method is very important for industrial purposes in the development of UWB antenna.

3. **Accurate and easy method for circuit modeling**

   This thesis demonstrates an accurate and easy method to synthesize UWB planar monopole antenna to RLC circuit. It is a contribution for UWB system developer by giving such an easy way to include antenna in the circuit simulation of UWB system, particularly the RF parts. The advantage is that the circuit extracted by the presented method has exactly the same characteristic as the UWB antenna.

7.3 Further Improvement and Extension

In this section we list some future improvement and extension that could be done related to this work.

1. **Design a smaller UWB planar monopole antenna with better performance**

   This thesis has shown a feasibility to get better performance with smaller size UWB planar monopole antenna. It is still very possible to miniaturize this antenna to fit more applications. Different way of feeding, thinner dielectric substrate can be tested in implementation. Improvement of performance is also a potential issue because it is not an easy task to make the performance good at all antenna orientations.

2. **Derivation of simple formula to design UWB planar monopole antenna**

   Design using CAD (Computer Aided Design) software is a powerful way and preferable since it provides flexibility, but the method seems like "trial and error". Genetic algorithm and other algorithms have been developed for optimization to reduce the "trial and error" by human to be done by computer. There are some handy formulas to design narrowband PMA such as formula for rectangular PMA which is available on textbook [40], but none for UWB. Therefore, a successful derivation of formula to design UWB PMA can be a big influence to RF component design. It will be great if the structure of UWB antenna or UWB filter could be just calculated based on material characteristics and the desired operating bandwidth.

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BIOGRAPHY

Personal Information

Name	Adi Mahmud Jaya Marindra
Sex	Male
Nationality	Indonesian
Place, Date of Birth	Balikpapan, July 10, 1989

Education

Bachelor degree

Thesis	Implementation of OFDM-based transmitter on FPGA Xilinx Spartan-3E
Research Interests	Modern communication systems, digital system design on FPGA, microcontroller-based systems, robotics
Field of Study	Signal and electronic systems, telecommunication
Program	Electrical Engineering
Department	Electrical Engineering
University	Universitas Gadjah Mada, Indonesia
Duration	September 2006 - May 2010 (3 years and 8 months)

Master degree

Thesis	Development of UWB Planar Monopole Antenna for UWB Technology: Design, Performance Evaluation and Circuit Modeling
Research Interests	Antenna design, UWB radio propagation
Field of Study	Information and communication technology
Program	Computer Engineering
College	International College
University	King Mongkut's Institute of Technology Ladkrabang, Thailand
Duration	June 2011 - May 2013 (2 years)

LIST OF PUBLICATIONS

Some parts of this work are published in the following articles.

International Conference Proceedings

1. Adi Mahmud Jaya Marindra, Sathaporn Promwong and Jun-ichi Takada ,"SPICE-Compatible Equivalent Circuit Modeling of UWB Antenna Using Impedance and Admittance Approximation," Proc. of the IEEE International Conference on Engineering, Applied Sciences, and Technology (ICEAST), Bangkok, Thailand, November 21-24, 2012.

2. Adi Mahmud Jaya Marindra, Sathaporn Promwong and Jun-ichi Takada ,"Comprehensive Characterization of a Novel UWB Elliptical Planar Monopole Antenna," Proc. of IEEE Region 10 Conference (TENCON), Cebu, Philippines, November 19-22, 2012.

3. Adi Mahmud Jaya Marindra, Sathaporn Promwong,"Impacts of Reducing Ground Plane Effects on UWB Planar Monopole Antenna Performance," Proc. of The 5th AUN/SEED-Net Regional Conference on Information and Communications Technology (RCICT), Manila, Philippines, October 18-19, 2012.

4. Adi Mahmud Jaya Marindra, Sathaporn Promwong and Jun-ichi Takada, Performance Evaluation of Ultra Wideband Printed Antenna by System Characterization," Proc. of The 9th Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology Conference (ECTI-CON), Hua Hin, Thailand, May 16-18, 2012.

Conference Guide & Abstract Book

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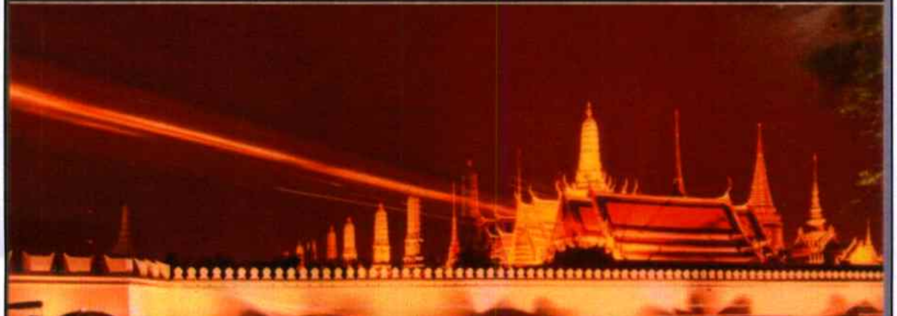


ECTI Association · IEEE Thailand Section · JIST · ICROS · NECTEC · ptt Group · Thaioil Group

SPICE-Compatible Equivalent Circuit Modeling of UWB Antenna Using Impedance and Admittance Approximation

Adi Mahmud Jaya Marindra*, Sathaporn Promwong† and Jun-ichi Takada‡
*International College, †Dept. of Telecommunication Engineering, Faculty of Engineering
*†King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand 10520
Email: {s4601102, kpsathap}@kmitl.ac.th
‡Graduate School of Science and Engineering, Tokyo Institute of Technology
O-okayama Minami 6 Bldg., 2-12-1, O-okayama, Meguro-ku, 152-8550, Tokyo, Japan
Email: takada@ide.titech.ac.jp

***Abstract*—In communication system design, equivalent circuit modeling of radio frequency (RF) component is an important matter for predicting the overall system performance. This paper presents a method for synthesizing equivalent circuit of UWB antennas. Simulation program with integrated circuit emphasis (SPICE)-compatible circuit modeling is preferly adopted since it has been popularly used for simulation of circuit/system behavior. By applying rational fit approximation to impedance and admittance, the obtained poles and residues can be represented as the component values of the circuit. In this work, a UWB elliptical planar monopole antenna is used as a numerical example. The results show that the frequency response of modeled circuits agree accurately with simulation using other electromagnetic software. Instead of simulated impedance and admittance, the measured impedance and measured admittance also can be modeled using this method as well.**

***Index Terms*—UWB antenna, equivalent circuit, SPICE, rational fit, impedance, admittance**

I. Introduction

Nowadays, research in ultra wideband (UWB) technology has been considered for numerous kinds of application [1]. Different approach of UWB compared to the existing narrowband technologies imposes new design challenges for UWB system designers. One of the challenges is to model an equivalent circuit of UWB antenna so that the antenna can be included in co-simulation with transmitter/receiver circuits. By including the antenna in the system, the overal system performance can be predicted [2]. Moreover, effects of RF components to the other components also can be known. And aside for UWB system design, modeling an equivalent circuit for UWB antenna would have some other advantages. For example, it can provide useful insights into UWB antenna geometry and design [3].

In 2002, the Federal Communication Commission (FCC) released the UWB frequency allocation from 3.1 GHz to 10.6 GHz including its spectrum restriction [4]. Although some countries have their own regulation, it is agreed that UWB occupied bandwidth should be not less than 500 MHz and the fractional bandwidth not less than 0.2. Since having this extremely wide frequency band, it is not easy to contrive a circuit model complying approppriate broadband characteristics. Equivalent circuit model of UWB antenna based on patch cavity model was introduced by [5]. However, the frequency domain characteristic of the synthesized circuit is still not accurately fit the antenna characteristic. In this paper, a simple method for synthesizing equivalent circuit of UWB antenna is presented. SPICE-compatible equivalent circuit is preferly adopted since it has been popularly used for simulation of circuit/system behavior [6].

As a numerical example, equivalent circuit of a compact UWB elliptical planar monopole antenna is synthesized. Two kinds of equivalent circuit model are proposed based on vector approximation of the antenna frequency domain parameters. First model is derived by approximation of the antenna impedance, and the second one is derived by its admittance. The value of components in the circuits is obtained by the residues and poles from the approximated functions of impedace or admittance vector.

II. Impedance/Admittance Vector Approximation

Frequency domain response of a UWB antenna can be represented either by impedance or admittance in the form of complex vector. The vector then can be approximated using vector fitting technique as a rational function which is formed by residues and poles [7]. Supposing a complex vector of $F(s)$ is a frequency domain response of a UWB antenna, the rational fit approximation of the vector can be written as

$$F(s) = \sum_{k=1}^{N} \frac{\text{res}_k}{s - p_k} + d + s \times e \quad (1)$$

where res_k and p_k are the k-th complex residues and complex poles, respectively. $s = j\omega$ is complex angular frequency, d is constant term, and e is proportional term of $F(s)$.

The impedance/admittance vector can be approximated to rational function by finding poles and residues for some certain

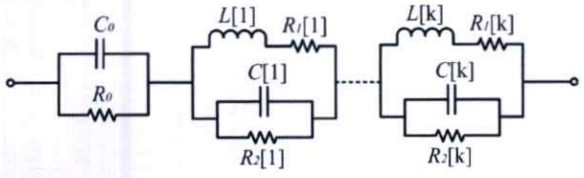


Fig. 2. Equivalent circuit model for impedance approximaation

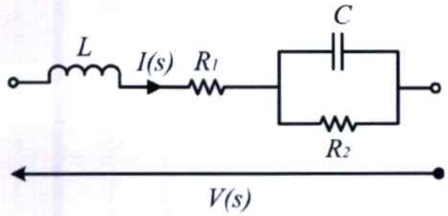


Fig. 3. Lumped circuit for admittance model

B. Admittance Model

Similar way also can be done for poles and residues obtained from admittance approximation. The suitable RLC circuit for admittance model is shown in Fig. 3. The equivalent admittance of the circuit can be derived as

$$\begin{aligned} Y(s) &= \frac{I(s)}{V(s)} \\ &= \frac{1}{(sL+R)+\frac{\frac{1}{sC}R_2}{\frac{1}{sC}+R_2}} \\ &= \frac{1+sCR_2}{s^2LCR_2+s(R_1CR_2+L)+R_1+R_2} \\ &= \frac{\left(s\frac{1}{L}+\frac{1}{LCR_2}\right)}{\left(s^2+\left(\frac{R_1}{L}+\frac{1}{CR_2}\right)s+\left(\frac{R_1}{LCR_2}+\frac{1}{LC}\right)\right)} \end{aligned} \tag{9}$$

And then the following relation can be established

$$\begin{aligned} \mathrm{res}_1+\mathrm{res}_2 &= \frac{1}{L} \\ -(p_1+p_2) &= \frac{R_1}{L}+\frac{1}{CR_2} \\ p_1p_2 &= \frac{R_1}{LCR_2}+\frac{1}{LC} \\ -(\mathrm{res}_1p_2+\mathrm{res}_2p_1) &= \frac{1}{LCR_2} \end{aligned} \tag{10}$$

Solution for value of components in this equivalent circuit model is given as

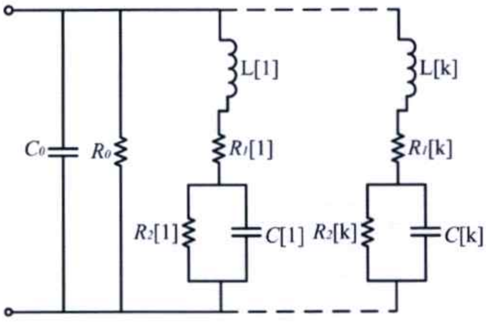


Fig. 4. Equivalent circuit model for admittance approximaation

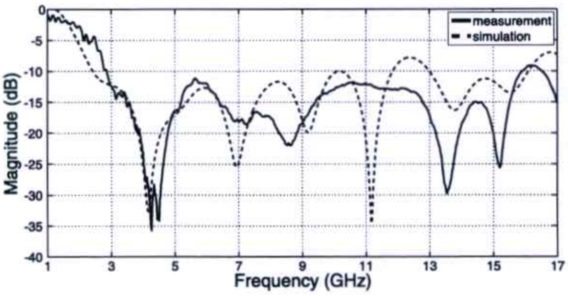


Fig. 6. Return loss of the modeled UWB antenna

$$\begin{aligned} L &= \frac{1}{(\mathrm{res}_1+\mathrm{res}_2)} \\ R_1 &= \frac{1}{(\mathrm{res}_1+\mathrm{res}_2)}\times\left[-(p_1+p_2)+\frac{(\mathrm{res}_1p_2+\mathrm{res}_2p_1)}{(\mathrm{res}_1+\mathrm{res}_2)}\right] \\ C &= \frac{(\mathrm{res}_1+\mathrm{res}_2)}{p_1p_2+\left[-(p_1+p_2)+\frac{(\mathrm{res}_1p_2+\mathrm{res}_2p_1)}{(\mathrm{res}_1+\mathrm{res}_2)}\right]\times\frac{(\mathrm{res}_1+\mathrm{res}_2)}{(\mathrm{res}_1p_2+\mathrm{res}_2p_1)}} \\ R_2 &= -\frac{1}{C}\times\frac{(\mathrm{res}_1+\mathrm{res}_2)}{(\mathrm{res}_1p_2+\mathrm{res}_2p_1)} \end{aligned} \tag{11}$$

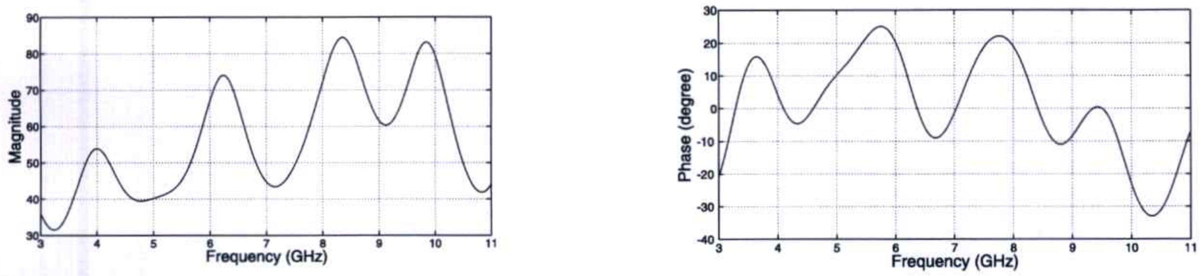
After getting the value of the components, the equivalent circuit model for admittance approximation can be represented as in Fig. 2 for k-order. The R_0 and C_0 are also determined based on the constant term d and the proportional term e, where $R_0 = \frac{1}{d}$ and $C_0 = e$.

IV. The Modeled UWB Antenna

The UWB elliptical planar monopole antenna modeled in this paper is dipicted in Fig. 5. It was simulated using CST Microwave Studio and fabricated on Teflon substrate which has dielectric constant of 2.5 and thickness of 1.6 mm. Its detail dimensions are: Wf=4.42, Wc=2.5, Wg=42, Lf=19, Lc=9, Lg=24.3, a=26, b=19, gap=0.2 (all values are in mm). Looking at its simulated and measured return loss ($|S_{11}|$) in Fig. 6, the return loss is under -10 dB for wide frequency range. It is clear that the antenna has broadband characteristic covering UWB unlicensed bandwidth allocated by FCC (3.1 GHz - 10.6 GHz).

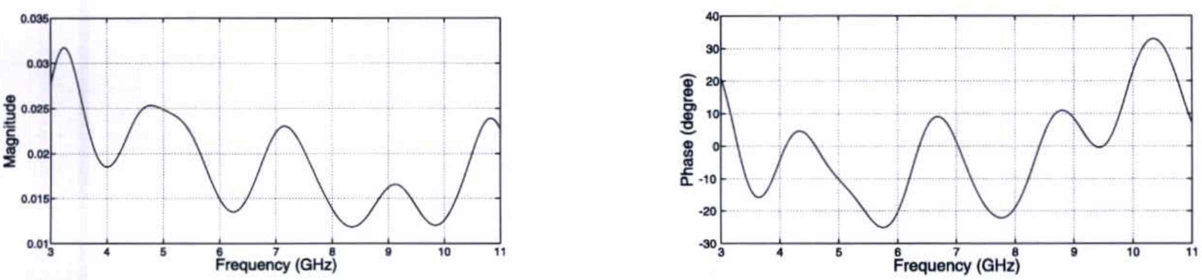
(a) (b)

Fig. 5. The modeled UWB antenna (a) Structure (b) Prototype



(a) (b)

Fig. 7. Impedance of the modeled UWB antenna (a) Magnitude (b) Phase



(a) (b)

Fig. 8. Admittance of the modeled UWB antenna (a) Magnitude (b) Phase

As the approximated vectors, impedance and admittance of the modeled UWB antenna are presented in Fig. 7 and Fig. 8, respectively. Representations of them are limited to 3 GHz to 11 GHz considering the used bandwidth of UWB. For specific comparison, the value of impedance and admittance are taken from simulation in CST Microwave Studio which uses finite difference time domain (FDTD) analysis. Indeed, vectors of impedance and admittance from measurement also can be used as reference for this equivalent circuit modeling.

V. Results and Discussion

Results of impedance approximation including residues, poles, and the circuit parameters are summarize on Table I. Then, the synthesized equivalent circuit can be arranged as shown by Fig. 9. The equivalent circuit based on impedance approximation is composed by serial connection of the lumped circuit elements since $Z_{\text{equivalent}} = Z_1+Z_2+Z_3+...+Z_k$ for k numbers of order. The obtained equivalent circuit is then simulated in SPICE to see its frequency response and matched with the approximated impedance. Based on Fig. 10, the impedance of the equivalent circuit agrees very well with the impedance obtained from CST Microwave Studio simulation. It is obvious that the deviation or error between both frequency responses in the form of impedance is extremely small. This means the applied method provides good accuracy for modeling UWB antenna equivalent circuit.

A similar way is also acquired from equivalent circuit modeling based on admittance approximation, and definitely with different equivalent circuit style. The residues, poles, and circuit parameters are listed in Table II. The equivalent circuit is obtained by parallel connection of the lumped circuit as seen in Fig. 11 because the $\frac{1}{Y_{\text{equivalent}}} = \frac{1}{Y_1} + \frac{1}{Y_2} + \frac{1}{Y_3} + ... + \frac{1}{Y_k}$ for k numbers of order. Fig. 12 also shows that the frequency response of the equivalent circuit agrees accurately with the approximated admittance. One weakness of this method is the presence of negative value of the components, which available in theory and simulation but having more complicated realization in practice.

TABLE I
IMPEDANCE APPROXIMATION RESULTS AND EQUIVALENT CIRCUIT PARAMETERS

Order	Impedance Approximation				Circuit Parameters					
	Residues	Poles	d	e	L(e-22)	R_1(e10)	C(e-12)	R_2(e-11)	R_0	C_0
1	-1.7757e11+1.4424e11i	-5.5423e9+6.6916e10i	40.944	0	3.4198	-5.9901	-2.8159	2.0485	0.024424	0
2	2.1326e11+7.4158e+010i	-3.5854e9+6.1318e10i			22.635	1.7737	2.3445	-4.0148		
3	2.0283e11+3.9254e10i	-3.6695e9+5.2168e10i			113.04	64.264	2.4651	-7.2646		
4	1.1504e11-2.3496e9i	-2.722e9+3.9457e10i			-1479.4	-352.79	4.3463	-5.219		
5	5.4328e10-7.3519e10i	-2.3038e9+1.6697e10i			19.794	-2.4898	9.2033	4.9283		
6	6.3109e10+1.4542e10i	-2.5784e9+2.4777e10i			385.36	313.11	7.9228	-1.2066		

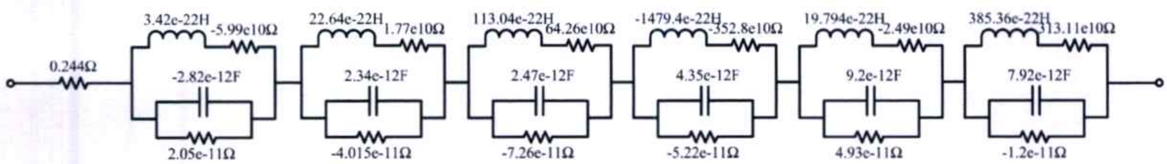
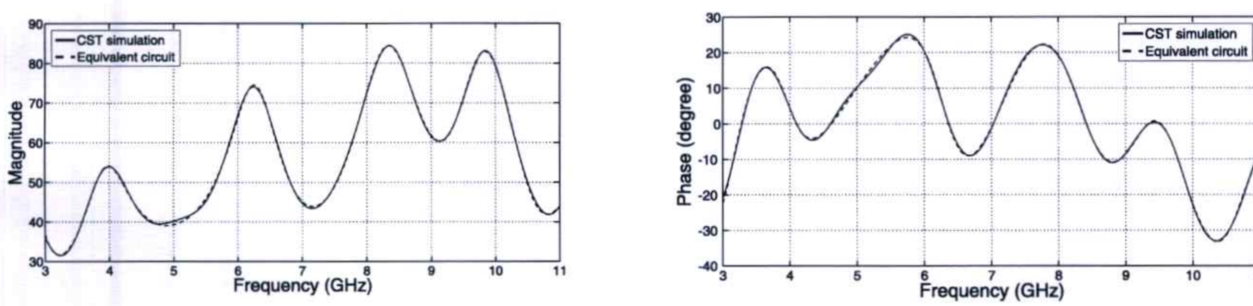


Fig. 9. Equivalent circuit of the UWB antenna by impedance approximation



(a) (b)

Fig. 10. Impedance approximation errors between CST MWS simulation and equivalent circuit (a) Magnitude (b) Phase

By all the results, both impedance and admittance approximation method has been proven very accurate for equivalent circuit modeling of UWB antenna. The synthesized equivalent circuits provide relatively similar frequency response (impedance/admittance) compared with the real antenna frequency response. The accuracy is influenced by the number of order chosen as shown in Fig. 13. The normalized RMS error [8] shows that increasing the number of order will yield a perfect fitting of frequency response. Consequently, higher number of order will increase the complexity of the circuit. In our case, 6 numbers of order is considered to be accurate enough to maintain the equivalent circuit in lower complexity. Trade-off between accuracy and complexity of the equivalent circuit should be considered very well. In Fig. 13, it is apparent that the impedance approximation model offers slightly better accuracy than the admittance model. Nevertheless, basically both methods can be chosen based on the requirements and purposes.

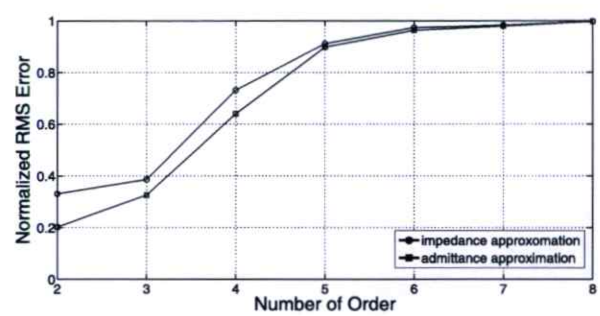


Fig. 13. Normalized RMS Error for each order, 1=perfect ; 1-∞= more error

VI. CONCLUSION

This paper presents a simple approach for synthesizing equivalent circuit of UWB antenna. The circuit is obtained by corresponding SPICE-compatible equivalent circuit with rational fit approximation of frequency domain response such impedance or admittance. By this method, two different kinds of equivalent circuit structure with similar responses can be extracted. The results show that the impedance/admittance of the equivalent circuit agrees very accurately with the approximated one from other electromagnetic software. Even this method has a weakness yielding negative values for some circuit components, but it is still available in theory and system simulation.

TABLE II
ADMITTANCE APPROXIMATION RESULTS AND EQUIVALENT CIRCUIT PARAMETERS

Order	Admittance Approximation				Circuit Parameters					
	Residues	Poles	d	e	L(e-9)	R_1	C(e-23)	R_2(e11)	R_0	C_0
1	1.7682e7+1.6311e7i	-2.4751e9+6.7099e10i	0.022595	0	28.277	1820.2	26.146	-64.369	44.258	0
2	1.8459e7-1.8252e7i	-3.1641e9+5.8531e10i			27.087	-1481.9	29.945	54.71		
3	9.6472e7-2.3143e8i	-6.7571e9+4.6151e10i			5.1828	-538.78	8.189	1.0395		
4	-2.7966e8+4.4972e7i	-7.1739e9+4.0339e10i			-1.7879	-1.2283	-10655	-6870		
5	3.8804e7+3.3713e7i	-2.4358e9+1.9711e10i			12.885	252.05	348.02	-19.561		
6	-6.2319e7+6.0749e7i	-4.7237e9+2.5604e10i			-8.0233	162.36	166.48	20.236		

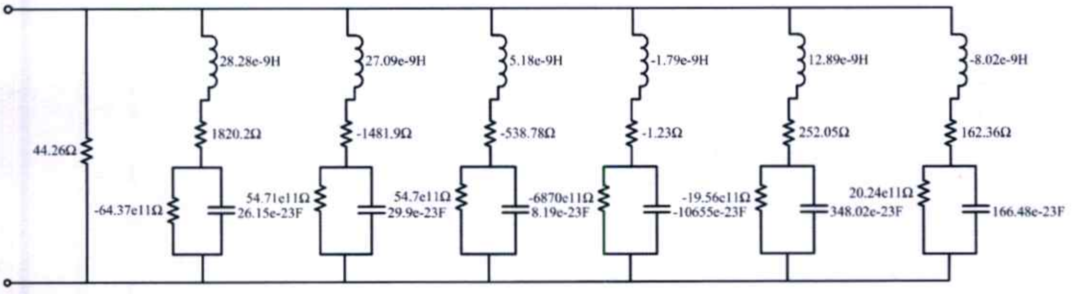
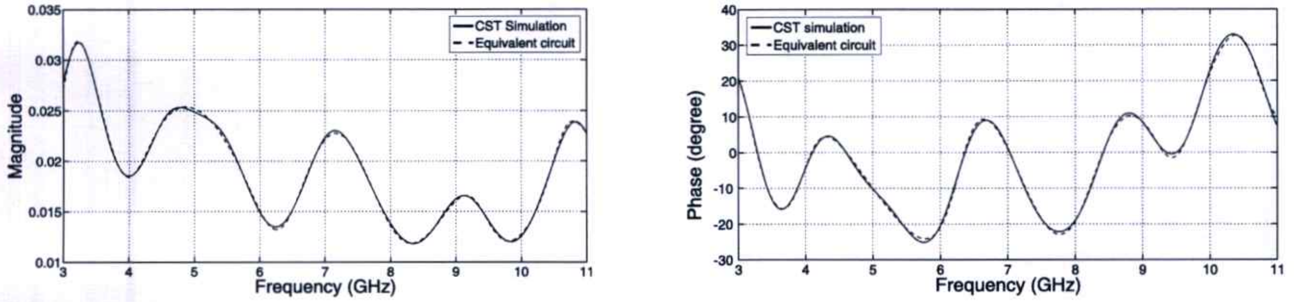


Fig. 11. Equivalent circuit of the UWB antenna by admittance approximation



(a) (b)

Fig. 12. Admittance approximation errors between CST MWS simulation and equivalent circuit (a) Magnitude (b) Phase

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Comprehensive Characterization of a Novel UWB Elliptical Planar Monopole Antenna

Adi Mahmud Jaya Marindra*, Sathaporn Promwong† and Jun-ichi Takada‡
*International College, †Dept. of Telecommunication Engineering, Faculty of Engineering
*†King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand 10520
Email: {s4601102, kpsathap}@kmitl.ac.th
‡Graduate School of Science and Engineering, Tokyo Institute of Technology
2-12-1-S6-4, O-okayama, Meguro-ku, 152-8550, Tokyo, Japan
E-mail: takada@ide.titech.ac.jp

***Abstract*—The rise of research in ultra wideband (UWB) antenna design must be followed by a proper method of antenna characterization. The emerging concept of UWB impulse radio (UWB-IR) compels the performance evaluation of UWB antenna should be assessed in different ways from narrowband antennas. In this paper, a comprehensive characterization of UWB antenna will be discussed. Based on the theory of antenna transfer function in frequency domain, some UWB transmission parameters in time domain are derived, i.e. waveform correlation, waveform width stretch ratio, and waveform relative gain. For practical testing, we propose a novel UWB elliptical planar monopole antenna as the characterized antenna. The results show that the overall performance and characteristic of the proposed antenna is very good, especially at the antenna boresight. The derived parameters can quantitatively characterize the UWB antenna for all the measured directions so that the detail of transmission performance of the UWB antenna could be known. Hopefully, the characterization scheme with the proposed antenna presented in this paper provide useful insight either for UWB antenna design or for evaluating UWB antenna performance.**

***Index Terms*—ultra wideband (UWB), UWB elliptical planar monopole antenna, characterization, performance**

I. Introduction

For recent years, ultra wideband (UWB) technology has draw more attentions on high-speed communications, wireless body area network, radar, and localization systems [1], [2]. Comparing with conventional narrowband systems, the reasons of UWB utilization tends on providing high capacity and low power communication. But despite of its advantages, the huge bandwidth of UWB ($\geq$ 500 MHz) emerges different approach for UWB antenna and propagation. A clear difference comes from UWB with impulse radio (IR) scheme, where the system must transmit and receive very short impulses for communication. In this scheme, role of the antennas as front-end devices should be assessed in different ways and considerations [3]. Moreover, extension of Friis' transmission formula should be used instead of the original one for antenna and link budget evaluation [4], [5].

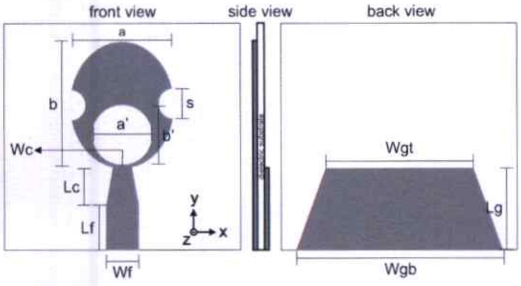
Even having different way of operation, quality of UWB antenna basically can be analyzed in frequency domain by its complex transfer function. Variations of its transfer function magnitude and group delay could indicate the antenna performance [6]. Nevertheless, for clearer understanding about its transmission behavior, characterization in time domain is also required. Most of several works on UWB antenna characterization emphasize more on the issue of distortion due to propagation and antenna dispersion using correlation or fidelity factor [7]–[11]. Another performance parameter was also written in [6], [12], the stretch ratio, which is quantified based on waveform energy capture. And additionally, waveform relative gain is also important parameter to be observed for knowing the antenna time domain gain.

In this paper, a comprehensive characterization of a novel UWB elliptical planar monopole antenna will be discussed. To consider the utilization of antenna in UWB applications, the proposed novel UWB antenna is a compact size antenna made on printed circuit board (PCB). So, in addition of proposing a novel UWB antenna design, this paper also prove that the antenna has good transmission performance using the comprehensive method of characterization. Started by doing frequency domain measurement using two identical antennas, the obtained channel transfer function can be utilized to build simulations of waveform transmission. Then three UWB transmission parameters due to the antenna are derived and investigated, i.e. waveform correlation (fidelity), waveform stretch ratio and waveform relative gain. Since the proposed antenna is an omnidirectional antenna, all quantity of those parameters will be preferably provided for H-plane as the main plane of radiation.

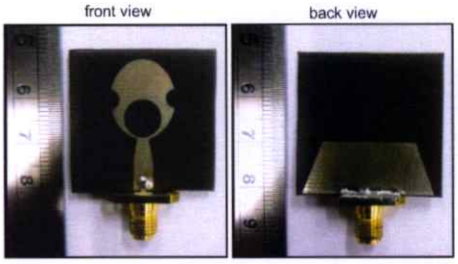
II. The Novel UWB Antenna Design

The novel UWB antenna examined in this paper is a compact elliptical planar monopole antenna with slots on patch and trapezoidal ground plane. The overall size of the antenna is very small, not more than 3 cm x 3 cm. The geometry and the prototype of the antenna are depicted in Fig. 1.

For this proposed antenna, elliptical shape is chosen for the patch/pole because it is simple in structure but more flexible in modification than rectangular or circular shape. Trapezoidal shape for ground plane is used for maintaining stability of the antenna radiation especially at high frequencies. However, the trapezoid shape for ground plane has bad impact to the antenna return loss at particular frequencies. Therefore, some methods are necessary for lowering the return loss. Based on



(a)



(b)

Fig. 1. The novel UWB elliptical planar monopole antenna (a) Geometry (b) Prototype

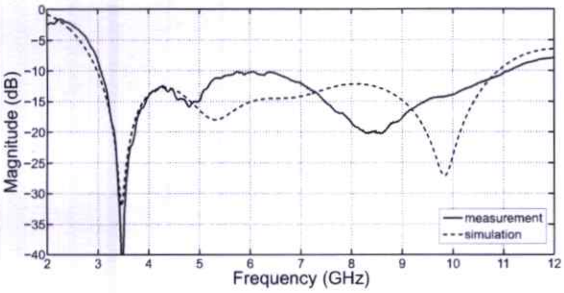


Fig. 2. Return loss of the proposed novel UWB antenna

our parametric studies in simulation, a big circular slot and two concave slots on the patch are very useful to provide lower return loss. Furtheremore, an existing method by [13] which is tapered feedline is also used for lowering the return loss.

The antenna was simulated using CST Microwave Studio and fabricated on Teflon substrate which has dielectric constant of 2.5 and thickness of 1.6 mm. Its detail dimensions after optimization are listed in Table I:

TABLE I
DIMENSIONS OF THE UWB ANTENNA (IN MM)

Wf	Wc	Wgb	Wgt	Lf	Lc	Lg	a	b	a'	b'	s
4.42	2.5	28	20	6	5	11	14	17	8	8	4

From its simulated and measured return loss ($|S_{11}|$) in Fig. 2, it is clear that the antenna has UWB characteristic covering UWB unlicensed bandwidth allocated by FCC (3.1 GHz - 10.6 GHz). The measurement of return loss agree well with the simulation where the measured return loss is under -10 dB ranging from 3.05 GHz to 11.1 GHz.

III. Frequency Domain Measurement

Two port or S_{21} antenna measurement was done in an anechoic chamber using HP 8510C Vector Network Analyzer. The VNA was operated in the response measurement mode where Port 1 as the transmitter and Port 2 as the receiver. In the measurement, two identical antennas were used as Tx and Rx antenna. The Tx antenna was fixed while the Rx antenna was rotated at horizontal direction (azimuth plane) to consider the transmission performance for all Rx orientations. Position was started at 0° which means that the positive z axis of both antennas are pointed each other. A new S_{21} measurement was done every 10° of Rx rotation.

TABLE II
MEASUREMENT SETUP PARAMETERS

Measurement Parameter	Value
Frequency range	3 GHz to 11 GHz
Number of frequency points	801
Dynamic range	80 dB
Tx & Rx antenna height	1.2 m
Distance (d) Tx-Rx	1 m, line of sight (LOS)
Rx rotation range	$0^\circ - 350^\circ$
Rx rotation step	10°
Rx rotation cut	azimuth plane

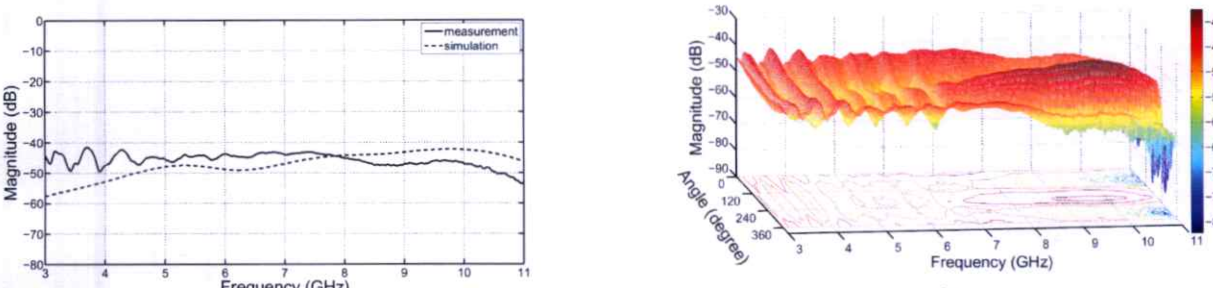
For complete measurement properties, the measurement setup parameters are listed in Table II. The measurement is only limited to azimuth plane of the antenna, but more planes or spherical measurement for deeper analysis is recommended [14].

IV. UWB Antenna Transfer Function and Its Imperfections

The purpose of the frequency domain measurement is to get channel transfer function of the two identical antenna system. Concept of transfer function in UWB sufficiently describes UWB antenna radiation as well as antenna gain when the measurement of transfer function is done for whole points of its radiation plane. Precisely, taking antenna radiation at particular frequencies as commonly done for narrowband antennas is inappropriate for UWB antennas since it can not fully represent the antenna radiation and the transmission characteristics for entire bandwidth.

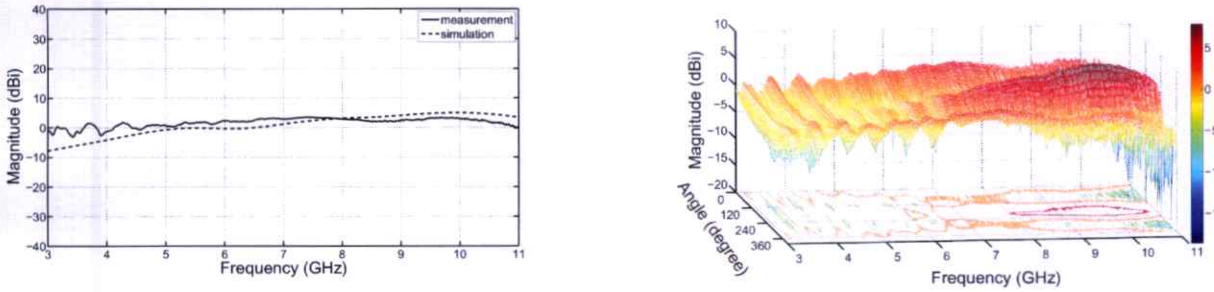
From the measurement, free space channel response including antennas $H_c(f)$ is obtained. In the relationship with the antenna transfer functions, it can be written using the extension of Friis' transmission formula [4], [15] as

$$\frac{V_r(f)}{V_t(f)} = H_c(f) = H_f(f,d)\mathbf{H}_t(f,\theta_t,\varphi_t)\mathbf{H}_r(f,\theta_t,\varphi_t) \quad (1)$$



(a) (b)

Fig. 3. Magnitude of channel transfer function (S_{21}) (a) at 0° (simulation vs measurement) (b) H-plane



(a) (b)

Fig. 4. Magnitude of antenna transfer function (a) at 0° (simulation vs measurement) (b) H-plane

where

$$H_{\mathrm{f}}(f,d)=\left(\frac{c}{4\pi f d}\right)e^{-j\frac{2\pi f}{c}d} \tag{2}$$

is the free space transfer function for electric field representation. $\mathbf{H}_{\mathrm{t}}(f,\theta_{\mathrm{t}},\varphi_{\mathrm{t}})$ and $\mathbf{H}_{\mathrm{r}}(f,\theta_{\mathrm{t}},\varphi_{\mathrm{t}})$ are correspondingly complex transfer functions of the transmitter antenna and the receiver antenna relative to isotropic antenna towards θ and φ direction.

For measurement using two identical antennas, the antenna transfer function which also can be supposed as antenna gain in the term of voltage transfer (not power) can be written as

$$\mathbf{H}_{\mathrm{t}}(f,\theta_{\mathrm{t}},\varphi_{\mathrm{t}})=\mathbf{H}_{\mathrm{r}}(f,\theta_{\mathrm{t}},\varphi_{\mathrm{t}})=\sqrt{\frac{H_{\mathrm{c}}(f)}{H_{\mathrm{f}}(f,d)}} \tag{3}$$

In this work, the channel transfer function from two identical antenna measurement is shown in Fig. 3. The simulation (Fig. 3) using CST Microwave Studio at specific angle is agree well with the measurement. And using Eq. 3, the simulation vs measurement of antenna transfer function ($|\mathbf{H}_{\mathrm{r}}(f,\theta_{\mathrm{t}})|$ in dB) at a specific angle and measurement along H-plane are presented in Fig. 4. The simulation agrees very well with the measurement result. By observing the antenna transfer function, it is obvious that the antenna has good omnidirectionality with stronger radiation at the antenna backside (ground plane side). In the view of its frequency axis, the proposed antenna has enough flat transfer function especially at (0°) with little wavy at lower frequencies.

A perfect transmission occurs when the channel transfer function $H_{\mathrm{c}}(f)=1$, or at least having flat magnitude due antenna gain obviously exist. Nevertheless, even in case of using isotropic antennas on both transmitter and receiver, $H_{\mathrm{c}}(f)$ will be equal to H_{f}. Consequently, the channel transfer function will not be flat and decreased together with increasing of frequency f due to the change of reception area of receiver [15]. To compensate the dependency of f, each antenna transfer function might be made to be increasing at higher frequencies (contradictory with $H_{\mathrm{f}}(f)$) in effort to get better transmission [16]. But still, such that compensation strategy has a weakness in real transmission since $H_{\mathrm{f}}(f)$ is also distance dependent. Hence, the imperfection of UWB antenna transfer function could not be avoided. Flat and smooth antenna transfer function seems adequate as a UWB antenna requirement to obtain a good antenna performance [17].

The requirement of flat transfer function needs to be noticed and overcame in planar omnidirectional UWB antenna design, as a similar phenomenon also occurs in [7], [11]. However, it is not an easy challenge since the electric field radiation of antenna always changes naturally along different frequencies. Higher standard deviation and variation in the antenna transfer function will degrade the antenna performance. Impacts of unflat antenna transfer function for the proposed antenna can be corresponded to Section V.

V. Derivation of Characterization Parameters

A. Waveform Model

For investigating time domain transmission of the UWB antenna, a rectangular passband waveform [18] is used as the transmitted signal which given by

$$v_{\mathrm{t}}(t) = \frac{A}{f_{\mathrm{b}}}[f_{\mathrm{H}}\mathrm{sinc}(2f_{\mathrm{H}}t) - f_{\mathrm{L}}\mathrm{sinc}(2f_{\mathrm{L}}t)] \quad (4)$$

and its spectrum

$$V_{\mathrm{t}}(f) = \begin{cases} \frac{A}{2f_{\mathrm{b}}} & \||f| - f_{\mathrm{c}}| \leq \frac{f_{\mathrm{b}}}{2} \\ 0 & \||f| - f_{\mathrm{c}}| > \frac{f_{\mathrm{b}}}{2} \end{cases} \quad (5)$$

where A is the maximum amplitude, f_{b} is the occupied bandwidth, f_{c} is the center frequency, $f_{\mathrm{L}} = f_{\mathrm{c}} - f_{\mathrm{b}}/2$ and $f_{\mathrm{H}} = f_{\mathrm{c}} + f_{\mathrm{b}}/2$ are the minimum and maximum frequencies.

After knowing the channel transfer function and determining the transmitted waveform, the receiver antenna output waveform $v_{\mathrm{r}}(t)$ is given by

$$v_{\mathrm{r}}(t) = \int_{-\infty}^{\infty} V_{\mathrm{t}}(f)H_{\mathrm{c}}(f)e^{j2\pi ft}\mathrm{d}f \quad (6)$$

And in case of using isotropic antennas on both side, the receiver output waveform $v_{\mathrm{r-iso}}$ can be written as

$$v_{\mathrm{r-iso}} = \int_{-\infty}^{\infty} V_{\mathrm{t}}(f)H_{\mathrm{f}}(f)e^{j2\pi ft}\mathrm{d}f \quad (7)$$

where $V_{\mathrm{t}}(f)$ is the spectral density of the transmitted waveform.

B. Waveform Correlation (Fidelity)

The waveform correlation is a measure of similarity between two waveforms as a function of a time-lag applied to one of them. As UWB antennas cause distortion in the waveform transmission, waveform correlation can be used to denote the antenna performance. The compared waveforms are totally similar when the correlation coefficient is equal to 1, and vice versa. Comparison between the received waveform and the transmitted waveform, like in [7], will include propagation or distance decays whereas it must be excluded for antenna characterization. Therefore, the correlation (C) should be formulated by comparing the received waveform and the received waveform in case of using isotropic antennas so that the correlation is purely due to the examined antenna. Hence, the waveform correlation can be written as

$$C = \frac{\max\left|\int_{-\infty}^{\infty} v_{\mathrm{r}}^{*}(t).v_{\mathrm{r-iso}}(t+\tau)dt\right|}{\sqrt{\int_{-\infty}^{\infty}|v_{\mathrm{r}}(t)|^2\,dt.\int_{-\infty}^{\infty}|v_{\mathrm{r-iso}}(t)|^2\,dt}} \quad (8)$$

C. Waveform Width Stretch Ratio

Waveform width stretch ratio (SR) indicates how much the antenna causes energy spreading or width stretching to the waveform. If the width of the waveform is increasing, longer inter-pulse gaps is necessary resulting lower transmission rate. The higher SR means the worse performance of the antenna.

The derivation of SR is based on comparing energy distribution between two waveforms. Even either $v_{\mathrm{t}}(t)$ or $v_{\mathrm{r}}(t)$ has non-zero energy for all time t, but most of its energy is distributed around its maximum amplitude. Hence, the waveform width can be defined as the waveform period containing a certain part of the total energy. For every waveform $v(t)$, the normalized cumulative energy function can be written as

$$\mathrm{E_v}(t) = \frac{\int_{-\infty}^{t}|v(t)|^2}{v(t)} \quad (9)$$

which apparently has energy value between 0 and 1. Then, the waveform width for p energy portion of waveform v is defined by

$$\mathrm{W}(v) = \mathrm{E_v^{-1}}\left(1-\frac{1-p}{2}\right) - \mathrm{E_v^{-1}}\left(\frac{1-p}{2}\right) \quad (10)$$

In the similar case with waveform correlation, the comparison should be done between the received signal using tested antennas and the received signal in assumption using ideal isotropic frequency independent antennas. Then, SR is obtained by

$$\mathrm{SR} = \frac{\mathrm{W}(v_{\mathrm{r}})}{\mathrm{W}(v_{\mathrm{r-iso}})} \quad (11)$$

D. Waveform Relative Gain

Waveform relative gain in this paper can be defined as the time domain gain and derived based on how the antenna affects the peak of waveform amplitude. Again, for excluding distance decays, the waveform relative gain is written as

$$G_{\mathrm{w}} = \frac{\max|v_{\mathrm{r}}(t)|}{\max|v_{\mathrm{r-iso}}(t)|} \quad (12)$$

Another time domain gain considering the use of correlation receiver, named transmission gain [15], also can be used as a reference. It will provide a higher gain due to the feasibility of a simple receiver mechanism, i.e. correlation receiver, is also included in the gain calculation.

VI. Results and Discussion

Results of each characterization parameter are shown in Fig. 5, 6, and 7, respectively. Observing from Fig. 5, the planar monopole antenna characterized in this paper has excellent waveform correlation (fidelity) about 0.9 or more than 0.8 for most angles. But on the antenna ground plane side, the waveform correlations are dominantly under 0.8. The lowest correlation is found for 190° with value of 0.65. Correspond to the antenna transfer function at the angle of 190° (Fig. 4), this can probably happen due to the sudden increasing of transfer function at higher frequency. As the standard deviation of antenna transfer function higher, the waveform correlation becomes worse.

Waveform width stretch ratio (SR) provides other different view of the antenna performance. In this characterization, 0.9 energy portion is used for waveform comparison. From Fig. 6, the width stretch ratio is nearly to 1 for antenna front and

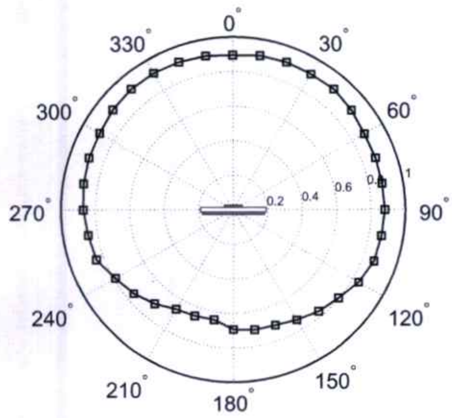


Fig. 5. Waveform Correlation (antenna fidelity); 1=best, 0=worst

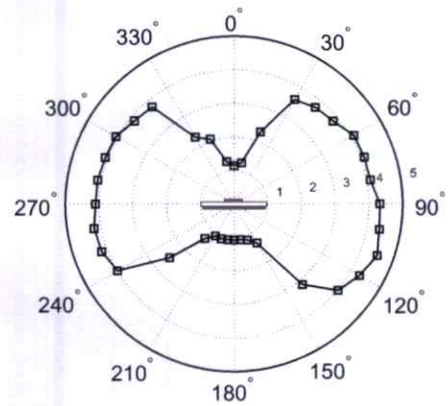


Fig. 6. Waveforn width stretch ratio; 1=best, ∞=worst

antenna backside which means excellent performance. The SR is mostly rising when the antenna pointed at 90° and 270° or around its x-axis (both positive and negative). But it can be confirmed with Fig. 4 where the rising of SRs are much influenced by the lower and the fluctuate antenna transfer function.

The third parameter, waveform relative gain is agree as well as the width stretch ratio where the performance of the antenna degraded around 90° and 270°. In Fig. 7, the waveform relative gain due to the antenna is around 2 dBi for the antenna front and back side. The highest value is 3.79 dBi and the lowest value is -4.85 dBi. The low value of waveform relative gain is reasonable since the proposed UWB antenna is omnidirectional and small size. Nevertheless, this waveform relative gain has been optimized in simulation process by keeping the antenna transfer function high at entire UWB bandwidth. Therefore, this antenna has sufficiently good waveform relative gain.

Overall, the novel UWB elliptical planar monopole antenna proposed in this paper has a very good performance, especially at the antenna boresight (angle of 0°). At 0°, the antenna has waveform correlation of 0.89, waveform width stretch ratio of 1.14, and waveform relative gain of 2.62 dBi. However,

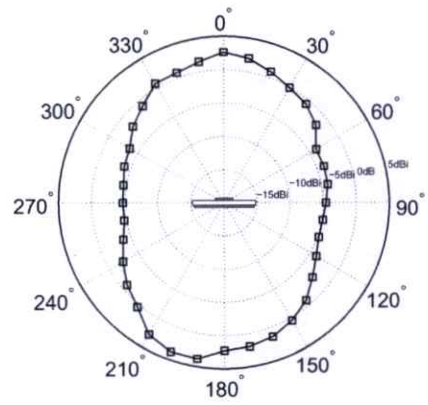


Fig. 7. Waveforn relative gain; higher dB value means better

it is not easy to get similar transmission performance for all expected directions due to the natural changes of radiation vs frequency causing unflat transfer function. The proposed novel UWB antenna has lower values of waveform correlation at the antenna backside (-z axis of the antenna) and lower values of waveform width stretch ratio and waveform relative gain at the antenna sides (+x and -x axis of the antenna). The issue of transfer function imperfection should be considered well and overcame in the design process for better performance.

VII. Conclusion

This paper discusses a comprehensive characterization of a novel UWB elliptical planar monopole antenna. The proposed antenna has compact size and very good result in characterization with some reasonable lower performances at specific directions. Three parameters based on quality of waveform transmission are derived and quantified in the antenna characterization, i.e. waveform correlation, waveform width stretch ratio, and waveform relative gain. In order to assess UWB antenna performance, concept of transfer function in frequency domain and comprehensive characterization in time domain such in this paper should be used instead of showing return loss, radiation pattern at particular frequencies, and antenna gain at specific point like in narrowband antenna concept.

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Impacts of Reducing Ground Plane Effects on UWB Planar Monopole Antenna Performance

Adi Mahmud Jaya Marindra*, Sathaporn Promwong†
*International College, †Dept. of Telecommunication Engineering, Faculty of Engineering
King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand 10520
Email: {s4601102, kpsathap}@kmitl.ac.th

***Abstract*—Reducing ground plane effects is a way to reduce domination of ground plane and the employed copper area on UWB planar monopole antenna. Some proposed techniques such as adding certain slots have been proposed with little effect on antenna parameters, i.e. impedance bandwidth and radiation pattern. This paper presents a quantitative analysis of impacts happened in a case of reducing ground plane effects on UWB elliptical planar monopole antenna. Since time domain evaluation is essential requirement for UWB antennas, the impacts will be presented both in frequency domain and time domain to comprehensively compare the antenna performances. The results in time domain show that reducing ground plane effects slightly decrease the antenna performance for some transmission parameters such as waveform correlation and waveform width stretch ratio, but it can control excessive radiation at ground plane side to have better omnidirectionality at azimuth direction. The authors also recommend to quantitavely evaluate UWB antennas by the presented scheme to know impacts and distinguish every little modification on UWB antenna design.**

***Index Terms*—ultra wideband (UWB), UWB elliptical planar monopole, ground plane effects, performance**

I. Introduction

Since the approval of ultra wideband (UWB) frequency allocation between 3.1 to 10.6 GHz by the Federal Communication Commission (FCC), a lot of research in UWB antenna development have been carried out for different types and applications [1]–[3]. The FCC also defines fractional bandwidth and occupied bandwidth of UWB should be equal to or greater than 0.2 and 500 MHz, respectively [4]. Compared to narrowband technology, this huge bandwidth feature of UWB emerges different approach for UWB antenna and propagation. The UWB antenna characteristics should be viewed in the broad range of bandwidth. Notably for UWB with impulse radio (IR) scheme, role of the antennas in UWB systems should be assessed in different ways and considerations [5]–[7].

Various UWB antenna designs have been proposed to overcome those challenges. Planar antenna such planar monopole antenna is more considerable due to its attractive features such as solid, low cost, low profile, having omnidirectional properties, easily fabricated, and easily integrated with circuit board [8], [9]. One problem for UWB planar monopole antennas is their performance are highly affected by the ground plane size. This kind of antenna usually needs optimization of ground plane size to comply UWB bandwidth requirement, whereas changing ground plane shape or size will affect impedance matching and radiation pattern.

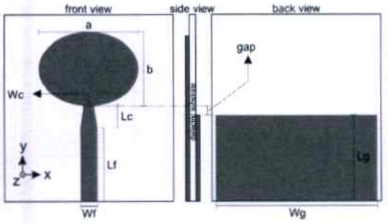
Some techniques have been proposed to reduce ground plane effects by adding certain slots on ground plane or radiator of the antenna. By those techniques, the employed copper area of the antenna will be decrease with very little effect on the antenna parameters [10], [11]. However, although those techniques are claimed having little effect on the antenna parameters, a deeper analysis is still necessary to validate the changing of antenna performance in the term of its transmission behavior. This paper presents a quantitative analysis of impacts happened in a case reducing ground plane effects on UWB elliptical planar monopole antenna. This study is aimed to investigate quantity of consequences of changing the antenna design to the antenna transmission performance.

As an examined case, two kinds of UWB elliptical planar monopole antenna were evaluated and compared. First antenna is a common elliptical planar monopole antenna, and the second one is a slot-added elliptical planar monopole antenna which uses techniques of reducing ground plane effects. Performance evaluation is done by measuring a pair of identical antenna as a system using vector network analyzer (VNA), so that its transmission behavior could be characterized. After doing measurement, the antenna performances are quantified by investigating parameters in frequency domain including transfer function and group delay, and quantitative parameters in time domain including waveform correlation [12]–[14], waveform width stretch ratio [15], and waveform relative gain [16]. All those parameters will be analyzed to show the impacts of reducing ground plane effects to the antenna performance.

II. UWB Antenna Designs and Configurations

A. The Common Elliptical Planar Monopole Antenna

The common elliptical planar monopole antenna examined in this paper is dipicted in Fig. 1. It was simulated using CST Microwave Studio and fabricated on Teflon substrate which has dielectric constant of 2.5 and thickness of 1.6 mm. Its detail dimensions are: Wf=4.42, Wc=2.5, Wg=42, Lf=19, Lc=9, Lg=24.3, a=26, b=19, gap=0.2 (all values are in mm). The use of tapered feed-line before elliptical patch is inspired from [8] to increase impedance matching at higher frequencies. By looking at its simulated and measured return loss ($|S_{11}|$) in Fig. 2, it is clear that the antenna has broadband characteristic



(a)

(b)

Fig. 1. The common elliptical planar monopole antenna (a) Structure (b) Prototype

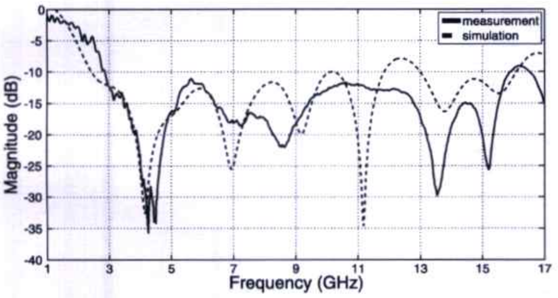
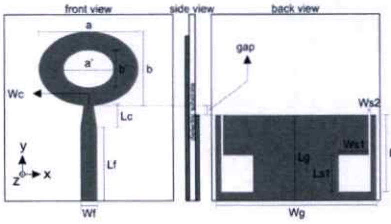
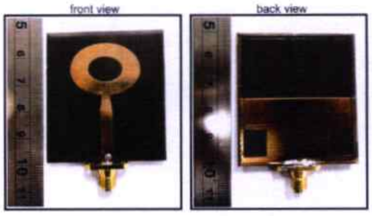


Fig. 2. Return loss of the common elliptical planar monopole antenna



(a)



(b)

Fig. 3. The slot-added elliptical planar monopole antenna (a) Structure (b) Prototype

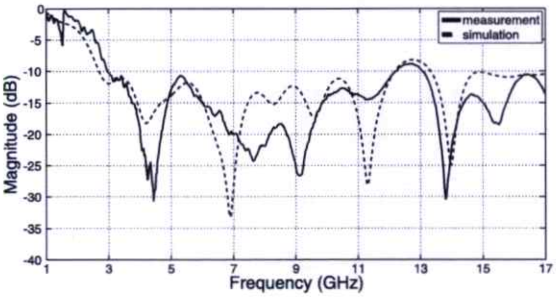


Fig. 4. Return loss of the slot-added elliptical planar monopole antenna

covering UWB unlicensed bandwidth allocated by FCC (3.1 GHz - 10.6 GHz).

B. The Slot-added Elliptical Planar Monopole Antenna

For an antenna with reduced ground plane effects, a slot-added elliptical planar monopole antenna is depicted in Fig. 3. It was simulated and fabricated in the same media as the previous antenna with detail dimensions as follow: Wf=4.42, Wc=2.5, Wg=42, Lf=19, Lc=9, Lg=24.3, a=26, b=19, gap=0.2 a'=13, b'=9.5, Ws1=8, Ws2=0.5, Ls1=10, Ls2=21.3 (all values are in mm). The design is principally similar with the previous antenna, but with some slots added on the patch and ground plane as done in [10], [11]. By parametric study [9], its simulated and measured return loss ($|S_{11}|$) are made to be not much different with the previous antenna, as shown in Fig. 4. Therefore, the purpose of reducing groundplane effects is achieved since the parameter of impedance matching (shown by return loss) is just little bit affected. It is also clear that the slot-added elliptical planar monopole antenna also has broadband characteristic and covers 3.1 GHz to 10.6 GHz.

III. Measurement Setup

Two port or S_{21} antenna measurement was done in an anechoic chamber using HP 8510C VNA as illustrated in Fig.5. The VNA was operated in the response measurement mode where Port 1 as the transmitter and Port 2 as the receiver. Both Tx and Rx antenna were rotated at horizontal direction (azimuth plane) to consider antenna performance for all orientations. Position was started at 0° which means that the positive z axis of both antennas are pointed each other. A new S_{21} measurement was done every 10° of rotation. Direction of Tx and Rx is changed with relation of $\phi_{\mathrm{Tx}} = -\phi_{\mathrm{Rx}}$. For complete measurement properties, the measurement setup parameters are detailed in Table I.

TABLE I
MEASUREMENT SETUP PARAMETERS

Measurement Parameter	Value
Frequency range	3 GHz to 11 GHz
Number of frequency points	801
Dynamic range	80 dB
Tx & Rx antenna height	1.3 m
Distance (d) Tx-Rx	1 m, line of sight
Tx & Rx rotation range	0° − 350°
Tx & Rx rotation step	10°
Tx & Rx rotation cut	azimuth plane

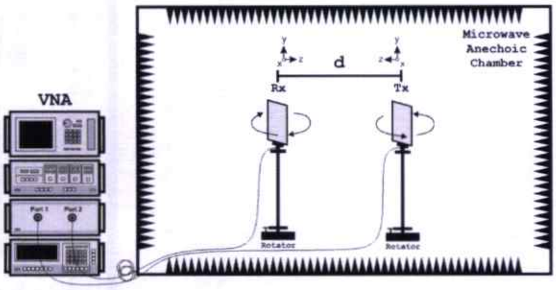


Fig. 5. Measurement setup in anechoic chamber

IV. Derivation of the Investigated Parameters

A. Parameters in Frequency Domain

1) System Transfer Function: System transfer function can be defined as the ratio between the voltage received at the Rx-antenna terminal and the voltage at the input of the Tx-antenna. Shortly, if $H_{\rm tx}$ is transfer function of the transmitter antenna, $H_{\rm rx}$ is transfer function of the receiver antenna, and $H_{\rm f}$ is free space transfer function, the system transfer function $H(f)$ can simply expressed as

$$H(f) = H_{\rm tx}(f)H_{\rm f}(f)H_{\rm rx}(f) \tag{1}$$

where

$$H_{\rm f}(f,d) = \left(\frac{c}{4\pi f d}\right) e^{-j\frac{2\pi f}{c}d} \tag{2}$$

System transfer function $H(f)$ can be directly obtained from measurement. Hence, the system response can be completely determined when the system transfer function is known. If the receiver antenna is rotated at azimuthal plane, the equation (1) can be rewritten as

$$H(f,\phi) = H_{\rm tx}(f,\phi)H_{\rm f}(f)H_{\rm rx}(f,\phi) \tag{3}$$

To minimize the distortion in the received signal waveform, the transfer function is required to have flat magnitude and linear phase response over the operational band. By the equations above, the antenna transfer function also can be derived by

$$H_{\rm tx}(f,\phi) = H_{\rm rx}(f,\phi) = \sqrt{\frac{H(f,\phi)}{H_{\rm f}(f)}} \tag{4}$$

2) Group Delay: The average of the group delay is equal to the time needed for a signal (at a given frequency) to travel from one antenna terminal to the other. Group delay is used to evaluate the phase response of transfer function because it also can be defined as the rate of change of total phase shift. Mathematically, group delay can be written as a negative derivative of the phase response $\angle H(f)$ with respect to frequency.

$$\tau = -\frac{d[\angle H(\omega)]}{d\omega} = -\frac{1}{360^\circ}\frac{d[\angle H(f)]}{df} \tag{5}$$

In UWB system, constant group delay is required which implies the phase changes linearly with frequency. When the group delay is not constant, the pulse waveform will be spread out in the time domain.

B. Parameters in Time Domain

For investigating time domain transmission behavior of the UWB antenna, let choose a rectangular passband waveform [17] as the transmitted signal model which is given by

$$v_{\rm t}(t) = \frac{A}{f_{\rm b}}[f_{\rm H}{\rm sinc}(2f_{\rm H}t) - f_{\rm L}{\rm sinc}(2f_{\rm L}t)] \tag{6}$$

and its spectrum

$$V_{\rm t}(f) = \begin{cases} \frac{A}{2f_{\rm b}} & \||f| - f_{\rm c}| \le \frac{f_{\rm b}}{2} \\ 0 & \||f| - f_{\rm c}| > \frac{f_{\rm b}}{2} \end{cases} \tag{7}$$

where A is the maximum amplitude, $f_{\rm b}$ is the occupied bandwidth, $f_{\rm c}$ is the center frequency, $f_{\rm L} = f_{\rm c} - f_{\rm b}/2$ and $f_{\rm H} = f_{\rm c} + f_{\rm b}/2$ are the minimum and maximum frequencies. For the waveform occupying the entire UWB band, $f_{\rm L}$ = 3.1 GHz and $f_{\rm H}$ = 10.6 GHz.

After knowing the channel transfer function and determining the transmitted waveforms, the receiver antenna output waveform $v_{\rm r}(t)$ is given by

$$v_{\rm r}(t) = \int_{-\infty}^{\infty} V_{\rm t}(f)H_{\rm c}(f)e^{j2\pi ft}{\rm d}f \tag{8}$$

And in case of using isotropic antennas on both side, the receiver output waveform $v_{\rm r-iso}$ can be written as

$$v_{\rm r-iso} = \int_{-\infty}^{\infty} V_{\rm t}(f)H_{\rm f}(f)e^{j2\pi ft}{\rm d}f \tag{9}$$

where $V_{\rm t}(f)$ is the spectral density of the transmitted waveform. From $v_{\rm r-iso}$ and $v_{\rm r}(t)$, three parameters regarding to the waveform transmission quality due to antennas are derived below.

1) Waveform Correlation: The waveform correlation (or usually also mentioned as 'antenna fidelity') is a measure of similarity between two waveforms as a function of a time-lag applied to one of them. As UWB antennas cause distortion in the waveform transmission, waveform correlation can be used to denote the antenna performance. It ranges between 0 and 1. If the correlation coefficient is equal to 1, it means the waveform is totally similar or having a perfect signal transmission.

Comparison between the received waveform and the transmitted waveform, like in [13], will include propagation or distance decays whereas it must be excluded for antenna characterization. The correlation (C) should be formulated by comparing the received waveform and the received waveform in case of using isotropic antennas. Hence,

$$C = \frac{\max\left|\int_{-\infty}^{\infty} v_{\rm r}^*(t).v_{\rm r-iso}(t+\tau)dt\right|}{\sqrt{\int_{-\infty}^{\infty}|v_{\rm r}(t)|^2dt.\int_{-\infty}^{\infty}|v_{\rm r-iso}(t)|^2dt}} \tag{10}$$

2) Waveform Width Stretch Ratio: Waveform width stretch ratio (SR) indicates how much the antenna causes energy spreading or width stretching to the waveform. If the width of the waveform is increasing, longer inter-pulse gaps is necessary resulting lower transmission rate [15]. The higher SR means the worse performance of the antenna.

The derivation of SR is based on comparing energy distribution between two waveforms. Although $v_t(t)$, $v_r(t)$, and $v_{r-iso}(t)$ has non-zero energy for all time t, but most of the energy is usually distributed around the maximum amplitude. Hence, the waveform width can be defined as the waveform period containing a certain part of the total energy. For every waveform $v(t)$, the normalized cumulative energy function can be written as

$$\mathrm{E_v}(t) = \frac{\int_{-\infty}^{t} |v(t)|^2}{v(t)} \tag{11}$$

which apparently has energy value between 0 and 1. Then, the waveform width for p energy portion of waveform v is defined by

$$\mathrm{W}(v) = \mathrm{E_v^{-1}}\left(1 - \frac{1-p}{2}\right) - \mathrm{E_v^{-1}}\left(\frac{1-p}{2}\right) \tag{12}$$

In the similar case with waveform correlation, the comparison should be done between the received signal using tested antennas and the received signal in assumption using ideal isotropic frequency independent antennas. Then, SR is obtained by

$$\mathrm{SR} = \frac{\mathrm{W}(v_r)}{\mathrm{W}(v_{r-iso})} \tag{13}$$

3) Waveform Relative Gain: Waveform relative gain in this paper can be defined as the time domain gain and derived based on how the antenna affects the peak of waveform amplitude. Again, for excluding distance and propagation decay, the waveform relative gain is written as

$$G_w = \frac{\max |v_r(t)|}{\max |v_{r-iso}(t)|} \tag{14}$$

Another time domain gain considering the use of correlation receiver, named transmission gain [12], also can be used as a reference. It will provide a higher gain due to the feasibility of a simple receiver mechanism is also included in the gain calculation, i.e. correlation receiver.

V. Results and Impacts Analysis

All investigated parameters are presented in Fig. 6 to Fig. 11. Fig. 6 shows the system transfer function between two identical UWB antennas using the common elliptical planar monopole antennas and using the slot-added elliptical planar monopole antennas. Fig. 6 (a) and (b) imply that reducing ground plane effects by making slots on the ground plane and radiator will cause changing to the magnitude of the system transfer function at azimuth plane. The changing of transfer function is very related to the changing of antenna radiation

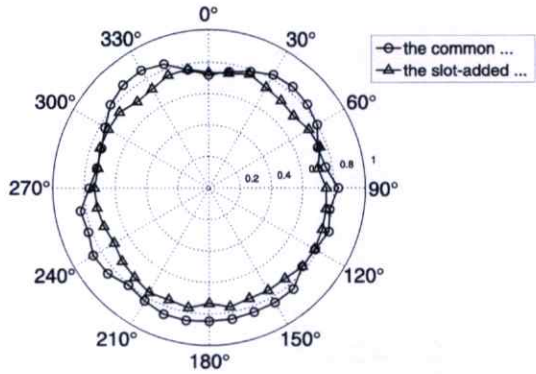


Fig. 9. Waveform correlation

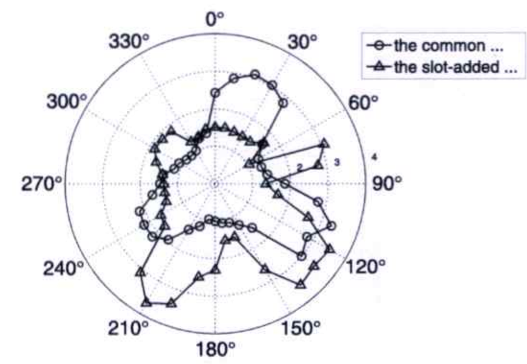


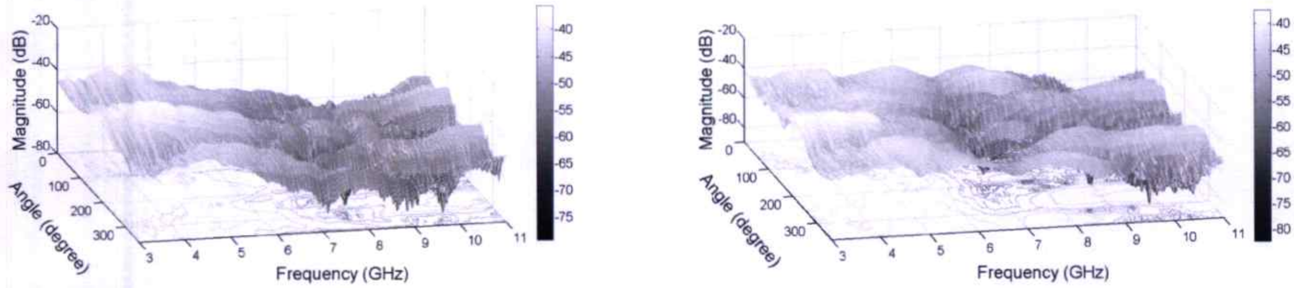
Fig. 10. Waveform width stretch ratio

due to the added slots which modify mutual coupling between the ground plane and the radiator. Since UWB antenna works for wide frequency range, attention to the UWB antenna radiation changing should be paid as the electric field vs frequency at one point (far-field). Consequently, if the radiated electric field distribution changed then the transmission characteristics of the UWB antennas are also different.

Fig. 7 (a) and (b) show that the group delay of the links is relatively constant but still having ripples at some frequencies. The group delays of the antenna systems laying on around 4 nanoseconds with measurement distance of 1 meter. It is difficult to see the impact of reducing ground plane effects using group delay since the difference is not significant.

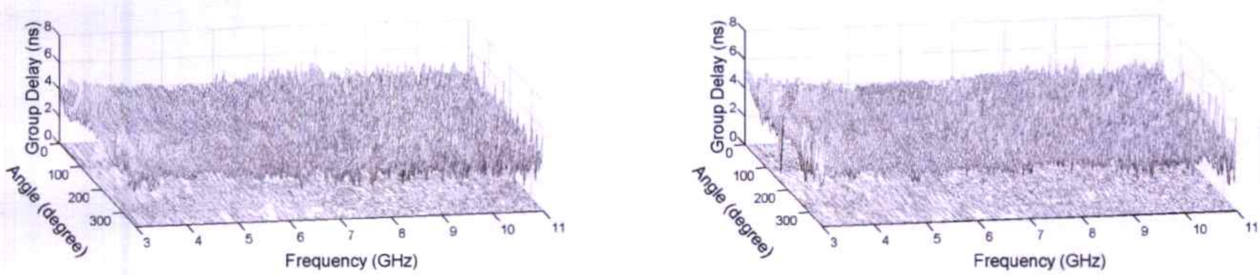
By looking at parameters in frequency domain, the differences of reducing ground plane effects can be observed. However, the quality or performance comparison of the antenna will be more clearly seen by quantitative evaluation in time domain. The transmission of UWB waveform by the antenna links are illustrated in Fig. 8. These illustrations are taken when the identical antennas are facing each other or at 0° of the measurement. Agree with the mean value of group delay, the received waveform comes around 4 nanoseconds after the waveform is transmitted. The received waveforms of each antenna system look experienced different amount of distortion as seen on the figure.

Fig.9 presents the quantity of waveform correlation of both



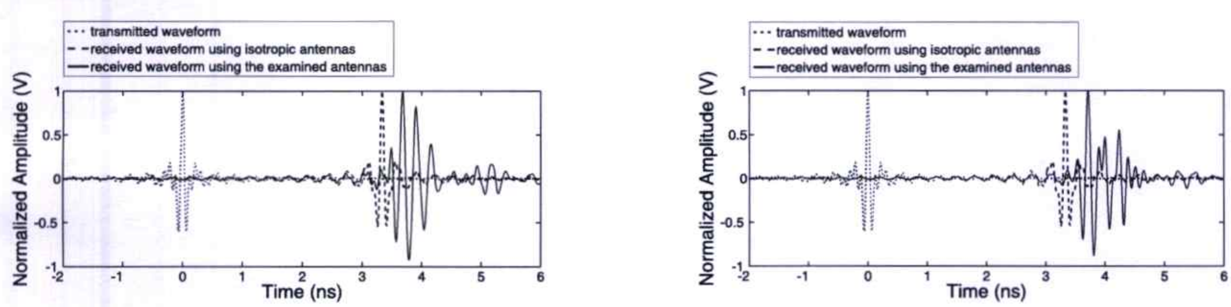
(a) (b)

Fig. 6. System transfer function of two-identical-antenna system (a) Using the common elliptical planar monopole antenna (b) Using the slot-added elliptical planar monopole antenna



(a) (b)

Fig. 7. Group delay of two-identical-antenna system (a) Using the common elliptical planar monopole antenna (b) Using the slot-added elliptical planar monopole antenna



(a) (b)

Fig. 8. Illustration of waveform transmissions (a) The common elliptical planar monopole antenna system (b) The slot-added elliptical planar monopole antenna system

UWB antenna systems. The figure shows that the waveform correlation for both antennas is more than 0.7 for every angle. It means that the distortion due to antennas is low enough. In this parameter, reducing ground plane effects on the UWB elliptical planar monopole antenna obviously decrease the value of waveform correlation at every antenna angle. It means the applied techniques for reducing ground plane effects degrade the antenna performance.

Fig. 10 shows the antenna performance by the parameter of waveform width stretch ratio (SR). By this parameter, the smaller value means the better antenna performance. We can see that the higher values of SR are dominated by the slot-added elliptical planar monopole antennas. Even not absolutely for all antenna angles, but generally the common elliptical planar monopole antenna has lower SR. Hence, reducing ground plane effects also has bad impact to the UWB antenna performance in the term of waveform width stretch ratio.

Reducing ground plane effects also decreases waveform relative gain at particular antenna angles as shown in Fig. 11. Since some parts of copper on ground plane and radiator are corrugated, the waveform relative gain is decreasing at the antenna ground plane side. From the figure, the common elliptical planar monopole antenna has higher waveform relative gain at its ground plane side. Adding slots at the ground plane makes the waveform relative gain to be more evenly distributed to all orientation, which is around -5 dB. Reducing ground plane effects gives a good impact to excessive radiation at ground plane side so that the antenna transmission has better

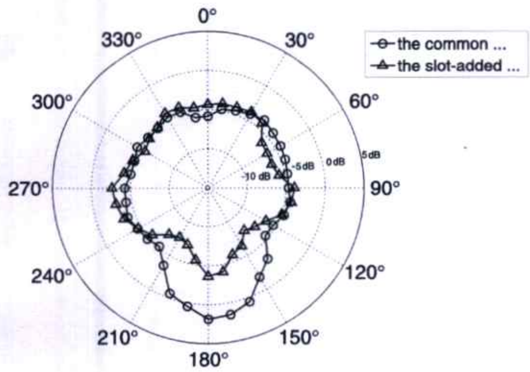


Fig. 11. Waveform relative gain

omnidirectionality at azimuth direction.

Generally, reducing ground plane effects gives little impacts to all parameters. As seen at previous section, the return loss of the antenna is not much change between before and after applying the techniques. Since it changes the antenna radiation characteristics, the transmission behavior in frequency domain and time domain are also change. But by quantitative evaluation in time domain, the change of transmission can be known in the form of degradation. Meanwhile, it can control the excessive waveform relative gain at the ground plane side.

VI. Conclusions

In this paper, the impacts of reducing ground plane effects on UWB elliptical planar monopole antenna has been discussed. The analysis is based on a case study using proposed technique by adding slots on ground plane and radiator in the antenna design. Reducing ground plane effects can degrades the antenna performance regarding to UWB waveform transmission, but it can control excessive waveform relative gain at the antenna ground plane side. Although the degradation of transmission behavior is not severe, hopefully the information and analysis in this paper can be useful considerations for UWB antenna designers.

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Performance Evaluation of Ultra Wideband Printed Antenna by System Characterization

Adi Mahmud Jaya Marindra*, Sathaporn Promwong† and Jun-ichi Takada‡
*International College, †Dept. of Telecommunication Engineering
*†King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand 10520
Email: {s4601102, kpsathap}@kmitl.ac.th
‡Graduate School of Science and Engineering, Tokyo Institute of Technology
2-12-1-S6-4, O-okayama, Meguro-ku, 152-8550, Tokyo, Japan
E-mail: takada@ide.titech.ac.jp

Abstract—**A lot of Ultra Wideband (UWB) antenna designs, especially printed antenna, have been proposed so far. However, among those proposed designs, only single unit antenna analysis i.e. return loss and radiation pattern at particular frequencies are usually observed. This paper reports a deeper transmission analysis by considering UWB antenna as a system; so called system characterization. For a specific case, a pair of UWB printed monopole antenna with known single unit antenna performance was used for this study. Two-identical-antenna system was measured with Vector Network Analyzer (VNA), then its system transfer function, group delay, and waveform distortion are investigated. The results show that even the single unit antenna performance looks good enough but not so that well when the antenna is considered as a system. Nonlinear transfer function and group delay at some frequency ranges inflicts distortion in the waveform transmission which is crucial for UWB impulse radio scheme. Antenna performance evaluation in this study is provided in the term of its distortion by showing pattern of correlation between the transmitted and the received waveform.**

I. INTRODUCTION

It has been generally agreed that UWB is a tremendous technology for short-range wireless communication as it has low complexity system, low cost, low power, high data rate, and coexistence ability with other systems. Its low power operation also leads the UWB technology as a green technology because it will reduce energy consumption emitted by wireless equipment. For unlicensed commercial use, bandwidth of UWB technology has been approved by Federal Communication Commission (FCC) ranged from 3.1 to 10.6 GHz. FCC defines UWB fractional bandwidth and occupied bandwidth should be equal to or greater than 0.2 and 500 MHz, respectively. Further considerations has been completely declared in [1].

In UWB communication, large amount of data is transformed into impulse or non-sinusoidal wave in extremely short period below nanoseconds. In this term, the antenna poses the most difficult technological problem. The UWB antennas play in role of transmitting and receiving pulse instead of sinusoidal wave in conventional narrowband systems. The antenna behaves like a filter and reshapes the spectra of the pulses. UWB antenna seems more challenging since it has different approach compared to conventional narrowband antenna existed.

Due to this challenge, many antenna designers are precisely interested to propose various kinds of UWB antenna design [2], [3]. Printed antenna such printed monopole antenna is more interesting as it is solid, low cost, low profile, omnidirectional, easily fabricated, and easily integrated with circuit board. It seems very promising and more suitable to be used in UWB compact devices for WPAN applications. However, among proposed printed antenna designs, only single unit antenna analysis i.e. return loss and radiation pattern at particular frequencies are usually observed whereas evaluating the antenna by system characterization is essential. It is necessary to consider transmitting/receiving UWB antennas as a system, not only as a single unit in the design [4].

The aim of this paper is to show the performance of UWB printed monopole antenna by considering it as a system. The antenna performance was evaluated by doing frequency domain measurement by using VNA. Afterward, some main parameters including system transfer function, group delay, and waveform distortion are investigated. The large bandwidth of UWB system incurs that showing the antenna performance in time domain such distortion would be necessary and more obviously observable. Related to distortion, similarity of the waveform will be pointed out using correlation coefficient at each angle of antenna radiation.

II. THE STUDIED UWB ANTENNA

The UWB antenna studied in this paper is shown in Fig.1; a printed monopole antenna with microstrip feed and slotted rectangular ground plane on its back side. Detail dimensions of the antenna are: Wf=4.42, Wfs=1.5, Wp=25, Wg=42, Wgs=4.42, Lf=24, Lfs=8, Lc=4, Lg=24, Lgs=2.21 (all values are in mm). The antenna was fabricated on Teflon substrate which has dielectric constant of 2.5 and thickness of 1.6 mm.

One of the fundamental requirements in UWB antenna design is to make the antenna return loss ($|S_{11}|$) to be very low over UWB bandwidth [5]. Fig.2 shows the simulated and measured S_{11} of the studied UWB antenna. The figure evidently shows that both of the simulation and measurement results provide good agreement. Measurement result shows that the return loss of the studied UWB antenna could achieve 5:1 bandwidth which ranging from 2.87 GHz to 14.37 GHz

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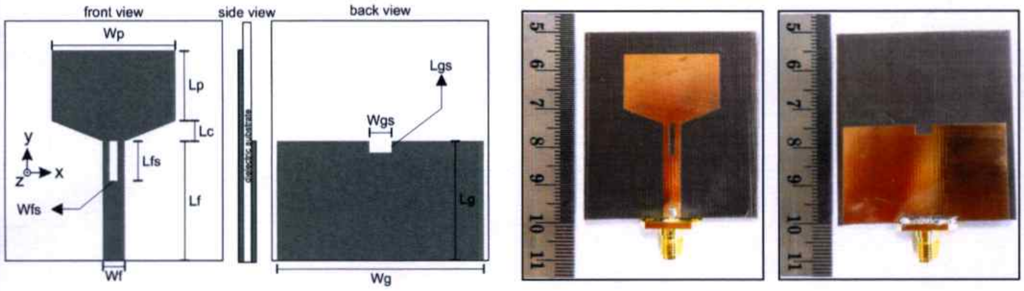
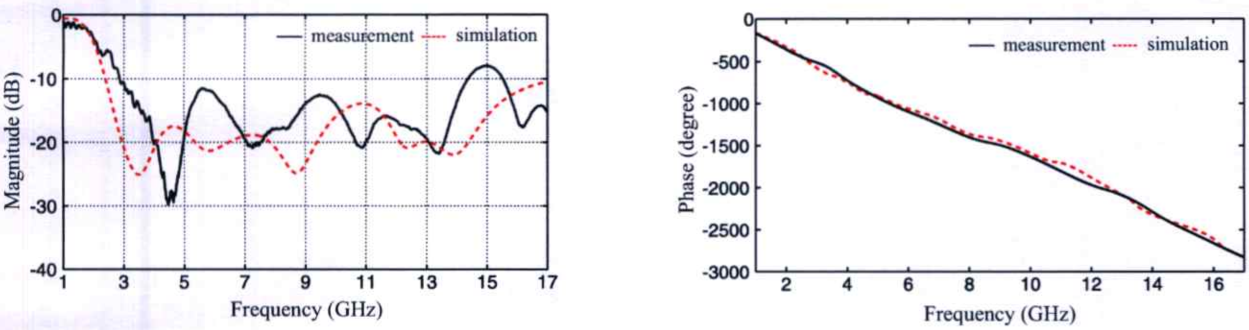


(a) Geometry

(b) Prototype

Fig. 1. The studied UWB antenna (a) Geometry (b) Prototype



(a) Magnitude

(b) Phase

Fig. 2. Return loss of the studied UWB antenna (a) Magnitude (b) Phase

for return loss < -10 dB. From bandwidth point of view, the studied antenna is obviously able to cover approved UWB band. Additionally, phase of the antenna S_{11} is also linear over UWB bandwidth.

III. Measurement Setup and The Investigated Parameters

Two port or S_{21} antenna measurement was done in an anechoic chamber using HP 8510C VNA as illustrated in Fig.3. The VNA was operated in the response measurement mode where Port 1 as the transmitter and Port 2 as the receiver. The Tx antenna was fixed while the Rx antenna was rotated at horizontal direction (azimuth plane) to consider antenna performance for all orientations. Position was started at 0° which means that the positive z axis of both antennas are pointed each other. A new S_{21} measurement was done every 5° of Rx rotation. For complete measurement properties, the measurement setup parameters are detailed in Table 1. Hereafter, the following subsections present brief theory of the investigated parameters.

A. System Transfer Function and Antenna Transfer Function

The system transfer function $H(f)$ is a vital parameter to obtain the impulse response affected by channel. It can be defined as the ratio between the voltage received at the Rx-antenna terminal and the voltage at the input of the Tx-antenna. It has been explained in [6] that UWB impulse radio transmission can be formulated using the extension of Friis' Transmission Formula. Shortly, if H_{tx} is transfer function of

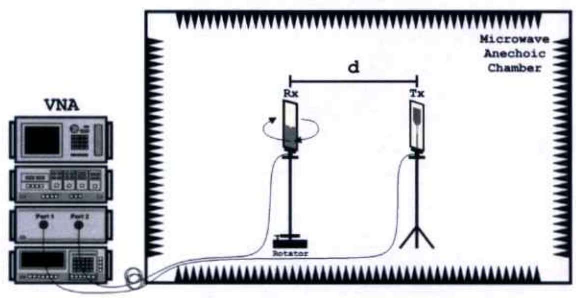


Fig. 3. Measurement by using VNA in an anechoic chamber

TABLE I
MEASUREMENT SETUP PARAMETERS

Measurement Parameter	Value
Frequency range	2 GHz to 12 GHz
Number of frequency points	801
Dynamic range	80 dB
Tx & Rx antenna height	1.2 m
Distance (d) Tx-Rx	1 m, line of sight (LOS)
Rx rotation range	$0° - 360°$
Rx rotation step	5°
Rx rotation cut	azimuth plane

the transmitter antenna, H_{rx} is transfer function of the receiver antenna, and H_{f} is free space transfer function, the system transfer function can simply expressed as

$$H(f) = H_{\mathrm{tx}}(f)H_{\mathrm{f}}(f)H_{\mathrm{rx}}(f) \tag{1}$$

where the

$$H_f(f) = \left(\frac{\lambda}{4\pi d}\right) e^{-j\frac{2\pi}{\lambda}d} \quad (2)$$

System transfer function $H(f)$ can be directly obtained from measurement. Hence, the system response can be completely determined when the transfer function is known. If the receiver antenna is rotated at azimuthal plane, the equation (1) can be rewritten as

$$H(f,\phi) = H_{tx}(f)H_f(f)H_{rx}(f,\phi) \quad (3)$$

To minimize the distortion in the received signal waveform, the transfer function is required to have flat magnitude and linear phase response over the operational band. Those requirements lead the antenna to have a good performance [7]. By the equations above, the antenna transfer function which denotes the antenna gain can be also obtained by

$$H_{tx}(f) = H_{rx}(f,0^\circ) = \sqrt{\frac{H(f,0^\circ)}{H_f(f)}} \quad (4)$$

B. Group delay

The average of the group delay is equal to the time needed for a signal (at a given frequency) to travel from one antenna terminal to the other. Group delay is used to evaluate the phase response of transfer function because it also can be defined as the rate of change of total phase shift. Mathematically, group delay can be written as a negative derivative of the phase response $\angle H(f)$ with respect to frequency.

$$\tau = -\frac{d[\angle H(\omega)]}{d\omega} = -\frac{1}{360^\circ}\frac{d[\angle H(f)]}{df} \quad (5)$$

In UWB system, constant group delay is required which implies the phase changes linearly with frequency. When the group delay is not constant, the pulse waveform will be spread out in the time domain [5].

C. Waveform distortion

Regarding to evaluate the antenna performance in time domain, the distortion can be obtained using post-processing software. The purpose is to illustrate the distortion caused by antenna and channel by comparing the transmitted and the received waveform. The transmitted signal shall be defined by taking one of simple waveform for UWB communication [8].

In this study, let we consider the rectangular pass-band waveform as the transmitted signal which given by

$$v_t(t) = \frac{A}{f_b}[f_H \mathrm{sinc}(2f_H t) - f_L \mathrm{sinc}(2f_L t)] \quad (6)$$

$$V_t(f) = \begin{cases} \frac{A}{2f_b} & \||f| - f_c| \le \frac{f_b}{2} \\ 0 & \||f| - f_c| > \frac{f_b}{2} \end{cases} \quad (7)$$

where A is the maximum amplitude, f_b is the occupied bandwidth, f_c is the center frequency, $f_L = f_c - f_b/2$ and $f_H = f_c + f_b/2$ are the minimum and maximum frequencies.

It has been shown above that $V_t(f)$ is a spectral density of the transmitted waveform. Thus, the received signal in time domain can be easily derived using inverse fourier transform,

$$v_r(t) = \int_{-\infty}^{\infty} V_t(f)H(f)e^{j2\pi ft}df \quad (8)$$

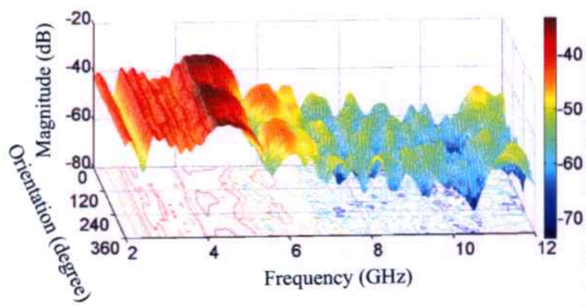
After the received signal is obtained, not only comparing with the transmitted signal, but the correlation coefficient between those two waveforms also can be determined by the following equation

$$C = \frac{\max\left|\int_{-\infty}^{\infty} v_t^*(t).v_r(t+\tau)dt\right|}{\sqrt{\int_{-\infty}^{\infty}|v_t(t)|^2 dt.\int_{-\infty}^{\infty}|v_r(t)|^2 dt}} \quad (9)$$

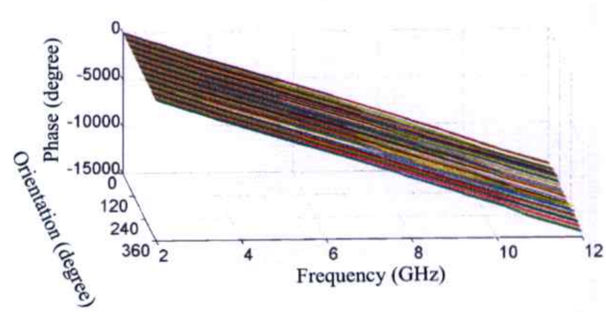
The correlation coefficient is a measure of similarity of two waveforms as a function of a time-lag applied to one of them. It ranges between 0 and 1. If the correlation coefficient is equal to 1, it means the waveform is totally similar or having a perfect signal transmission.

IV. Results and Discussion

All investigation results are presented as a graph for each parameter. Fig.4 depicts the system transfer function between two identical UWB antennas. Fig.4(a) implies that the magnitude of the transfer function is not linear with some dips occurred at particular frequencies. Fig.4(b) shows phase of the transfer function which rightly looks linear. Nevertheless, the Rx antenna orientation does not affect the transfer function so much recalling the studied UWB antenna is an omnidirectional antenna.



(a) Magnitude



(b) Phase

Fig. 4. System transfer function (a) Magnitude (b) Phase

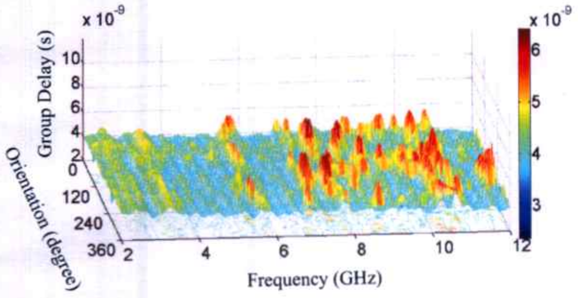


Fig. 5. Group delay

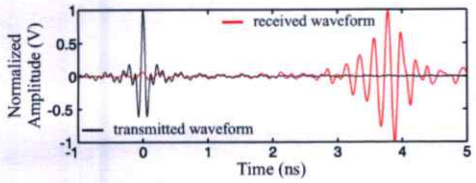


Fig. 6. Example of the transmitted and the received waveform comparison

Apparently, the constancy of group delay is according to the phase of the transfer function. It can be observed from Fig.5 that the group delay is quite constant around 3.8 ns with some small ripples located near 6 GHz and at the range between 7 GHz to 11 GHz. The ripples are reasonable since it can be associated with the dips occured in the magnitude of the transfer function. It can be caused by either the antenna performance itself or noise in the measurement. The low magnitudes or dips in the transfer function which very near to VNA dynamic range limit can possibly lead the noise involved to the measurement data.

The waveform distortion cannot be obviously known by $H(f)$ itself, but it definitely depends on its nonlinearity. To see the characteristic of signal transmission in time domain, suppose a rectangular pass-band waveform which has A = 1 V, f_b = 7.5 GHz, and f_c = 6.85 GHz is applied to Tx antenna while Rx is at 0° orientation. Then, Fig.6 shows the comparison between the transmitted waveform and the normalized received waveform. They look dissimilar since the received waveform has been distorted and spreaded out. The received waveform is delayed nearly 3.8 ns as the value of the group delay.

To measure the similarity of the waveforms, the equation of correlation coefficient was applied. The results of correlation coefficient for every orientation can be plotted such a pattern as depicted in Fig.7. Two other waveforms having A = 1 V, f_b = 1.4 GHz, f_c = 4.1 GHz for Japan low-band UWB and A = 1 V, f_b = 3 GHz, f_c = 8.75 GHz for Japan high-band UWB are also considered so that the antenna performance for various signal spectrums can be known. It is very obvious that the correlation coefficient for full-band UWB signal is worse than others as it has the widest spectrum and transmitted by more transfer function nonlinarity. The average of correlation coefficient for full-band UWB signal is 0.535, for low-band UWB signal is 0.915, for high-band UWB signal is 0.802.

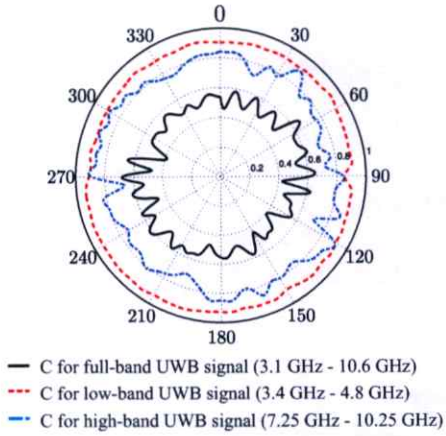


Fig. 7. Correlation coefficient pattern of the studied UWB antenna

V. Conclusion

By presenting system transfer function, group delay, and correlation coefficient of a UWB printed monopole antenna, this paper has pointed out that system characterization can be used as a proper way to evaluate UWB antenna performance. Especially for impulse radio scheme, single antenna analysis which usually done seems insufficient for UWB antenna benchmarking. Although the return loss of UWB antenna complies the UWB bandwidth requirement, but probably its signal transmission performance is not perfectly good. When the UWB antenna applied as a system, nonlinearity of the transfer function at some particular frequencies inflicts distortion in the signal transmission. Investigating time domain behaviour of two-identical-antenna system could give appropriate comprehension for UWB antenna evaluation. Experimental scheme shown in this paper can be used for comparing or evaluating other UWB antennas.

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