Super-Wideband Planar Monopole Antennas

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A thesis submitted to the
Electrical Engineering Department
in partial fulfillment of the requirements for the degree of
MS IN ELECTRONIC ENGINEERING

Faculty of Engineering
Capital University of Science and Technology
Islamabad

April 2017

DECLARATION

It is declared that this is an original piece of my own work, except where otherwise acknowledged in text and references. This work has not been submitted in any form for another degree or diploma at any university or other institution for tertiary education and shall not be submitted by me in future for obtaining any degree.

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April 2017

Dedicated to my parents and wife for their affectionate love, moral support and encouragement

CERTIFICATE OF APPROVAL

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ACKNOWLEDGMENT

First and foremost I would like to thank Allah Almighty, who gave me the courage to continue my graduate studies with research work. The determination granted by Allah helped me to tolerate the hard times to produce this thesis.

I would like to express my gratitude to my supervisor Prof. Dr. M. Mansoor Ahmed for his guidance, support and encouragement. My research work is the result of his determination, appreciation and creative thinking. His exceptional theoretical concepts and research experience helped me during this research work. Working with him has been a great experience for me. Without his guidance and support this thesis would never been accomplished.

I would like to thank Mr. Arslan Kiyani, PhD Scholar in Department of Engineering, Macquarie University, Sydney, Australia and Mr. Muhammad Mateen Hassan, Lecturer, Capital University of Science and Technology, Islamabad, for their guidance and help throughout this research work. Their motivation and encouragement helped me a lot to complete this thesis. Working with them has been a great experience. I greatly appreciated the help of Dr. Aamer Iqbal Bhatti, Professor in Electrical Engineering Department at Capital University of Science and Technology and Mr. Hafiz Jaffar from National Development Complex (NDC) for the testing of antennas.

I want to appreciate all teachers of Capital University of Science and Technology, who taught me during my course work, by delivering their precious and valuable thoughts, in building my concepts.

ABSTRACT

Over the past few years, wireless communication systems have been developed with an astonishing rate and wireless terminals for future applications are required to provide diverse services. This rising demand prompts the need for antennas able to cover multiple bandwidths for various systems. Since the allocation of UWB frequency spectrum (3.1 GHz to 10.6 GHz) by the Federal Communications Commission (FCC) for ultra wideband (UWB) wireless communications, UWB has been rapidly evolving as a potential wireless technology and UWB/SWB antennas have consequently drawn more attention from both academia and industries worldwide. A competent UWB/SWB antenna should be capable of operating over an ultra-wide bandwidth as assigned by the FCC and also cover cellular and radar communication frequency bands. At the same time, a small and compact antenna size is highly desired, due to the integration requirement of entire UWB systems. This thesis focuses on SWB planar monopole antenna design and analysis. Studies have been undertaken covering the areas of UWB fundamentals and antenna theory. Extensive investigations were also carried out on two different SWB antennas.

The first type of antenna studied in this thesis is elliptical planar monopole antenna. The conventional microstrip feed line replaced with tapered microstrip feed line to enhance the operating bandwidth substantially. The trapezoid ground plane is also utilized to get impedance matching at lower frequency bands. The antenna has achieved the simulated impedance bandwidth of 62.5:1 in the frequency range of 0.4-25 GHz and measured bandwidth of 28.5:1 in the frequency range of 0.7-20 GHz. The proposed antenna also exhibits stable radiation patterns and good gain over the entire bandwidth.

The second type of antenna is planar hexagonal monopole antenna. The feeding mechanism is same as the first antenna to achieve enhanced impedance bandwidth. In this design, two parasitic elements are used with the main patch radiator to match the impedance at lower frequencies as well as to minimize the effect of radiations caused by feed line. Simulations and measurements are carried out and it is observed that the antenna is capable of operating over an extremely wide bandwidth. The simulated ratio bandwidth is 147:1 in the frequency range of 0.17-25 GHz while the measured one is 66.6:1 in the range of 0.3-20 GHz. Good radiation patterns and gain are also obtained from the proposed antenna.

It is also observed that the proposed antennas are smaller in size than the previously reported SWB antennas. These features have demonstrated that the proposed antennas can be an excellent choice for various wireless communication systems. It is needed to mention that the proposed antennas are measured till 20 GHz due to the limitation of SMA connector.

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LIST OF ACRONYMS

3G	Third generation
4G	Fourth generation
ABW	Absolute bandwidth
BDR	Bandwidth division ratio
CDMA	Code division multiple access
CST	Computer simulation technology
EMC/EMI	Electromagnetic compatibility/interference
FCC	Federal communication commission
FBW	Fractional bandwidth
GPS	Global positioning system
GSM	Global system for mobile
HFSS	High frequency structure simulator
ISM	Industrial scientific and medicine
MIMO	Multiple-input Multiple-output
PMAs	Planar monopole antennas
PCB	Printed circuit board
PBW	Percentage bandwidth
PEMA	Planar elliptical monopole antenna
PRMA	Planar rectangular monopole antenna
PHMA	Planar hexagonal monopole antenna
RBW	Ratio bandwidth
SWB	Super-wideband
UMTS	Universal mobile telecommunication service
UWB	Ultra-wideband
VSWR	Voltage standing wave ratio
VHF/UHF	Very high and ultra high frequency
Wi-Fi	Wireless fidelity
WLAN	Wireless local area network

LIST OF SYMBOLS

A, B	Width and length of elliptical patch
ε_{eff}	Effective dielectric constant
f_l, f_h	Lower and higher frequency
h	Thickness of substrate
L, W	Length and width of hexagonal patch
r	Radius of cylindrical monopole antenna
t	Gap between patch and ground plane
Z_{in}	Input impedance
Z_0	Characteristics impedance
λ	Wavelength

Chapter 1

INTRODUCTION

Antennas are considered significant and indispensable components of wireless communication systems. The definition of antenna according to the IEEE is, *"a mean for radiating or receiving radio waves"* [1]. In other words, in transmission mode, the antenna takes electromagnetic waves from a transmission line, and radiates them in air, while in receiving mode, the antenna collects the incident electromagnetic waves and converts them back into guided waves.

In this thesis, planar monopole antennas (PMAs) are developed for super-wideband (SWB) applications which can support existing wireless communication services, such as GSM/UMTS, GPS, CDMA standard, WLAN/Wi-Fi, ultra-wideband (3.1-10.6 GHz), Ku-band (12-18 GHz) and vehicular radar band (22-29 GHz), etc.

1.1 Motivation

Several factors that motivated this investigation on SWB antennas are described below:

In the past two decades, wireless communication technology has influenced almost every field of human society. Following the rapid development of wireless terminals as well as the growing demands for new services, cell phones provide a freedom such that we can communicate with each other with ease, the technologies of UWB, wireless local area network (WLAN) provides the facility and access to internet without the usage of expensive cables, and the third-generation (3G) and fourth-generation (4G) communication technologies have emerged.

It is a common practice for single radio device to provide several services over a wide frequency range. For these types of devices, the ability to generate multiple frequency bands will eventually depend on their antennas performance. To achieve these requirements, multiple antennas are installed, and each one covers a specific frequency band. However, these antennas occupy much space in the device. Most importantly, such installations of multiple antennas generate electromagnetic compatibility/interference (EMC/EMI) problems and also increase the system complexity. Therefore, an antenna is required which provides wideband response to cover all the operating frequency bands of these wireless communication systems.

Due to the limited space available in portable devices, compact printed antennas are required. The dimensions of antenna often dominate the size of the whole system. To scale down the system size, methods are required to reduce the size of ultra-wideband (UWB) and SWB antennas.

In addition to the demand of wideband and small size antennas, the systems are usually required to be able to compensate the degradation of the signal due to the complexity of the propagation channel. In such channels, signals always suffer from fading effects. With the use of dual-polarized antennas, the performance of wireless communication systems can be greatly enhanced.

1.2 Organization of the Thesis

The thesis is organized in six chapters as follows:

Chapter 1 is an introduction, providing basic insight about SWB antennas, It also outlines the motivation and key contributions of the thesis.

Chapter 2 presents the background study of UWB technology and basics of SWB radio technology. The chapter also provides a brief introduction of applications and benefits associated with SWB technology.

Chapter 3 presents a brief history of wideband antennas and SWB antennas.

Chapter 4 and 5 presents the proposed planar monopole antenna (PMA) designs. These chapters briefly explain the design steps which led to the final proposed designs.

Chapter 6 provides the overall conclusion of the thesis, followed by a brief summary of all the designs and suggestions for future work.

1.3 Key Contributions

The major contributions in this thesis are given below.

Firstly, a planar elliptical monopole antenna is designed and realized for super-wideband communication systems by simply replacing the microstrip feed line with tapered microstrip feed line and by modifying the ground plane. The proposed antenna exhibits 48.5% reduction in its physical size than the previously reported designs. On the other hand, the proposed PEMA can still achieve extremely wide impedance bandwidth in the frequency range of 0.4-25 GHz.

Secondly, a hexagonal-shaped planar monopole antenna is designed and presented for super-wideband performance. A tapered microstrip feed line is used to excite the hexagonal patch radiator and two parasitic elements are introduced in the design to achieve SWB response. The electrical dimension of the proposed design is $0.107\lambda \times 0.107\lambda$, which is smaller than the previously reported data. Also, the proposed design is able to operate in the frequency range of 0.17-25 GHz.

Lastly, the proposed PMAs are fabricated and measured for the validation of simulation results. It is observed that the measured responses of the proposed designs are much similar to the simulated results.

All the antennas proposed in this thesis are able to provide super-wideband response with good radiation characteristics, which make them suitable for many communication systems, such as GSM/UMTS (800/850/900/950/1800/1900/2100 MHz), GPS (1227.60 MHz and 1575.42 MHz), ISM (2.4 GHz and 24.25 GHz), WLAN/Wi-Fi (3.6/4.9/5/5.9 GHz), radio determination applications (4.5-7 GHz, 13.4-14 GHz), UWB communication (3.2-10.6 GHz), radio astronomy (22.5 GHz, 24.05-27 GHz), etc.

Chapter 2

SUPER-WIDEBAND TECHNOLOGY

2.1 Introduction

Ultra-wideband (UWB) systems are pulse based systems because it transmits higher data rate by sending energy pulses than a narrow-band frequency carriers. These pulses have short durations, generally some nanoseconds, that result in UWB frequency spectrum. The idea of impulse radio was first developed in the 1900s with Marconi, when impulse measurement techniques were used to analyze the transient behavior of microwave networks [2]. After that, in the 1960s, these techniques were utilized to design wideband antennas that result in the development of short-pulse radars and communication systems [3]. In the 1980s, Federal Communication Commission (FCC) allocated Industrial Scientific and Medicine (ISM) bands for unlicensed wideband communications. In 2002, the amendments were made in Part 15 by FCC, which directed unlicensed radio devices to include the operation of UWB devices. For this purpose, a bandwidth of 7.5 GHz was also allocated, i.e., 3.1-10.6 GHz [4]. According to the FCCs rules, a signal having 500MHz spectrum can be utilized in UWB systems. It means that UWB is no more restricted to impulse radio.

Recently, a new research in a public safety domain aims for sensors which is able to provide high data-rate, high resolution screening and high channel capacity. Also, to improve Doppler resolution and range, sensors which support super-wideband (SWB) signaling will be the solution for the problem. SWB radio technology could be the possible approach that enables high-resolution sensing in matter as well as in free space. SWB-RT has some unique advantages as compared to narrow-band technology, and it also improves UWB radio technology advanced features, which include precise screening, super resolution in communication systems and enhanced channel capacity, etc.

2.2 Applications of SWB Technology

SWB communication system provides some unique features that makes it suitable for various applications.

1. SWB technology has the capability to transmit excessive data using less system power within a limited range. So, high data rate transmission between computers and consumer electronics will provide new experiences in home and for personal entertainment.

2. SWB offers an advanced tracking mechanism for indoor locations than a Global Positioning System (GPS). The moving objects can be tracked within an indoor environment with a precision of specific distance. Also, it can be used to find casualties in a collapsed building, injured tourists in a remote area and so on.

3. In imaging and radar applications, SWB technology is used in the surroundings of battlefield to detect enemies and lethal weapons. It has also gained interest in medical diagnostics where X-ray systems are less beneficial.

4. Wireless sensor networks can also utilize SWB technology because the installation cost and maintenance of system can reduce significantly by deploying SWB sensor networks. Also, these networks are able to collect and distribute a large amount of data in a timely manner.

2.3 Benefits of SWB Technology

SWB technology has a number of benefits that are attractive for radar and wireless communication. Some of the primary advantages are explained below:

1. Through SWB technology, a huge capacity can be achieved as high as hundreds of Mbps or even several Gbps with distance of almost 1 to 10 meters.

2. SWB technology provides highly secure and reliable solution for wireless communication. The signals are noise like due to low energy density, which makes detection entirely difficult. One reason is that SWB signals have a particular shape so, it is near to impossible for noise to eliminate the pulse because the noise spreads uniformly across the entire spectrum to demolish the pulse. Hence, SWB is the most secure communication technology available, ever.

3. Lastly, UWB/SWB systems are low cost and less complex. It does not modulate and demodulate complex carriers which eliminate the use of amplifiers, oscillators, mixers and filters.

2.4 Requirements for SWB Antenna

It is a known fact that antenna plays an important part in wireless communication systems including UWB/SWB systems. So, the difficulties and challenges are high in designing a SWB antenna than a narrow band antenna.

Firstly, the performance of a SWB antenna should be constant over the whole operational band.

Secondly, omni-directional or directional radiation patterns are required depending on the application. Omni-directional radiation properties are usually demanded in cell phones and hand-held devices. While, the high gain and directional patterns are required in radar and other directional systems.

Thirdly, a SWB antenna should be compact so that it can be installed in SWB systems. It is also preferred that the antenna exhibits low profile configuration for easy integration with printed circuit board (PCB).

Fourthly, a SWB antenna should optimize the overall system performance. For example, the antenna is designed in such a way that the device complies with the essential power emission mask governed by the FCC or other regulatory bodies.

Finally, a SWB antenna should attain good transient characteristics. In the case of narrow band, it is approximated that the antenna acquires the same properties over the entire bandwidth and basic performance parameters, such as return loss and gain, with minimum variations. In contrast, SWB systems use short pulses for data transmission, which occupy a huge bandwidth. Thus, the antenna can be used as a "band-pass filter" not as a "spot filter". In this scenario, the antenna parameters will have to be handled as a function of frequency and will impose significant effects on the input signal. As a result, an efficient time domain performance is achieved, i.e. less distortion in pulse at receiver side, which is a primary concern of SWB antenna.

2.5 Definition of Bandwidth

In general, the input impedance (Z_{in}) of an antenna changes with frequency even the characteristics impedance (Z_0) of feed remains same. If an antenna is well matched to its feed across a certain frequency range, that frequency range is defined as its impedance bandwidth VSWR $\leq$ 2. We can define antenna bandwidth in several ways: absolute bandwidth (ABW), percentage bandwidth (PBW), fractional bandwidth (FBW) and ratio bandwidth (RBW). They are all defined as follows:

$$ABW = f_h - f_l \qquad \textit{Eq (2.1)}$$

$$PBW = 2\frac{f_h - f_l}{f_h + f_l} \times 100\% \qquad \textit{Eq (2.2)}$$

$$FBW = 2\frac{f_h - f_l}{f_h + f_l} \qquad \textit{Eq (2.3)}$$

$$RBW = f_h / f_l \qquad \textit{Eq (2.4)}$$

where f_h and f_l is the highest and lowest frequency, respectively.

The absolute bandwidth describes the width of the whole frequency range within which the antenna operates. The percentage bandwidth or the fractional bandwidth has originally been used to describe conventional narrowband antennas and microwave devices. The ratio bandwidth is used to express the bandwidth of UWB and SWB antennas and devices.

Chapter 3

LITERATURE REVIEW

This chapter deals with a brief overview of the past development in ultra-wideband and super-wideband PMAs. The chapter starts with the introduction of initial development in wideband antennas. Different design techniques are discussed which are adopted to increase impedance bandwidth of PMAs.

3.1 Historical Background

The biconical antennas were the earliest antennas with wideband characteristics developed by Oliver Lodge [5]. At the early stage, three-dimensional antenna structures were designed such as conical/biconical antennas [6], directional and omni-directional coaxial fed horn antenna [7], spheroidal antennas [8, 9], etc. In 1939, Carter improved the Lodge's conical monopole antenna by introducing tapered feed [6, 10]. It was the first design that provides broadband transition between a feed line and radiator.

Lindenblad's coaxial horn antenna was the most promising UWB antenna [11]. He improved the design of a sleeve dipole by gradually transforming the impedance of feed section. During the late 1930 and early 1940, an array of Lindenblad's horn antenna was used to transmit the audio part of television signal. This horn element represents the research effort in television industry. During the period of 1940's, researchers also explored other horn designs such as conical horn [12] and rectangular horn [13].

Rumsey et al. were the first who reported antennas with a ratio bandwidth of 10:1, in the late 1950 and early 1960. These antennas were called as frequency independent antennas [3]. The antennas include in this category are equiangular

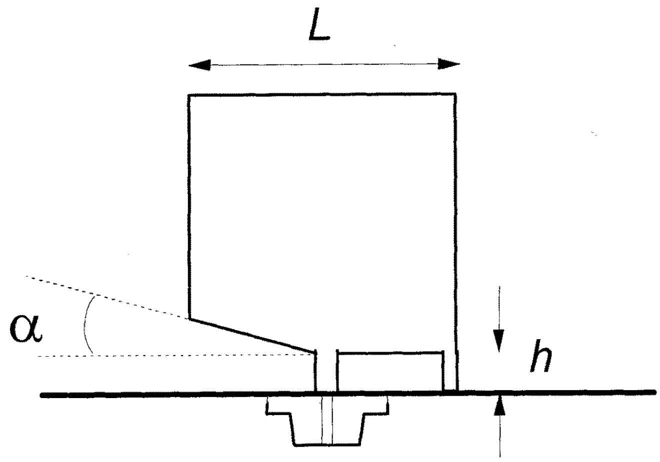


FIGURE 3.1: Metal-plate antenna with short post and bevelling technique [18].

spiral antennas and log-periodic dipole antennas. From 1990's onward, many new antennas have been presented for UWB and SWB applications. The detailed overview of these antennas are presented in next sections.

3.2 Super-Wideband Antennas

3.2.1 SWB Metal-plate Monopole Antennas

G. Dubost [14], in 1976, proposed first broadband metal-plate monopole antenna (MPMA). The rectangular MPMA is the simple structure, but its ratio bandwidth is only 2:1. P. V. Anob enhanced the impedance bandwidth of MPMA by changing the feed location [15]. After that, the author in [16] widened the bandwidth to 10:1 by combining the short pin and bevelling technique, as shown in Figure 3.1. In [17], the author enhanced the impedance bandwidth of metal-plate antenna by using trident feed as shown in Figure 3.2. Its ratio bandwidth is 8.3:1 from 1.38 to 11.45 GHz with improved stability of radiation pattern. N. P. Agrawall proposed an elliptical metal-plate antenna and achieved an impedance bandwidth of 1.21-13 GHz and ratio bandwidth of 10:1 [18].

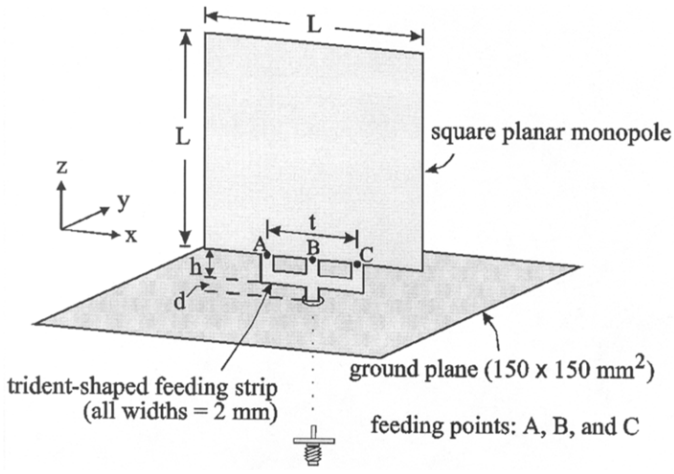


FIGURE 3.2: Metal-plate antenna with trident feed [19].

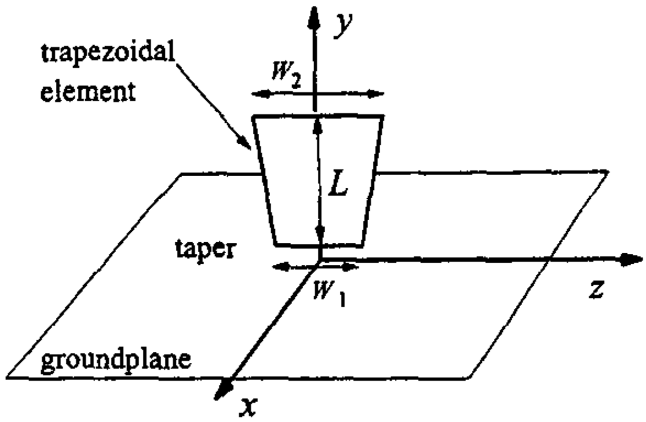


FIGURE 3.3: Trapezoid metal-plate antenna [21].

In [19], J. A. Evans developed a trapezoid metal-plate antenna, as shown in Figure 3.3, and achieved 13:1 ratio bandwidth . The interesting MPMA is the planar inverted cone antenna (PICA) mounted vertically above a ground plane as shown in Figure 3.4. The author not only present a simple structure but also reported an impedance bandwidth more than 10:1. A modified PICA was also reported with greater bandwidth [20]. The modification was made in PICA by adding two circular holes. It provides omni-directional radiation performance over a bandwidth of 7:1.

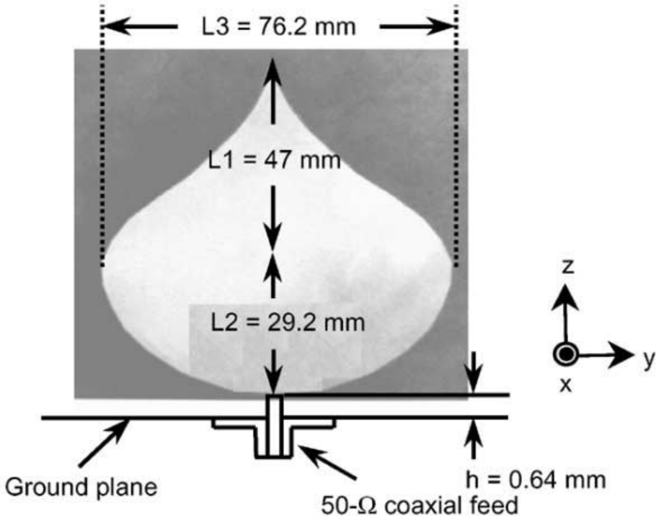


FIGURE 3.4: Planar inverted cone antenna [22].

3.2.2 SWB Printed Monopole Antennas

The planar metal-plate antennas can achieve SWB bandwidths, but they require perpendicular ground planes. Compared with metal-plate antenna, printed/planar antenna are more promising in SWB applications due to their light weight and easy integration with devices, etc. Many planar antenna are reported in the literature for wideband systems. These printed antennas are either fed with a microstrip line or Coplanar Waveguide (CPW). To extend the bandwidth of printed monopole antennas, number of shapes like heart-shape, U-shape, circular-shape, etc are reported in the literature.

3.2.2.1 SWB CPW-fed Printed Monopole Antennas

An example of CPW-fed antenna is the printed semi-elliptical monopole, as shown in Figure 3.5 [21, 22]. This design provides a ratio bandwidth of 19.7:1 The structure is composed of a trapezoid ground plane fed by a tapered CPW feed. After that, J. Liu [23] improved the bandwidth of CPW-fed printed elliptical antennas by incorporating semi-ring with tapered feed line. From this design, the authors achieved an impedance bandwidth from 1.02 to 24.1 GHz with a ratio

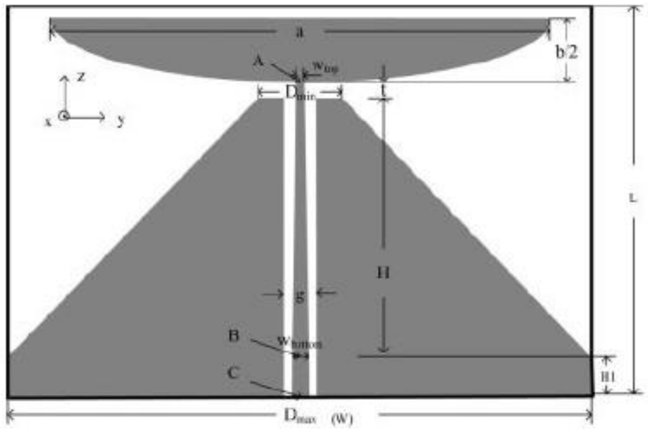


FIGURE 3.5: CPW-tapered line fed semi-elliptical monopole [24].

bandwidth of 23:1. The design also offers good radiation characteristics and gain in the entire bandwidth. Inspired from this, in [24], a CPW trident shaped feed line based hexagonal patch radiator was presented for SWB performance. This design was smaller than the design reported in [23]. The reported design was able to provide an impedance bandwidth in the frequency range of 2.76-40 GHz.

A propeller shape CPW-fed planar monopole antenna was presented in [25] for SWB applications. The authors modified circular monopole shape into a propeller shape to achieve an impedance bandwidth from 3 to 35 GHz. The presented antenna also provides almost omni-directional radiation characteristics in SWB range. A modified inverted triangular CPW-fed antenna was presented in [26]. The inverted triangular structure base consists of two rectangular-shaped notches and a parasitic rectangular patch as shown in Figure 3.6. According to the simulated and measured results, the antenna was able to resonate in the frequency range of 3.06-35 GHz.

3.2.2.2 SWB Microstrip-fed Planar Monopole Antennas

Generally, a microstrip-fed planar monopole antenna consists of a radiating patch and a ground plane. The radiating patch, ground plane and microstrip feed line are printed on a substrate. These kinds of planar antennas possess the features of

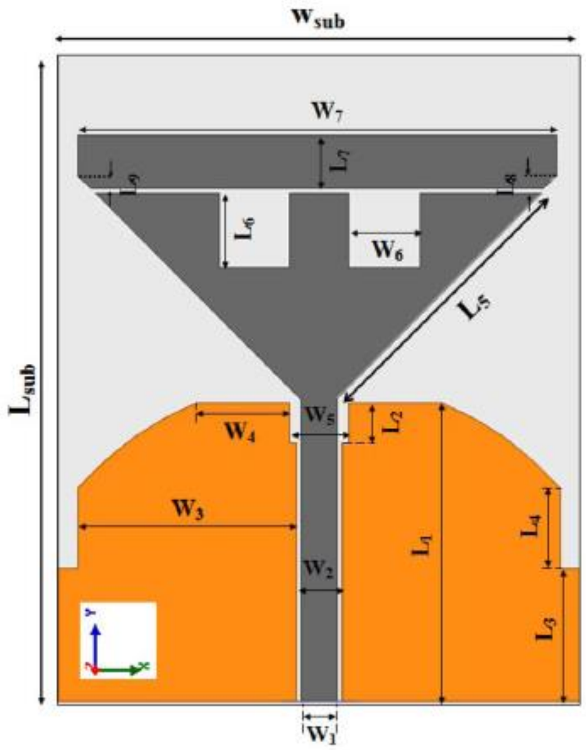
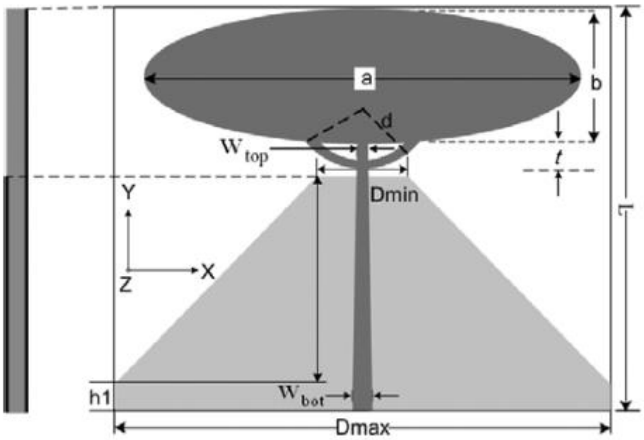


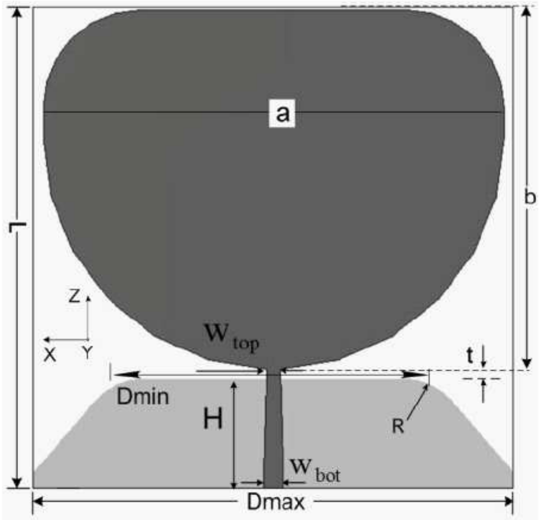
FIGURE 3.6: Inverted-triangular CPW-fed monopole antenna [29].

low cost and easy fabrication. However, they provide a ratio bandwidth of about 3.52 with the frequency range from 2.78 to 9.78 GHz. To enhance the bandwidth of these planar antennas, many techniques are presented in the literature.

In [27], a holy-leaf shaped planar monopole antenna was presented for wideband applications. A square notch is designed on the groove-shaped ground plane to enhance the impedance bandwidth. Through this modification, the antenna provides measured -10dB bandwidth from 2.1 to 15.4 GHz. Same technique was applied on a clover structure to get SWB response [28]. A cube like planar monopole antenna was reported in [29] for SWB directional radiation characteristics. According to the authors, the antenna was able to provide extremely wide impedance bandwidth in the frequency range of 50 GHz to 200 GHz, but its experimental validation was not available. Some modified shape planar monopole antennas



(a)



(b)

FIGURE 3.7: (a) Tapered semi-ring fed elliptical monopole antenna [32] (b) Tapered line fed monopole antenna with grooved ground plane [33].

were also presented to increase the ratio bandwidth, such as hut-shape radiating element [30], convex-shaped slot patch [31], etc.

In literature, tapered feed line is also used to increase impedance bandwidth of PMAs. In [32, 33], the authors utilized tapered semi-ring feed connected to an elliptical patch and tapered feed-line with small groove-shaped ground plane to get super-wideband performance, as shown in Figure 3.7(a,b). Same technique was presented in [34] with semi-circular shaped patch. A novel elliptical slot antenna was designed for wideband applications [35]. The 45^0 rotated elliptical slot was etched from ground plane and excited by a circular patch. Tapered microstrip line was used to get maximum impedance matching. The simulations shown that the antenna offered 20:1 ratio bandwidth in the frequency range of 2.54-40 GHz. A dual-branch feed asymmetric monopole antenna was presented in [36]. The antenna consists of a asymmetric trapezoid ground plane and a modified rectangular patch. Through this configuration, the authors observed 2:1 VSWR bandwidth of 31:1 from 1.05 to 32.7 GHz.

3.3 Summary

A historical background of wideband antennas is presented. The recent progress in the development of super-wideband antennas has been reviewed. Some types of metal-plate monopole antennas, CPW-fed printed antennas and microstrip/tapered microstrip line fed printed antennas are presented.

Chapter 4

PLANAR ELLIPTICAL MONOPOLE ANTENNA

A planar elliptical monopole antenna (PEMA) has been designed, which is able to provide SWB response. To achieve extremely wide impedance bandwidth, an elliptical radiating patch is fed using tapered microstrip feed line. Also, the proposed trapezoid ground structure is playing an important role in the enhancement of antenna's bandwidth.

4.1 Antenna Specifications

This section briefly explain the design steps involved in the construction of proposed planar monopole antenna.

4.1.1 Proposed Design

The proposed antenna consist of an elliptical patch and a modified trapezoid ground plane, as shown in Figure 4.1. The ground plane and monopole are etched on the back and top surfaces of Rogers RT/Duroid 5880 substrate having thickness (h) 1.57mm, relative permittivity (ϵ_r) 2.2 and loss tangent 0.0009. The elliptical patch, with maximum length A and width B, is fed using tapered microstrip line. The impedance of a tapered feed line is gradually changed from 50Ω to 75Ω at the radiation element. The width of the feed line at the bottom end (W_{bot}) is 4.2mm, corresponding to a characteristic impedance of 50Ω, and the width at the top end (W_{top}) is 2.2mm, having characteristic impedance of 75Ω. The trapezoid ground

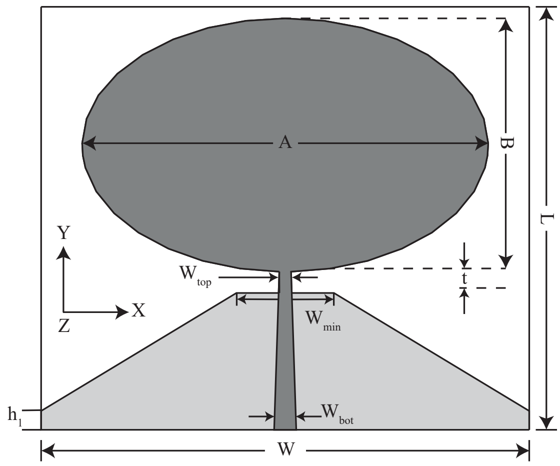


Figure 4.1: Design layout of the proposed SWB planar elliptical monopole antenna.

Table 4.1: Dimensions of the proposed SWB planar elliptical monopole antenna [mm].

W	L	A	B	W_{bot}
80	80	76	48	4.2
W_{top}	W_{min}	h_1	t	–
2.2	16	4	1	–

plane is also a part of matching network. Furthermore, the gap t between the radiation element and trapezoid ground plane plays an important role in enhancing the bandwidth. The overall optimized design dimensions are listed in Table 4.1.

4.1.2 Design Procedure

The construction of monopole antenna starts with the basic structure of PEMA, named Antenna I, as shown in Figure 4.2(a). The figure shows that a microstrip line connected to an elliptical patch etched on the top side of the substrate and a conventional rectangular ground plane is placed on the bottom side. The dimensions of the ellipse are calculated by using the expression given below [37]:

$$f_l = \frac{7.2}{\{(L + r + t) \times k\}} \; GHz \qquad \textit{Eq (4.1)}$$

where f_l is the lowest resonant frequency in the operating bandwidth, L denotes the side length of the patch radiator, r is the radius of cylindrical monopole antenna and t is the gap between patch radiator and ground plane, respectively. Here, k belongs to the effective dielectric constant (ε_{eff}) which arises due to the presence of dielectric. For elliptical patch radiator, the values of L and r are realized in terms of its major and minor axes, which are given as follows [37]:

$$L = 2B, \; r = \frac{A}{4} \qquad \textit{Eq (4.2)}$$

where B and A represent the length and width of ellipse. The width of microstrip line is calculated by using the standard feed-line equation [1].

$$W_f = \left[\frac{8e^A}{e^{2A} - 2}\right] h \qquad \textit{Eq (4.3)}$$

where

$$A = \frac{Z_0}{60}\left\{\frac{\varepsilon_r + 1}{2}\right\}^{1/2} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left\{0.23 + \frac{0.11}{\varepsilon_r}\right\} \qquad \textit{Eq (4.4)}$$

After calculating the required parameters, the conventional PEMA is simulated in High Frequency Simulation Software (HFSS) and the respective VSWR result is depicted in Figure 4.3. It is noted that Antenna I operates in the frequency range of 0.9-25 GHz, but an impedance mismatch is seen from 8 to 20 GHz.

To improve matching, a microstrip feed line is replaced with a tapered microstrip line. This modification is named as Antenna II, as shown in Figure 4.2(b), and

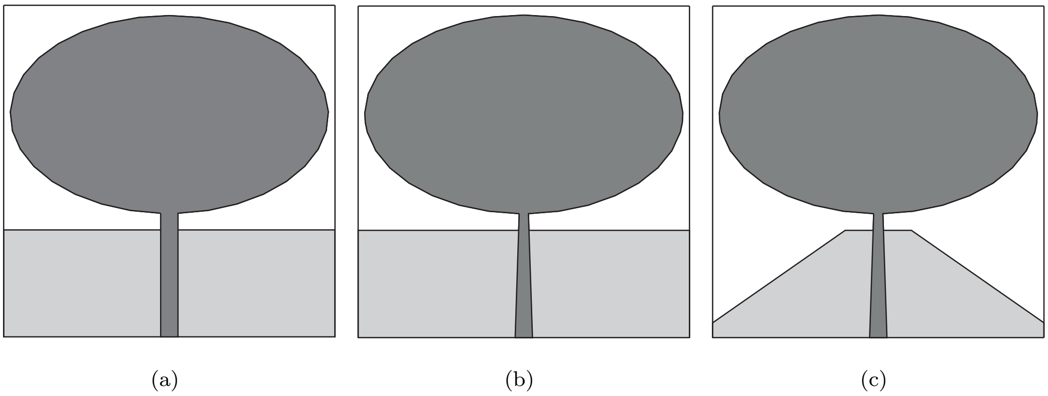


FIGURE 4.2: Design stages of SWB planar elliptical monopole antenna. (a) Antenna I. (b) Antenna II. (c) Antenna III.

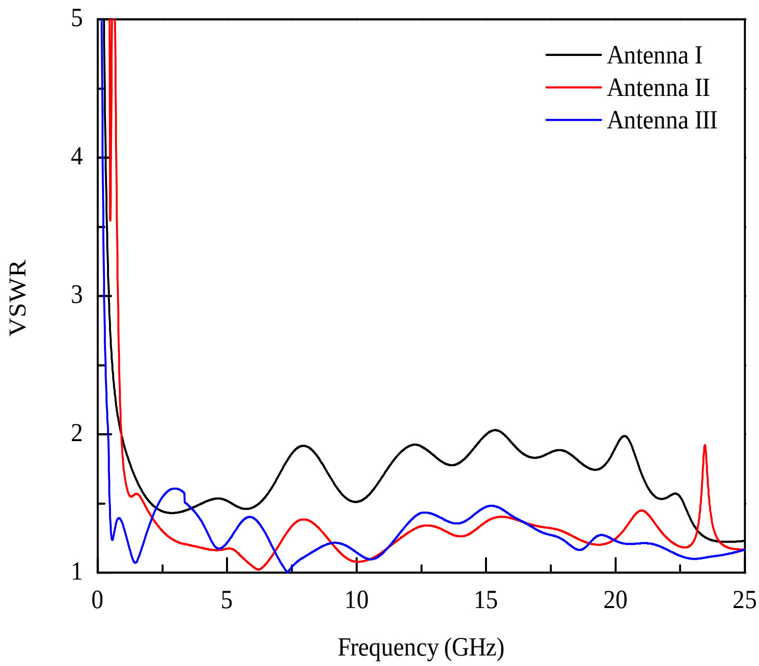


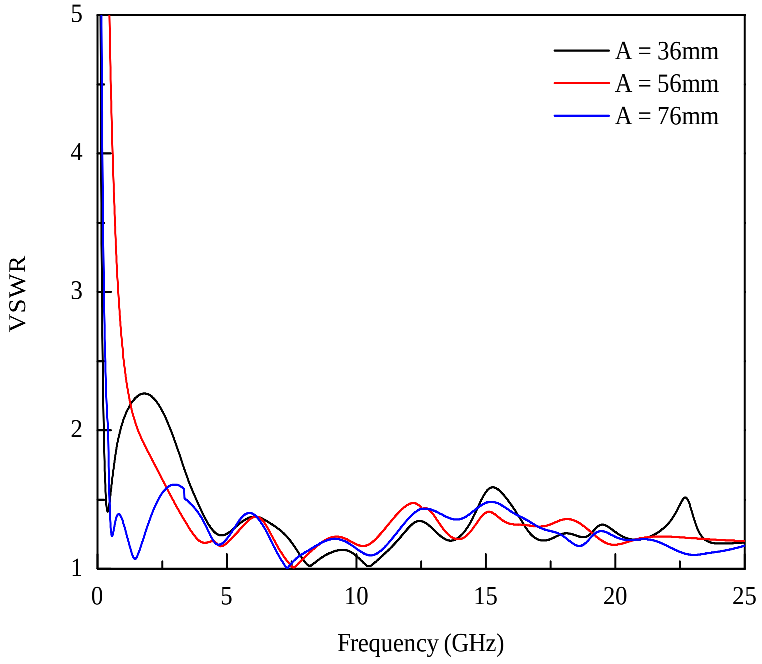
FIGURE 4.3: Variation of VSWR for different antenna designs.

the VSWR result is presented in Figure 4.3. It is observed that according to VSWR < 2 criterion, the tapered microstrip line allows the antenna to operate well in the frequency range of 0.9-25 GHz. To further match the impedance at lower frequencies, the rectangular ground plane is modified by changing its shape to trapezoid as shown in Figure 4.2(c). It is a known fact that the feed-line and ground plane structures control the current distribution of the antenna, which results in good impedance matching [17, 36]. The change in ground plane's shape further decreases the lower frequency limit from 900 MHz to 400 MHz, as shown in Figure 4.3.

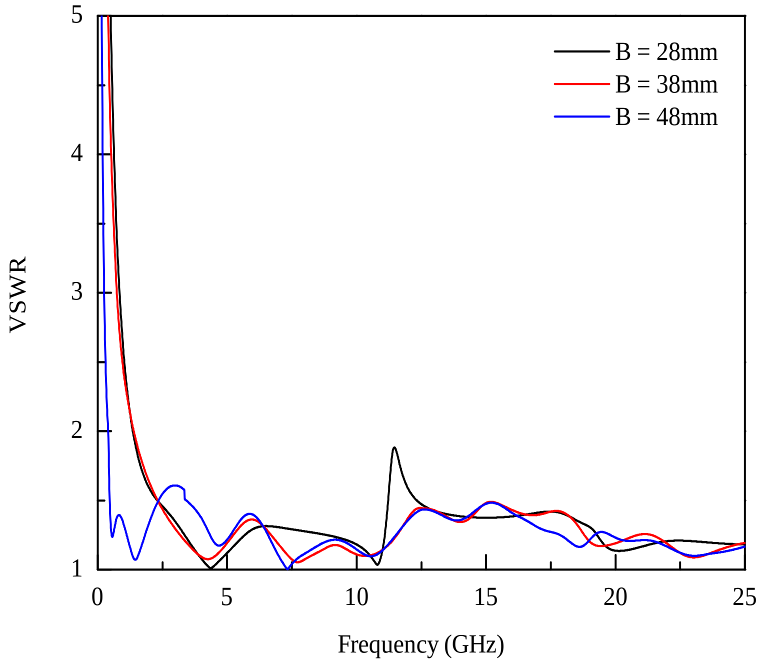
4.2 Parametric Analysis

A parametric analysis is performed to get optimized antenna parameters. Figure 4.4 shows that how VSWR changes by changing the width and length of elliptical patch. It is observed from Figure 4.4(a) that the lower frequency limit decreases from 2.83 GHz to 400 MHz when the elliptical patch width A increased from 36mm to 76mm. Moreover, when radiator length B is increased from 28mm to 48mm, the lower frequency limit is reduced from 1.35 GHz to 400 MHz, as shown in Figure 4.4(b). By considering the impedance bandwidth and overall size of the antenna, the values of A and B are fixed at 76mm and 48mm, respectively.

The gap between the radiation element and ground plane also plays an important role in impedance matching. The effect of design parameter t on impedance matching is depicted in Figure 4.5. When the value of t is set to the minimum available limit, the impedance bandwidth is decreased and also a band-notched response is occurred from 3.36 GHz to 4.2 GHz. However, when t is increased to 2mm, an impedance mismatch is created, causing the VSWR to exceed in the range of 10-20 GHz. So, a gap of about 1mm provides maximum impedance matching, which is clear from Figure 4.5.



(a)



(b)

FIGURE 4.4: Effect of elliptical patch dimensions on VSWR. (a) Width A. (b) Length B

4.3 Results and Discussion

The proposed SWB-PEMA is simulated using HFSS and the results are verified using CST Microwave Studio. It is observed from Figure 4.6 that the VSWR results taken from both softwares are well in agreement. The discrepancies between the results are due to the mesh generation because the two simulators are based on different analytical techniques. The simulated 2:1 VSWR bandwidth covers frequency range from 0.4 to 25 GHz with a ratio bandwidth of 62.5:1.

The proposed antenna is fabricated by using micro-milling machine and the VSWR measurement is carried out using Agilent Technologies N5232A VNA from 300 MHz to 20 GHz due to the limitations of SMA connector. A prototype of the proposed PEMA is depicted in Figure 4.7 and the comparison between simulated and measured results is shown in Figure 4.6. A good agreement is observed between simulated and measured VSWR results. The measured ratio bandwidth in the frequency range of 0.7-20 GHz is 28.5:1. The deficiency in results is due to imperfect soldering of SMA connector and fabrication tolerances.

The simulated E-plane ($\phi = 0^0$) and H-plane ($\phi = 90^0$) radiation patterns are illustrated in Figure 4.8. For the first resonant frequency, shown in Figure 4.8(a), the antenna exhibits omni-directional characteristics for both E-plane and H-plane. For resonant frequency 5GHz, somehow directional radiation properties are observed for E-plane and H-plane, as shown in Figure 4.8(b). For third resonant frequency, depicted in Figure 4.8(c), omni-directional pattern is observed for E-plane while bi-directional (dipole like) pattern is observed for H-plane. For the frequencies greater than 10.55 GHz, given in Figure 4.8(d, e, f), ripples are observed in the patterns since the antenna operates in higher order modes. Figure 4.9 presents the effect of input impedance over frequency in terms of its real and imaginary parts. It is observed that the real part is oscillating around 50Ω while the imaginary part fluctuates around 0Ω. This provides an overview that the

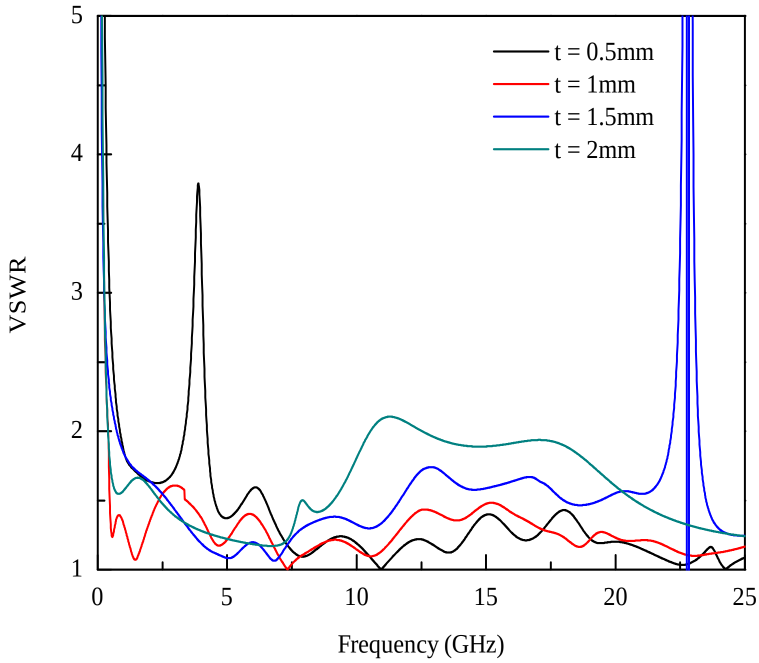


FIGURE 4.5: Effect of gap t on VSWR.

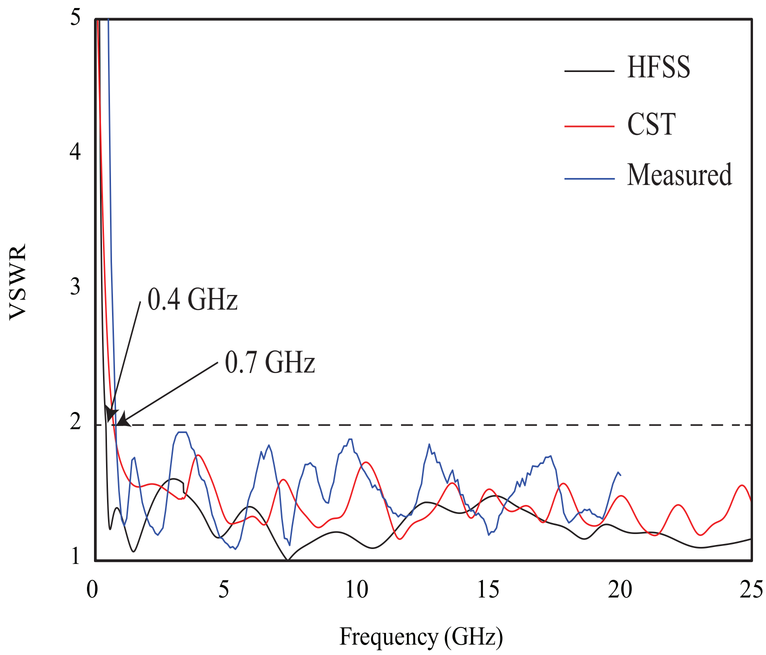


FIGURE 4.6: Comparison between simulated and measured VSWRs of the proposed SWB planar elliptical monopole antenna.

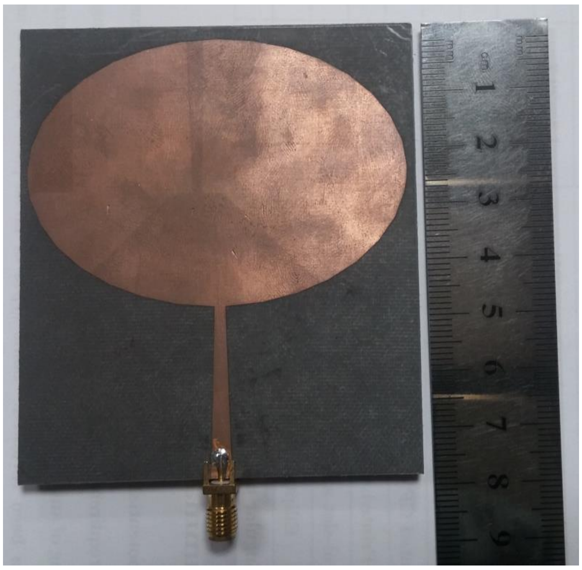


FIGURE 4.7: Prototype of the proposed SWB planar elliptical monopole antenna.

overall input impedance of the proposed antenna is nearly 50Ω. The simulated peak gain of the proposed PEMA is given in Figure 4.10. It is observed that the gain increases with the increase in frequency. This effect occurs because at higher frequencies the electrical dimensions of radiation element are larger than the wavelength. The simulated peak gain has a minimum value of 1.34 dBi at 0.5 GHz and approximately 16 dBi at 23 GHz.

Figure 4.11 demonstrates the simulated current density along the surface of the proposed PEMA. For the first two resonances 1.5 GHz and 5 GHz, shown in Figure 4.11(a, b), it is observed that the surface current density is high on the feed line. For the next three resonances, illustrated in Figure 4.11(c, d, e), a high current concentration is noted on the feed line and lower part of the radiator. For the last resonance, shown in Figure 4.11(f), a dense current is distributed at lower portion of the feed line.

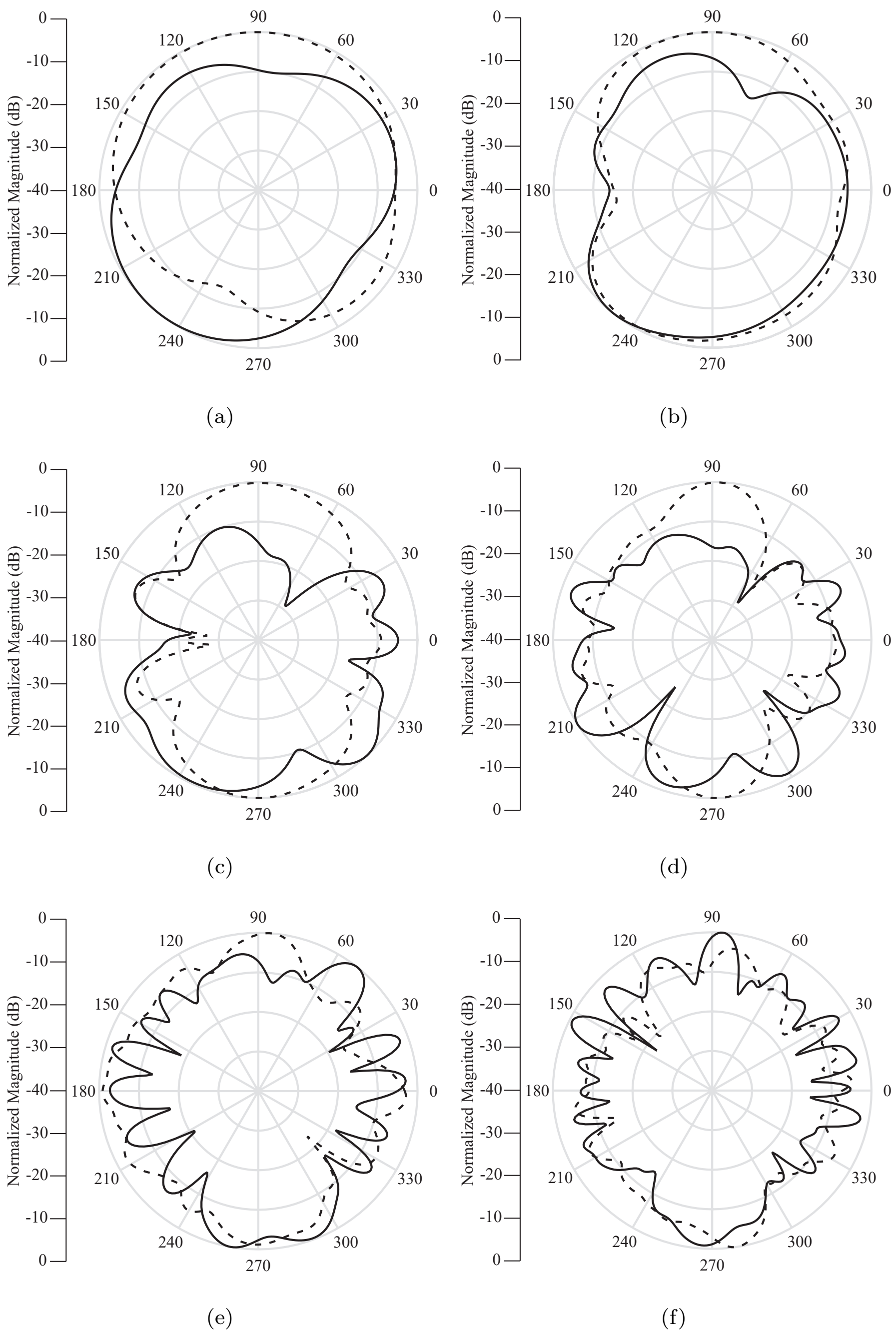


FIGURE 4.8: Simulated radiation patterns at (a) 1.5 GHz, (b) 5 GHz, (c) 10.5 GHz, (d) 15 GHz, (e) 19 GHz, and (f) 23 GHz (Solid line: E-plane, Dashed line: H-plane).

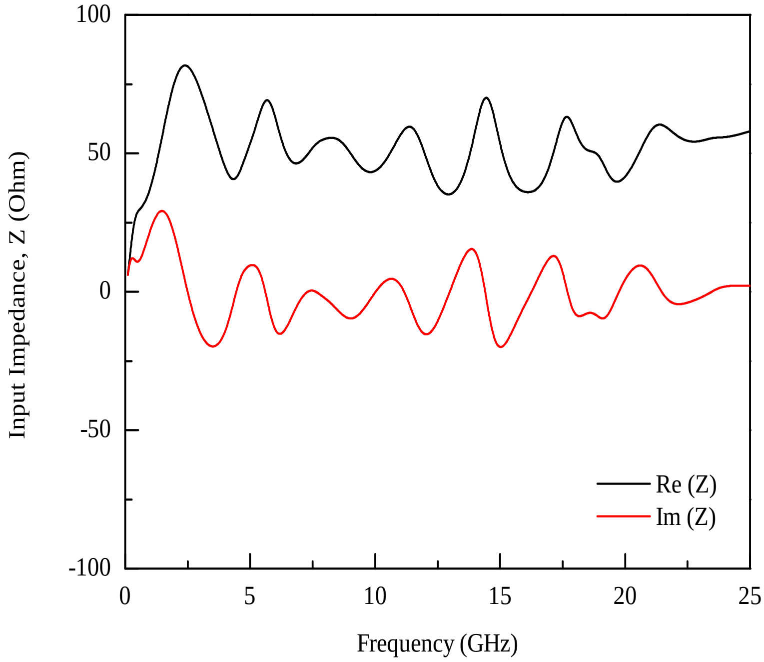


FIGURE 4.9: Simulated input impedance of the proposed SWB planar elliptical monopole antenna.

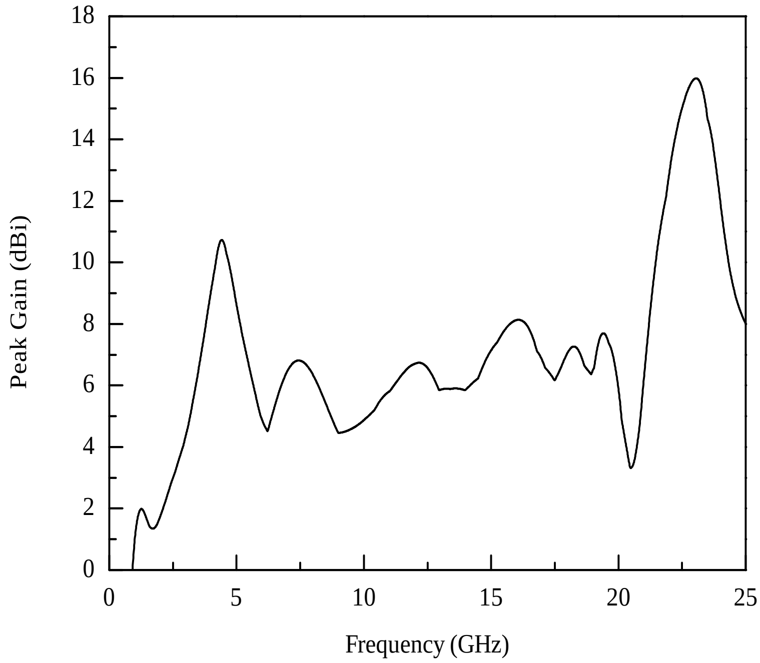
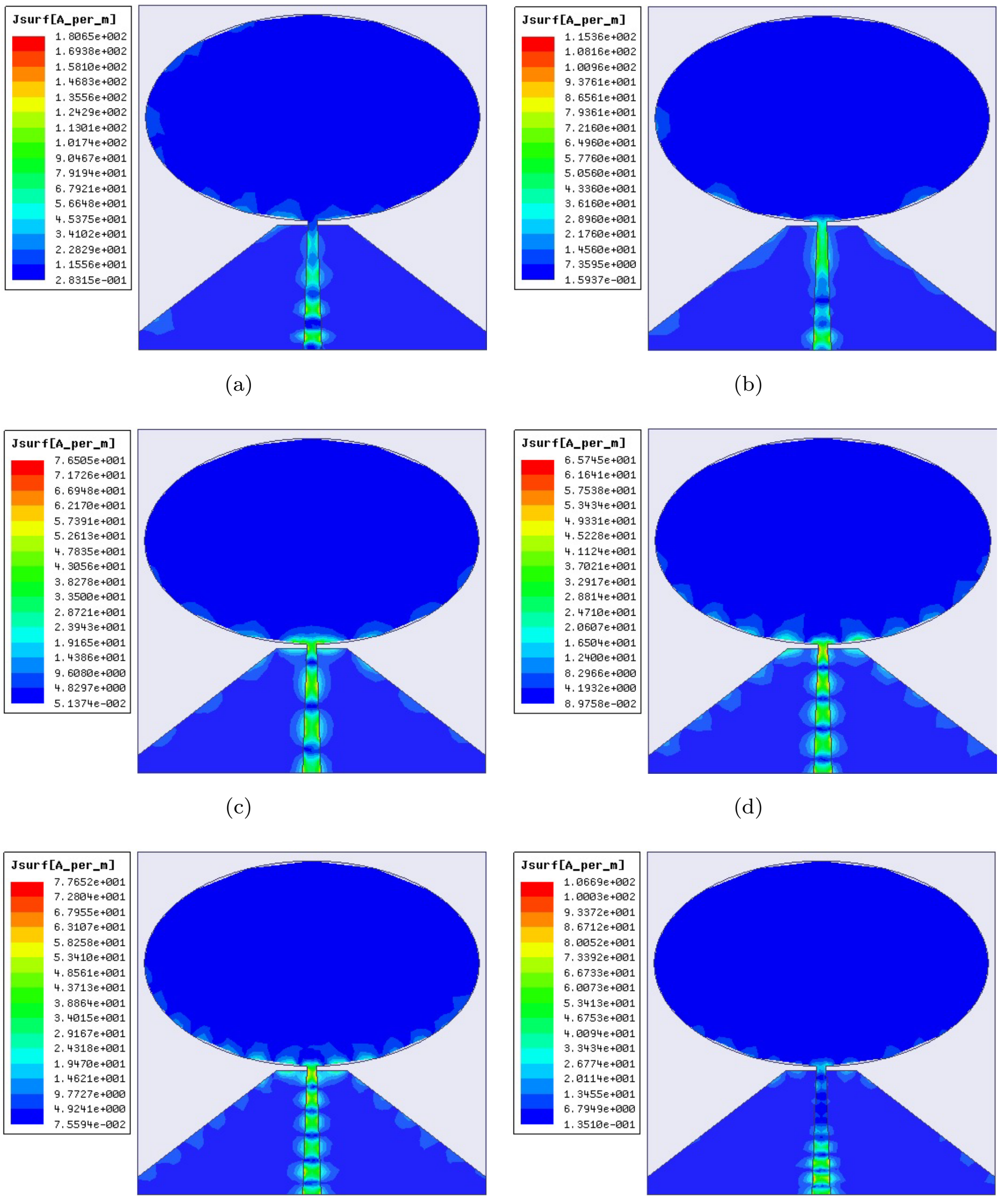


FIGURE 4.10: Simulated peak gain of the proposed SWB planar elliptical monopole antenna.



(f)

FIGURE 4.11: Simulated surface current density at (a) 1.5 GHz, (b) 5 GHz, (c) 10.5 GHz, (d) 15 GHz, (e) 19 GHz, and (f) 23 GHz.

4.4 Summary

A planar elliptical monopole antenna with tapered microstrip feed line and trapezoid ground plane is designed for super-wideband applications. The simulated as well as measured results demonstrate that the proposed antenna design is suitable for many existing as well as future wireless communication systems. The simulation shows a ratio bandwidth of 62.5:1, which is achieved from 0.4-25 GHz, while the measured ratio bandwidth is 28.5:1 in the frequency range of 0.7-20 GHz. The proposed antenna exhibits good radiation characteristics and gain in the entire operating bandwidth. The antenna design is useful for cellular applications, UWB applications, satellite systems, defence systems, etc.

Chapter 5

HEXAGONAL PLANAR MONOPOLE ANTENNA

In this chapter, a hexagonal-shaped PMA has been designed for super-wideband communication applications. By adopting the technique of [38, 39] and by using tapered microstrip feed line, an impedance bandwidth of 197.29% is achieved in the frequency range of 0.17-25 GHz.

5.1 Antenna Design

This section briefly explain the proposed SWB antenna design and procedure used for its construction.

5.1.1 Proposed Design

The proposed antenna is composed of a hexagonal-shaped patch radiator connected with a tapered microstrip feed line that are etched on the top side of the substrate, as illustrated in Figure 5.1. A rectangular ground plane is designed on the back surface of substrate for better impedance matching. In order to match the impedance at lower frequencies and to minimize unwanted radiations generated from feed line, two parasitic elements are designed on the top face of the substrate. The substrate used for design purpose is Roger RT/Duroid 5880 having thickness (h) 1.57mm, the relative permittivity (ϵ_r) 2.2 and loss tangent 0.0009. The impedance of a tapered microstrip feed line is gradually changed from 50Ω to 75Ω at the radiation element. The width of the feed line at the bottom end (W_{bot}) is 3.8mm, corresponds to a characteristic impedance of 50Ω, and the width at the top end (W_{top}) is 1.8mm, corresponds to a characteristic impedance of 75Ω. Also,

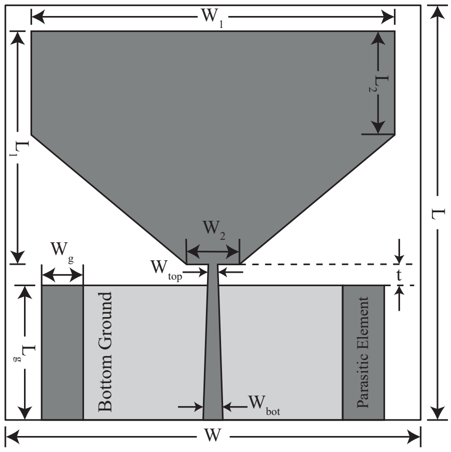


FIGURE 5.1: Design layout of the proposed hexagonal SWB planar monopole antenna.

TABLE 5.1: Dimensions of the proposed hexagonal SWB planar monopole antenna [mm].

L	W	L_1	W_1	L_2	W_2
80	80	45	70	20	10.2
L_g	W_g	W_{bot}	W_{top}	t	–
29	8	3.8	1.8	1	–

the gap t between the hexagonal-shaped patch and the ground plane plays an important role in enhancing the bandwidth. The overall optimized design dimensions are listed in Table 5.1.

5.1.2 Design Steps

The construction of PMA starts with the basic design of planar rectangular monopole antenna (PRMA), named Antenna I, as shown in Figure 5.2(a). The figure shows that a microstrip line connected to a rectangular patch designed on the top face of the substrate and a conventional rectangular ground plane is placed on the bottom side. Initially, the dimensions of the rectangular patch are calculated by using Eqn. (4.1). The operating frequency used for the calculation of design parameters is 900MHz. For rectangular patch, the values of L are r are calculated by using the equation as follows [37]:

$$L = W,\ r = \frac{L}{2\pi} \qquad Eq\ (5.1)$$

where L and W are the length and width of the rectangular patch. The dimensions of the microstrip line are calculated by using the standard feedline equation as given in Eqn. (4.3). After that, the conventional PRMA is simulated in HFSS and the respective VSWR result is depicted in Figure 5.3. It is noted that Antenna I provides an oscillatory response in the band of interest. To remove these oscillations, a modification is introduced in the rectangular patch by changing its shape to a hexagonal patch, as shown in Figure 5.2(b), which results in a smooth transition from one resonant mode to another. This modification is named as Antenna II and the VSWR result is presented in Figure 5.3. It is observed that according to VSWR < 2 criterion, Antenna II operates in the frequency range of 2.73-20.2 GHz.

In order to increase the impedance bandwidth, a microstrip line is replaced with tapered microstrip line, as shown in Figure 5.2(c). The change in feed line structure decreases the lower frequency limit from 2.73 GHz to 1.12 GHz and increases the upper frequency range limit from 20.2 to 21.75 GHz. Through this modification, a band-notched response is noted in the frequency range of 21.75-22.41 GHz. For further improvement at lower frequency limit and to remove notch-band, two parasitic elements are designed on the top of substrate [38, 39], as shown in Figure 5.2(d). Usually, a parasitic element behaves like a passive resonator which resonates at slightly lower frequency than the main radiator. Furthermore, the parasitic elements are behaving like a ground plane that minimize radiations generated from feed line. From figure 5.3, it is observed that by using parasitic elements, the lower frequency limit decreases from 1.12 GHz to 170 MHz and also the notch-band response is removed. The final simulated design offers good impedance matching in the frequency range of 0.17-25 GHz.

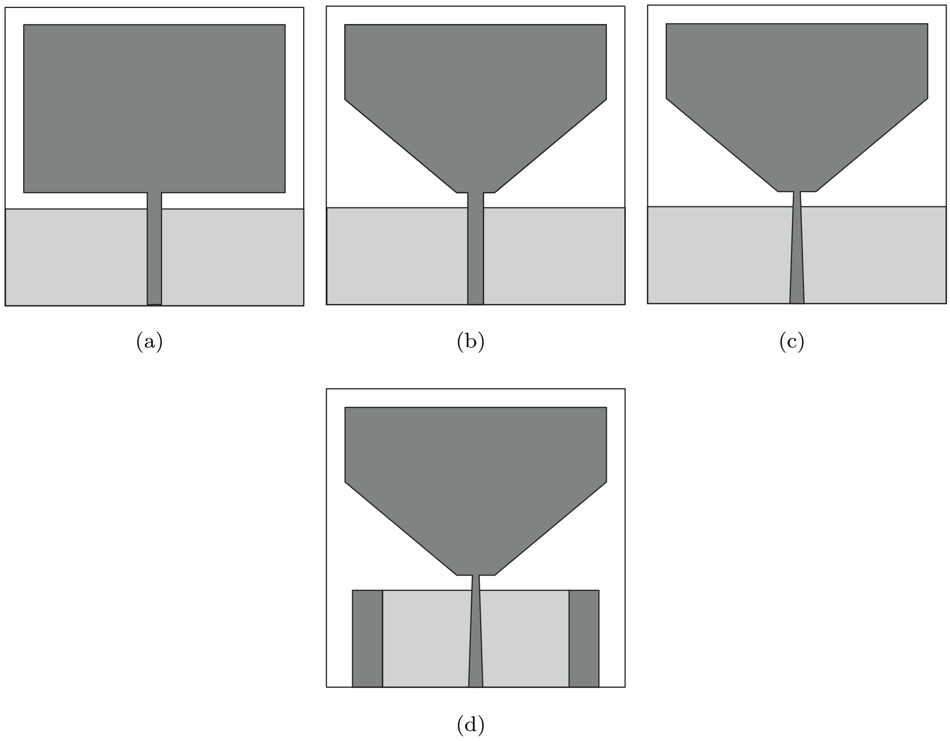


FIGURE 5.2: Design steps of hexagonal PMA (a) Antenna I (b) Antenna II (c) Antenna III (c) Antenna IV.

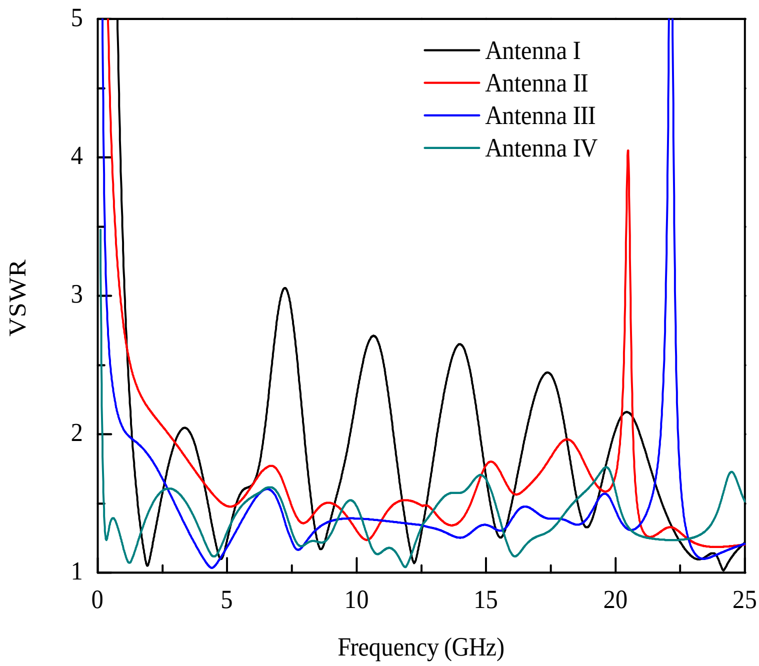


FIGURE 5.3: Variation of VSWR for different antenna designs.

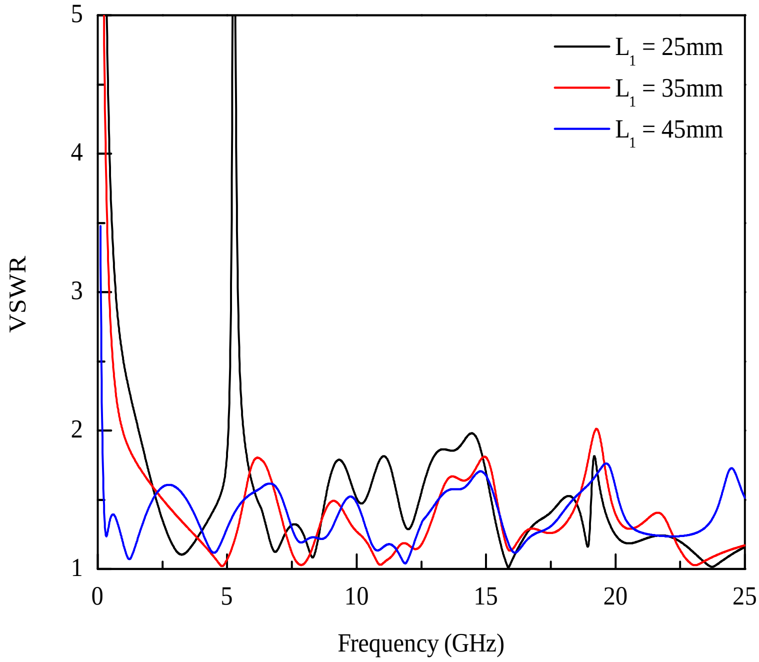
5.2 Parametric Study

A parametric analysis is performed to get optimized parameters. Figure 5.4 shows the change in VSWR by changing the length and width of hexagonal patch. It is observed from Figure 5.4(a) that the lower frequency limit decreases from 1.58 GHz to 170 MHz when the patch length L_1 is increased from 25 to 45mm. Furthermore, when patch width W_1 is increased from 30 to 70mm, the lower frequency limit is reduced from 1.29 GHz to 170 MHz, as shown in Figure 5.4(b). From this analysis, it is also observed that the lowest width value (30mm) offers high reflections for lower and higher frequencies. So, by observing the impedance bandwidth and overall size of the PMA, the values of L_1 and W_1 are fixed at 45mm and 70mm, respectively.

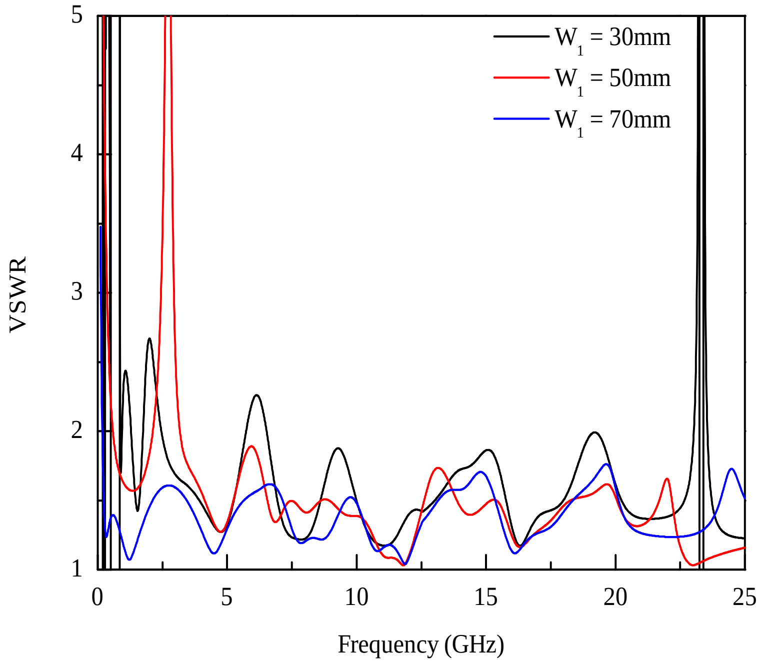
The gap between the radiation element and the ground plane also plays an important role in impedance matching. The effect of design parameter t on impedance matching is depicted in Figure 5.5. When the value of t is set to the minimum available limit, the lowest frequency limit is increased to 3GHz. However, when t is increased to 2mm, an impedance mismatch is observed at higher frequencies. So, a gap of about 1mm provides maximum impedance matching in the desired band.

5.3 Results and Discussion

The proposed super-wideband PHMA is simulated using HFSS and the results are verified using CST Microwave Studio. It is observed from Figure 5.6 that the VSWR results extracted from both softwares are well in agreement. The simulated 2:1 VSWR bandwidth covers frequency range from 170 MHz to 25 GHz with a ratio bandwidth of 147:1. After the verification of the results, the proposed PHMA is fabricated by using micro-milling machine and the VSWR measurement is carried out using Agilent Technologies N5232A vector network analyzer in the frequency



(a)



(b)

FIGURE 5.4: Effect of hexagonal patch dimensions on VSWR. (a) Length L_1. (b) Width W_1

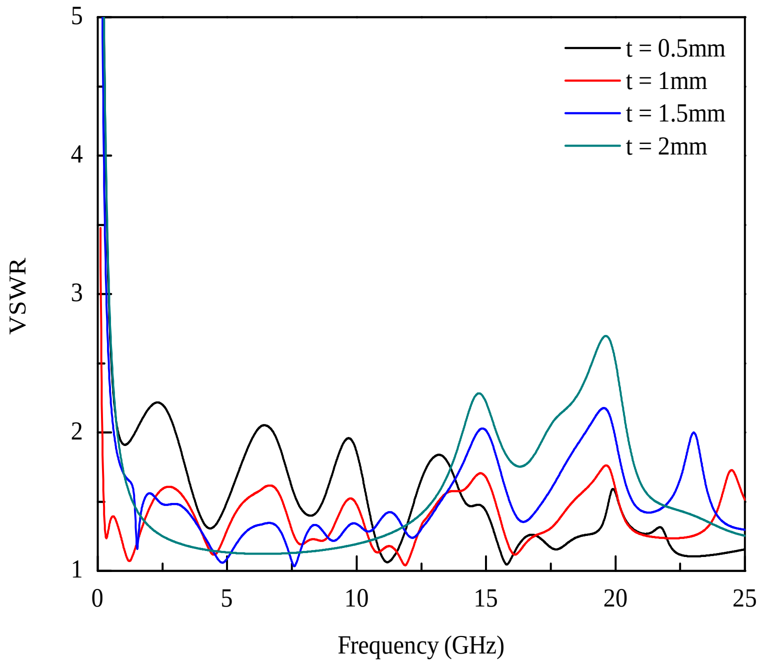


FIGURE 5.5: Effect of gap t on VSWR.

range of 0.1-20 GHz. A prototype of the proposed PMA is depicted in Figure 5.7 and the comparison between simulated and measured results is shown in Figure 5.6. A good agreement is observed between simulated and measured VSWR results. The measured ratio bandwidth in the frequency range of 0.3-20 GHz is 66.6:1. The deficiency between the results is due to the imperfect soldering of SMA connector and fabrication tolerances.

The simulated E-plane ($\phi = 0^0$) and H-plane ($\phi = 90^0$) radiation patterns are demonstrated in Figure 5.8. For the first resonant frequency, shown in Figure 5.8(a), the antenna exhibits bi-directional pattern for E-plane and omni-directional characteristics for H-plane. For resonant frequencies 4.5 GHz and 7.85 GHz, directional radiation properties are observed for E-plane while omni-directional patterns are observed for H-plane, as shown in Figure 5.8(b, c). For fourth resonant frequency, depicted in Figure 5.8(d), antenna offers bi-directional radiation pattern for E-plane and directional pattern for H-plane. For the frequencies greater than

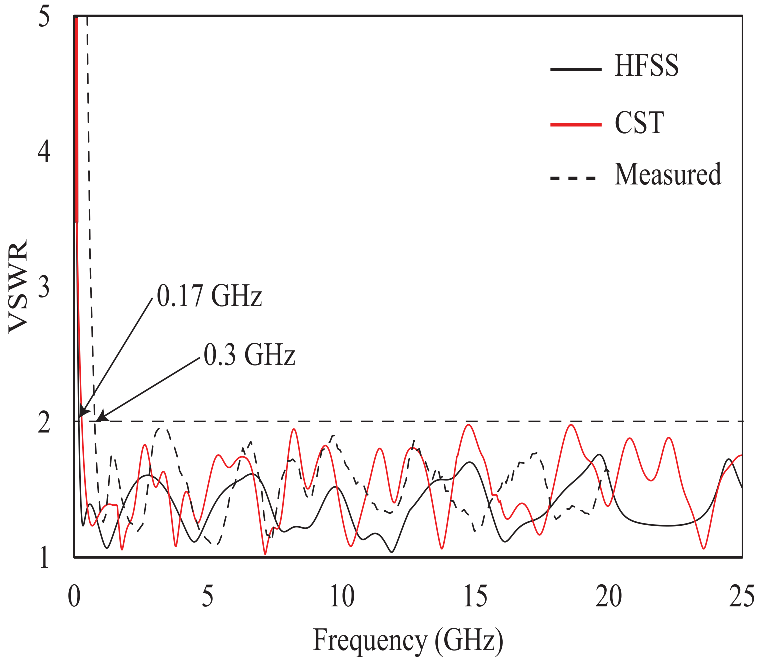


FIGURE 5.6: Comparison between simulated and measured VSWR of the proposed hexagonal SWB planar monopole antenna.

FIGURE 5.7: Prototype of the proposed hexagonal SWB planar elliptical monopole antenna.

12 GHz, given in Figure 5.8(e, f), ripples are observed since the antenna operates in higher order modes. Figure 5.9 presents the effect of input impedance over frequency in terms of its real and imaginary parts. It is observed that the real part is oscillating around 50Ω while the imaginary part fluctuates around 0Ω. This provides an overview that the average input impedance of the antenna is approximately 50Ω. The simulated peak gain of the proposed PHMA is given in Figure 4.10. It is observed that the antenna gives average stable gain of 7 dBi in the frequency range of 7-18 GHz. The minimum gain observed is 0.85 dBi at 2.93 GHz and the maximum gain is 16.14 dBi at 24.42 GHz. This effect occurs because at higher frequencies, the electrical dimensions of radiation element are larger than the wavelength. The simulated current density along the surface of the proposed PHMA is depicted in Figure 5.11. For the first two resonances, shown in Figure 5.11(a, b), it is observed that the surface current density is high on the feed line. For the next two resonant frequencies, illustrated in Figure 5.11(c, d), a high current concentration is noted on the feed line and lower part of the radiator. For 16 GHz, the current density is distributed along the feed line, lower portion of the radiator and upper part of the ground plane as shown in Figure 5.11(e). For the last resonance, shown in Figure 5.11(f), a dense current is distributed on the upper portion of the feed line.

5.4 Comparative Analysis

A comparison between previously presented and proposed SWB antennas is done in terms of electrical dimensions, ratio bandwidth, and Bandwidth Dimension Ratio (BDR). The term BDR allows antenna designers to distinguish the size and bandwidth characteristics of their designs with other structures. BDR is defined as:

$$BDR = \frac{Bandwidth\%}{\lambda_{length} \times \lambda_{width}} \qquad Eq\ (5.2)$$

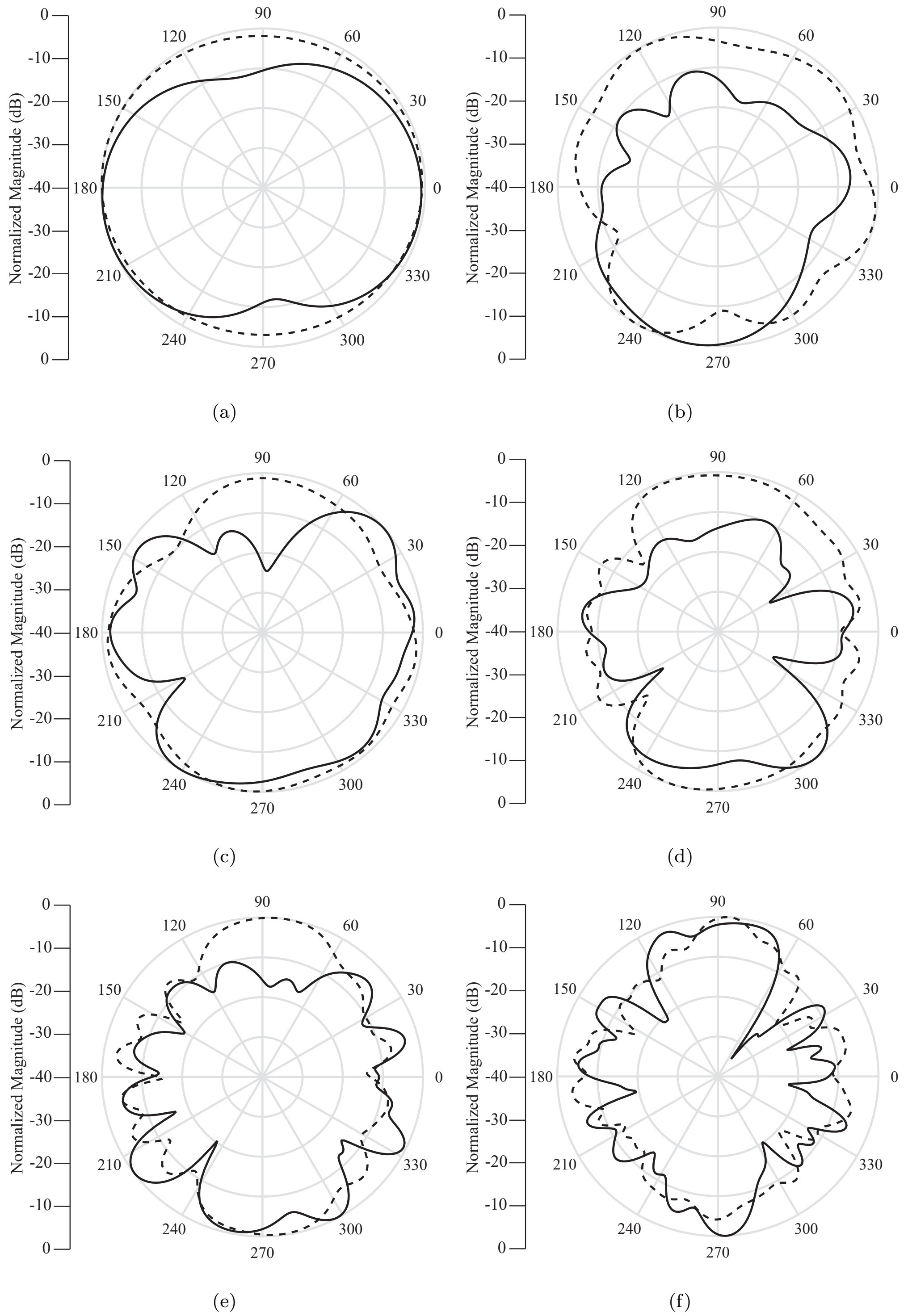


Figure 5.8: Simulated radiation patterns at (a) 1.2 GHz, (b) 4.5 GHz, (c) 7.85 GHz, (d) 12 GHz, (e) 16 GHz, and (f) 22.25 GHz (Solid line: E-plane, Dashed line: H-plane).

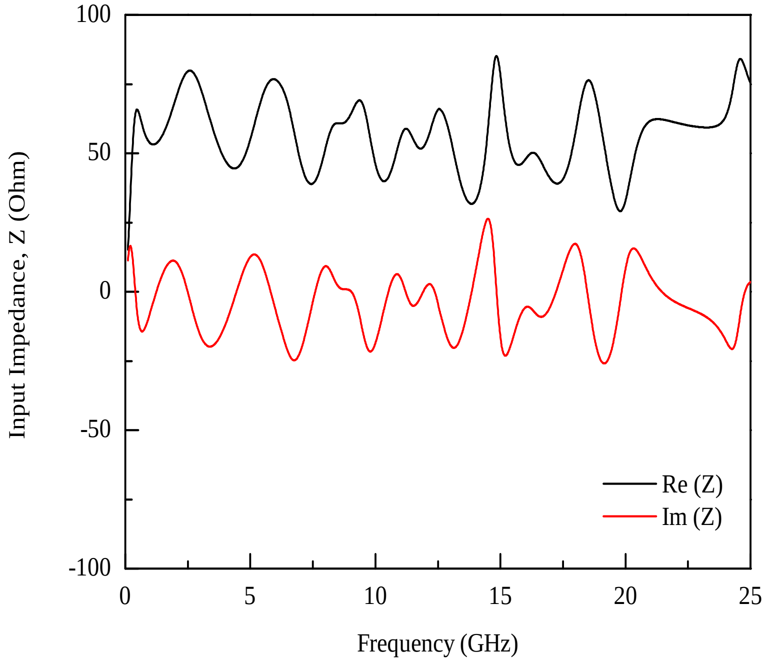


FIGURE 5.9: Simulated input impedance of the proposed hexagonal SWB planar monopole antenna.

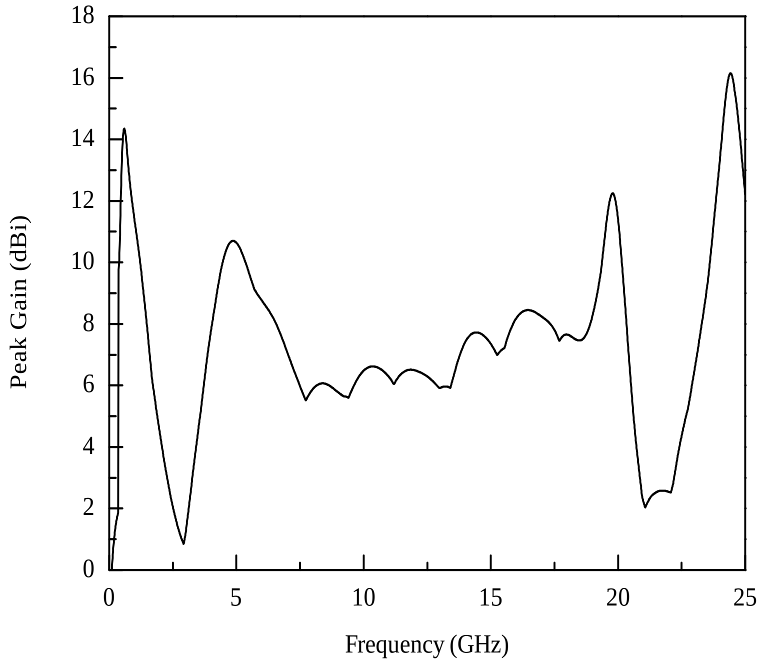


FIGURE 5.10: Simulated peak gain of the proposed hexagonal SWB planar monopole antenna.

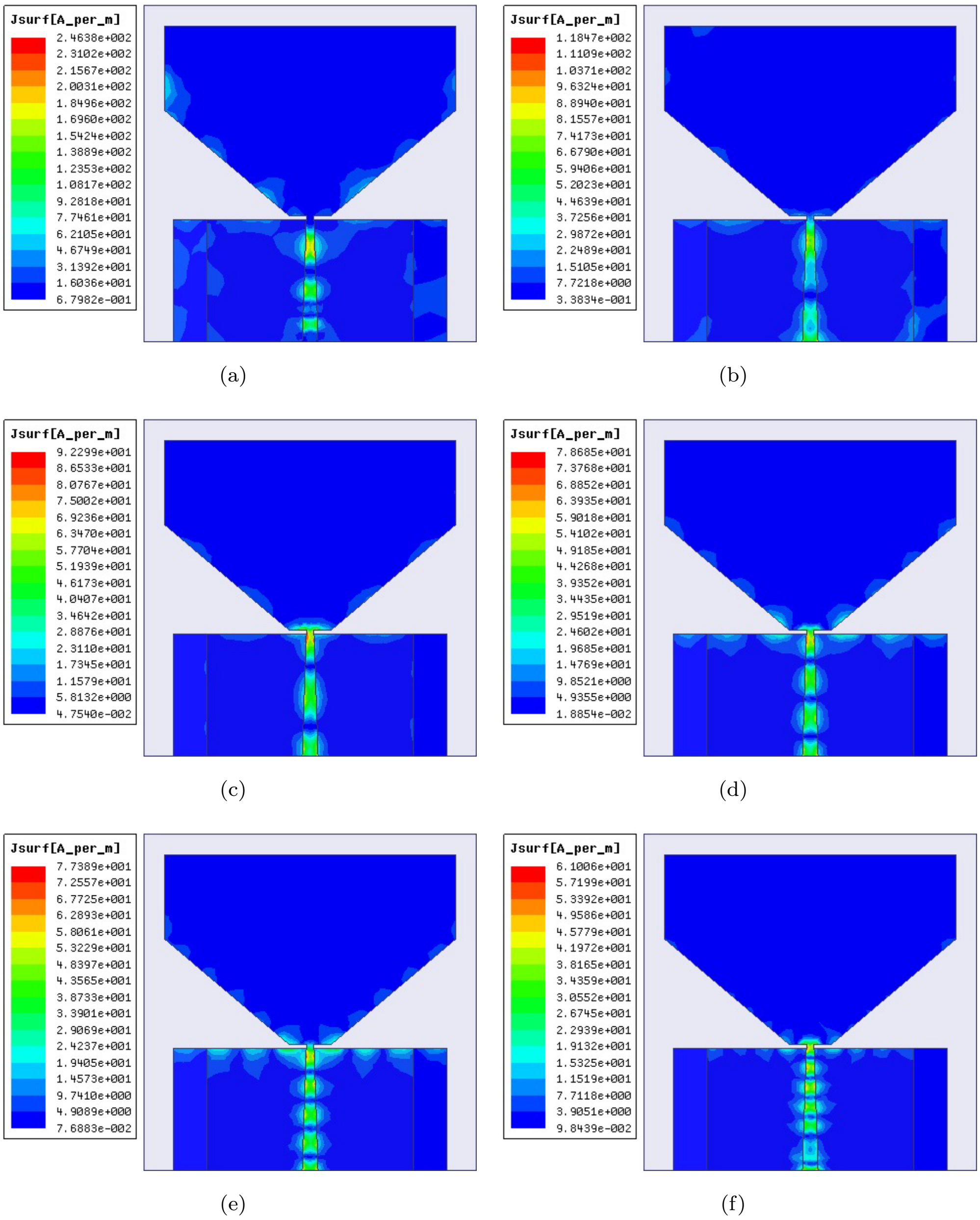


FIGURE 5.11: Simulated surface current density at (a) 1.2 GHz, (b) 4.5 GHz, (c) 7.85 GHz, (d) 12 GHz, (e) 16 GHz, and (f) 22.25 GHz.

where, λ is the wavelength at lower resonant frequency. The comparative analysis between the proposed SWB antennas and other SWB antenna designs are presented in Table 5.2. It is observed that the proposed antennas offer good properties with small size than the antennas presented in [23, 32, 33, 40], and their performance is better than the antennas of [25, 34, 36, 41, 42]. Also, the designed antennas offer a BDR of 3227 and 3286.

TABLE 5.2: Comparison of proposed antenna with other SWB antennas.

S. No.	Antenna Type	Bandwidth (%)	Ratio BW	Dimensions (mm^2)	BDR	f_{low} (GHz)
1.	[23]	183.75	23.6 : 1	124 × 110	1012	1.02
2.	[25]	168.4	11.6 : 1	38 × 55	–	3
3.	[32]	184.83	25 : 1	124 × 120	950.77	1.08
4.	[33]	188.8	34.7 : 1	150 × 150	1083	0.72
5.	[34]	175.5	15.3 : 1	42 × 52.25	–	1.3
6.	[36]	187.5	31 : 1	67 × 80	–	1.05
7.	[40]	185	25 : 1	150 × 150	1682	0.64
8.	[41]	172	13.06 : 1	35 × 77	2735	1.44
9.	[42]	164	10 : 1	18.5 × 22	2541	3.8
10.	Design-I	193.7	62.5 : 1	$0.107\lambda \times 0.107\lambda$	3227	0.4
11.	Design-II	197.2	147 : 1	$0.107\lambda \times 0.107\lambda$	3286	0.17

5.5 Summary

A super-wideband hexagonal-shaped planar monopole antenna has been designed for super-wideband communication applications. The proposed PHMA design configuration gives enhanced bandwidth than other reported designs. The simulated VSWR shows that the proposed design offers a ratio bandwidth of 125:1 from 0.17 to 25 GHz, while measured result demonstrates a ratio bandwidth of 66.6:1 in the range of 0.3-20 GHz. The proposed antenna exhibits good radiation properties and provides good gain in the entire operating bandwidth. It is also observed that the proposed PHMA design is suitable for VHF/UHF bands, cellular communication bands, WLAN/Wi-Fi, radar communication, satellite communication, etc.

Chapter 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

The SWB technology is the most promising solution for many existing as well as future wireless communication systems, such as WPAN, because of its strength to achieve high transmission data rate. As the only non-digital part of SWB system, antenna is still a challenging part because the requirements of SWB antenna are strict as compared to a narrow band antenna. Therefore, in this work, SWB antennas are presented for UWB system as well as for existing and future communication applications.

In the first part of this thesis, an elliptical PMA is designed and fabricated for super-wideband communication. A step-by-step description is provided that how the proposed design is constructed. So, the final antenna design consists of an elliptical patch radiator which is fed using a tapered microstrip fed line and a modified trapezoid ground plane. The proposed PEMA design is simple and smaller than previously reported designs. From simulations, it is observed that according to VSWR $\leq$ 2, the proposed antenna has a ratio bandwidth of 62.5:1. Also, the proposed design offers good radiation characteristics and provide good gain in the entire operating bandwidth. For the validation of simulated results, the proposed PEMA is fabricated and measured. It is observed that the measured results are well in agreement with the simulated data.

In the second part, a hexagonal-shaped PMA is designed and fabricated for super-wideband applications. A design procedure is discussed that is used for the development of proposed PMA. The final proposed design consists of an hexagonal patch radiator which is fed using a tapered microstrip fed line and a conventional rectangular ground plane. Two parasitic elements are designed on top side of the substrate to minimize undesired radiations from the feed line. From simulations, it is observed that according to VSWR $\leq$ 2, the proposed antenna has a ratio bandwidth of 147:1. Also, the proposed design exhibits good radiation properties and gain in the entire operating bandwidth. The proposed design is fabricated and measured for the validation of simulation results. It is observed that the measured VSWR is laying in the frequency range of 0.2-25 GHz with a ratio bandwidth of 125:1.

6.2 Future Work

Based on the conclusion drawn above and the limitations of the presented work, future work can be carried out in the following areas:

Firstly, it is noted that the proposed designs exhibit distorted radiation characteristics at higher frequencies, which can lead to improper transmission and reception of signals. So, a solution can be proposed to overcome this problem.

Secondly, for mobile and portable devices, the antenna size should be small especially for WPAN applications. Therefore, future research should focus on further reducing the size of antennas by finding out new methods.

Thirdly, the measurements of the proposed antenna are done in an indoor environment. However, in future, antennas might be embedded in hand-held communication devices. So, it is necessary to investigate the device's effect on antenna performance.

Lastly, MIMO and massive MIMO communication systems has gained a lot of attention by many researchers and it is the most promising technology which is able to provide enhanced channel capacity and high data rate. Therefore, an array of SWB antennas with reduced mutual coupling can be developed for these systems.

REFERENCES

[1] C. A. Balanis, *Antenna theory: analysis and design.* John Wiley & Sons, 2016.

[2] L. W. Fullerton, "Time domain radio transmission system," Dec. 18 1990, US Patent 4,979,186.

[3] V. H. Rumsey, "Frequency independent antennas," in *1958 IRE International Convention Record*, vol. 5, 1966, pp. 114–118.

[4] FCC, "Revision of part 15 of the commission's rules regarding ultra-wideband transmission systems, First note and order," 2002.

[5] O. J. Lodge, "Electric telegraphy," May 21, 1901, US Patent 674, 846.

[6] P. S. Carter, "Wide band, short wave antenna and transmission line system," December 5, 1939, US Patent 2, 181, 870.

[7] S. A. Schelkunoff, "Ultra short wave radio system," March 18, 1941, US Patent 2, 235, 506.

[8] S. Schelkunoff, *Advanced Antenna Theory.* New York: John Wiley and Sons, Ltd, 1952.

[9] L. N. Brillouin, "Broad band antenna," November 30, 1948, US Patent 2, 454, 766.

[10] P. S. Carter, "Short wave antenna," October 10, 1939, US Patent 2, 175, 252.

[11] N. E. Lindenblad, "Wide band antenna," April 29, 1941, US Patent 2, 239, 724.

[12] A. P. King, "Transmission, radiation, and reception of electromagnetic waves," May 26, 1942, US Patent 2, 283, 935.

[13] M. Katzin, “Electromagnetic horn radiator,” April 9, 1946, US Patent 2, 398, 095.

[14] G. Dubost, M. Nicolas, and H. Havot, “Theory and applications of broadband microstrip antennas,” in *6th European Microwave Conference*. IEEE, 1976, pp. 275–279.

[15] P. Anob, K. Ray, and G. Kumar, “Wideband orthogonal square monopole antennas with semi-circular base,” in *Antennas and Propagation Society International Symposium*, vol. 3, 2001, pp. 294–297.

[16] M. Ammann and Z. N. Chen, “A wide-band shorted planar monopole with bevel,” *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 4, pp. 901–903, 2003.

[17] K.-L. Wong, C.-H. Wu, and S.-W. Su, “Ultrawide-band square planar metal-plate monopole antenna with a trident-shaped feeding strip,” *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 4, pp. 1262–1269, 2005.

[18] N. P. Agrawall, G. Kumar, and K. Ray, “Wide-band planar monopole antennas,” *IEEE Transactions on Antennas and Propagation*, vol. 46, no. 2, pp. 294–295, 1998.

[19] J. Evans and M. Amunann, “Planar trapezoidal and pentagonal monopoles with impedance bandwidths in excess of 10:1,” in *Antennas and Propagation Society International Symposium*, vol. 3, 1999, pp. 1558–1561.

[20] S.-Y. Suh, W. L. Stutzman, and W. A. Davis, “A new ultrawideband printed monopole antenna: The planar inverted cone antenna (PICA),” *IEEE Transactions on Antennas and Propagation*, vol. 52, no. 5, pp. 1361–1364, 2004.

[21] X.-R. Yan, S.-S. Zhong, and X.-X. Yang, “Compact printed monopole antenna with super-wideband,” in *International Symposium on Microwave, Antenna,*

Propagation and EMC Technologies for Wireless Communications, 2007, pp. 605–607.

[22] X.-R. Yan, S.-S. Zhong, and X.-L. Liang, "Compact printed semi-elliptical monopole antenna for super-wideband applications," *Microwave and Optical Technology Letters*, vol. 49, no. 9, pp. 2061–2063, 2007.

[23] J. Liu, S. Zhong, and K. P. Esselle, "A printed elliptical monopole antenna with modified feeding structure for bandwidth enhancement," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 2, pp. 667–670, 2011.

[24] M. Akbari, M. Koohestani, C. Ghobadi, and J. Nourinia, "Compact CPW-FED printed monopole antenna with super-wideband performance," *Microwave and Optical Technology Letters*, vol. 53, no. 7, pp. 1481–1483, 2011.

[25] A. Gorai, A. Karmakar, M. Pal, and R. Ghatak, "A CPW-fed propeller shaped monopole antenna with super wideband characteristics," *Progress In Electromagnetics Research C*, vol. 45, pp. 125–135, 2013.

[26] A. Siahcheshm, J. Nourinia, Y. Zehforoosh, and B. Mohammadi, "A compact modified triangular CPW-fed antenna with multioctave bandwidth," *Microwave and Optical Technology Letters*, vol. 57, no. 1, pp. 69–72, 2015.

[27] H.-Y. Xu, H. Zhang, K. Lu, and X.-f. Zeng, "A holly-leaf-shaped monopole antenna with low RCS for UWB application," *Progress In Electromagnetics Research*, vol. 117, pp. 35–50, 2011.

[28] S. K. Palaniswamy, M. Kanagasabai, S. A. Kumar, M. G. N. Alsath, S. Velan, and J. K. Pakkathillam, "Super wideband printed monopole antenna for ultra wideband applications," *International Journal of Microwave and Wireless Technologies*, pp. 1–9, 2015.

[29] H. M. Bernety, B. Zakeri, and R. Gholami, "A compact directional super-wideband antenna," in *2013 21st Iranian Conference on Electrical Engineering (ICEE)*, 2013, pp. 1–4.

[30] F. A. Tahir and A. H. Naqvi, "A compact hut-shaped printed antenna for super-wideband applications," *Microwave and Optical Technology Letters*, vol. 57, no. 11, pp. 2645–2649, 2015.

[31] Z.-J. Tang, X.-F. Wu, and J. Zhan, "Novel compact band-notched UWB antenna using convex-shaped slot patch," *Microwave and Optical Technology Letters*, vol. 57, no. 1, pp. 201–203, 2015.

[32] J. Liu, K. P. Esselle, S. G. Hay, and S. Zhong, "Achieving ratio bandwidth of 25:1 from a printed antenna using a tapered semi-ring feed," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 1333–1336, 2011.

[33] J. Liu, K. P. Esselle, S. G. Hay, and S.-S. Zhong, "Study of an extremely wideband monopole antenna with triple band-notched charactersistics," *Progress In Electromagnetics Research*, vol. 123, pp. 143–158, 2012.

[34] M. Samsuzzaman and M. T. Islam, "A semicircular shaped super wideband patch antenna with high bandwidth dimension ratio," *Microwave and Optical Technology Letters*, vol. 57, no. 2, pp. 445–452, 2015.

[35] J. Lao, R. Jin, and J. Geng, "A rotated elliptical slot antenna with ultra-wide bandwidth," *Microwave and Optical Technology Letters*, vol. 55, no. 2, pp. 308–310, 2013.

[36] J. Liu, K. Esselle, S. Hay, and S. Zhong, "Compact super-wideband asymmetric monopole antenna with dual-branch feed for bandwidth enhancement," *Electronics Letters*, vol. 49, no. 8, pp. 515–516, 2013.

[37] K. Ray, "Design aspects of printed monopole antennas for ultra-wide band applications," *International Journal of Antennas and Propagation*, vol. 2008, 2008.

[38] K. Ray and Y. Ranga, "Ultra-wideband printed modified triangular monopole antenna," *Electronics Letters*, vol. 42, no. 19, p. 1, 2006.

[39] ——, "Ultrawideband printed elliptical monopole antennas," *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 4, pp. 1189–1192, 2007.

[40] Y. Dong, W. Hong, L. Liu, Y. Zhang, and Z. Kuai, "Performance analysis of a printed super-wideband antenna," *Microwave and Optical Technology Letters*, vol. 51, no. 4, pp. 949–956, 2009.

[41] K.-R. Chen, J.-S. Row *et al.*, "A compact monopole antenna for super wideband applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 488–491, 2011.

[42] S. Singhal and A. K. Singh, "CPW-fed phi-shaped monopole antenna for super-wideband applications," *Progress In Electromagnetics Research C*, vol. 64, pp. 105–116, 2016.

LIST OF PUBLICATIONS

1. **U. Rafique**, G. I. Kiani, M. M. Ahmed and S. Habib, "Frequency selective surface absorber for WLAN security," *Proceedings of the* 5^{th} *European Conference on Antennas and Propagation (EuCAP 2011)*, pp. 872-875, 2011.

2. **U. Rafique**, M. M. Ahmed, M. A. Haq and M. T. Rana, "Transmission of RF signals through energy efficient window using FSS," *Proceedings of the* 7^{th} *IEEE International Conference on Emerging Technologies (ICET 2011)*, pp. 1-4, 2011.

3. W. Afzal, **U. Rafique**, M. M. Ahmed, M. A. Khan and F. A. Mughal, "A tri-band H-shape microstrip patch antenna for DCS and WLAN applications," *Proceedings of the* 19^{th} *International Conference on Microwave, Radar and Wireless Communications (MIKON 2012)*, pp. 256-258, 2012.

4. **U. Rafique**, S. A. Ali, M. A. Khan and M. M. Ahmed, "A wideband slot-coupled inverted microstrip patch antenna for wireless communications," *Proceedings of the 2012 International Conference on Emerging Technologies (ICET 2012)*, pp. 1-4, 2012.

5. F. A. Mughal, M. M. Ahmed, K. Hayat, **U. Rafique** and Q. D. Memon, "A wideband power divider for microwave applications," *Proceedings of the* 9^{th} *IEEE International Conference on Emerging Technologies (ICET 2013)*, pp. 1-4, 2013.

6. F. A. Mughal, M. M. Ahmed and **U. Rafique**, "An efficient power divider for dual-band microwave applications," *Proceedings of the 2013* 11^{th} *IEEE International Conference on Frontiers of Information Technology (FIT 2013)*, pp. 42-44, 2013.

7. Q. D. Memon, M. M. Ahmed, N. M. Memon and **U. Rafique**, "An efficient mechanism to simulate DC characteristics of GaAs MESFETs using swarm optimization," *Proceedings of the* 9^{th} *IEEE International Conference on Emerging Technologies (ICET 2013)*, pp. 1-5, 2013.

8. M. A. Bashir, M. M. Ahmed, **U. Rafique** and Q. D. Memon, "Design of a Ku-band high gain low noise amplifier," *Proceedings of the 2013 IEEE International RF and Microwave Conference (RFM 2013)*, pp. 168-171, 2013.

9. **U. Rafique**, S. A. Ali and G. Shabbir, "Ultra-wideband patch antenna for microwave communications," *Proceedings of the* 17^{th} *International Multi Topic Conference (INMIC 2014)*, pp. 10-13, 2014.

10. M. Muzammel, G. Shabbir and **U. Rafique**, "Energy efficient approach for clustering algorithm in wireless sensor networks," *Proceedings of the* 17^{th} *International Multi Topic Conference (INMIC 2014)*, pp. 46-51, 2014.

11. **U. Rafique** and M. A. Khan, "MIMO microstrip patch antennas for high connectivity with reduced mutual coupling," *Proceedings of the 2016 Advances in Wireless and Optical Communications (RTUWO 2016)*, pp. 120-124, 2016.

12. A. M. Khan, M. M. Ahmed, M. Rafiq and **U. Rafique**, "Breakdown in a high power microwave antenna," *Proceedings of* 12^{th} *IEEE International Conference on Emerging Technologies (ICET 2016)*, pp. 1-5, 2016.

13. A. M. Khan, M. M. Ahmed, M. Rafiq and **U. Rafique**, "Design of an efficient high power microwave antenna," *Proceedings of* 19^{th} *International Multi Topic Conference (INMIC 2016)*, pp. 1-6, 2016.

14. S. S. Saleem, M. M. Ahmed, **U. Rafique** and U. F. Ahmed, "Optimization of linear antenna array for low SLL and high directivity," *Proceedings of* 19th *International Multi Topic Conference (INMIC 2016)*, pp. 1-6, 2016.

15. A. M. Khan, M. M. Ahmed and **U. Rafique**, "Fast and efficient techniques for high current interruption using electrical exploding fuses," *Accepted in 2017 IEEE Pulsed Power Conference.*

16. **U. Rafique**, S. A. Ali, M. T. Afzal and M. Abdin, "Bandstop filter design for GSM shielding using frequency selective surfaces," *International Journal of Electrical and Computer Engineering*, vol. 2, no. 6, pp. 846-850, 2012. **(Scopus)**

17. **U. Rafique** and S. A. Ali, "Ultra-wideband patch antenna for K-Band applications," *TELKOMNIKA Indonesian Journal of Electrical Engineering*, vol. 12, no. 12, pp. 8252-8256, 2014. **(Scopus, EI)**

18. J. S. Malik, **U. Rafique**, S. A. Ali and M. A. Khan, "Novel patch antenna for multiband celular, WiMAX and WLAN applications," *Turkish Journal of Electrical Engineering and Computer Sciences* (In Press). **(IF: 0.518)**.