DESIGN AND IMPLEMENTATION OF ULTRA WIDEBAND ANTENNA WITH MULTIPLE NOTCHED BANDS

A Thesis Submitted in Fulfillment of the Requirement for the Award of the Degree of

DOCTOR OF PHILOSOPHY

Submitted by

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September, 2017

CERTIFICATE

I, **Ajeet Pratap Singh,** hereby certify that the work which is being presented in this thesis entitled **"Design and Implementation of Ultra Wideband Antenna with Multiple Notched Bands"** in fulfillment of requirements for the award of degree of the Doctor of Philosophy in Electronics and Communication Engineering from Thapar University, Patiala, Punjab is an authentic record of my own work carried under the supervision of **Dr. Rajesh Khanna** and **Dr. Hardeep Singh.**

The matter presented in this thesis has not been submitted in any other University/Institute for the award of any degree or diploma.

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ABSTRACT

The Federal Communications Commission (FCC) assigned 7.5GHz (3.1-10.6) ultra wideband (UWB) for unlicensed use in February 2002. Characteristics such as wide impedance bandwidth and low power emission limit of -41.3dBm/MHz has generated countless opportunities to design a high data rate UWB communication system. However, over the designed bandwidth of UWB system, there exist narrow band services for other communication systems, such as 3.4-3.69GHz for WiMAX, 5.15-5.35GHz and 5.725-5.825GHz for WLAN, 7.25-7.75GHz for downlink of X-band satellite communication and 8.02-8.4GHz for satellite communication band (ITU) system, which creates interference with the UWB system. Therefore, it is necessary for UWB antenna to perform notched band function in these frequency bands to avoid these interferences.

A novel compact UWB planar antenna is developed from the conventional rectangular monopole antenna. To improve the impedance bandwidth, three bevel slots on the lower portion of the radiator patch and a single bevel slot on the ground plane of the conventional antenna are etched. The antenna so obtained, has a stable radiation pattern over a whole UWB bandwidth.

A compact ultra wideband (UWB) antenna with dual notch band characteristic has been proposed. The antenna has two U- shaped slots on the radiating patch. The proposed antenna can reduce the interference of UWB with WiMAX and WLAN. The proposed antenna has a small size of $26 \times 27 mm^2$ and achieved an operating bandwidth (VSWR<2) from 2.6GHz to 10.8GHz, with one frequency notched band at 3-3.9GHz (WiMAX) and other at 5-5.9GHz (WLAN).

A microstrip feed ultra wideband (UWB) antenna with triple notch band characteristic has been proposed. Three U-shaped structures are etched on the radiating patch. The proposed antenna reduces the interference of UWB with WiMAX, WLAN and ITU. The proposed antenna achieved an operating bandwidth (S_{11}<-10dB) from 2.68GHz to 12GHz, except at notch band 3-3.85GHz , 5-5.9GHz and 8-8.8GHz.

A novel small CPW fed UWB antenna with five notch band characteristic has been presented to suppress the potential interferences in ultra wideband systems. This proposed antenna has a small dimension of $30 \times 32 \times 1.6 mm^3$ over the operating bandwidth (S_{11}<-10dB) from 2.8GHz to 11.6GHz. By introducing five U-shaped slots, five notches are achieved in WiMAX (3.1-4GHz), WLAN (5-5.4GHz and 5.7-5.9GHz), X-band downlink (7.2-7.75GHz), and ITU service band (8-8.4GHz).

These proposed plannar monopole UWB antennas are simulated, fabricated and tested. Measured results shows a good agreement with simulated results. In addition, these presented antennas have stable gain and omnidirectional radiation patterns, which make them suitable for UWB wireless applications.

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Ajeet Pratap Singh

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ABBREVIATIONS

FCC	Federal Communications Commission
IEEE	Institute of Electrical and Electronics Engineers
UWB	Ultra Wideband
WLANs	Wireless Local Area Networks
Wi-MAX	Worldwide Interoperability For Microwave Access
HIPERLAN	High-Performance Radio LAN
UMTS	Universal Mobile and Telecommunication Systems
Wi-Fi	Wireless Fidelity
ISM	Industrial, Scientific and Medical
IMT	International Mobile Telecommunications
ITU	International Telecommunication Unit
WCDMA	Wide Code Division Multiple Access
MSA	Microstrip Patch Antenna
FR4	Flame Resistant 4
PCB	Printed Circuit Board
CPW	Coplanar Waveguide
SMA	Subminiature Version A
EM	Electromagnetic Waves
RF	Radio Frequency
TE	Transverse Electric
TM	Transverse Magnetic
TEM	Transverse Electric Magnetic
VNA	Vector Network Analyzer
VWSR	Voltage Standing Wave Ratio
PSD	Power Spectral Density
EIRP	Equivalent Isotopically Radiated Power
BW	Band Width
GHz	Giga-Hertz
dB	Decibel
dBi	Decibel with Respect to Isotropic
AR	Axial Ratio
2-D	Two Dimensional

3-D	Three Dimensional
MIC	Microwave Integrated Circuits
DGS	Defected Ground Structure
PIFA	Planar Inverted-F Antenna
PICA	Planar Invested Cone Antenna
EBG	Electromagnetic Band Gap
SRR	Split Ring Resonator
CSRR	Complementry Split Ring Resonator
GPS	Global Positioning System

CHAPTER 1
INTRODUCTION

1.1 INTRODUCTION

In the present era, communication of information from one point to another point is one of the major requirements. Mobile, multimedia and computer communications have an increased role to playing our day-to-day lives for providing communication everywhere. The demand for high data rate service puts an open challenge for all system designers, to develop new high data rate communication systems for the future.

Ultra wideband technology is an upcoming technology used in various applications like short-range communication, indoor communication, imaging systems, high accuracy radars and other communication systems. As compared to other usual wireless communication systems, the UWB system operates with an extremely wide bandwidth in RF band and possesses extremely high data rates. Because of its exclusive characteristics and applications, antenna design for UWB has various complex issues like broadband response in terms of impedance, gain and radiation patterns, along with compact size.

Both industry and academic are paying more attention and effort for the development of various commercial UWB systems. The fast development of UWB systems requires new UWB antenna designs for various systems. Recently, various UWB antennas are emerging [1-9], in these, the planar UWB antenna is getting more attention due to simple fabrication, low cost, low complexity, light weight, low power level and high data rate for short distance wireless communication [10,11].

In 2002[1] Federal Communications Commission (FCC) has approved the frequency band from 3.1GHz to 10.6GHz for commercial UWB application. However, over the proposed bandwidth of UWB system, there exist some narrow band services, for example 3.4-3.69GHz for WiMAX, 5.15-5.35GHz and 5.725-5.825GHz for WLAN, 7.25-7.75GHz for the downlink of X-band and 8.02-8.4GHz for satellite communication band (ITU) system, which create interference with the UWB system. Table 1.1 shows different bands of wireless communication. Thus, it is essential for UWB antenna to perform notched band function in these frequency ranges to avoid signal interferences.

Table 1.1 Different types of wireless application and its frequency band

Wireless Applications	Frequency Band (GHz)	Bandwidth (MHz)
UMTS	1.92-2.17	250
ZIGBEE	2.40-2.485	85
Bluetooth	2.40-2.48	80
WLAN IEEE 802.1b/g	2.40-2.484	84
WiMAX	2.50-2.69	190
WLAN IEEE 802.11a	5.15-5.35	200
	5.725-5.825	100
WiMAX IEEE 802.16	3.40-3.69	290
	5.25-5.85	600
HIPERLAN2	5.47-5.725	255
X-Band (Down Link)	7.25-7.75	500
ITU 8GHZ	8.02-8.4	380
UWB	3.1-10.6	7500

1.1.1 UWB Definition and Technology

The most important events that happened during the development of a UWB system are summarized in Table 1.2. However, a lot of work in UWB area was done before 1960 [12-15]. In 1989, the term "Ultra-Wideband" firstly appeared in the publication of the U.S. Department of Defense which referred to UWB systems having a minimum 1.5GHz of total bandwidth, or a -20dB fractional bandwidth exceeding 25% [16]. Fractional bandwidth was defined as BW/F_c, where $BW = F_H - F_L$ indicates -20dB bandwidth and $F_c = (F_H + F_L) / 2$, F_H and F_L are upper and lower -20dB cutoff frequencies, respectively. Similar definition was also adopted by the FCC in the US for systems having a minimum 500 MHz bandwidth, or a -10dB fractional bandwidth exceeding 20% [17]. In 2002, FCC recognized UWB as a wonderful technology for increasing short-range communications and exact location applications, and approved unlicensed low-power UWB transmissions for the commercial spectrum allocations. This FCC ruling is accepted by various countries worldwide, government agencies, industries and institutions, speedy intensifying research works and resources to obtain a host of stimulating UWB applications.

Table 1.2 UWB development timeline

Milestone	Year
Electromagnetic Waves (Heinrich Hertz)	1893
First Wireless Communication (Marconi)	1894 to 1901
Phased Array Radar (Zemov)	1950
Advanced Developments in Time-Domain Electromagnetic (Roos)	1960
Avalanche Transistor & Tunnel Diode Detector Early (Roos)	1970
Short Range Radar Sensor (Roos)	1972
Narrow Baseband Pulse Fixture (Morey)	1970
Advances in Radar Technology (US DOD)	1980 to 1990
Commercial UWB Devices & Systems (US FCC)	1990
IEEE Standards on UWB (US FCC)	2002-till date

Thus, for transmission of data over a huge spectrum with less-power consumption an UWB wireless technology has been used, with a capability to share spectrum with some other communication systems and transmit signals through doors and other obstructions. The basic idea behind this is to generate, transmit and receive very short-duration bursts of RF energy, usually a few tens of picoseconds to a few nanoseconds. Therefore, the most important difference between traditional RF communication and UWB communication is that in RF the traditional carrier-wave modulation is used, whereas in UWB narrow pulses are used for transmission of information. Therefore, in the UWB communication system, the information signal can be modulated by the short pulses.

Figure 1.1 shows the time-domain and frequency-domain characteristic of a narrowband communication system and a UWB communication system. In narrow band communication system, the information signal generally modulates a sine-wave carrier. However, in the frequency domain, power spectral density (PSD) of the spectrum is quite high and the signal occupies a narrow bandwidth (e.g. few MHz). However, in the UWB communication system normally generates very short pulses in order of few nanoseconds, resulting in a very small power spectral density (PSD) and extremely large bandwidth in the frequency domain.

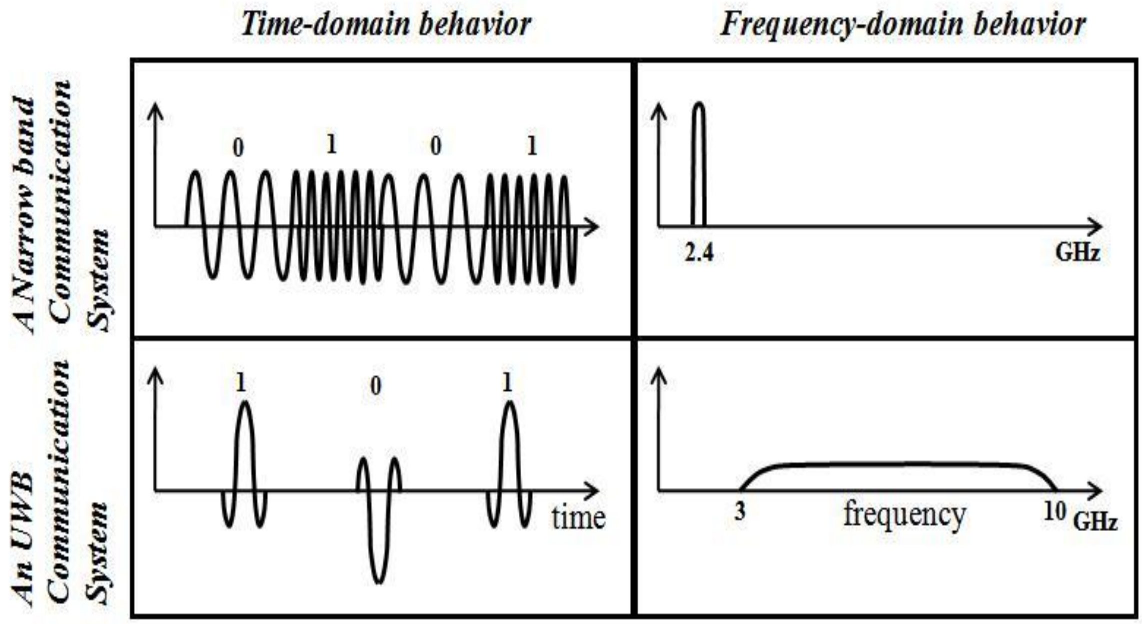
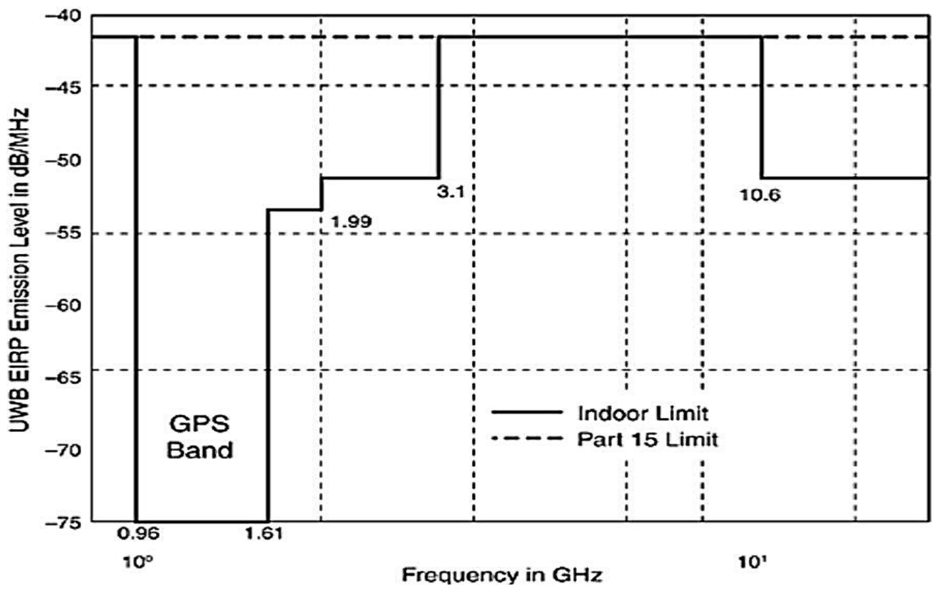
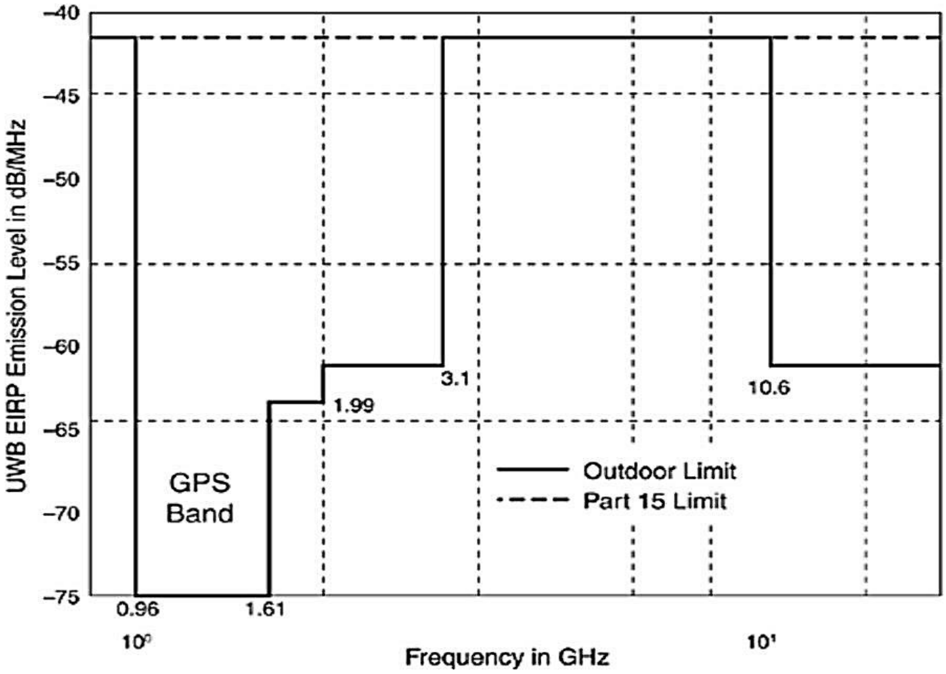


Figure 1.1 Time-domain and frequency-domain behaviour of narrowband communication system and UWB communication system [18]

The spectral masks of the FCC's regulation of UWB system are shown in Figure 1.2 [19]. In February 2002, the FCC approved the UWB spectral mask and maximum power spectral density level of -41.3dBm/MHz of radiation throughout the UWB frequency band and protected existing system with other communication systems [1]. Operation in UWB range wants a lower power level that enables quiet coexistence with narrowband systems. Therefore, various challenges are present in front of the RF antenna designer and system designed to meet these specifications in UWB communication range.



(a) Indoor limits



(b) Outdoor limits

Figure 1.2 UWB spectral masks [19]

1.1.2 UWB Applications

The FCC has summarized the major promising applications of UWB technology to: (i) Imaging systems likes Ground Penetrating Radars (GPRs), medical imaging and surveillance imaging, (ii) Vehicular radar systems and (iii) Communications and measurement systems. Among these promising applications, the global interest is in communication.

Wireless UWB technology gives a solution for large bandwidth, low-power consumption, and high-data-rate transmission of 480 Mbps at 3 meters and 110 Mbps at 10 meters for the next generation of electronic devices consumer [20]. Figure 1.3 shows the application of wireless UWB, related to needs of multimedia customer electronics, PC peripherals, and mobile devices [21]. High data rate wireless UWB system enables wireless home theater center, transfer of data amongst cell phones, transfer of data from digital camcorders, printing of pictures from a camera without PC and other handheld devices such as digital audio and video players [22].

Another application of UWB technology is locating and tracking systems. Figure 1.4 shows one of the most important applications of Geo-location that the system could track and provide precise position of the rescue team to the host in real time [23].

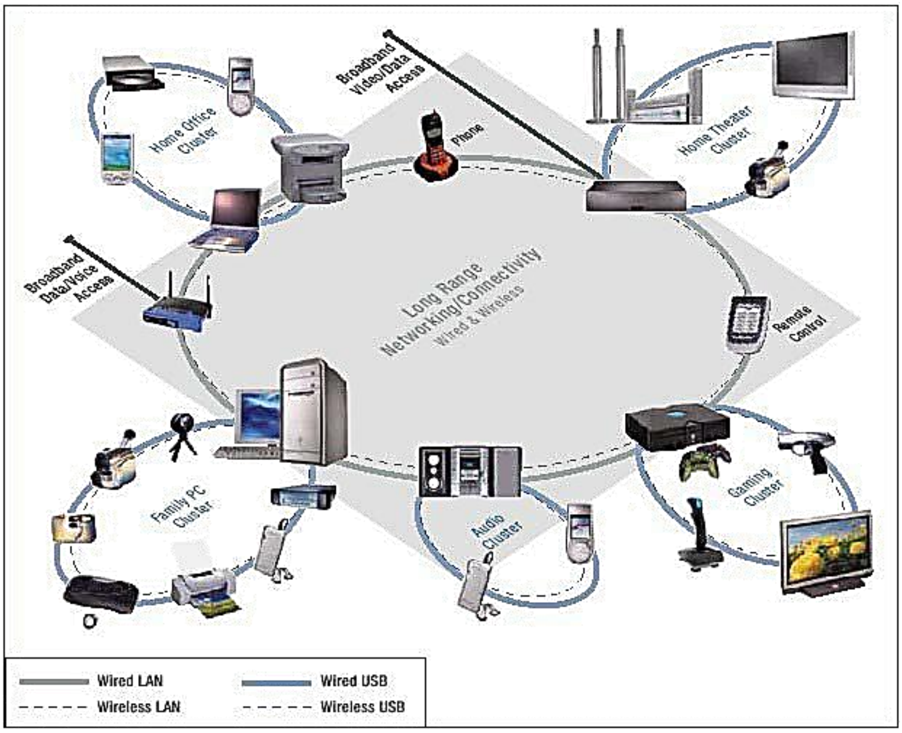


Figure 1.3 Applications of wireless UWB [21]

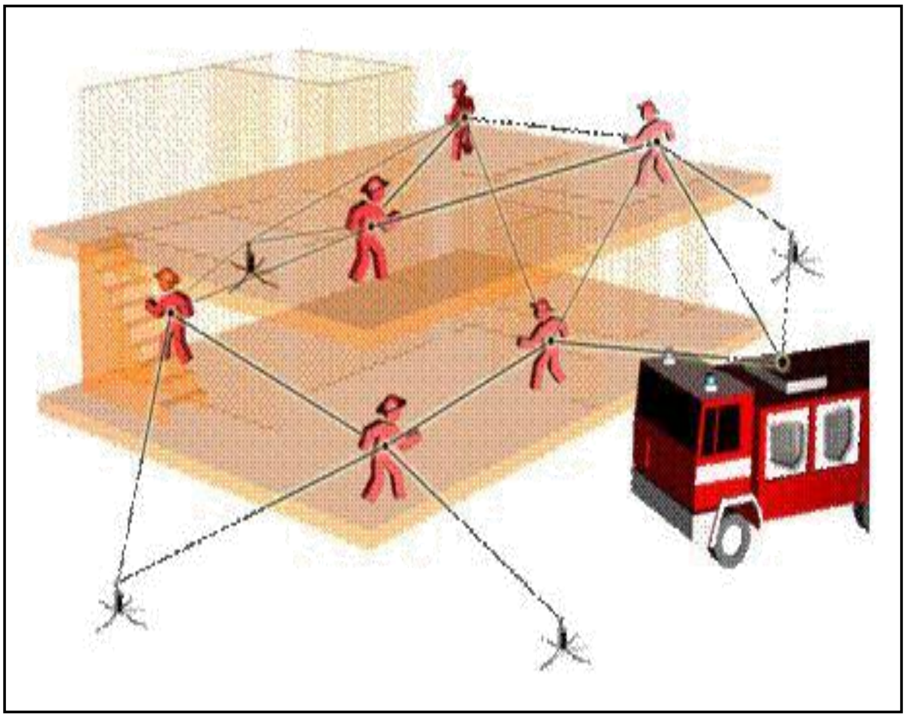


Figure 1.4 Application of UWB Geo-location systems [23]

A current development of pneumothorax detectors based on UWB by the Lawrence Livermore National Laboratory, shown in Figure 1.5. It transmits and receives nonhazardous EM pulses propagating through the particular areas of the human body and reflected by tissue, fluid and air [24].

Figure 1.5 Application of UWB imaging system [24]

UWB antenna is the main component of the UWB systems. It has been a main attraction of research in current years. With growing recognition of UWB systems, the designing of UWB antennas becomes a hot area of research. Because of its broad impedance bandwidth, easy design shape, effortless fabrication on PCB and omnidirectional radiation patterns, UWB antennas are preferred. The planar monopole antenna becomes a capable contestant for UWB wireless applications. Well, there are numerous narrow band communication systems having operating bandwidth less than 10.6GHz are existing with similar UWB frequency range and may produce interferences. To evade the interference, a notch or filter having band stop properties may be incorporated with UWB antennas to attain a band notch property at obstructing frequency range.

1.2 RESEARCH MOTIVATIONS

The main aim of the research work is to design and implement ultra wideband antennas with multiple notch bands such as 3.4-3.69GHz for WiMAX, 5.15-5.35GHz and 5.725-5.825GHz for WLAN, 7.25-7.75GHz for downlink of X-band and 8.02-8.4GHz for satellite communication band (ITU) system, which creates interference with the UWB system. The background of research work is created from the existing information gained from studying research papers in various standard journals in the field of UWB antennas. The following designs have been considered as major research motivations in this thesis.

1.2.1 Planar UWB Antenna Design

Antenna is an important part of any wireless communication system. In a UWB system (particularly pulse-based system), the antenna is needed to have a stable radiation pattern, high gain and an extremely wide bandwidth as shown in Figure 1.6. Because of these exclusive features, UWB antennas differ from conventional narrowband antennas. The motivation for the proposed work comes from the need of small, highly efficient and low-cost antennas which are appropriate for ultra wideband applications. As wireless devices are being more and more compact, increasing effort has been put to minimize the size of the UWB antennas due to the space constraint, which is becoming a new challenge for antenna designers. Therefore the design of a compact and planar UWB antenna is the main research topic of this thesis.

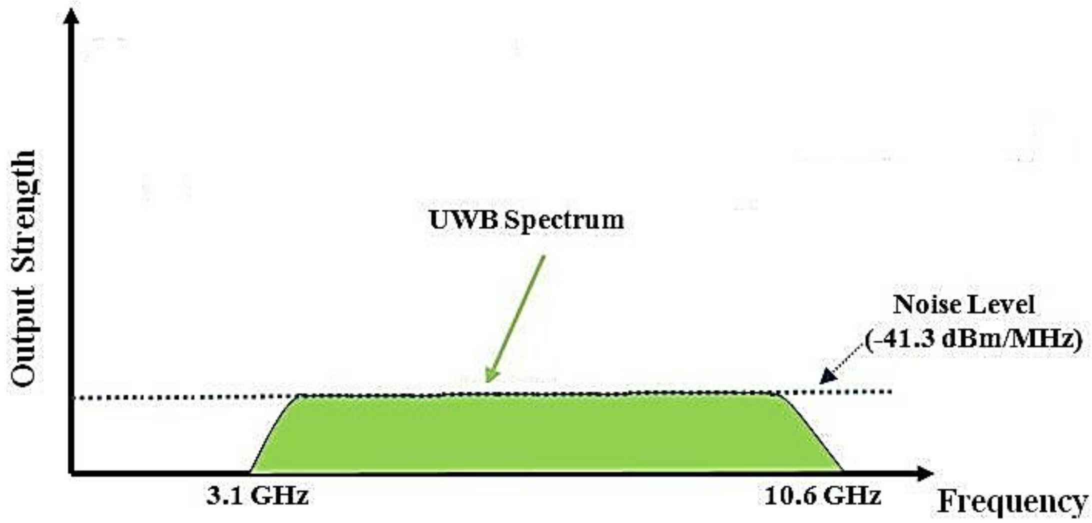


Figure 1.6 Power spectrum density of UWB communication system [12]

1.2.2 A Compact UWB Antenna with Notch Band at Lower Frequency Range

The operating frequency band of UWB systems overlaps with the presently existing systems like WLAN and WiMAX due to its wideband characteristic as shown in Figure 1.7. Therefore, it is compulsory to avoid interference of UWB with existing narrow band communication networks at the lower band. Initially, the conventional filters were used in the front end of RF receivers, by adding some narrow band rejections in UWB range, but this made the circuit very complex. Presently UWB antennas with a band notch characteristic have been proposed and designed. This section describes diverse methods to notch some frequency bands for example, etching slots and split ring resonators. Also, UWB antennas with dual notch bands are presented in this thesis.

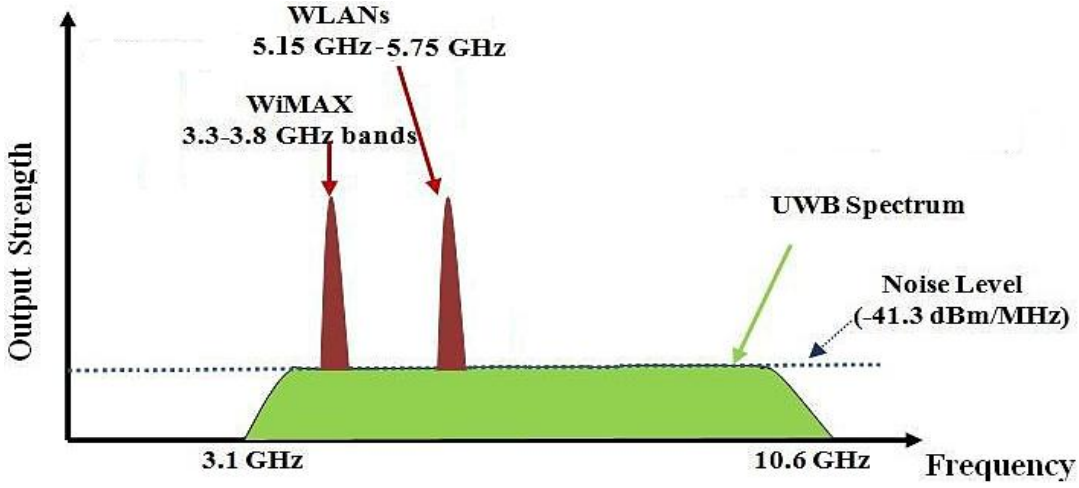


Figure 1.7 Power spectrum density of WLAN, WiMAX narrow-band and UWB systems [12]

1.2.3 A Strip Feed Triple Notched Band UWB Antenna at Lower and Upper Frequency Ranges

With the fast growth of wireless communication systems, the RF environment of a UWB system gets overlapped with other narrow band communication systems. In 2002 [1] Federal Communications Commission (FCC) has approved the frequency range from 3.1GHz to10.6GHz for commercial UWB application. However, in the proposed bandwidth of UWB system, there are certain narrow band services like, WiMAX (3.3-3.8GHz), WLAN (5.15-5.75GHz) and ITU service (8-8.5GHz) system, which creates interference with UWB systems, shown in Figure 1.8. Hence, the UWB system requires band rejection filters to avoid interference from other communication systems at lower as well as high frequency ranges.

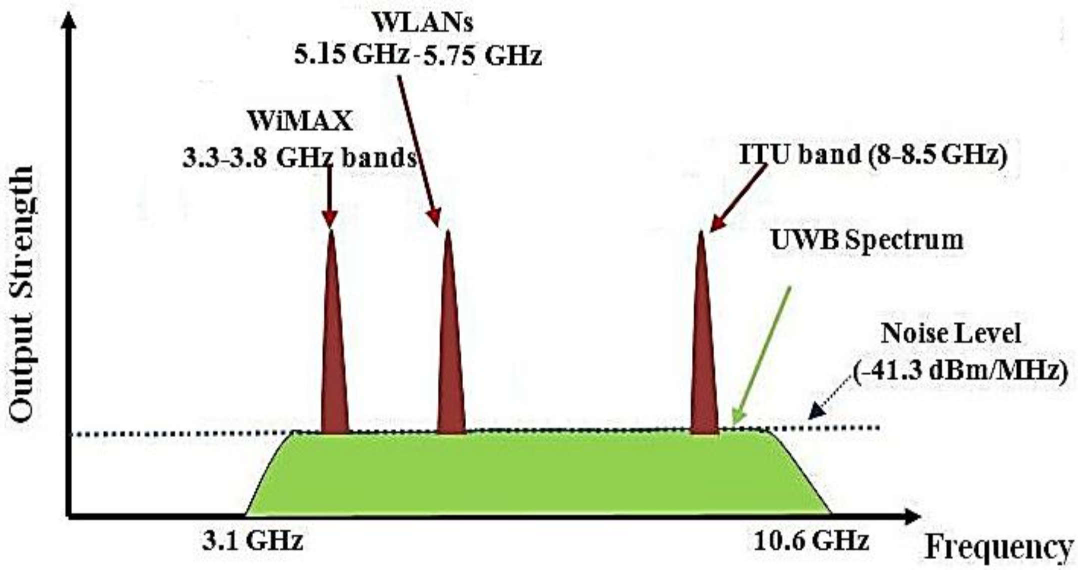


Figure 1.8 Power spectrum density of WLAN, WiMAX, ITU band and UWB systems [12]

1.2.4 A CPW Fed Multiband Notched Band UWB Antenna

Over the intended bandwidth of UWB system, there can be many narrow band services, for example, 3.4-3.69GHz band is for WiMAX, 5.15-5.35GHz and 5.725-5.825GHz band is for WLAN, 7.25-7.75GHz band is for downlink of X-band and 8.02-8.4GHz band is for satellite communication band (ITU) system, which can create interference with the UWB system shown in Figure 1.9. Thus, it is essential for UWB antenna performs multiple notch band operation in these frequency ranges to avoid the signal interferences. To resolve these problems, a novel design procedure of adding a multiband rejection filter to the CPW fed UWB antenna, has been discussed in this thesis.

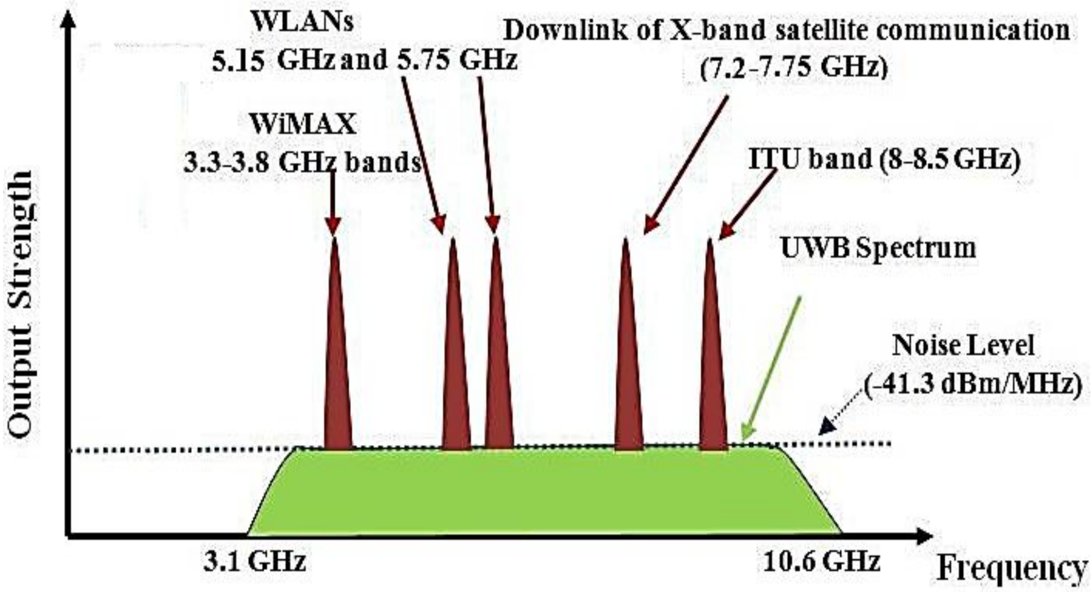


Figure 1.9 Power spectrum density of WLAN, WiMAX, downlink of X-band, ITU band and UWB systems [12]

1.3 PROBLEM STATEMENT

The main aim of the research work is to design and implement ultra wideband antennas with multiple notch bands. Subsequently, the design problems related to UWB antenna are considered and then projected antennas have been optimized. The problem statements of the research work are to prepare an overview and study of UWB microstrip antenna having a multiple notch band operation. To accomplish the aim of the research work, an appropriate literature survey is carried out in the area of UWB microstrip antennas with multiple notched bands performance. A detailed study is done regarding the different feeding techniques used with MSA and then strip feed and CPW fed microstrip antennas are proposed.

To attain the desired uniqueness from the UWB microstrip antenna, various slots are etched into the patch and/or on the ground plane of the proposed antenna. After carrying out the essential literature survey, in an area of UWB microstrip antennas with multiple notched bands, the following objectives were defined.

1.3.1 Research Objectives

1. To study different broad banding techniques and simulate a planar UWB microstrip patch antenna for wireless applications.
2. To design and simulate a UWB microstrip patch antenna with double notch band for WLAN and WiMAX application.
   i. Parametric study of proposed antenna.
   ii. Fabrication and testing of proposed antenna.
3. To design and simulate a compact UWB microstrip patch antenna with triple notch bands for WLAN, WiMAX and ITU bands.
   i. Parametric study of proposed antenna.
   ii. Fabrication and testing of proposed antenna.
4. To design and simulate a small CPW fed UWB patch antenna with five notch bands.
   i. Parametric study of the proposed antenna.
   ii. Fabrication and testing of proposed antenna.
5. Comparison of simulated and measured results for validation of results and applicability of the antenna for UWB wireless applications.

1.4 RESEARCH METHODOLOGY

1. The extensive literature survey is conducted to find existing UWB antennas available in the area of the UWB communication systems.
2. Detailed study of dual notch band, triple notch bands and multiple notch band antenna structures is done.
3. Design of new UWB planar antenna structures with and without notched band is carried out.
4. Parametric study of the antennas is done to evaluate the antenna's performance of different parameters like, return loss, VSWR, bandwidth, impedance matching, gain and radiation pattern.
5. For conducting simulation and design of proposed antenna, IE3D antenna design software has been used.

6. The antennas are fabricated in Printed Circuit Board (PCB) lab, on a commercially available Glass Epoxy FR4 substrate with dielectric constant of 4.4 and a height of 1.6mm.
7. Return loss and VSWR parameters of proposed antenna have been measured using a vector network analyzer (Anritsu MS2028C).
8. The field patterns and gain measurements have been done in the Anechoic Chamber.

1.5 KEY CONTRIBUTIONS

The research work concentrates on the problem identification, simulation and parametric study for the analysis of results. Fabrication and testing of the proposed antennas for different wireless applications is also done for verification of simulated results. The main contributions of this thesis are highlighted in the current section.

Contribution 1: A Compact UWB Planar Antenna Design

A compact rectangular UWB planar antenna is designed and examined. The anticipated antenna is compact in size with W×L ($26\times27mm^2$) and printed on a substrate FR4 with the dielectric constant (ε_r) of 4.4, substrate thickness (h_t) of 1.6mm and loss tangent (tan δ) of 0.02. The UWB antenna is evolved from the conventional rectangular monopole antenna. To improve the impedance bandwidth and impedance matching, three bevel slots to lower portion of the radiator patch and a single bevel slot to ground plane are implemented. Also, the proposed antenna has a steady radiation pattern over the whole UWB range.

Contribution 2: Optimization of a UWB Antenna with Dual Notched Band for WiMAX and WLAN Applications

A compact microstrip feed UWB antenna having double notch band characteristic has been projected. The antenna has two U-shaped stubs on the radiating patch of the antenna designed earlier in contribution 1. The proposed antenna reduces the interference of UWB with WiMAX and WLAN. The proposed antenna has a compact dimension of $26\times27mm^2$. The projected antenna obtained an operating bandwidth (VSWR<2) from 2.6-10.8GHz, with one frequency notched band at 3-3.9GHz (WiMAX) and other at 5-5.9GHz (WLAN). The proposed antenna exhibits an omnidirectional radiation pattern, make it suitable for UWB applications (the work was published).

Contribution 3: Design and Analysis of a Strip Feed Triple Notch Band UWB Antenna

A microstrip feed ultra wideband antenna with triple notch band characteristics has been proposed. The proposed antenna has three U-shaped stubs on the radiating patch of the antenna designed earlier in contribution 1. The proposed antenna reduces the interference of UWB with WiMAX, WLAN and ITU band. The suggested antenna has a compact dimension of $26\times27mm^2$. The projected antenna achieved an operating bandwidth (S_{11}<-10dB) from 2.68-12GHz except notch band 3-3.85GHz (WiMAX), 5-5.9GHz (WLAN) and 8-8.8GHz (ITU). The proposed antenna exhibits omnidirectional radiation patterns, make it suitable for UWB applications (the work was published).

Contribution 4: Design of CPW Fed Five Notched Band UWB Antenna for Wireless Applications

Small CPW fed UWB antenna with five notch band has been projected to suppress the interferences in ultra wideband systems. The projected antenna has a small dimension of $30\times32\times1.6mm^3$and operating bandwidth (VSWR<2) from 2.8GHz to 11.6GHz. By introducing five U-shaped slots, five notches are achieved in WiMAX (3.1-4GHz), WLAN (5-5.4GHz and 5.7-5.9GHz), X-band downlink (7.2-7.75GHz), and ITU service band (8-8.4GHz). The antenna is simulated, fabricated and measured. The measured result shows an excellent harmony with simulated results. Also, the projected antenna has omnidirectional radiation pattern; that makes it suitable for UWB applications (the work was published).

1.6 ORGANIZATION OF THESIS

The main aim of the research work is to design and implement ultra wideband antennas with multiple notch bands such as 3.4-3.69GHz for WiMAX, 5.15-5.35GHz and 5.725-5.825GHz for WLAN, 7.25-7.75GHz for downlink of X-band and 8.02-8.4GHz for satellite communication band (ITU) system, which creates interference with the UWB system. The background of research work is created from the existing information gained from studding research papers in various standard journals in the field of UWB antennas.

This thesis is organized into seven chapters; each chapter starts with an introduction of work done and concludes with the major results achieved and a comparative table between our results and some previous works presented in literature review has also been discussed in conclusion of each chapter. The gain suppression of our design is better than the design reported in [102,112,123].

Chapter 1 presents the basic introduction of ultra wideband systems and some other coexisting narrow bands, multiple notched bands along with motivation of research, research objectives, scope of thesis work, research methodology and the thesis organization too.

Chapter 2 discusses the theoretical concepts of microstrip patch antenna and UWB technology, and literature review on the growth of UWB antennas in earlier periods. The modern technology of creating notched bands in UWB antennas is also presented.

Chapter 3 deals with the first objective of the proposed work; i.e. the design and simulation of a planar UWB microstrip patch antenna for wireless applications.

Chapter 4 deals with the second objective of the proposed work; strip feed UWB patch antenna with a dual notch band for WLAN and WiMAX application. The performance of projected antenna is examined and verified both numerically and experimentally for the notch created for the notch created.

Chapter 5 deals with the third objective of the proposed work; UWB microstrip patch antenna with triple notch bands for WLAN, WiMAX and ITU service bands. The performance of the designed antenna is studied and verified both numerically and experimentally.

Chapter 6 deals with the fourth objective of the proposed work; CPW fed UWB patch antenna with five notch bands. The performance of proposed antenna is examined and verified both numerically and experimentally in terms of notch band creation.

Chapter 7 contains conclusions of this thesis work and proposes some future work of the current research work, presented in this thesis.

CHAPTER 2

LITERATURE REVIEW AND PRELIMINARIES

2.1 INTRODUCTION OF MICROSTRIP PATCH ANTENNA

2.1.1 Overview

A microstrip antenna is a printed antenna, with its basic geometry consisting of a very thin metallic layer (patch) placed above the ground plane. These antennas usually operate at frequencies between 1GHz to 100GHz [25]. Their operation can be explained by considering these antennas as planar resonant cavities that have leaking fields that flow from their edges and cause radiation [36]. Figure 2.1 illustrates a simple microstrip patch antenna.

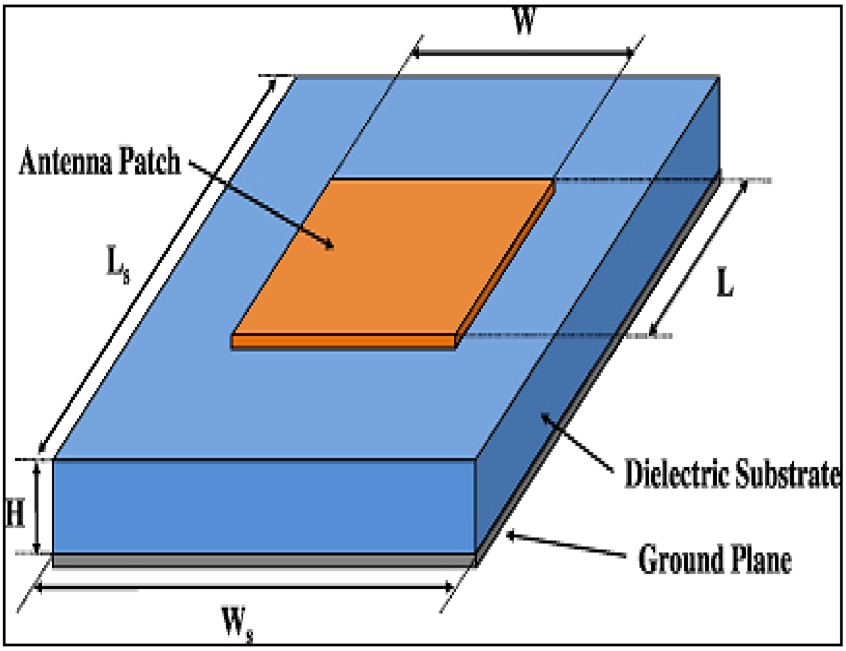


Figure 2.1 Microstrip patch antenna [26]

The operation of microstrip antennas can be examined with the help of fact that when these antennas are excited at the fundamental TM_{10} mode, the electric fields that are distributed on the patch surface due to excitation do not stop at the patch's boundary and extend towards the outer periphery of the antenna. These extended fields from the patch surface are called fringing fields and are radiated out by the antenna as Electromagnetic waves into free space [25,33]. The dielectric constant of substrates affects the performance of this antenna; the lower is the substrate dielectric constant that is used for making the antenna, more loosely bound are the fields and better is the radiation from the antenna.

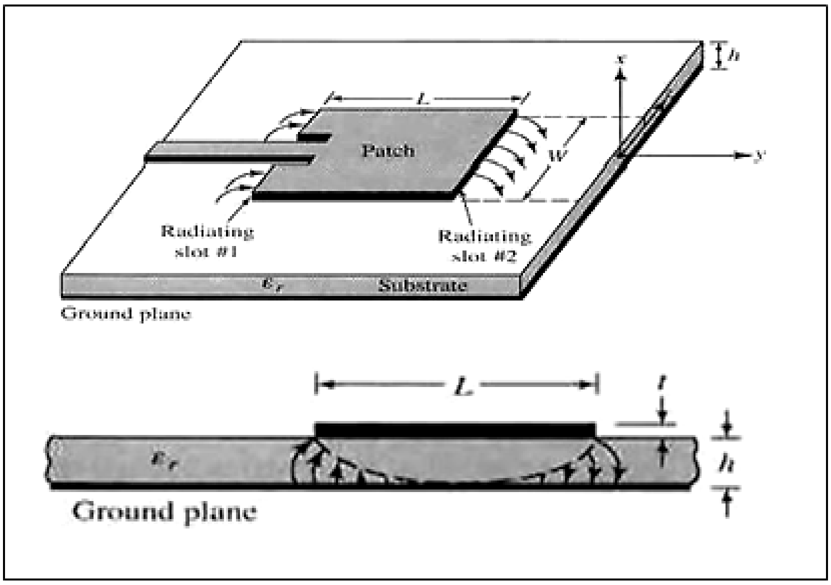


Figure 2.2 Microstrip antennas radiating from its edges [25]

This microstrip patch usually operates such that its pattern maximum, i.e. the major lobe of the antenna's pattern is normal to the patch and operates with its radiations concentrated mostly in the broadside directions. This behavior can also be cultivated by properly choosing the mode (field configuration) of excitation below the metal patch on the feed network [25]. Figure 2.2 shows a patch antenna radiating from its edges. The dimensions Length (L) and width (W) of the patch and height (h) of the substrate are chosen such that height h is far less than the operational wavelength and it is usually $0.03\lambda_0 < h < 0.05\lambda_0$. The length L of the patch element usually is given as $0.33\lambda_0 < L < 0.5\lambda_0$, where λ_0 is the free space wavelength at the frequency of operation.

2.1.2 Advantages and Disadvantages

Microstrip patch antennas are increasing in popularity for use in wireless applications due to their low-profile structure. Therefore, they are extremely compatible for embedded antennas in handheld wireless devices such as cellular phones, pagers, etc. Some of their principal advantages are listed below:

i. They are light in weight and the less volume.
ii. A planar configuration which makes them conformable to host surface.
iii. These are cost effective to fabricate and implement.
iv. These antennas can support both linear and circular polarization.
v. Capable of providing multiple resonances.
vi. They are mechanically sturdy when mounted on solid surfaces.

However, the conventional MSA suffers from a few disadvantages apart from possessing the mentioned characteristics:

i. They have a narrow bandwidth at the frequency of operation.
ii. These antennas have a low gain and efficiency.
iii. A low power handling capability.
iv. Surface wave Excitation.
v. Extraneous radiation from feeds and junctions [25].

Many techniques have been proposed by researchers that help in overcoming these disadvantages and allow these antennas to be efficiently used in the current communication systems. Some of these techniques are discussed in the next sections. The kind of output that is obtained from microstrip antennas also depends upon the kind of the feeding technique followed with this antenna.

2.2 FEED TECHNIQUES

The microstrip patch antennas can be excited by using a number of feeding techniques, these are:

i. Microstrip line feed
ii. Coaxial feed
iii. Aperture coupled feed
iv. Proximity feed

2.2.1 Microstrip Line Feed

In this feeding technique, a strip line adjoining the patch (of the same thickness as the patch) is photo etched on the substrate as shown in Figure 2.3. This extends from the boundary of the substrate to the patch and its dimensions decide the impedance matching that has to be achieved for the patch antenna's operation.

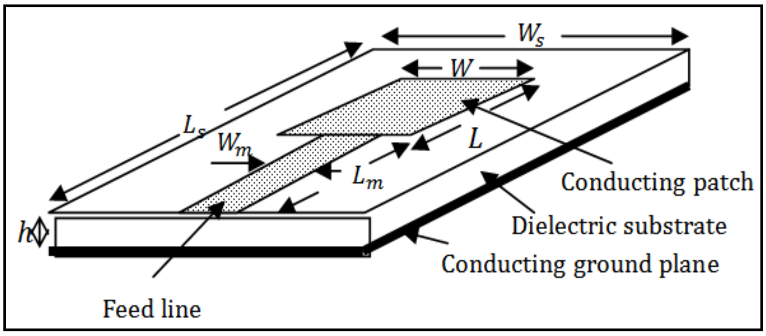


Figure 2.3 Microstrip line feed [27]

2.2.2 Coaxial Feed

The Coaxial feeding method consists of a coaxial wire whose intrinsic / active conductor is drilled through the antenna suitably to the patch surface and the extrinsic conductor / ground is connected to the ground layer of the patch antenna. The position of inner conductor of the coaxial cable connected at the patch can be varied to achieve effective impedance matching for the antenna. Figure 2.4 shows a coaxial feed patch antenna. This method of feeding in microstrip antenna is quite common as it is easy to fabricate and it presents a low level of spurious / false radiations.

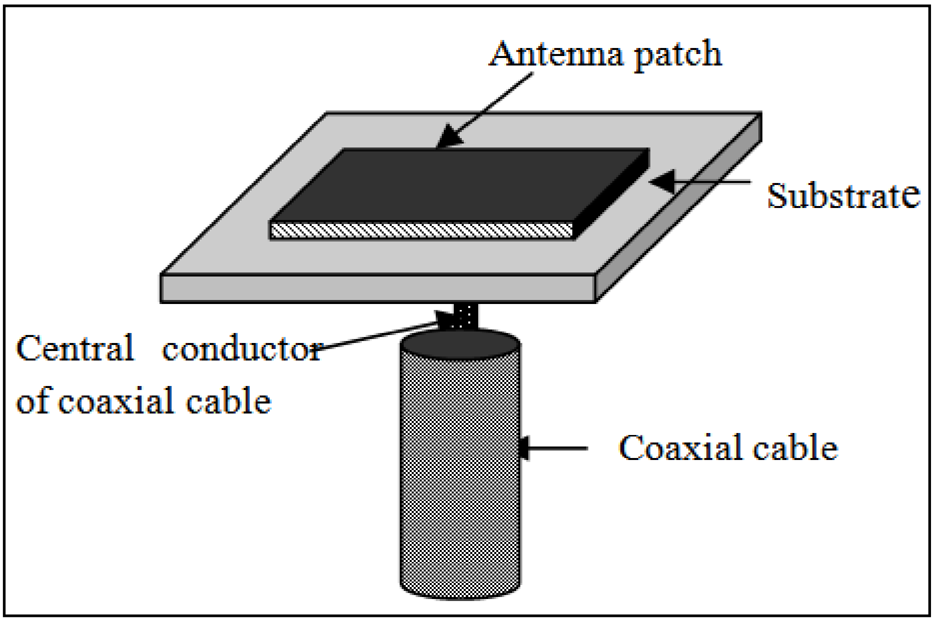


Figure 2.4 Coaxial feed rectangular microstrip patch antenna [27]

2.2.3 Aperture Coupled Feed

The aperture coupling method of feeding MSA consists of a metal ground plane sandwiched between two layers of substrates. On the upper substrate layer, a patch is printed and on the base of the lower substrate, a microstrip feed line is formed. The energy from the feed network is coupled to the patch through a slot in the ground plane that separates the upper and the lower substrates. This arrangement helps in optimizing the antenna's output by optimizing the feed structure and the radiating patch independently. To obtain a good bandwidth and low spurious fields from the antenna, a high dielectric constant material is used for the lower substrate (with feed line) and thick low dielectric constant material for the upper substrate (with patch printed over it) usually. The ground layer between the upper and the lower substrates also helps in isolating the feed from the radiating element and minimizes interference of spurious radiation to obtain polarization purity of the results [25]. Figure 2.5

shows the basic layout of an aperture coupled microstrip patch antenna. For such structures, the dimensions of the slot can also be optimized to achieve a good bandwidth at the resonant frequency of operation.

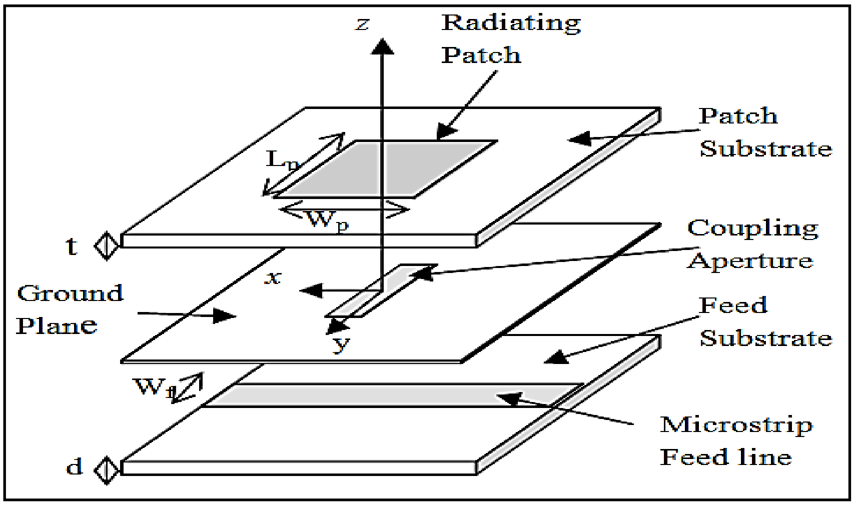


Figure 2.5 Aperture-coupled feed [27]

2.2.4 Proximity Coupled Feed

This type of feeding technique follows an electromagnetically coupled feeding mechanism shown in Figure 2.6. Here the patch antenna is parasitically coupled to the feed network where the transmission line is sandwiched in between the ground plane and patch which are printed on two separate substrates. Coupling of fields takes place from the transmission line to the metal radiator patch. Since the overall height of antenna increases, this technique of feeding MSA has been quite beneficial and it leads to an increased bandwidth by around 21% as compared to other feeding methods [25]

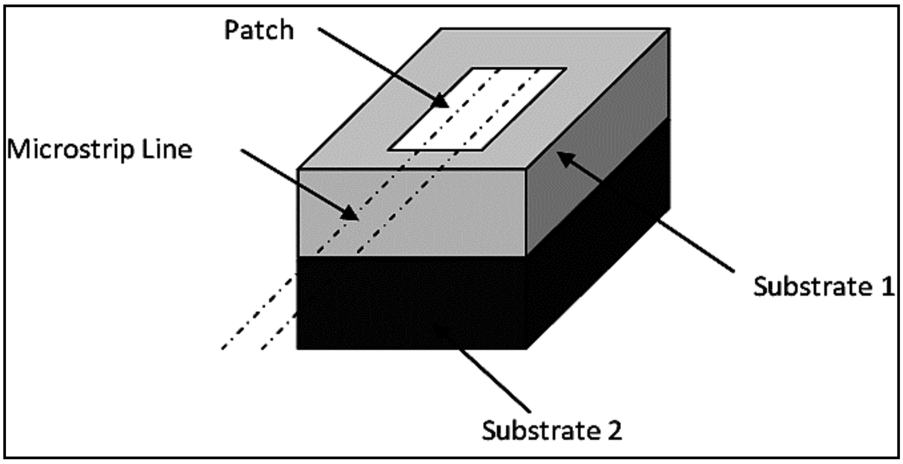


Figure 2.6 Proximity-coupled feed [37]

Table 2.1 Comparison of characteristics of different feed techniques

Characteristics	Microstrip Line Feed	Coaxial Feed	Aperture Coupled Feed	Proximity Coupled Feed
Spurious feed radiation	Quite much	Higher	Less	Least
Reliability	Better	Very poor due to soldering	Great	Great
Ease of fabrication	Easy	Complicated due to soldering and drilling needed	Easy but alignment required	Easy but alignment required
Impedance Matching	Simple to achieve	Simple to achieve	Simple to achieve	Simple to achieve
Bandwidth	2-5%	2-5%	13%	21%

2.3 METHODS OF ANALYSIS: Transmission Line Model

The transmission line model is a simple and most widely used method for the analysis of microstrip antennas. It represents the microstrip antenna's two radiating edges equivalently by two slots; these slots are separated by a transmission line with low-impedance and length L. The radiation from an MSA can be explained by considering fringing effects.

As the measurement of a microstrip patch are precise along the X and Y axis of patch dimensions. The electric fields that are distributed on the patch surface due to excitation do not stop at the patch's boundary and extend towards the outer periphery of the antenna and these fields at the boundaries of the patch undergo fringing along the length of the two radiating slots of the microstrip antenna. Along the XY- plane, fringing is related to the ratio of the length of the patch L to the height h of the substrate (L/h) and the dielectric constant ε_r of the substrate. As for microstrip antennas the ratio of length of patch to the height of substrate is far greater than one, fringing gets reduced; but it is still taken into effect as it changes the resonant behavior of the antenna. The same applies to the width of the antenna too.

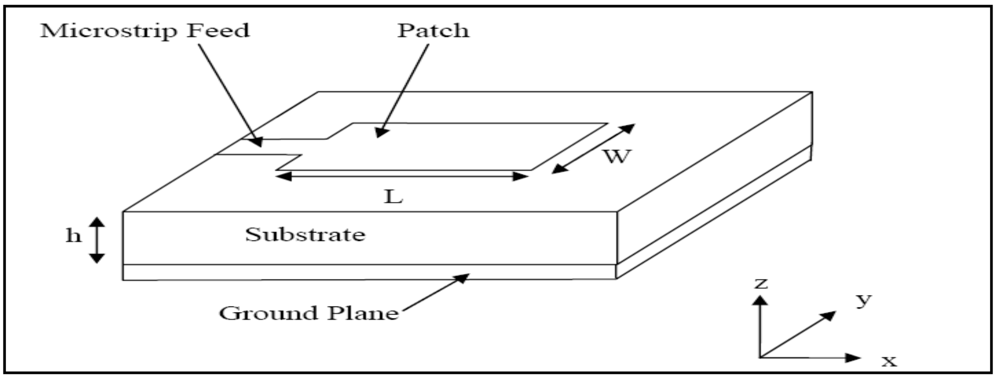


Figure 2.7 Microstrip patch antenna [25]

Fringing actually increases the electrical length of the MSA and allows the microstrip line to appear longer electrically as compared to its real dimensions of the antenna. Since some of the electromagnetic waves penetrate into the substrate and some are detached to the air. In order to account for the fringing effects, an effective dielectric constant ε_{reff} is introduced that is given by equation 2.1.

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{w}\right]^{-1/2} \tag{2.1}$$

Where ε_{reff} = Effective dielectric constant

ε_r = Dielectric constant of substrate

h = Height of dielectric substrate

W = Width of the patch

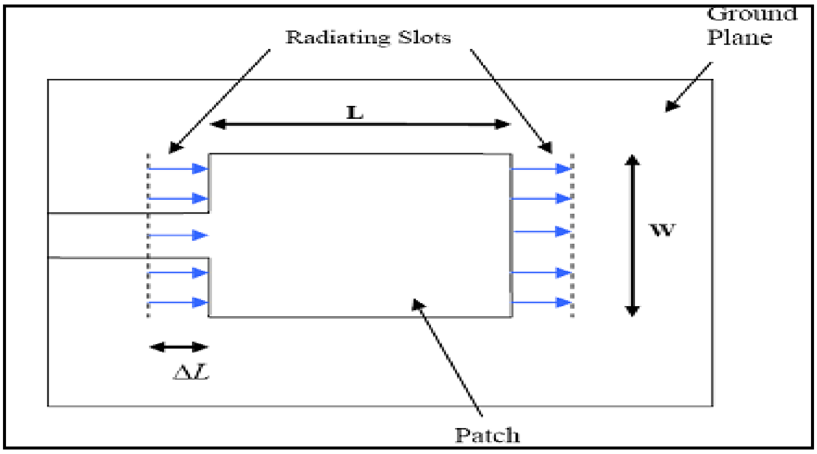


Figure 2.8 Top view of patch antenna [25]

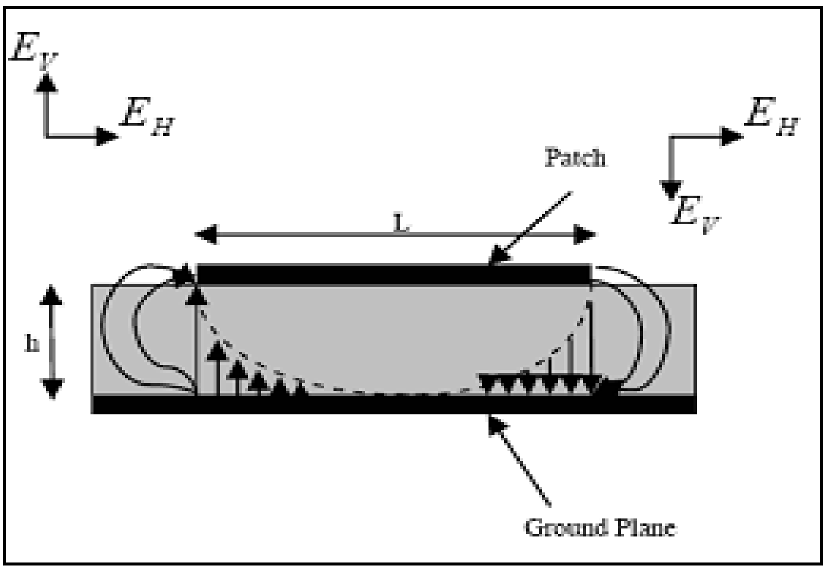


Figure 2.9 Side view of patch antenna [25]

The dimensions of the patch along its length have now been increased on each side by a length ΔL, that is presented empirically in [25] as:

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3)\left(\frac{w}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{w}{h}+0.8\right)} \tag{2.2}$$

Therefore the effective length of the patch is

$$L_{eff} = L + 2\Delta L \tag{2.3}$$

The effective length of the patch taking fringing effects into account, for a given resonant frequency is also given by

$$L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{reff}}} \tag{2.4}$$

In general, the resonant frequency for any TM_{mn} mode of a rectangular microstrip patch antenna, is presented by James and Hall

$$f_0 = \frac{c}{2\sqrt{\varepsilon_{reff}}}\left[\left[\left(\frac{m}{L}\right)^2 + \left(\frac{n}{W}\right)^2\right]\right]^{1/2} \tag{2.5}$$

where, m and n are the number of half wave cycles of magnetic or electric fields along L and W of the patch in the TM (Transverse Magnetic) or TE (Transverse Electric) mode of operation respectively. For effective radiation from the antenna, the width W of the patch is given by Bahl and Bhartia.

$$w = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{2.6}$$

These equations have been used to design and simulate rectangular microstrip antennas for the current research work.

2.4 FUNDAMENTAL ANTENNA PARAMETERS

An antenna plays the role of a transitional device and provides a means for converting guided waves in the transmission line to free space waves in the air on the transmitter side and vice versa at the receiver side. An antenna is defined as a means of transmitting and receiving EM (Electromagnetic) Waves. It is actually a transducer that converts an electrical signal to an Electromagnetic signal which is propagated out into free space. Figure 2.10 shows an antenna acting as a transitional structure (at the transmitter side) between a guided wave, flowing through a transmission line and a free space wave that is radiated out by the antenna into the air [25].

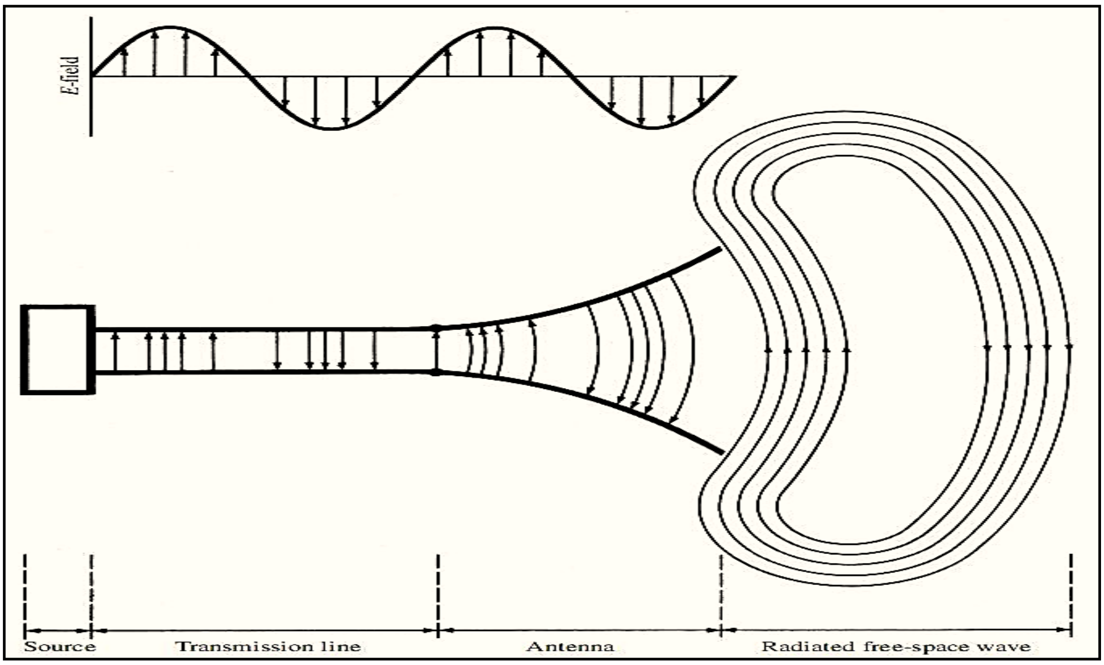


Figure 2.10Antenna as a transition device [25]

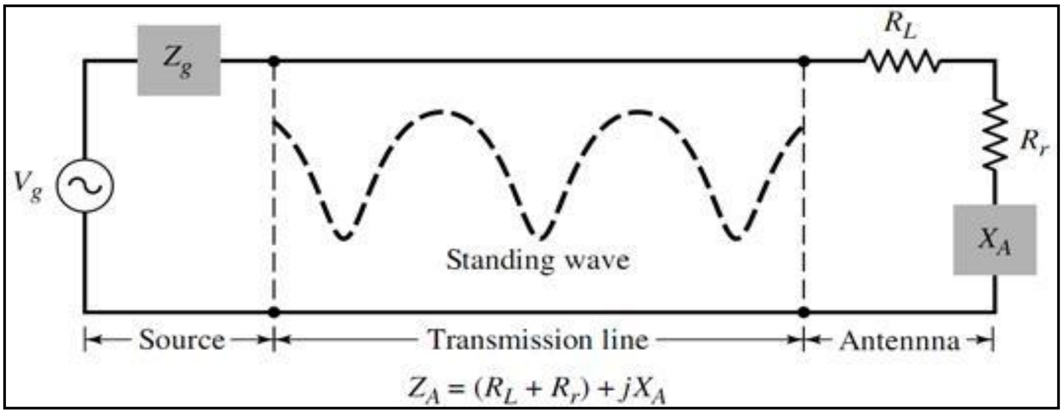


Figure 2.11 Thevenin equivalent of antenna in transmit mode [25]

The Thevenin equivalent of the antenna system of Figure 2.10in the transmit mode is shown in Figure 2.11, where the source is represented by an ideal generator, the transmission line by a line with characteristic impedance Z_C, and the antenna by a load Z_A [Z_A=(R_L+R_r)+jX_A] connected to the transmission line. The load resistance R_L represents the conduction and dielectric losses associated with the antenna structure, the radiation resistance R_r represents radiation from the antenna, and the reluctance X_A represents the imaginary part of the impedance associated with radiation by the antenna.

When microstrip antennas are designed, simulated, fabricated and tested for measurement of their performance; a few parameters, for example return loss (S_{11}), VSWR, impedance bandwidth, gain, current distribution and radiation pattern are required for their performance evaluation. These are briefly mentioned and explained in the further subsections.

2.4.1 Return Loss

Return loss is an important parameter when connecting transmission line to an antenna. It is correlated with the maximum transfer of power to the antenna because of impedance matching characteristics. Thus, it helps to measure the capability of a feed system of any antenna about how much power can be delivered from the source to the antenna. The return loss (RL) is also designated as the proportion of the power in the forward direction P_i to the power reversed / reflected back from the antenna of the source P_r.

It is usually expressed as a ratio in decibels (dB);

$$S_{11}(dB) = 10\log_{10}\frac{P_i}{P_r} \qquad (2.7)$$

Where, S_{11} (dB) is the return loss in dB, P_i is the incident power and P_r is the reflected power. If S_{11}= 0dB, then all the power is reflected from the antenna and no power is radiated. If S_{11}= -10dB, this implies that if 3dB of power is delivered to the antenna, -7dB is the reflected power. The rest of the power was received by or delivered to the antenna. This received power is radiated by the antenna.

2.4.2 VSWR

A voltage standing wave ratio is a measure of the amount of reflections received at the source because of the impedance mismatch between source and load that leads to formation of standing waves along the transmission line. For maximum transfer of power ideally from source to load, their impedances should be matched so as to give a reflection coefficient of zero ideally. If the reflection coefficient is denoted by Γ, then VSWR is denoted as:

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \qquad (2.8)$$

Since, the magnitude of Γ always in the range [0 to1]. The VSWR is always a real and positive number for antennas. The smaller the VSWR is, the better the antenna is matched to the transmission line and the more power is delivered to the antenna. The maximum VSWR is ∞, in the case all power is reflected from the antenna, which is short.

In general, if the VSWR<2 the antenna matching is considered very well. As the VSWR increases, more power is reflected from the antenna and therefore less power is transmitted to the transmission line, and poorly matched.

2.4.3 Impedance Bandwidth

The range of frequencies over which antenna maintain satisfactory value of VSWR<2 is called the impedance bandwidth of the antenna. It is also being described in terms of return loss (S_{11}). It is corresponding to the range of frequencies for which the antenna S_{11}<-10dB and is termed as the impedance bandwidth of the antenna. In broadband antennas, the ratio of upper to lower frequency is used for expressing their bandwidth. For example, a 10:1 bandwidth shows that the upper frequency of the radio band is 10 times greater than the lower frequency of the band. Narrowband antennas defined bandwidth in percentage bandwidth [13, 16, 22].

$$BW = \frac{F_H - F_L}{F_C} \times 100 \qquad (2.9)$$

where, F_H is the upper frequency of the band, F_L is the lower frequency of the band and F_C is the center frequency of operation.

2.4.4 Antenna Gain

The gain (G) of any antenna is described as the ratio of transmitting power in the direction of peak radiation to that of an isotropic source. It describes the directional capabilities of the antenna keeping in account the efficiency of that radiator. Usually, Gain of any radiating antenna is measured in the direction of maximum radiation is described as the proportion of the power per unit solid angle in the given direction to the power that would be obtained if the power input to the antenna is radiated isotropically. Mathematically, the gain G is as shown below.

$$G = \eta_e D \qquad (2.10)$$

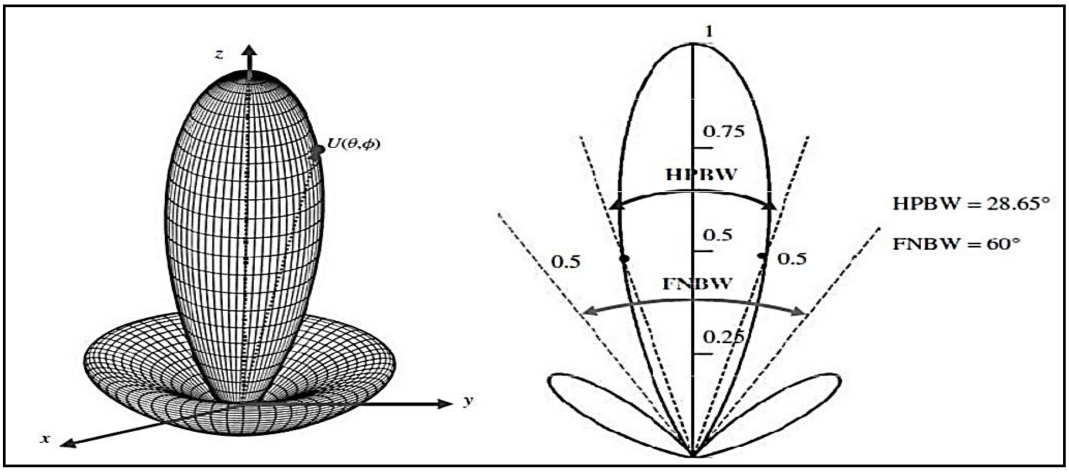
where, G is the gain of the antenna, η_e is the antenna's efficiency and D is the directivity of the antenna that is the amount of power delivered by the antenna along the direction of maximum output to the power distributed by an isotropic antenna [25].

2.4.5 Current Distribution

When a microstrip patch antenna is excited, there is a huge flow of current over the surface of the microstrip line. Due to these currents, electromagnetic waves are generated and join the patch to the ground plane. The maximum current flow in a particular portion of the patch antenna is more responsible for radiation at that portion. Moreover, the larger current loops are responsible for the lower frequency operation and the smaller current loops are responsible for higher frequency operation [35].

2.4.6 Radiation Pattern

A three-dimensional graphical representation of antenna radiation characteristics like power density (power pattern), field strength (field strength pattern), phase (phase pattern) or polarization (polarization pattern) as a function of space coordinates in the far field of the radiating antenna is called the radiation pattern of the antenna. It can also conveniently be represented as a 2D (dimensional) Figure as the elevation and azimuthal polar graph patterns of the antenna. These polar graphs in the elevation plane and the azimuthal plane can be used to determine the half power beam width and Side lobe level of the antenna's radiation pattern. Figures 2.12(a) and (b) show the radiation pattern of a half wave dipole antenna whose radiation intensity is given by $U(\theta) = Cos^2(\theta)$,where θ is the angle of observation [25].



(a) (b)

Figure 2.12 (a) 3-D Radiation pattern (b) Half Power Beam width [25]

The angular separation between those two points on the major lobe of the radiation pattern of the antenna where power has fallen to half of the maximum value is called the Half Power Beam Width of the antenna. An antenna that intends to cover a broader geographical coverage area should possess more HPBW in order to allow radiations in the major lobe to spread to a larger area. Figure 2.12 (b) shows a half power beam width of 28.65 degrees on the major lobe of the antenna's radiation pattern [25].

2.5 DEVELOPMENT OF UWB ANTENNAS

UWB antennas are generally referred as the antenna that covers a frequency range of 3.1-10.6GHz having a ratio bandwidth not less than 10:1 [38]. The improvements in UWB antenna are reviewed in this segment.

Sir Oliver Lodge proposed an initial biconical antenna with wideband properties [39], as illustrated in Figure 2.13. At the initial phase, the antenna has huge volumes like biconical/conical antennas [40], spheroidal antenna [41, 42], and omnidirectional and directional coaxial horn antenna [43]. Figure 2.14 shows the few of initial wideband antennas.

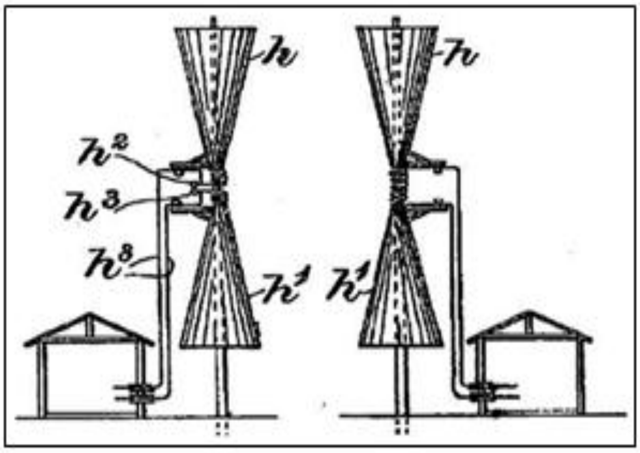
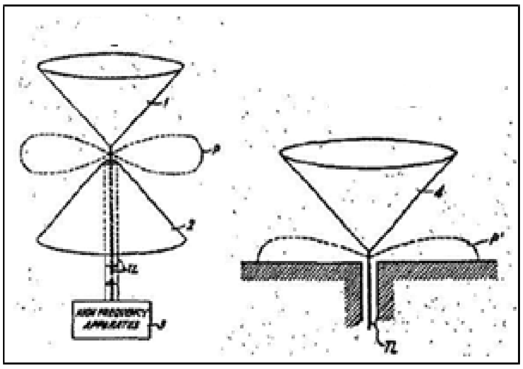
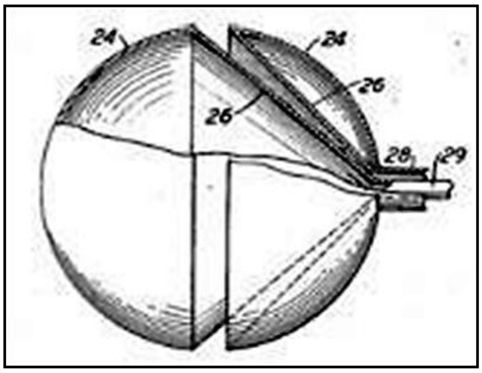


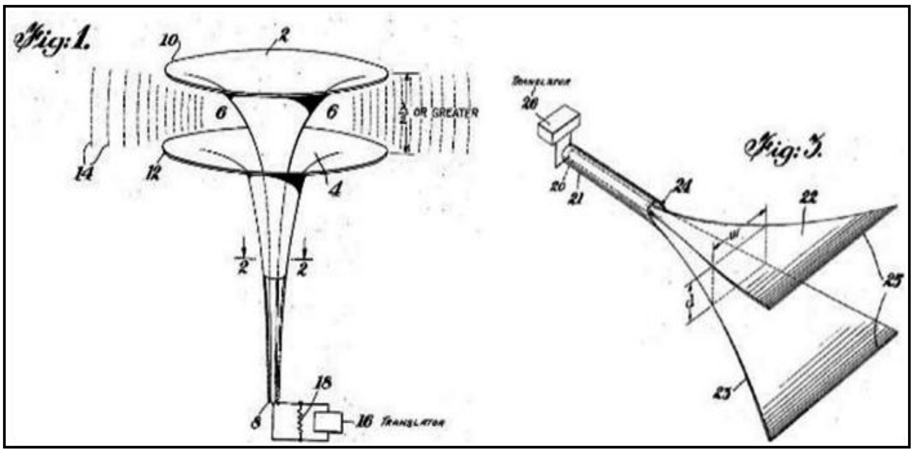
Figure 2.13 Initial wideband antennas [39]



(a) Biconical and conical antennas [40]



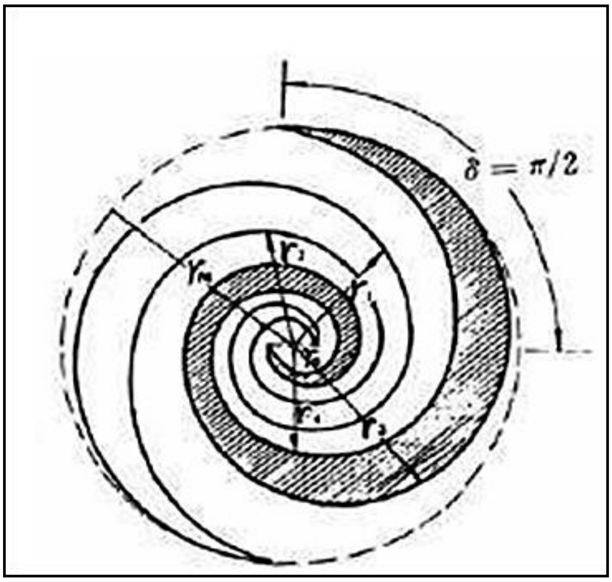
(b) Spheroidal antenna [41, 42]

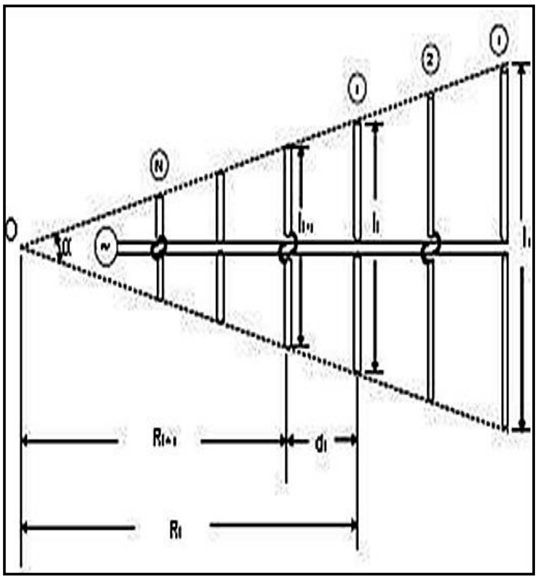


(c) Omnidirectional and directional coaxial horn [10]

Figure 2.14 Initial wideband antennas

A frequency independent antenna was reported in the late 1950 and early 1960 by Rumsey et al and these antennas have a ratio bandwidth more than 10:1 [38]. Figure 2.15 shows some conventional structure of antennas.





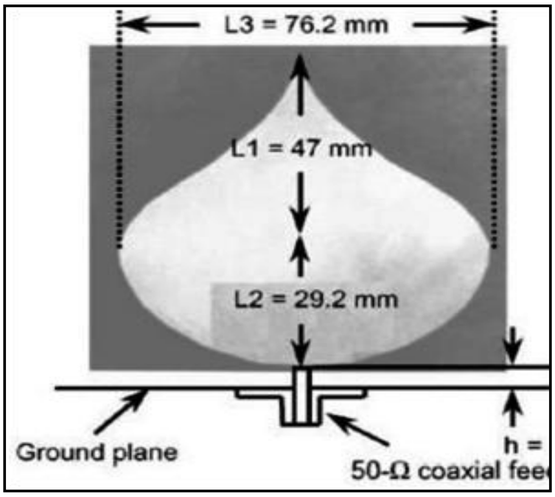
(a) An equiangular spiral antenna **(b) Log-periodic dipole antenna (right)**

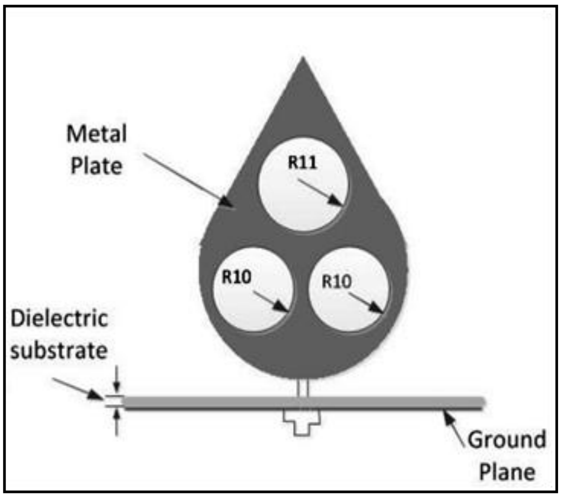
Figure 2.15 Frequency independent antennas [38]

From 1990s, a lot of novel shape UWB antennas had been projected, and these are summarized as three types [44] such as UWB metal plate monopole antenna, printed slot antenna and planar monopole antenna. These UWB antennas are reviewed in this section.

2.5.1 UWB Metal Plate Monopole Antennas

G. Dubost proposed first wideband metal plate monopole antenna. By optimization





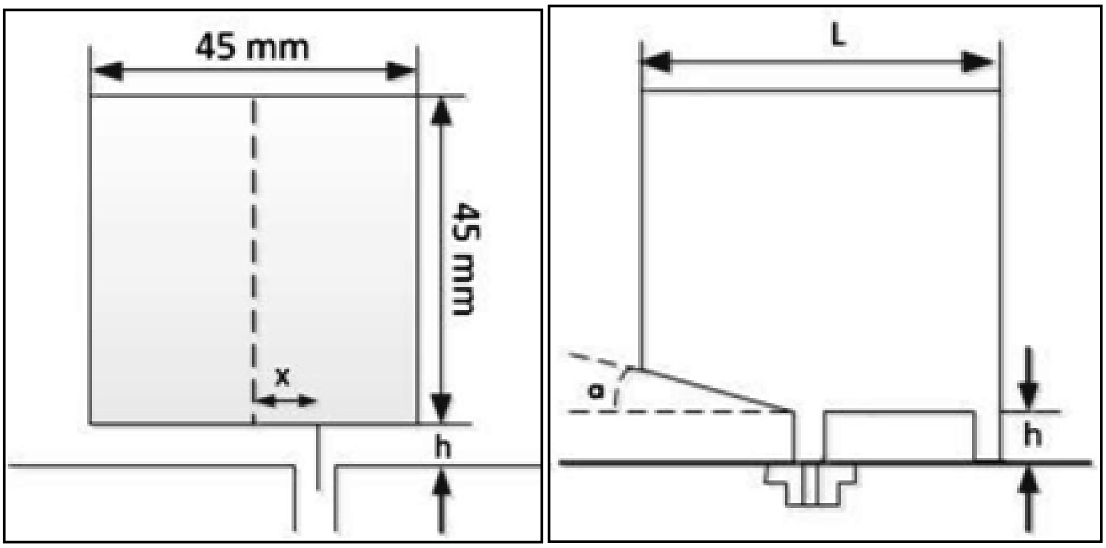
(a) Inverted cone antenna [48] **(b) Leaf shaped antenna [49]**

Figure 2.16 Metal plate monopole antenna

of metal plate monopole antenna shape, impedance bandwidth has been enhanced, like elliptical or disc shape [45,46], inverted cone and leaf-shaped monopole antenna, trapezium monopole antenna [47]. Figure 2.16 (a) shows the inverted cone antenna having only one flat component vertically mounted above ground plane. This antenna had radiation pattern bandwidth of 4:1 and an impedance bandwidth ratio of 10:1 [48].

In the early stage, the rectangular metal plate antenna has been comprehensively studied due to the easy shape and stable radiation pattern; however the impedance bandwidth was not good. Although, several methods have been proposed in order to enhance impedance bandwidth. Figure 2.16 (b) shows the leaf shape monopole antenna having an impedance bandwidth ratio more than 20:1, due to three circular holes, covering the frequency range from 1.3-29.7GHz [49].

The antennas with an offset feed [50], two and three feeds [51] and combining the short post and bevel technique [52] are recognized with the wideband properties. Figure 2.17 (a) shows the offset feeding and impedance bandwidth has been enhanced to 6:1 [50]. In [52], by combining the short post and bevel method the bandwidth is additionally enhanced to 10:1, as shown in Figure 2.17 (b).



(a) Offset feed [50] **(b) Short post and bevel [52]**

Figure 2.17 Rectangular metal plate antenna

2.5.2 UWB Slot Antennas

During the early period, UWB slot antennas were anticipated and studied [53-58]. These antennas are separated into two categories, for example UWB wide slot and UWB tapered slot.

2.5.2.1 UWB wide slot antennas

Earlier, many UWB wide slot antennas have been proposed to draw a diverse slot structure [53-56]. In [53], the planar slot antenna with U-shape strip feeding was made by the addition of rectangular cooper padding in the microstrip. Through the appropriate amendment in the physical dimension of the copper pad and it can attain a fractional bandwidth of more than 135.7%, in the frequency range of 2.3-12GHz the gain varies from 2-7dBi, shown in Figure 2.18.

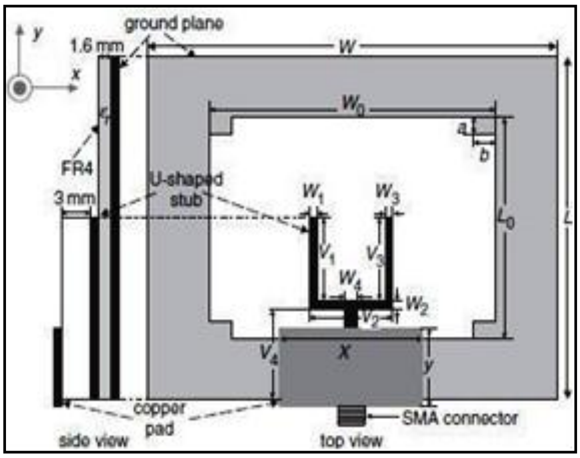


Figure 2.18 Printed U-shaped wide slot antenna [53]

Figure 2.19 show the geometry of Planar Invested Cone Antenna (PICA) antenna, by this structure impedance bandwidth of slot antenna can be enhanced and attain a ratio bandwidth of 13:1and frequency range of 2.2-30GHz [54].

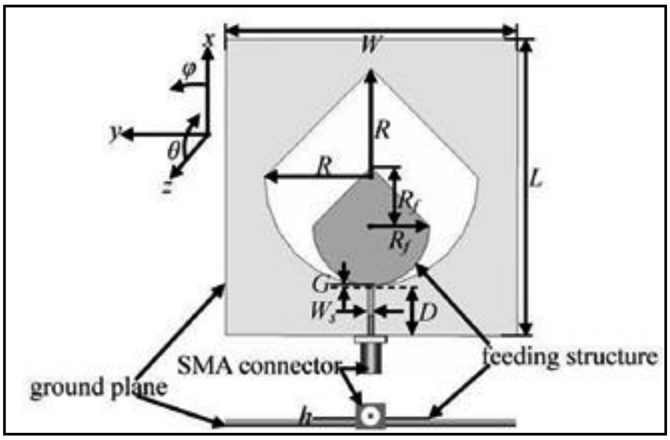


Figure 2.19 PICA slot antenna [54]

CPW fed is another feeding technique, and CPW fed slot antennas also provide a huge bandwidth. Figure 2.20 shows the elliptical patch antenna with an elliptical slot with CPW fed has a ratio bandwidth of 15:1and frequency range is 1.3-20GHz [55].

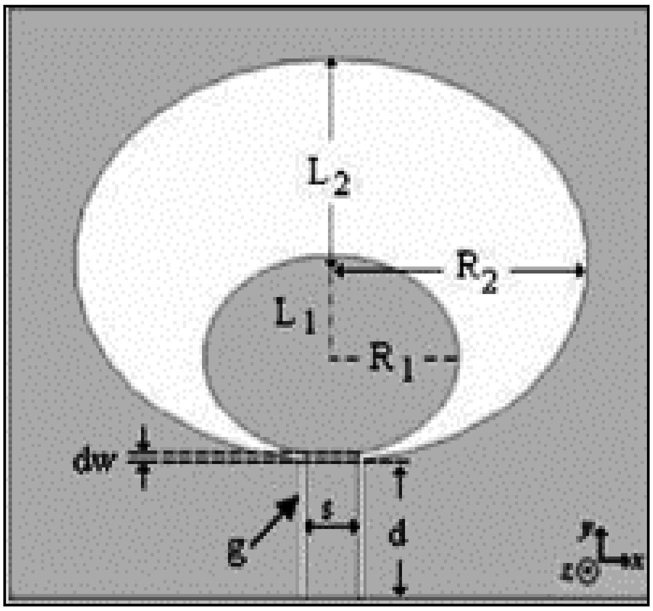


Figure 2.20 Elliptical slot antenna [55]

[In 2007, R K Sarin] proposed a microstrip feed wide slot antenna shown in Figure 2.21.The microstrip feed and wide slot is placed on opposite sides of the periodic dielectric substrate and getting a large bandwidth and high gain [56].

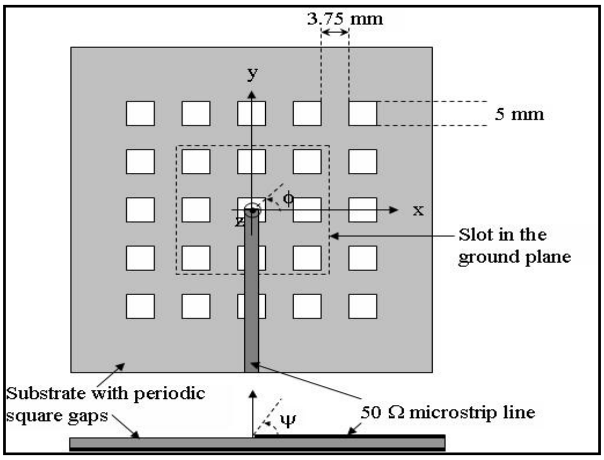
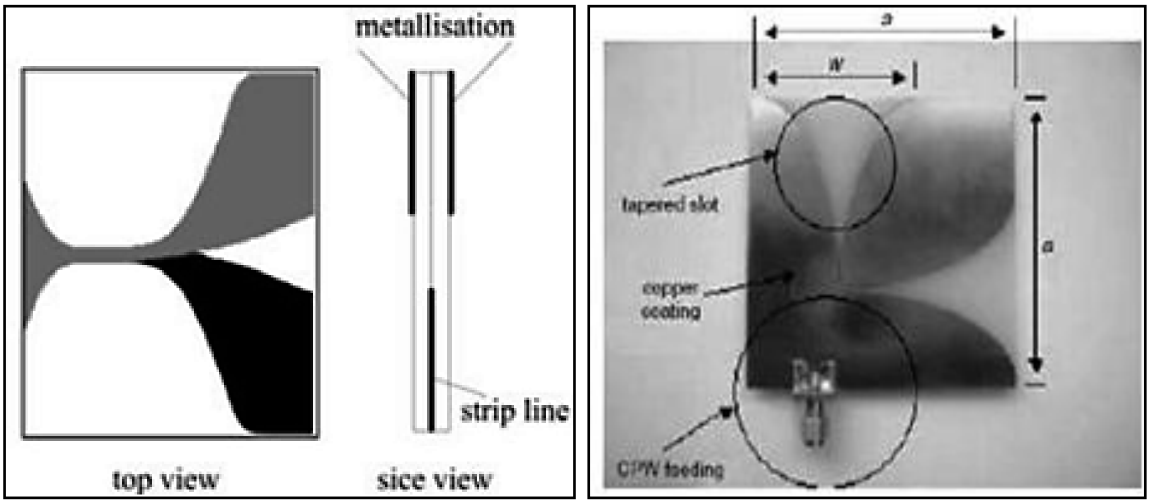


Figure 2.21 Wide slot antenna with periodic dielectric substrate [56]

2.5.2.2 UWB tapered slot antennas

A ratio bandwidth of a conventional Vivaldi antenna is less than 3:1. Figure 2.22 (a) shows a balanced antipodal Vivaldi tapered slot antenna having a ratio bandwidth of 15:1.The transition is due to the symmetric tapering of microstrip [57]. Consequently, the antenna covers a frequency range from 1.3-20GHz. Figure 2.27 (b) shows another style of antipodal Vivaldi antenna with CPW feed technique having a ratio bandwidth of 18:1 and frequency range from 1-18GHz [58].



(a) Convectional microstrip feed [57] **(b) CPW feed [58]**

Figure 2.22 Balanced antipodal Vivaldi antenna

2.5.3 UWB Planar Monopole Antennas

In earlier year, a lot of planar monopole antenna feed by the strip line [59-65] and the CPW [66-68] have been anticipated for UWB applications. Planar microstrip has some good characteristics like, low cost, simple structure, easy fabrication and omnidirectional radiation pattern. Therefore, the strip line and CPW fed types planar monopole antennas are reviewed:

2.5.3.1 Microstrip feed UWB monopole antennas

Figure 2.23 shows a small microstrip feed UWB monopole antenna, having a rectangular patch and a truncated ground plane, used for UWB application. The proposed antenna is designed frequency range from 3.1-11GHz for S_{11}<-10dB [59].

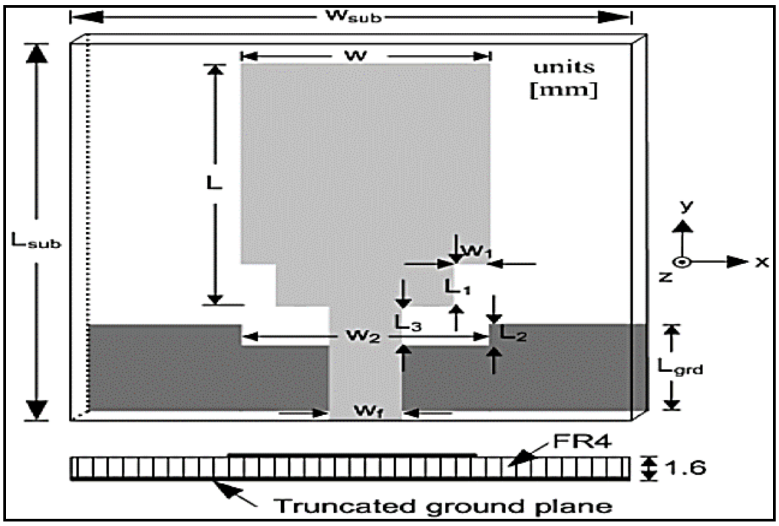


Figure 2.23 Microstrip feed monopole antenna [59]

Figure 2.24 show the microstrip feed antenna for wireless communication systems. The proposed antenna is designed for the frequency range from 1.65-10.6GHz for S_{11}<-10dB and provide communication services like DCS, WCDMA, UMTS, WLAN, DMB and UWB [60].

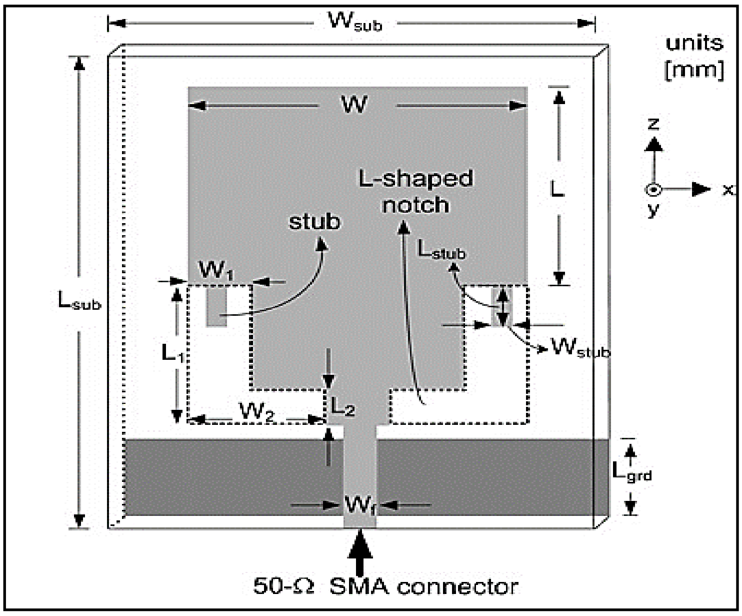


Figure 2.24 Wideband microstrip feed monopole antenna [60]

Figure 2.25 shows a microstrip feed planar circular asymmetrical dipole antenna having two different dielectric permittivity planar substrates. The model having lower dielectric permittivity substrates gives larger bandwidth, and frequency range is from 0.79-17.46GHz [61].

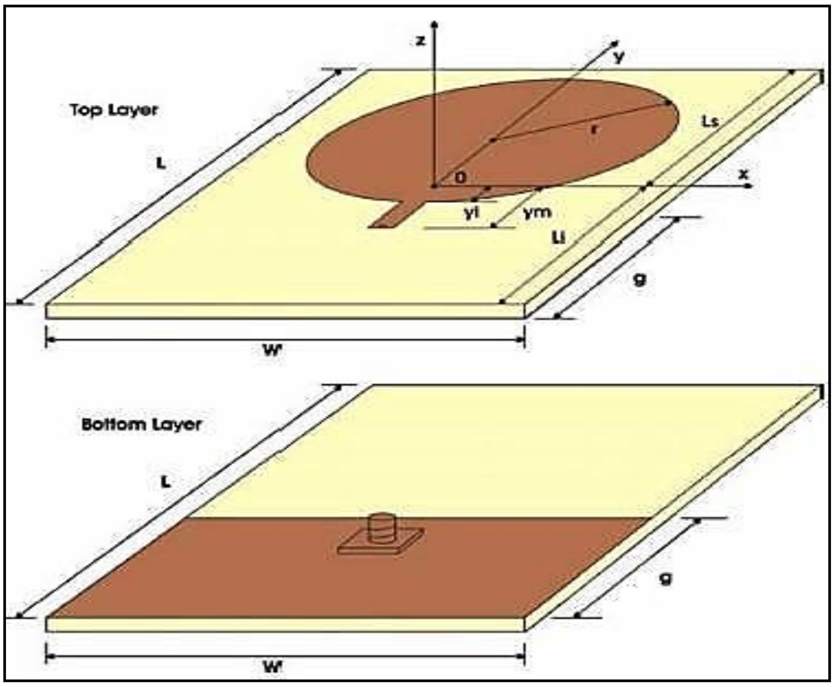


Figure 2.25 Planar circular asymmetrical dipole antenna [61]

Figure 2.26 shows a circular monopole fractal antenna having radial arrow fractal slots on radiating patch and Hilbert fractal slot on the ground plane. The path length of the surface currents of the radiating patch varies and shows multiband performance. The antenna has a wide frequency range from 1.65-14.6GHz for S_{11}<-10dB, a ratio bandwidth of 14:1 and a steady gain of 3dBi [62]. In [63], one more circular hexagonal fractal antenna was projected to have wide frequency range from 2.18-44.5GHz.

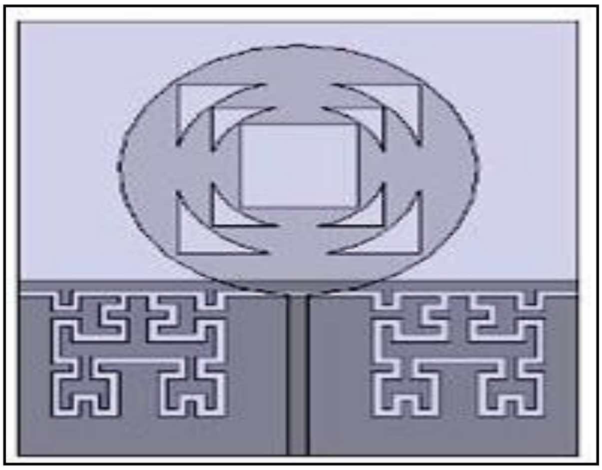


Figure 2.26 Circular fractal antenna [62]

Figure 2.27 show another planar microstrip feed antenna to get large bandwidth. By the introduction of semi elliptical fractal complementary slot, the ground plane effect can be reduced at the lower frequency end by suppression of electric current on the ground plane. Therefore, the antenna can achieve a wide frequency range from 1.44-18.8GHz for S_{11}<-10dB, a ratio bandwidth of 12:1, percentage bandwidth of 172%, a gain from 1-7dBi and omnidirectional radiation behavior at the lower frequency bands [64].

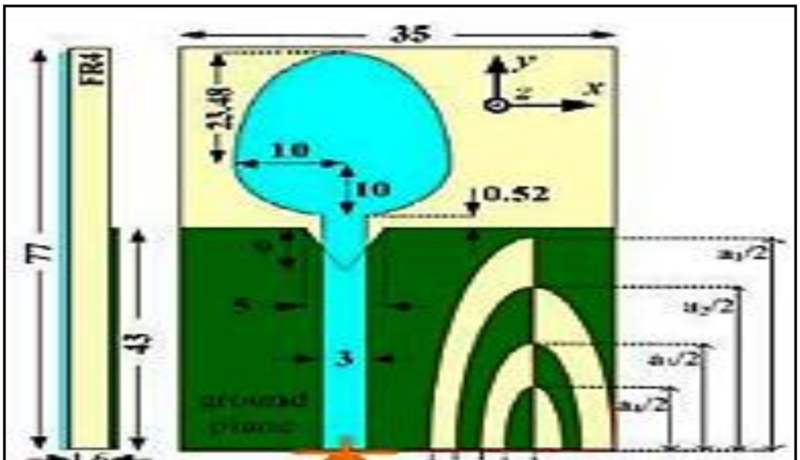


Figure 2.27 Elliptical egg-shape planar monopole antenna [64]

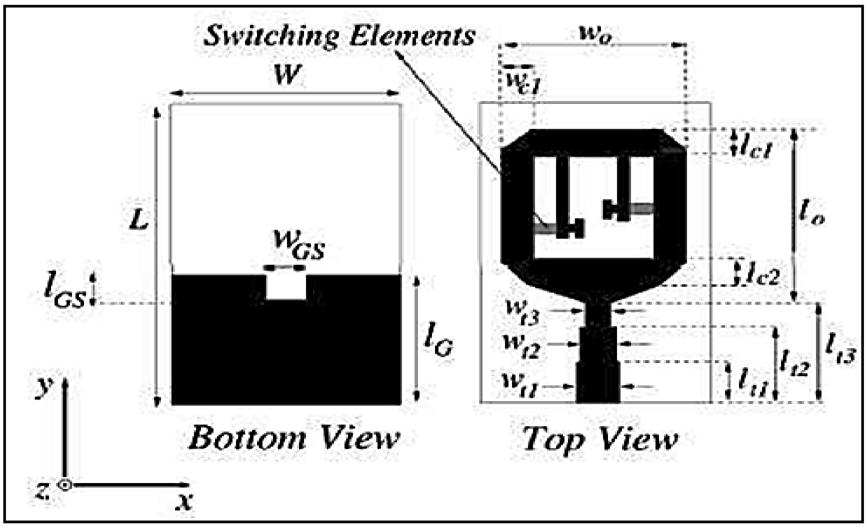


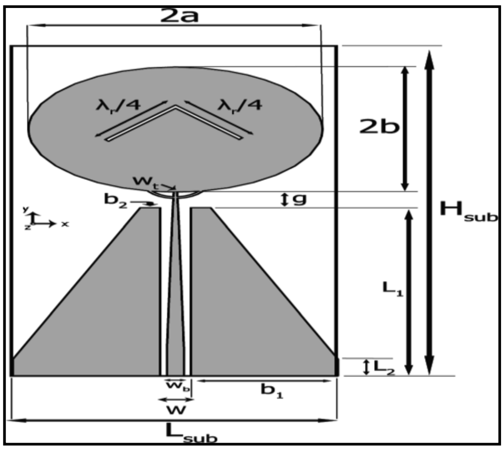
Figure 2.28 Compact monopole antenna [65]

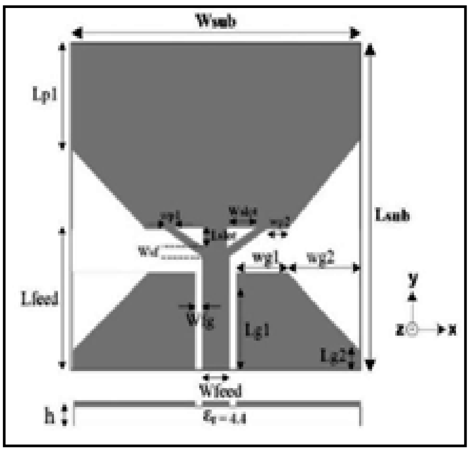
Figure 2.28 show a compact microstrip feed UWB monopole antenna for wireless application. The projected antenna achieved a wide frequency range from 3-33GHz and also shows double band notch properties [65].

2.5.3.2 CPW fed UWB monopole antennas

In this section, the performances of CPW fed UWB monopole antennas have been investigated.

[In 2015, Divitha Seetharamdoo], proposed a printed elliptical slotted monopole antenna with a triangular ground plane, fed by a semi-ring trident arm followed by a tapered CPW line shown in Figure 2.29 (a). The proposed antenna has a band width of 0.67-12GHz, better gain and stable radiation pattern. It can be used wideband spectrum sensing in the TV white space band in the context of cognitive radio applications [66].





(a) Elliptical [66] **(b) Trapezoid [67]**

Figure 2.29 CPW fed planar antenna

Figure 2.29 (b) shows CPW fed UWB monopole antenna having a wide frequency range from 2.76-40GHz for S_{11}<-10dB, a ratio bandwidth of 14.5:1 and percentage bandwidth of 174% [67].

Figure 2.30 shows a UWB antenna with the impedance bandwidth from 5-15GHz and a ratio bandwidth of 30:1 was proposed [68].

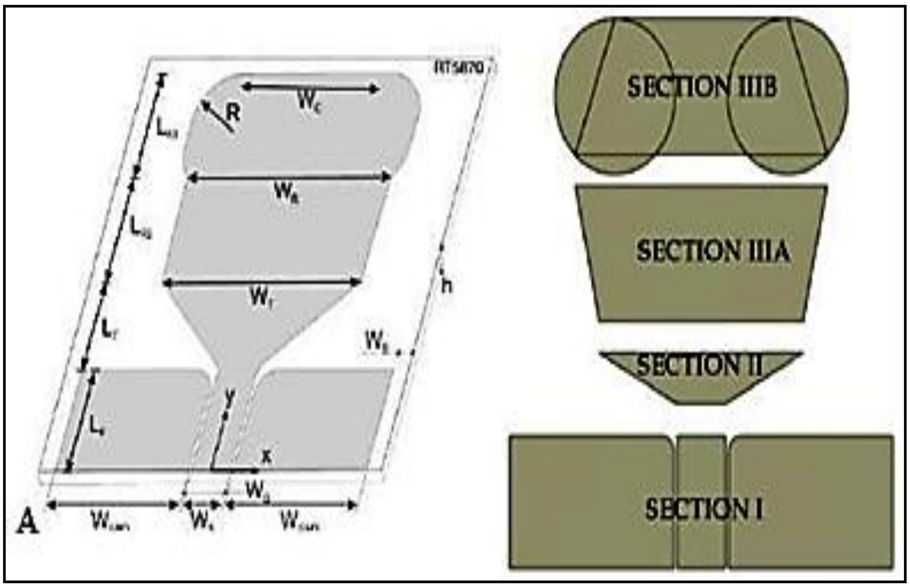


Figure 2.30 CPW fed planar monopole antenna [68]

Figure 2.31 show of planar elliptical slot antenna feed by coplanar waveguide with U-shaped tuning stub, to increase the coupling between the slot and the Feed line and widen the operating bandwidth from 2.76-40GHz for S_{11}<-10dB has been archived [69].

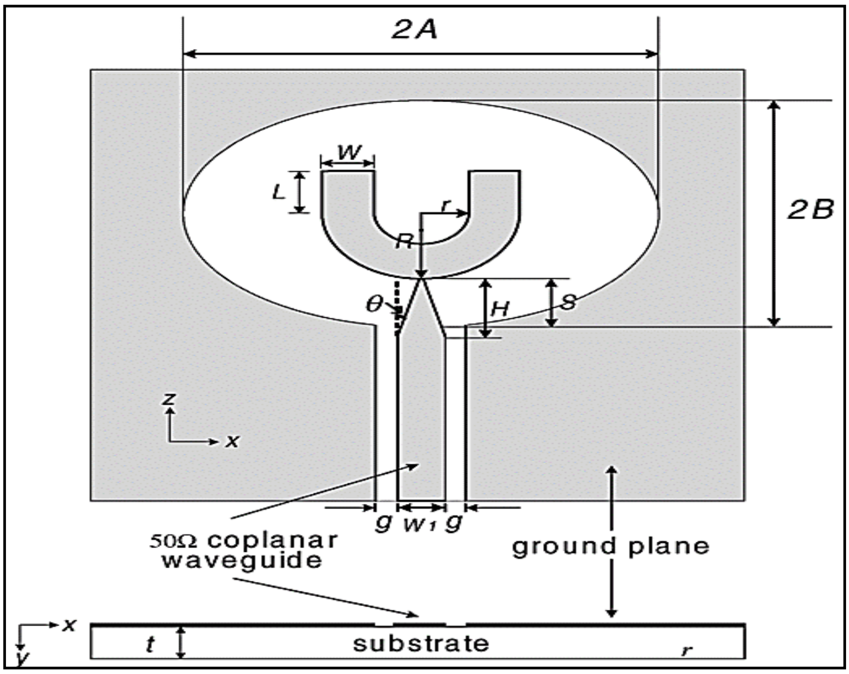


Figure 2.31CPW fed Elliptical slot antenna [69]

[In 2013, B. K. Kanaujia], proposed a CPW fed UWB antenna. The projected antenna gives a technique to reduce the monopole antenna by the loading of inverted L-strip over the usual monopole patch antenna to decrease the height of the antenna. The ground was vertically extended toward two sides of the single radiator and achieved an operating bandwidth of 2.6-13.04GHz for VSWR<2 [70].

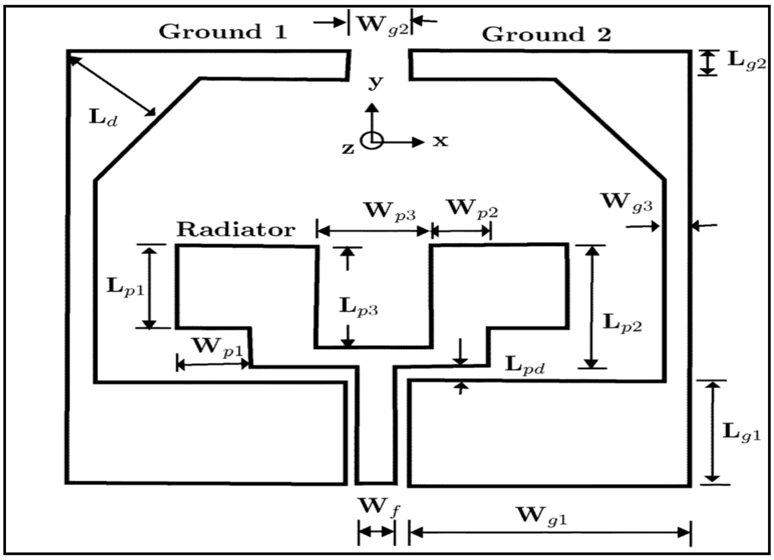


Figure 2.32 CPW fed inverted L-strip monopole UWB antenna [70]

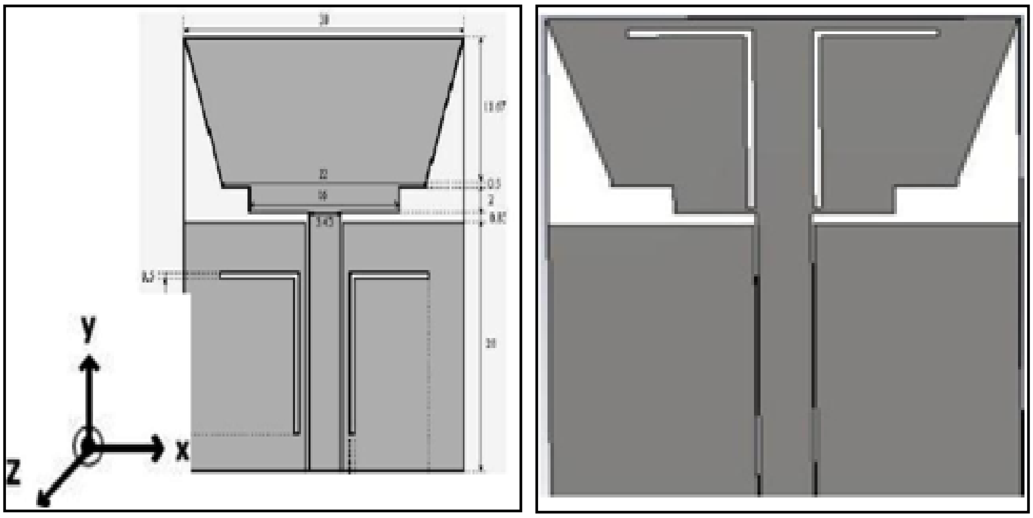
2.6 BAND NOTCHING TECHNIQUES IN UWB ANTENNA

To prevent the interference between the UWB, WLAN, WiMAX, X-band and ITU service band, a notch band function in UWB systems is required. Therefore, several design techniques have been projected to utilize planar UWB antenna to get notched bands for rejecting the WLAN, WiMAX, X-band and ITU service band, which include such as inserting slot structure, slitting on the edges, fractal feed structure, split ring resonators (SRR), complementary SRR, parasitic element, parasitic open circuit stub and electromagnetic band gap (EBG). UWB notched band antenna, is used for all UWB applications without interference with co-existing band.

2.6.1 Inserting Slots

UWB antennas comprising diverse cuts or slots, like, L-shaped [71], U-shaped [72-75], C-shaped [72, 76], V-shaped [77], meandered ground stub [78], and CPW slots [79] into a different radiator patch or ground plane or feeding strip were established to generate notches band characteristics. Generally, at notch frequency, the length of the slot or cut is roughly half or quarter wavelength. A few of them are illustrated here.

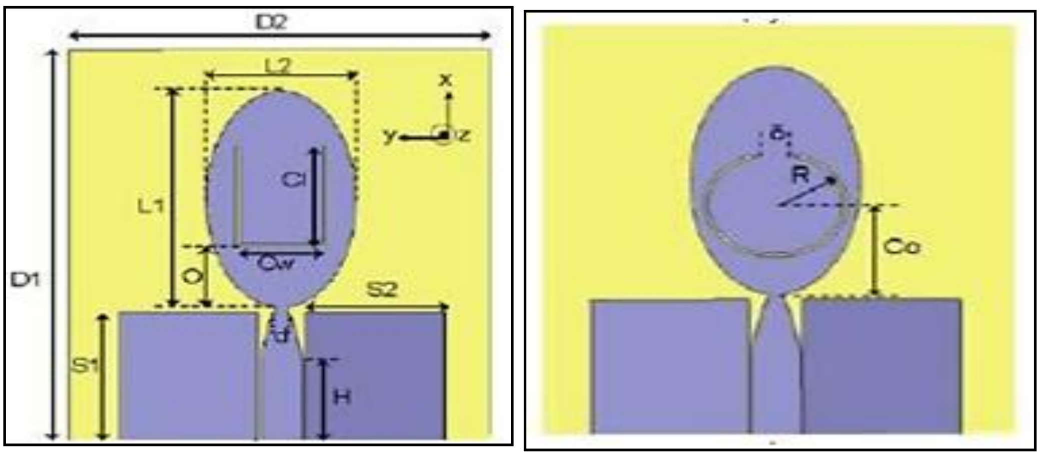
Figure 2.33 shows a compact elliptical CPW fed UWB antenna having two notch bands. The antenna size is 30×35 mm^2 and operating bandwidth (VSWR<2.5) 3.5-10GHz band. A frequency notched band at 5.65GHz is achieved by two inverted L slot near the CPW fed into the patch or into the ground plane and interference problem of WLAN at 5.5GHz, is removed in UWB communication. By the introduction of the two inverted L slots, the current flow has been stopped at 5.5GHz, and the radiation of the antenna suppressed [71].



(a) On ground plane (b) On patch

Figure 2.33 UWB antenna with two inverted L slots [71]

Figure 2.34 shows a compact elliptical CWP fed UWB antenna having U-shape and C-shape slots into the patch. Due to slots, the band notch function has been formed. At the notch frequency of 5.8GHz, the slot length is approximately λ /2 and the gain was reduced to 10dB in U-shape slot and 5dB in C-shape slot [72].



(a) U-shape slot (b) C-shape slot

Figure 2.34 CPW fed UWB antenna [72]

Figure 2.35 shows a microstrip feed single notched band planar UWB monopole antenna having a pair of meander lines in the ground. Due to a pair of meander lines a single notched band has been formed from 5.15-5.825GHz with gain suppression of 9dB [78].

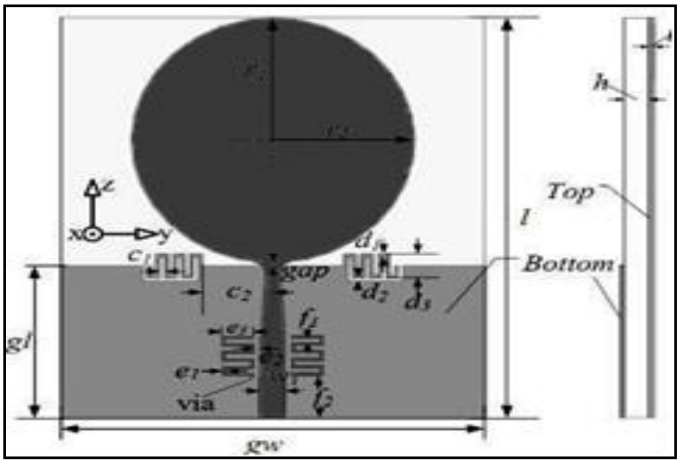


Figure 2.35 Microstrip fed UWB antenna incorporated with a pair of meander line [78]

Figure 2.36 shows a small CPW fed UWB monopole antenna achieving the frequency notch band function by inserting S-shape resonant structure on the feed line. Due to this a single notched band has been formed from 5.1-5.94GHz [79].

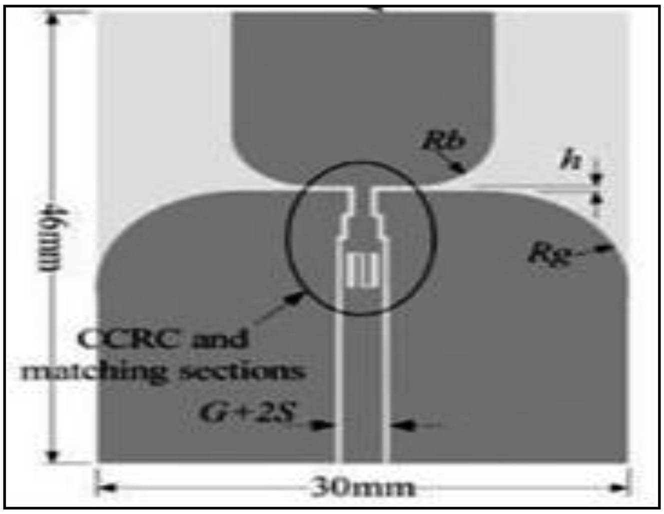
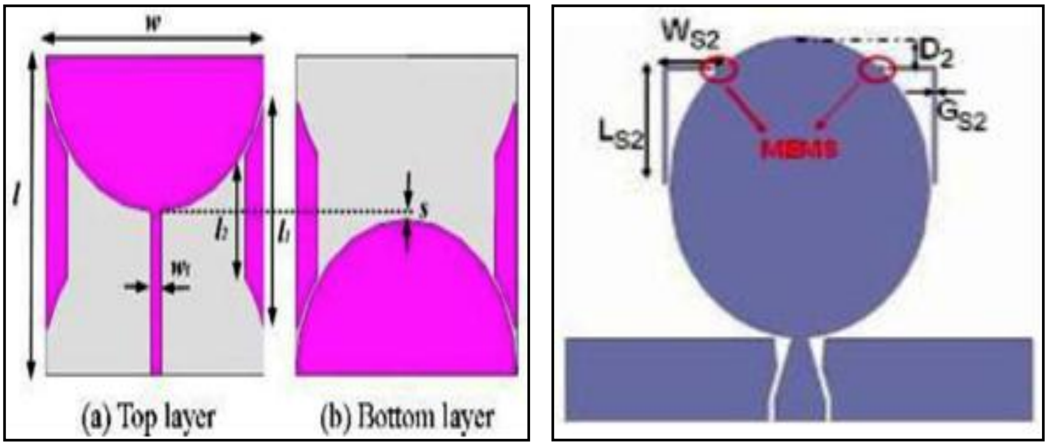


Figure 2.36 CPW fed UWB antenna with the single notched band function [79]

2.6.2 Parasitic Elements

Using parasitic elements is another technique by which a notched band function [80-84] can be formed. In [80], a microstrip fed UWB antenna with notched band property was studied. Figure 2.37 (a) shows, use of double parasitic elements in radiating patch at top and bottom layer. It achieved an operating bandwidth from 3-11GHz for S_{11}<-10dB and 9dBi gain suppression at notched band.

Figure 2.37(b) shows a CPW fed elliptical UWB monopole antenna having two resonating inverted L-shaped stubs, inserted into a radiating patch [81]. Due to this a single notched band has been formed at center frequency of 5.5GHz with 5dB gain reduction.



(a) Half circle shaped [80] **(b) Elliptical shaped [81]**

Figure 2.37 UWB antennas with parasitic strip

Figure 2.38 shows a CPW fed half circle UWB monopole antenna having notched band property in 5-6GHz by employing an extended strip and loaded strip. It also achieved a gain suppression of 10dB [84].

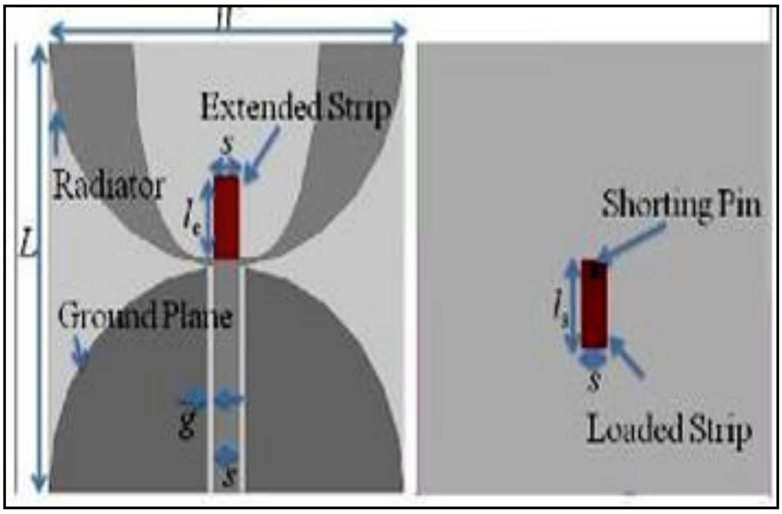


Figure 2.38 UWB antenna incorporated with an extended strip and a loaded strip [84]

2.6.3 Split Ring Resonant (SRR) and Complementary SRR (CSRR)

In [85] Pendry, projected an SRR and it is the electronically small size resonator to create notch band function for UWB antenna [86, 87]. Figure 2.39 shows a UWB antenna having SRR slot structure into radiating patch to create notch band function at 5.2GHz and gain suppression of 9dB [86]. In [88] obtain a single notched band property at 5.7GHz (WLAN).

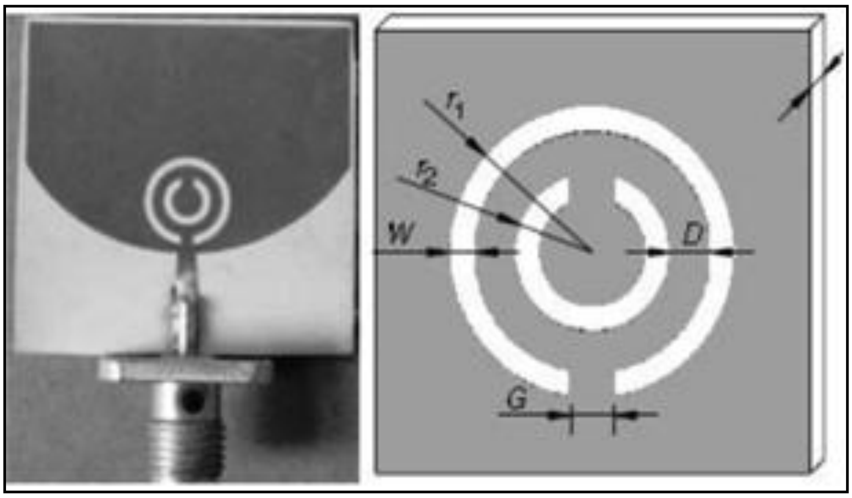


Figure 2.39 UWB antenna incorporated with SRR [86]

In 2015, C. Arora, S. S. Pattnaik, and R. N. Baral, proposed a bandwidth expansion and gain improvement of a microstrip patch antenna array at 5.8GHz (WiMAX). A split ring resonator has been proposed to load microstrip patch antenna array. The unloaded antenna array resonates at 5.8GHz with a gain of 4.3dBi and bandwidth of 425 MHz, though loaded with SRR the gain move towards to 5.7dBi and bandwidth enlarges to 610MHz, which corresponds to bandwidth improvement of 3% [89].

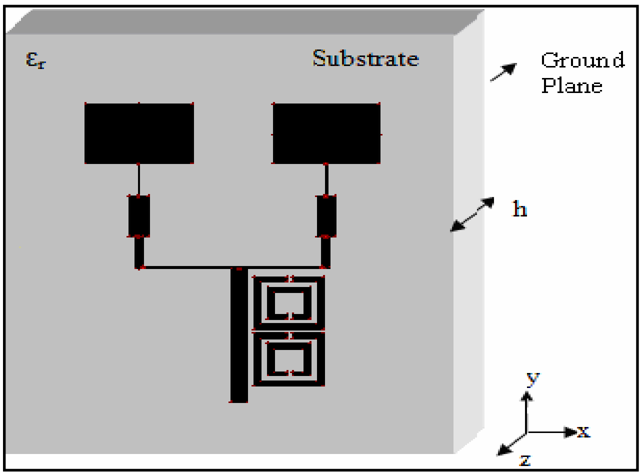
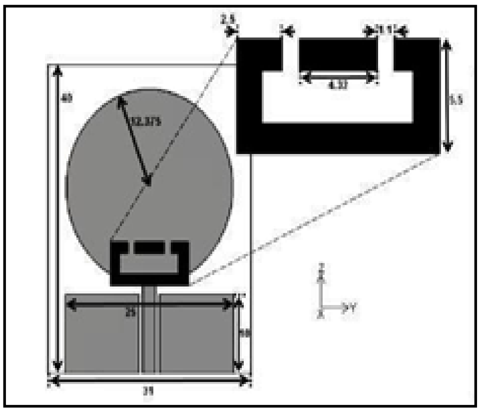
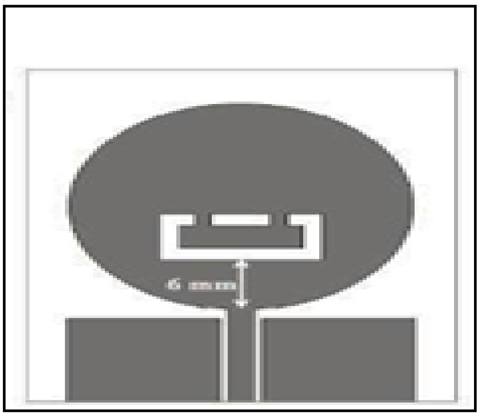


Figure 2.40 Antenna array incorporated with SRR [89]

2.6.4 Open Loop Resonant

Figure 2.41 (a) shows an open loop resonator that was located back side of radiating patch of UWB monopole antenna; providing nearly 11dBi gain suppression at a center notched frequency of 5.2GHz [90].Figure 2.41 (b) shows a double gap open loop resonator, etched on a patch of UWB monopole antenna; providing notch band at 4.2GHz with 5.8dBi gain suppression [91].

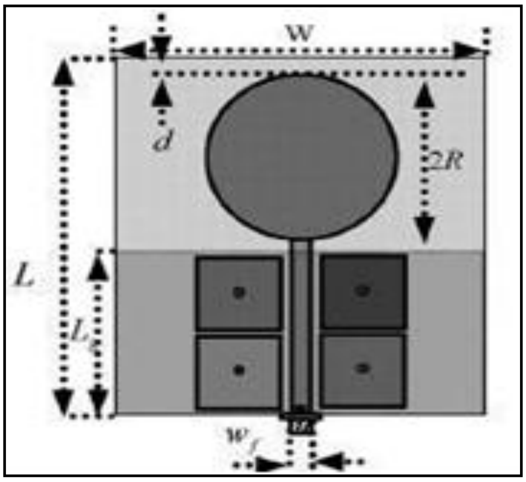



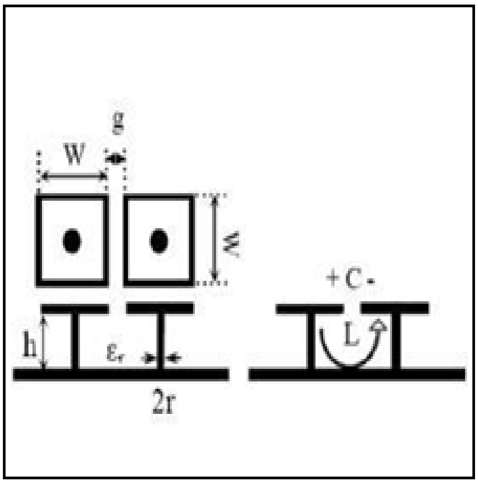
(a) Open loop resonator [90] **(b) Dual gap open loop resonator [91]**

Figure 2.41 Open loop UWB antenna

2.6.5 Electromagnetic Band Gap (EBG)

A notch band UWB antenna has also designed by using EBG structures [92-93]. Figure 2.42(a) shows the EBG structure of UWB antenna gives a band gap property [92]. In EBG metallic patches and ground planes are connected through short pins named vias.



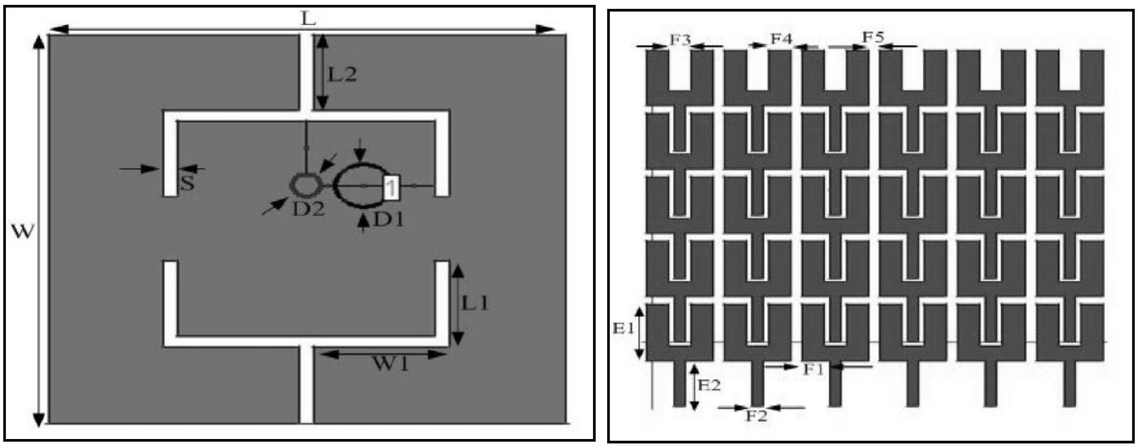


(a) EBG structure [92] **(b) Equivalent circuit of the EBG**

Figure 2.42 EBG structure of UWB antenna [92]

Figure 2.42 (b) illustrates an equivalent circuit of EBG, the current flow through the vias are indicated by inductor L and gap effect between the adjacent patches are indicated by a capacitor. The antenna achieved a centre notched band at 5.5GHz. It had a restricted band notched performance because of dielectric loss of the substrate.

In 2015, Arvind Chaubey, proposed a triple-band microstrip antenna with and without fork like electromagnetic band gap (EBG) structure for wireless mobile communication system. The proposed antenna consists of two simple Y-slots, integrating with compact size fork like EBG structure.



(a) Without EBG structure **(b) With EBG structure**

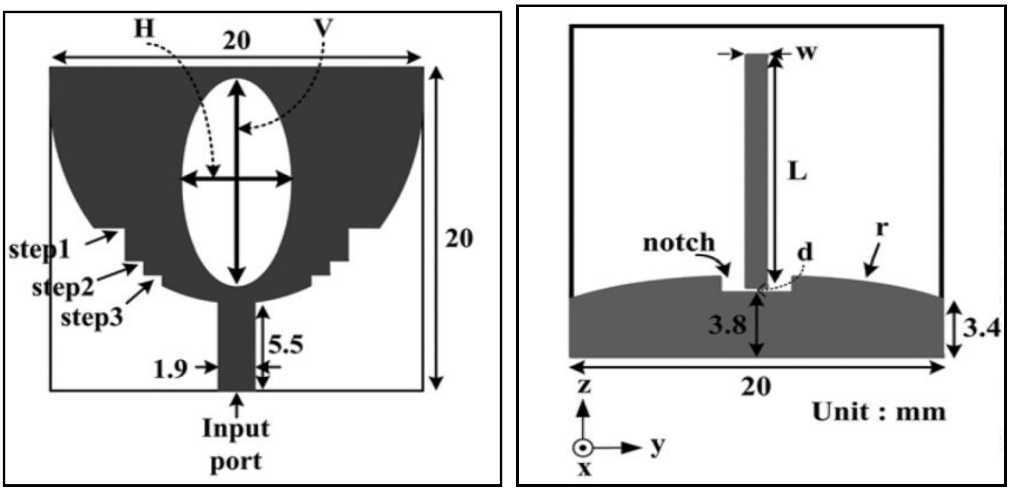
Figure 2.43 Multi band microstrip antenna

2.7 REVIEW OF MULTIPLE NOTCHED BAND UWB ANTENNAS

Although a lot of notched band techniques in UWB antennas have been reviewed in the previous section, commonly they are designed to attain one notched band property. In the present section, various techniques of multiple notched bands UWB antennas have been presented to eliminate the interference of one [94-99], two [100-109], three [110-117], four [118-121] and five [122-124] narrow band systems, with notched band functions.

2.7.1 Single Notched Band UWB Antennas

In 2006, K. H. Kim, proposed a single notch band UWB antenna with one parasitic strip. By creating the parasitic strip into the ground plane of the antenna, a band notch is generated. This antenna can operate over a 3.1-10.6GHz frequency range and band notch at 5.15-5.825GHz band [94].

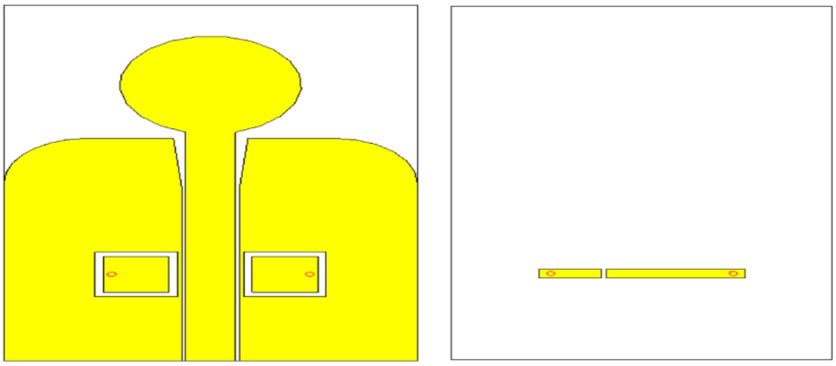


(a) Front view **(b) Back view**

Figure 2.44 Single notch band UWB antenna with parasitic strip [94]

In 2007, K. Chung, proposed compact single notch band UWB antenna. The projected antenna having two equal dimension monopole and a strip bar at the center, and achieved an operating bandwidth from 3.1-13GHz for S_{11}<-10dB, with one notch band at 4.9-6.0GHz [95].

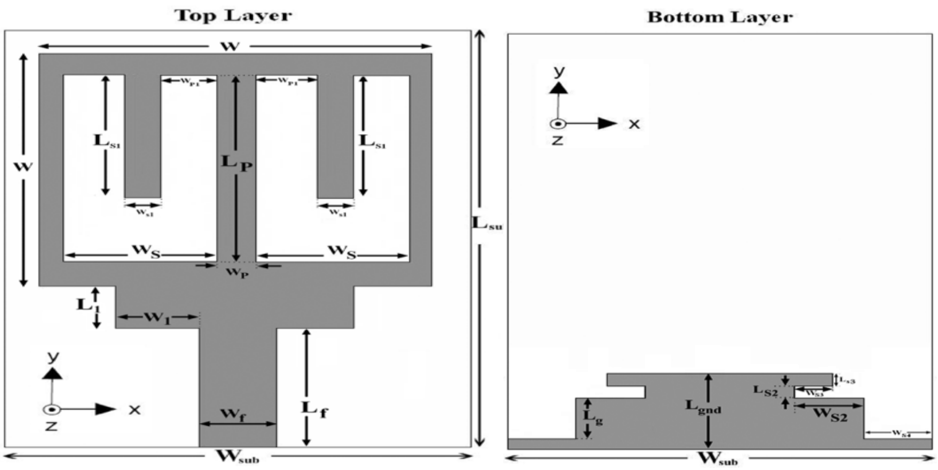
In 2016, M. R. Kamarudin, proposed a single notch band UWB antenna with CPW fed by using an electromagnetic band gap (EBG). In Figure 2.45, two structures are positioned adjacent to the transmission line of the UWB antenna. The band-notched characteristic can be disabled by switching the state of switch place at the strip line. Therefore, one notch band at 3.625-4.2GHz C-band satellite communication [96].



(a) Front view (b) Back view

Figure 2.45 Single notch band UWB antenna using electromagnetic band gap (EBG)[96]

In 2009, M. Ojaroudi, proposed a variable frequency notch band UWB antenna. The designed antenna has two U-shape slots in patch and T-shape sleeve into a notched ground plane that provides a wide bandwidth of 2.85-16.73GHz. By creating two U-shape slots into the patch, a frequency notch band of 5.02-5.97GHz is generated [97].



(a) Top layer (b) Bottom layer

Figure 2.46 Single notch band UWB antenna with parasitic strip [97]

In 2010, K. G. Thomas, proposed a single notched band UWB antenna. Figure 2.47shows the bevel slot into radiating patch and the ground plane, impedance bandwidth can be improved. By an additional radiation patch on ground, a notch band is generated from 5-6GHz and an operating bandwidth is 3.1-10.6GHz for S_{11}<-10dB [98].

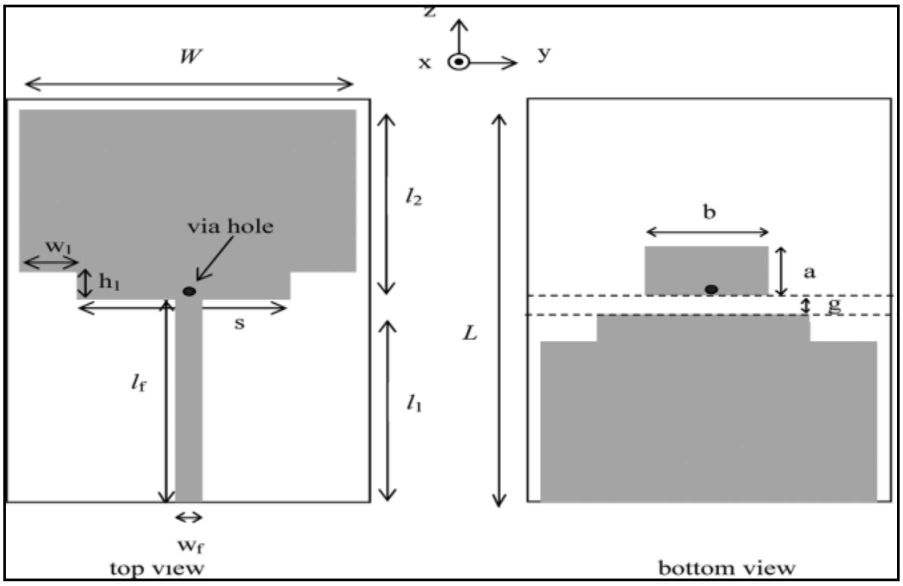


Figure 2.47 Single notched band UWB antenna [98]

In 2011, S. K. Koul, M. Kumar and A. Basu, proposed a single notch band UWB antenna. By etching E-shaped slot into the patch a band notch function is achieved. The UWB antenna operating bandwidth is from 2.8-11.8GHz for VSWR<2, and notch band at 5-6GHz (WLAN band) [99].

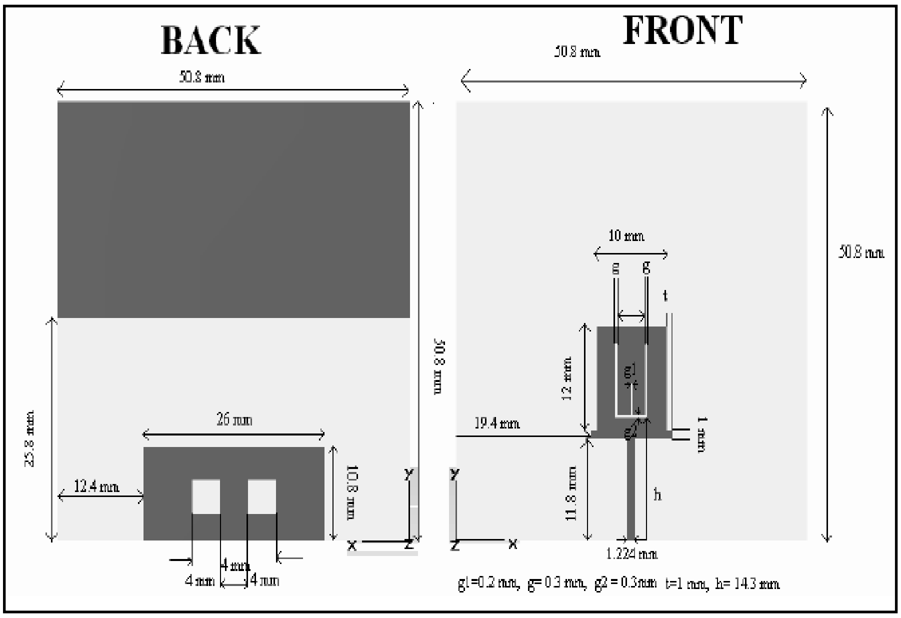
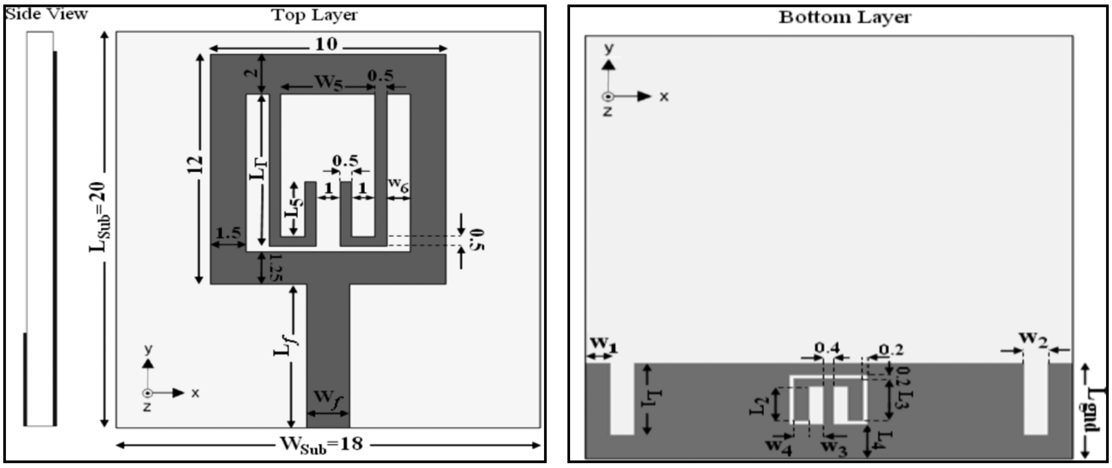


Figure 2.48 Single notched band microstrip feed UWB antenna [99]

2.7.2 Double Notched Band UWB Antennas

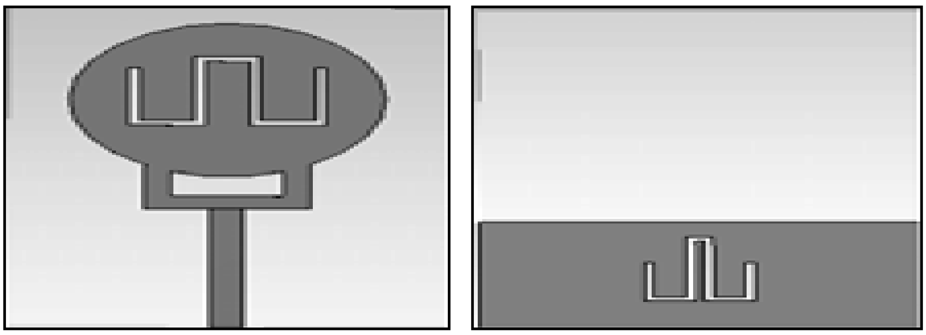
In 2010, M. Abdollahvand, proposed a compact dual notched band UWB monopole antenna for UWB applications. Two I-shape slots were created into ground plane, additional resonances are energized, and therefore the bandwidth has been enhanced up to 123%. By adding a pair of Γ shaped stubs into patch and a customized G slot on the ground, two notch bands are created and shown in Figure 2.49, and achieved an operating bandwidth from 2.8-11.8GHz for VSWR<2 for, with one notch band at 3.3-3.8GHz (WiMAX) and another notch band at 5.1-6GHz (WLAN) [100].



(a) Top Layer **(b) Bottom layer**

Figure 2.49 Dual notched band UWB monopole antenna [100]

In 2010 L.Y. Cai, proposed a compact dual notched band circular UWB monopole antenna. Figure 2.50 shows two W shaped slots etched into the radiating patch and the ground plane, which creates two notched bands and achieved an operating bandwidth from 3.0-10.8GHz for VSWR<2 for, with one notch band at3.4-3.8GHz (WiMAX) and another notch band at 4.8-6.2GHz (WLAN) [102].



(a) Top Layer **(b) Bottom layer**

Figure 2.50 Dual notched band UWB antenna [102]

2.7.3 Triple Notched Band UWB Antennas

In 2012, M.T. Islam, proposed a triple band notch UWB antenna with a modified partial ground plane. Figure 2.51 shows three resonating elements placed over a ground plane and these can produce three notched bands. The proposed antenna achieved an operating bandwidth of 2.9-11GHz (VSWR<2) having triple notch bands of 3.26-3.71GHz (WiMAX), 5.15-5.37GHz (WLAN) and 5.78-5.95GHz (WLAN) [110].

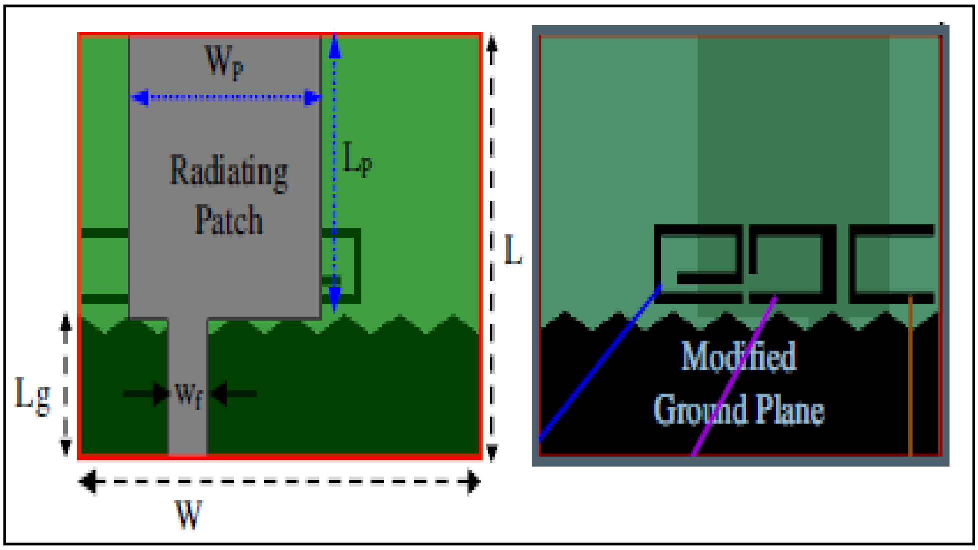


Figure 2.51 Triple notched band UWB antennas with modified ground plane [110]

In 2013, F. Zhu, proposed a triple notched band UWB antenna. Figure 2.52 shows an antenna having a rectangular notch stub into half circle shape patch and half circle shape ground plane and operating bandwidth from 3.1-10.6GHz for VSWR<2, with notch band at3.15-3.62GHz (WiMAX band), 5.1-5.38GHz and 5.72- 6.12 (WLAN band) [111].

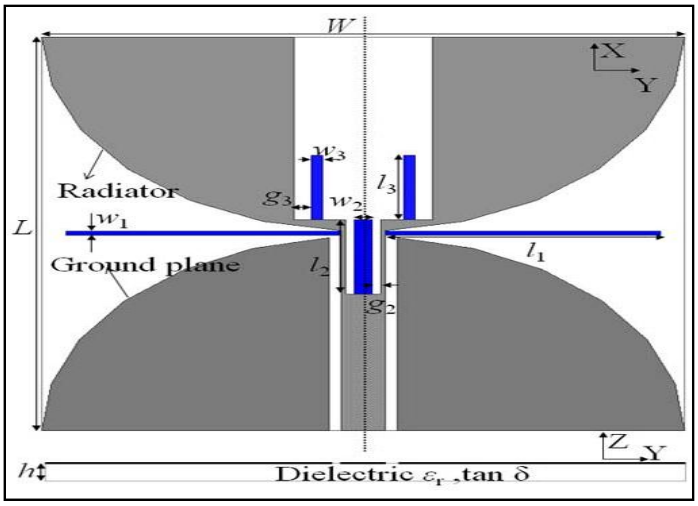


Figure 2.52 Triple notched band semi-circular UWB antenna [111]

In 2014, D. Sarkar, proposed a triple notched band microstrip feed compact UWB antenna. Figure 2.53 shows an antenna having a half circle shaped patch and ground plane and two ESCSRRs of dissimilar size are etched on the patch and two band notches 3.3-3.8GHz WiMAX and 5.15-5.85-GHz WLAN are achieved. Also, two rectangular split rings are placed near the feed line of the antenna. Due to this a notch band 7.9-8.4GHz X-band is obtained [112].

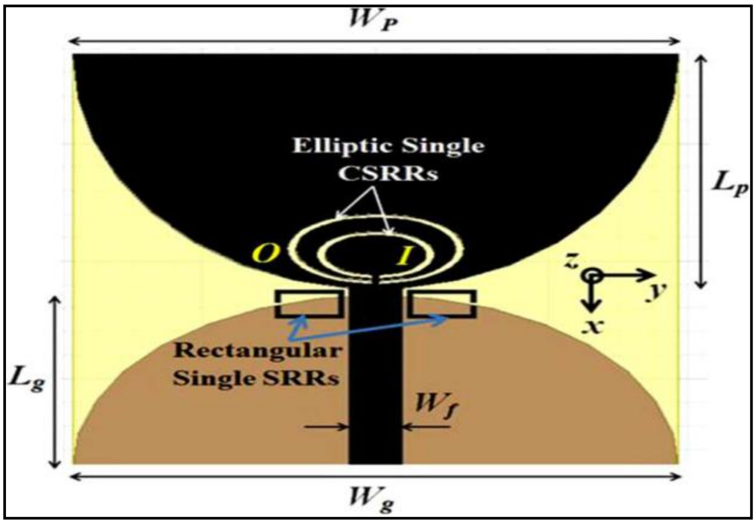


Figure 2.53 Triple notched band half circular UWB antenna [112]

2.7.4 Quadruple Notched Band UWB Antennas

In 2011, D.O. Kim, proposed quadruple notched band UWB antenna. Three CSRRs are etched on the radiating patch and its operating bandwidth is from 3.1-10.6GHz with VSWR<2. Due to these CSRRs four notch bands are created at of 2.37-2.9GHz, 3.27-3.76GHz, 5.2-5.89GHz and 8.06-8.8GHz [118].

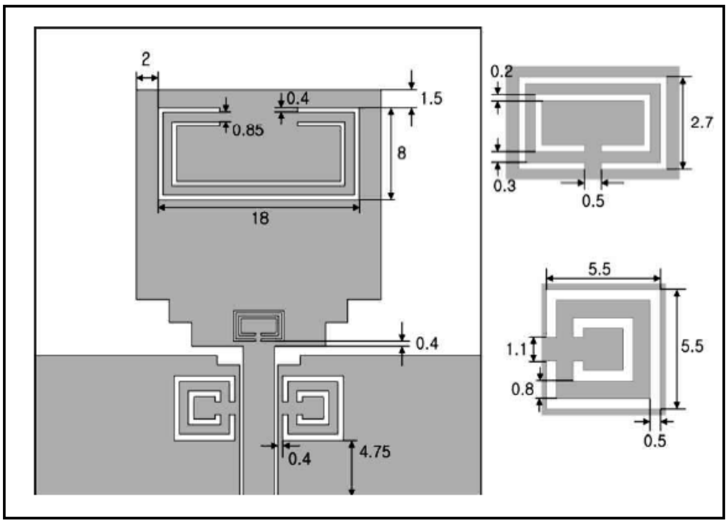


Figure 2.54 Quadruple notched band CPW fed UWB antenna [118]

In 2013, X. Li, proposed four notched bands compact CPW fed UWB antenna. Figure 2.55 shows the antenna having C-shaped parasitic strip to create a band notch at 8.01-8.55GHz for the ITU band, two C-shape slots, and an inverted U-shape slot created on patch to generate three band notches at 5.15-5.35GHz (WLAN), 5.75-5.85GHz (WLAN) and 7.25-7.75GHz X-band and its operating bandwidth is from 3.1-12GHz with VSWR<2 [120].

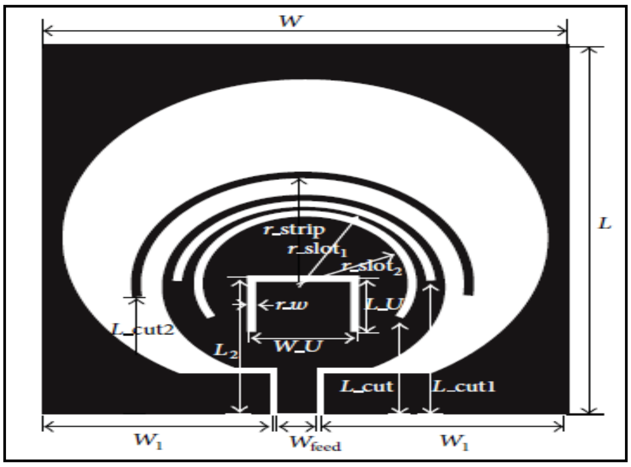


Figure 2.55 Quadruple notched band UWB antenna [120]

2.7.5 Five Notched Band UWB Antennas

In 2015, Md. M. Islam, proposed five notched bands compact microstrip feed UWB antenna having a peak gain of 1.62dBi. Five notched band functions have been generated at frequencies of 3.6GHz, 5.2GHz, 5.8GHz, 7.5GHz, and 8.3GHz by creating three C-shape slots into a patch and two C-shape slot into the ground. This proposed antenna achieved an operating bandwidth from 3.05-10.6GHz for VSWR<2, notch bands of 3.4-3.8GHz (WiMAX), 5-5.3GHz (WLAN), 5.6-6 (WLAN), 7.2-7.65GHz (X-band) and 7.95-8.55GHz (ITU-band) [122].

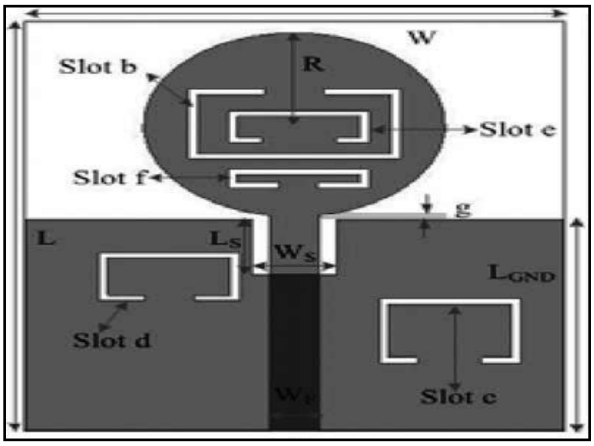
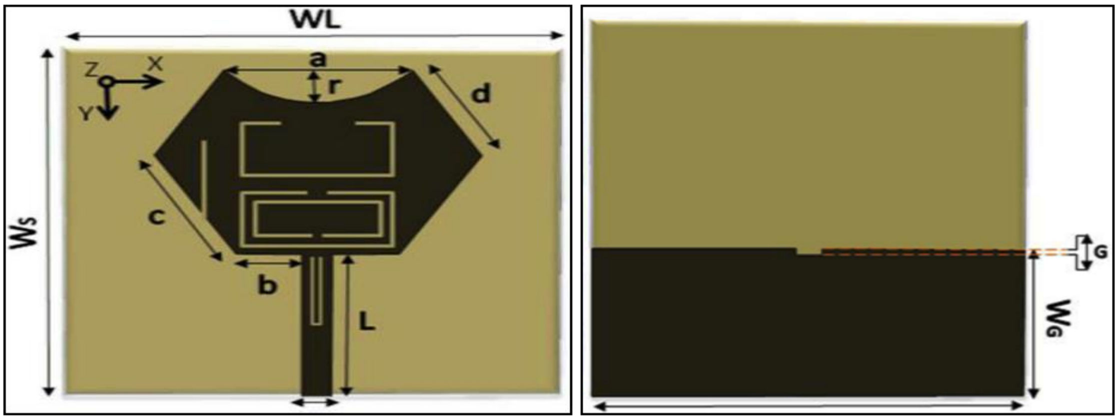


Figure 2.56 Five notched band circular UWB antenna [122]

In 2017, B. Hammache, proposed a UWB antenna with five notched bands having the frequency range from 2.5-11.58GHz with VSWR<2. The projected antenna has a size of 30x30 mm^2. Five slots are etched into the patch and feed line; provide notch bands of 3.21-3.53GHz (WiMAX), 3.85-4.5GHz and 5.05-5.75GHz(WLAN), 6.39-7.36GHz (C-band), and X- 8.025-8.4 GHz (X-band) [124].



(a) Top view **(b) Bottom view**

Figure 2.57 Five notched band UWB antenna [124]

2.8 CONCLUSION

In this chapter, development of UWB antenna, an introduction of microstrip antennas, different feed techniques for exciting the antenna, different notched band techniques for band stop filtering have been reviewed. The advantages of microstrip feed and CPW feed over other methods of feeding becomes a preferable choice for designing of antennas in current research work. In accordance with the objectives defined in the research work: design and implementation of ultra-wideband antenna with multiple notched bands. A literature review has been presented according to the design and results of the notched bands UWB antenna. In literature survey, it is clear that few UWB antennas having multiple notched band characteristics are available. Only few antennas, [122-124] can attain five notch bands properties and, these antennas have limited gain suppression. To deal with the problems recognized, it is necessary to develop UWB antennas with notched bands for upcoming UWB wireless commutations, which is the main aim of this research work.

CHAPTER 3

A COMPACT UWB PLANAR ANTENNA DESIGN

3.1 INTRODUCTION

In the literature review, it has been observed that different types of planar ultra wideband antennas having microstrip feed or coplanar waveguide feed are the most capable antennas for UWB application. The main advantages of such planar antennas are large bandwidth, steady radiation pattern, impedance matching and simple addition with RF and supplementary systems. In addition, these antennas can be easily fabricated and with low-cost technology.

Due to the significance of planar UWB antenna, a simple rectangular microstrip feed planar UWB antenna has been proposed in this chapter. Various impedance bandwidth improvement techniques, such as bevel slots on radiating patch and ground plane are introduced to attain UWB range. The bevel slot technique is also applied to a get large impedance bandwidth of a rectangular microstrip antenna. Designing of a compact planar UWB antenna with high impedance bandwidth and steady radiation pattern are the main objects of this chapter.

3.2 INITIAL RECTANGULAR MICROSTRIP UWB ANTENNA DESIGN

A rectangular microstrip antenna is selected as a fundamental structure due to its wide operating bandwidth and the adequate radiation patterns. Figure 3.1 illustrates the geometry of the proposed UWB antenna. The proposed antenna-1 has a very small size of W×L ($26\times27mm^2$) and printed on a substrate FR4 with ε_r = 4.4, thickness ht = 1.6mm and loss tangent tan δ = 0.02. The top and bottom patches, printed on the substrate are radiating patch and ground plane respectively. The width of the microstrip feed W_f = 3mm is set to attain 50Ω characteristic impedance which is linked to the end of the feeding strip and the edge of the ground plane. ‘g’ is the gap between the radiating patch and the ground plane. The proposed antenna has been designed with optimal parameters tabulated in Table 3.1. The electromagnetic software IE3D is used to design and simulate the antenna. Figure 3.2 and Figure 3.3, respectively shows the simulated return loss and VSWR results of the proposed UWB antenna-1.

Table 3.1 Proposed UWB antenna-1 dimensions

Parameters	W	L	W_P	L_P	W_g	L_g	W_f	g
Dimension (mm)	26	27	13	16	26	10	3	0.7

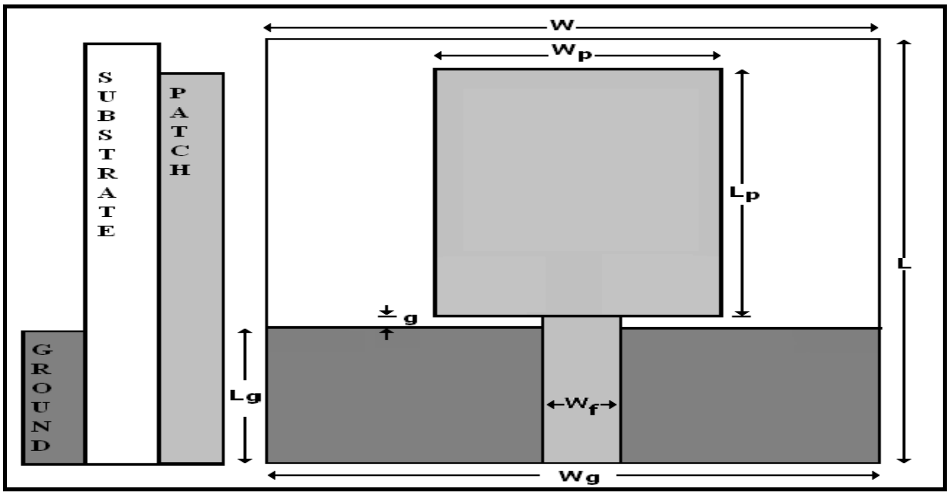


Figure 3.1 Geometry of the rectangular microstrip antenna-1

Figure 3.2 illustrates the simulated reflection coefficients S_{11}(dB) of the projected UWB antenna. It is evident that the projected antenna has wideband performance of 3.2GHz to 11.8GHz for S_{11}<-10dB, covering the whole UWB band. The antenna covers a bandwidth of 8.6GHz. Figure 3.3 illustrates the simulated VSWR of the projected UWB antenna. The VSWR curve also shows a satisfactory performance of the antenna over the entire UWB band.

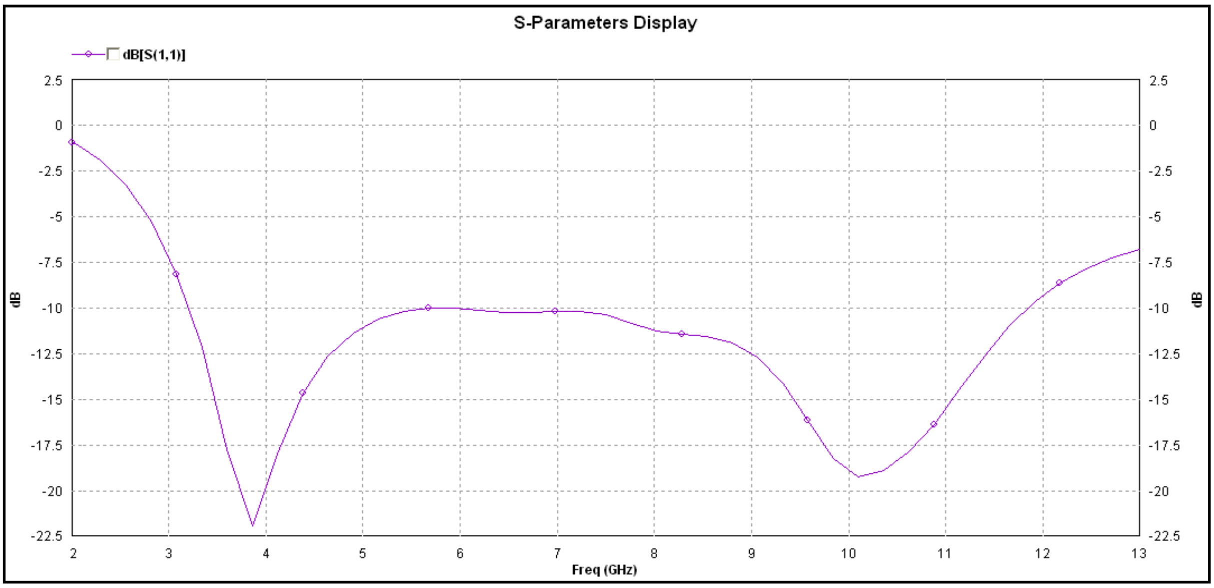


Figure 3.2 Simulated reflection coefficient S_{11}(dB) of rectangular microstrip antenna

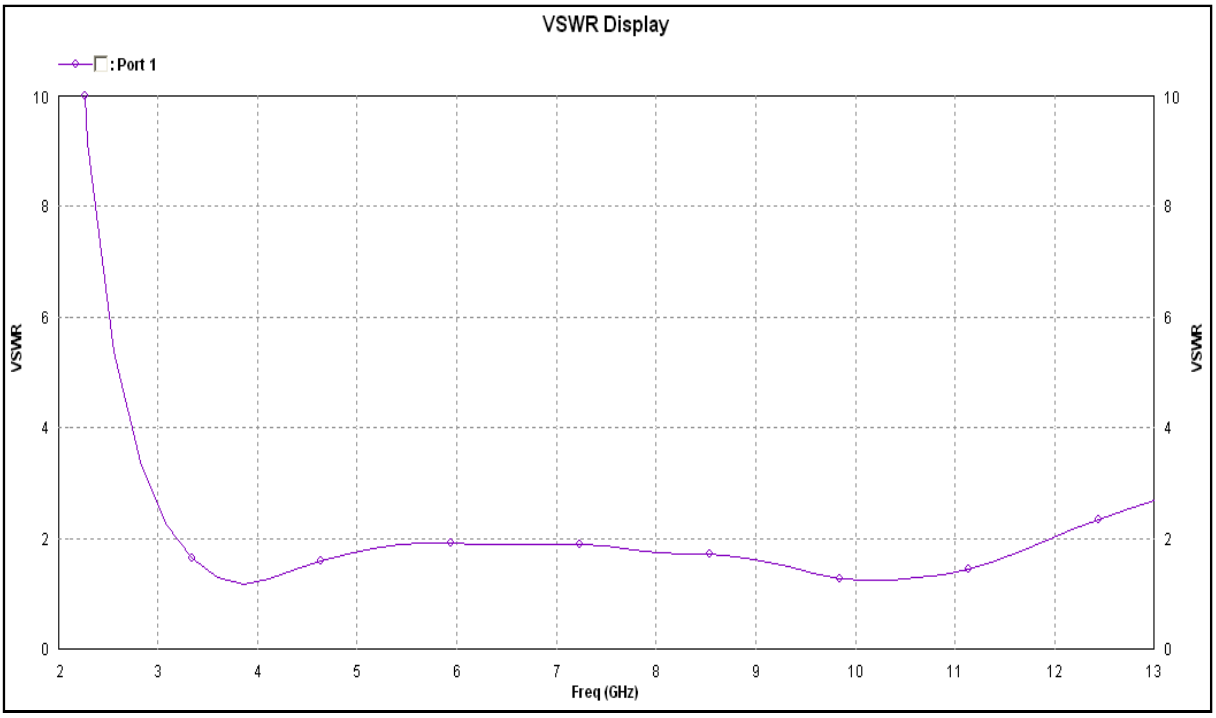


Figure 3.3 Simulated VSWR of rectangular microstrip antenna

3.3 PARAMETRIC ANALYSIS OF THE ANTENNA

A microstrip UWB patch antenna offers numerous parameters to the antenna designer that can be optimized to obtain a whole UWB band operation. The performance of projected antenna, in terms of return loss and impedance bandwidth by varying the individual parameters of the antenna is discussed in this section.

3.3.1 Effect of variations in the patch width (W_P)

The patch width of the antenna i.e. the radiating edges in a rectangular patch affects the operating frequency of the antenna operation. In proposed antenna, the patch width (W_P) has been varied to observe the effect of this variation on impedance bandwidth of operation. Figure 3.4 shows the variation in impedance bandwidth and return loss with the change in patch width from 12mm to 14mm.

It can be seen from Figure 3.4 and Table 3.2, that the upper bandwidth gets decreased with increasing of the patch width, whereas the lower bandwidth increased when the patch width is increased. The value of return loss in upper bandwidth increases with the increase of the patch width. Since UWB wireless applications need an impedance bandwidth from 3.1GHz to 10.6GHz, therefore the optimized patch width is selected as13 mm.

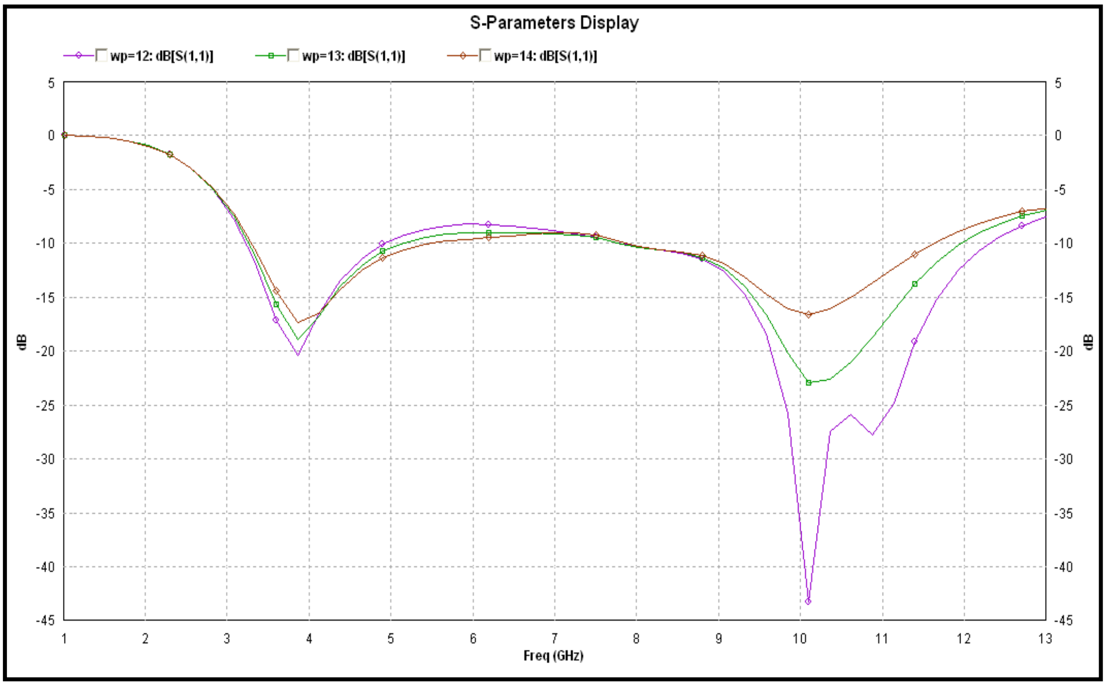


Figure 3.4 Simulated S_{11}(dB) of patch antenna-1 for different W_P

Table 3.2 Effect of variations in the patch width (W_P)

Patch Width (mm)	Resonant Band Lower (GHz)	Resonant Band Upper(GHz)	Lower Bandwidth (GHz)	Upper Bandwidth (GHz)
12	3.21-4.92	7.77-12.3	1.71	4.53
13	3.22-5.15	7.77-11.97	1.93	4.2
14	3.3-5.5	7.77-11.63	2.2	3.86

3.3.2 Effect of variations in the patch length (L_P)

The patch length in a rectangular patch antenna also affects the operating frequency of operation. In proposed antenna, the patch length (L_P) has been changed to observe the effect of this variation on resonant band of operation. Figure 3.5 shows the variation in impedance bandwidth and return loss with the change in patch length from 15mm to 17mm.

Table 3.3 Effect of variations in the patch length (L_P)

Patch Length (mm)	Resonant Band Lower (GHz)	Resonant Band Upper (GHz)	Lower Bandwidth (GHz)	Upper Bandwidth (GHz)
15	3.39-6.21	8.46-11.97	2.82	3.51
16	3.22-5.15	7.78-11.97	1.93	4.19
17	3.15-4.75	7.42-11.97	1.6	4.55

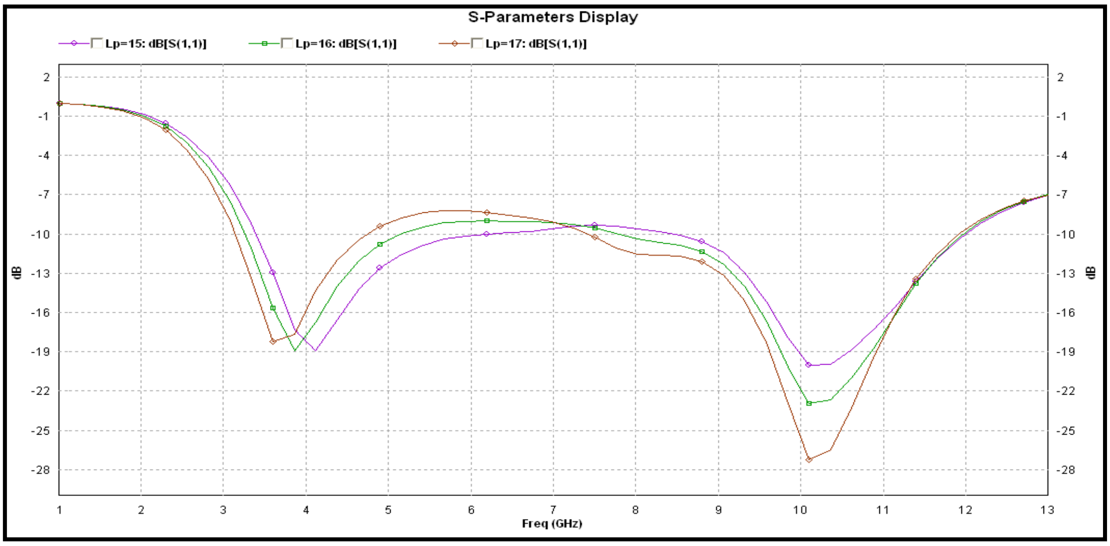


Figure 3.5 Simulated S_{11}(dB) of patch antenna-1 for different L_P

It can be concluded from Figure 3.5and Table 3.3, that the upper impedance bandwidth gets increased and shifted to lower value side and the lower impedance bandwidth decreased and also shifted to lower value side when the patch width is increased. The value of return loss decreases in upper bandwidth and increases in lower bandwidth with the increase of the patch width. Therefore, the optimized patch length of the patch selected as16mm.

3.3.3 Effect of variations in the ground plane width (W_g)

The width of ground plane W_g affects the antenna operating bandwidth. Figure 3.6 illustrates that, the reflection coefficients of the patch antenna, the value of S_{11}(dB) varies with the change of ground plane width W_g from 24mm to 28mm. It can be seen from Figure 3.6 and Table 3.4, that the upper impedance bandwidth gets decreased with increasing of the ground plane width, whereas the lower impedance bandwidth increased when the ground plane width is increased. The value of S_{11}(dB) in upper bandwidth and lower bandwidth decreases with the increase of the ground plane width. Therefore, optimum the ground plane width W_g is selected as 26mm.

Table 3.4 Effect of variations in ground plane width (W_g)

Ground Plane Width (mm)	Resonant Band Lower (GHz)	Resonant Band Upper (GHz)	Lower Bandwidth (GHz)	Upper Bandwidth (GHz)
24	3.3-5.03	7.89-12.1	1.73	4.21
26	3.22-5.15	7.78-11.97	1.93	4.19
28	3.23-5.18	8.4-11.73	1.95	3.33

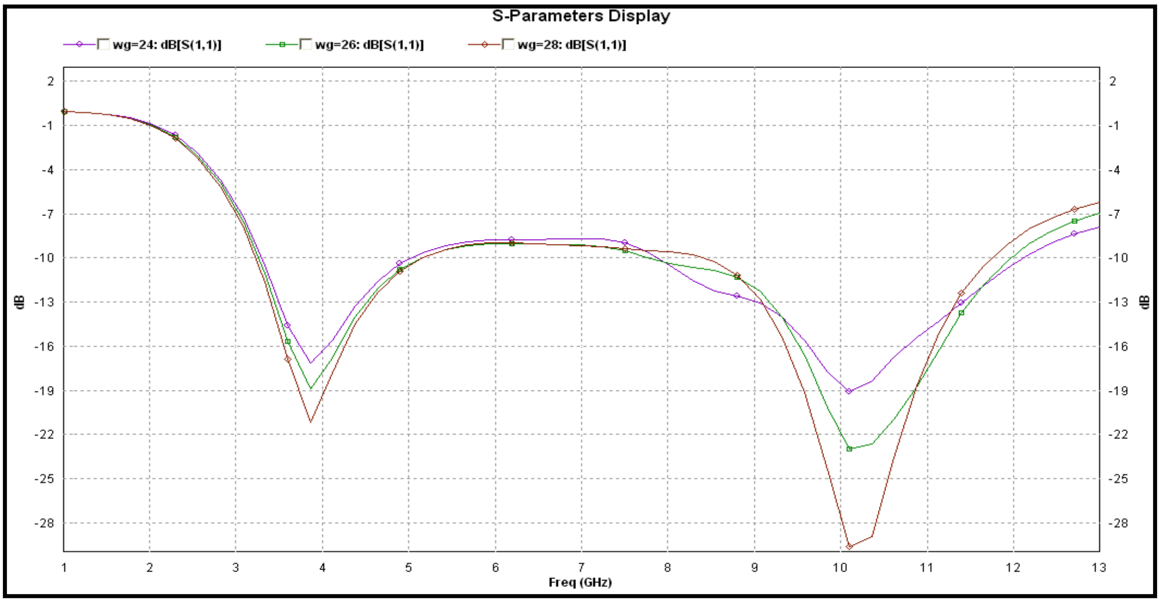


Figure 3.6 Simulated S_{11}(dB) of patch antenna-1 for different W_g

3.3.4 Effect of variations in the ground length (L_g)

Figure 3.7 illustrates that, the return loss of the patch antenna, S_{11}(dB) varies with the change of ground plane length L_g from 9mm to 11mm. It can be seen from Figure 3.7 and Table 3.5, that both the upper and lower impedance bandwidth gets decreased and shifted to lower value side with increasing the length of ground plane L_g. The value of return loss in upper and lower bandwidth decreases with the length of the ground plane L_g is increased. Therefore the optimum ground plane length L_g is selected as 10mm.

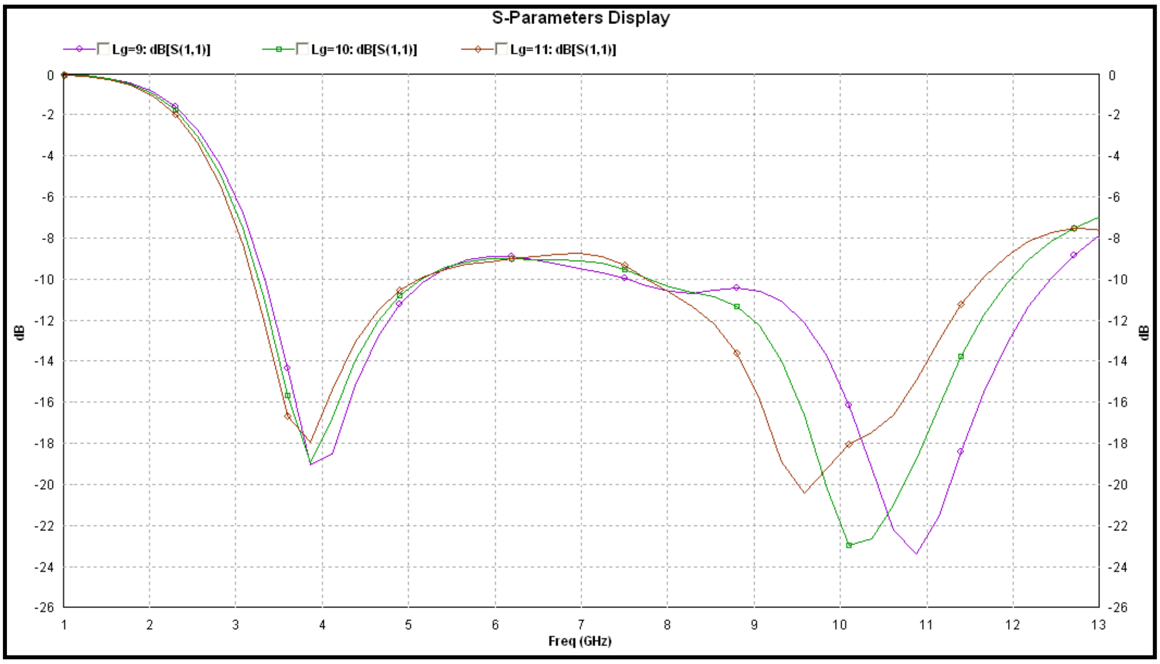


Figure 3.7 Simulated S_{11}(dB) of patch antenna-1 for different L_g

Table 3.5 Effect of variations in ground plane length (L_g)

Ground Plane length (mm)	Resonant Band Lower (GHz)	Resonant Band Upper (GHz)	Lower Bandwidth (GHz)	Upper Bandwidth (GHz)
9	3.34-5.22	7.51-12.42	1.88	4.91
10	3.22-5.14	7.8-11.97	1.92	4.17
11	3.19-5.11	7.79-11.62	1.92	3.83

3.3.5 Effect of variations in the feed gap (g)

The feeding gap g is another antenna designing parameter to observe the antenna performance. Figure 3.8 illustrates that, the reflection coefficients of the patch antenna,S_{11}(dB) varies with the change of feeding gap ‘g’ from 0.3mm to 0.7mm.

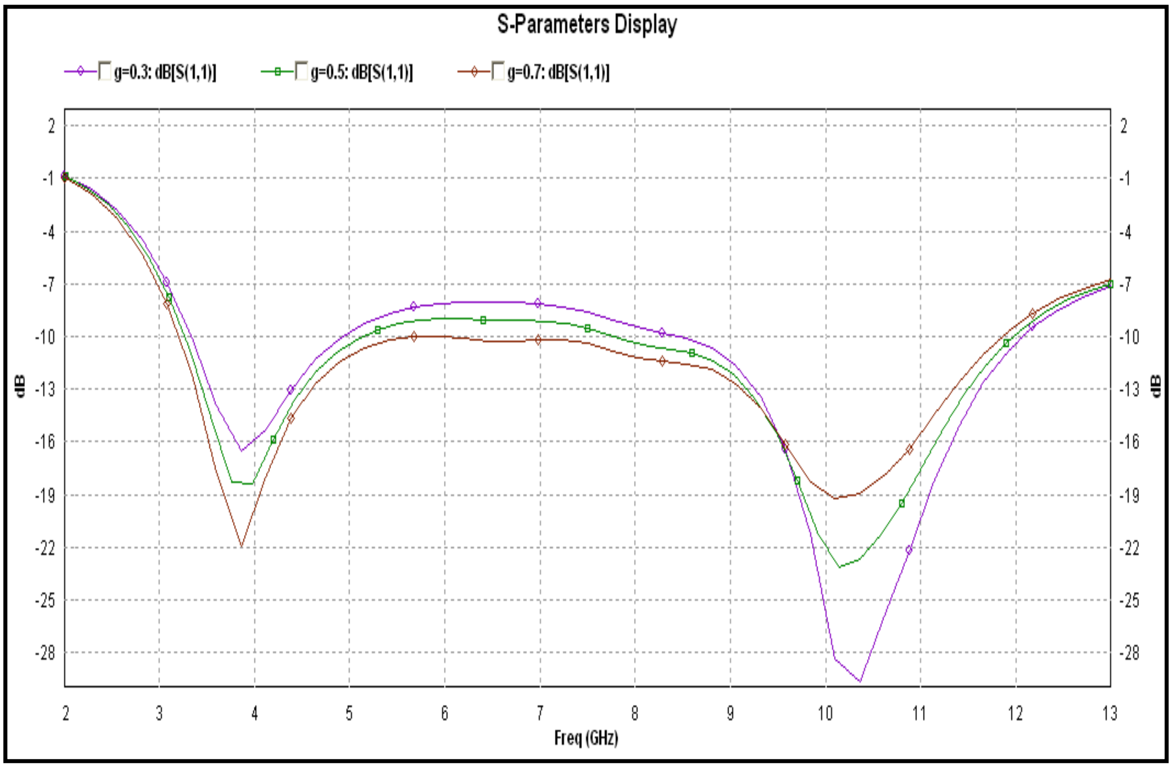


Figure 3.8 Simulated S_{11}(dB) of patch antenna-1 for different ‘g’

It is evident that the impedance bandwidth has been responsive to the gap ‘g’. The total impedance bandwidth (combination of lower and upper bandwidth) is increased when feeding gap ‘g’ is increased to 0.7mm. At ‘g’ equal to 0.7mm, the proposed antenna covers the whole UWB band. Therefore the optimum feeding gap ‘g’ is selected as 0.7mm. The results are shown in Table 3.6.

Table 3.6 Effect of variations in feed gap (g)

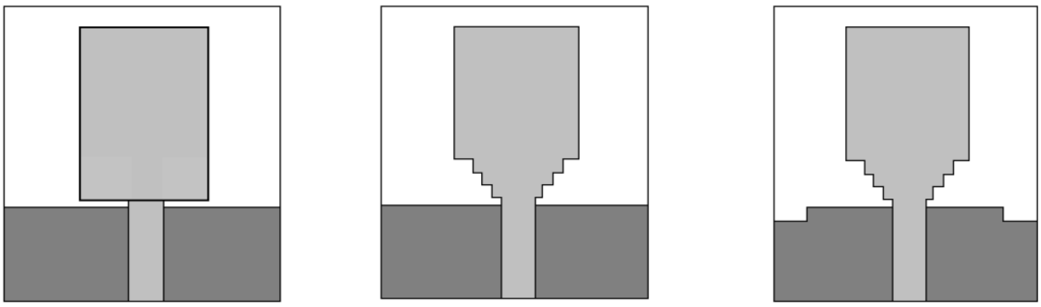
Feed Gap (mm)	Resonant Band Lower (GHz)	Resonant Band Upper(GHz)	Lower Bandwidth (GHz)	Upper Bandwidth (GHz)
0.3	3.33-4.92	8.48-12.07	1.59	4.53
0.5	3.26-5.13	7.68-11.98	1.87	4.3
0.7	3.2-11.84	3.2-11.84	8.64	8.64

3.4 MODIFIED UWB PLANAR MONOPOLE ANTENNA DESIGN

The parametric analysis has been carried out to improve the impedance bandwidth of an initial structure of the UWB antenna. Now, the bevel slots on radiating patch and bevel slots on ground plane are introduced, to further improve the bandwidth of the antenna. The bevel slot technique is used to get a large impedance bandwidth of a rectangular microstrip antenna at lower and upper frequency.

3.4.1 Structural parametric variations

Three different antenna structures are designed, during the antenna designing procedure, shown in Figure 3.9. Antenna-1 the perfect rectangular radiator antenna, Antenna-2 having bevel slots on radiator patch and Antenna-3 having bevel slots on radiator patch and ground plane both.



(a) Antenna-1 (b) Antenna-2 (c) Antenna-3

Figure 3.9 Three different antenna structures (Antenna-1, Antenna-2 and Antenna-3)

The patch length in a rectangular patch antenna affects the operating frequency of the antenna operation. In proposed antenna-2, the patch length has been changed by introducing bevel slots in the lower segment of the patch. The proposed antenna-3 has been designed by introducing a bevel slot in the ground plane of the antenna-2. It can be observed the effect of these modifications, on a resonant band of operation.

Figure 3.10 and Table 3.7 illustrates the reflection coefficient of antenna-1, 2 and 3. On the basis of impedance bandwidth and return loss value the performance of antenna-1, 2 and 3 are compared. The return loss of antenna-3 is better than antenna-1. Also, antenna-3 covers the entire UWB wireless application bandwidth from 3.1GHz-10.6GHz. Therefore, antenna-3 is selected as final structure for further designing process.

Table 3.7 Effect on bandwidth by structural parametric variations

Structure	Band Covered	Bandwidth
Antenna-1	3.2-11.8 GHz	8.6GHz
Antenna-2	3.05-5.02 GHz	1.97GHz
	6-10.1GHz	4.1GHz
Antenna-3	3.1-11.53GHz	8.43GHz

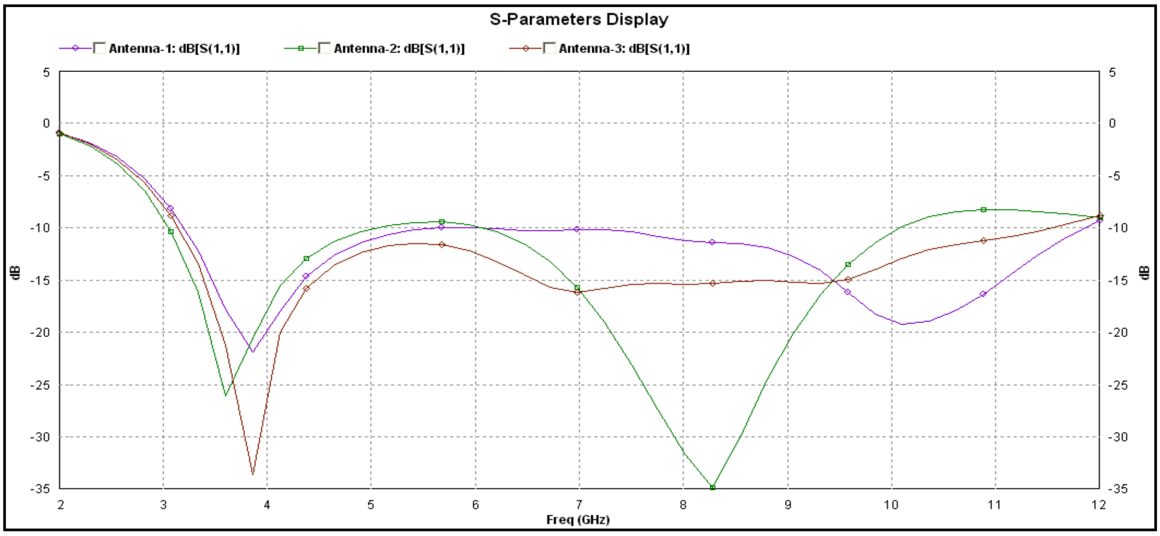
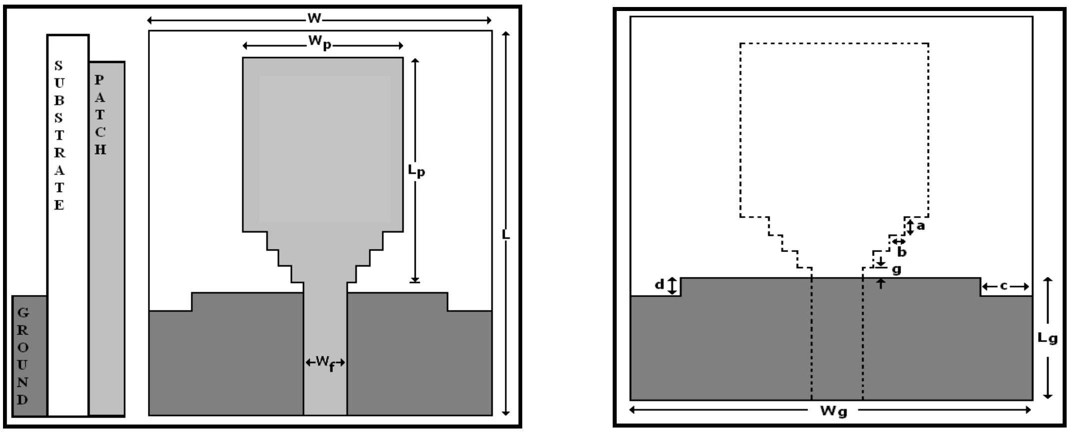


Figure 3.10 Simulated S_{11}(dB) of three UWB antenna-1, 2 and 3

3.4.2 Final Antenna Configuration

Figure 3.11 illustrates the final geometry and design of the modified UWB antenna-3. The geometry of antenna-1 is modified to get the geometry of the antenna-3. The proposed antenna-3 has a small dimension of W×L (26×27mm^2) and printed on a substrate FR4 with ε_r = 4.4, thickness ht = 1.6mm and loss tangent tan δ = 0.02. The top and bottom patches printed on the substrate are radiating patch and ground plane. The width of the microstrip feed W_f = 3mm is set to attain 50Ω characteristic impedance which is linked to the end of the feeding strip and the edge of the ground plane. 'g' is the feed gap between the radiating patch and the ground plane. The proposed antenna is designed with optimal parameters summarized in Table 3.8.



(a) Front View **(b) Back View**

Figure 3.11 Geometry of the proposed UWB antenna-3

Table 3.8 Proposed UWB antenna-3 dimensions

Parameter	W	L	W_P	L_P	W_g	L_g	W_f	g	a	b	c	d
Dimensions (mm)	26	27	13	16	26	10	3	0.7	1	1	3	1

Figure 3.12 illustrates the simulated reflection coefficients of the designed UWB antenna-3. It is clear that the projected antenna has wideband performance of 3.2GHz to 11.5GHz for S_{11}<-10 dB, covering the entire UWB range with a bandwidth of 8.3 GHz.

The simulated VSWR of the projected UWB antenna is illustrated in Figure 3.13. It is clear that the designed antenna has wideband performance of 3.2GHz to 11.5GHz for VSWR<2, covering the complete UWB range.

With the introduction of the bevels to the antenna structure, the return loss is improved as discussed in the section 3.4.1, over the entire range of UWB antenna.

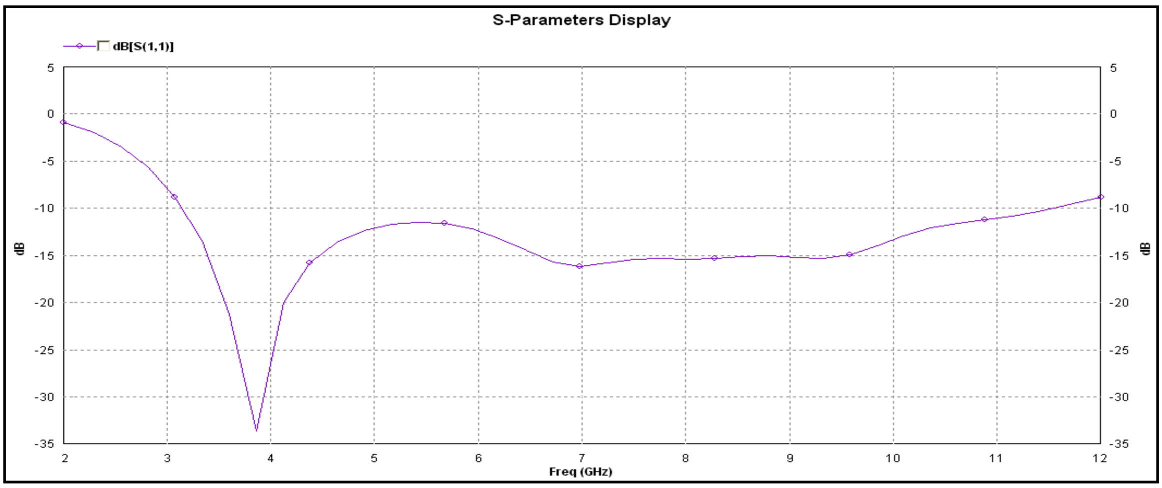


Figure 3.12 Simulated S_{11}(dB) of the rectangular microstrip antenna-3

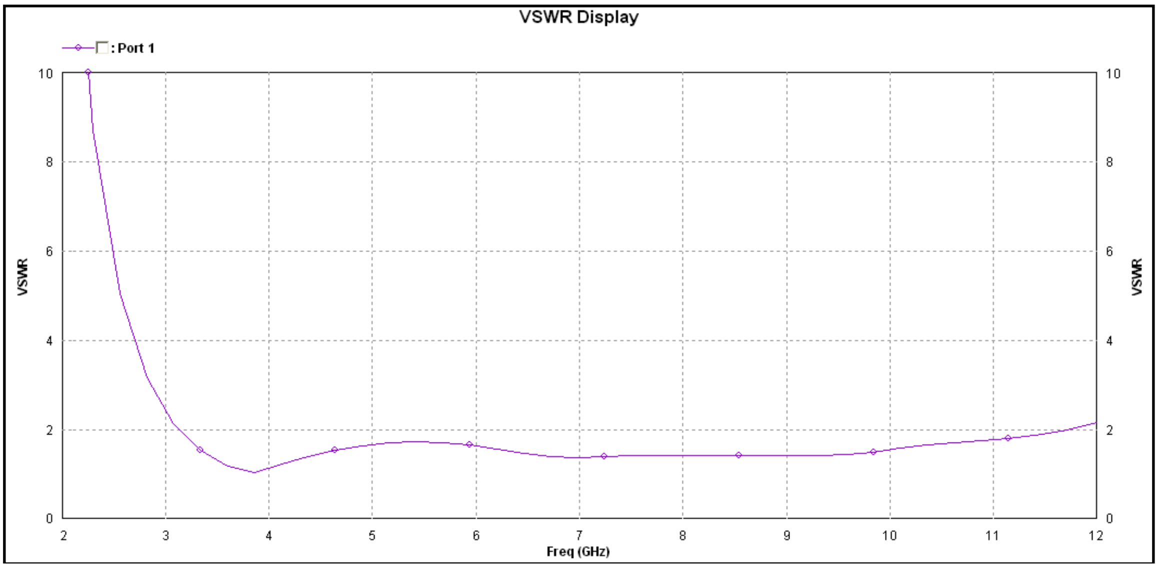
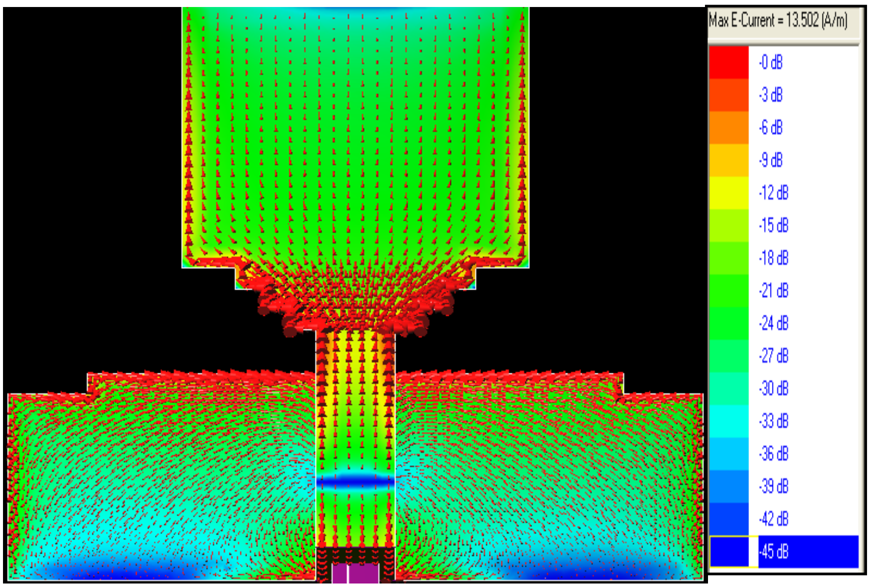


Figure 3.13 Simulated VSWR of the rectangular microstrip antenna-3

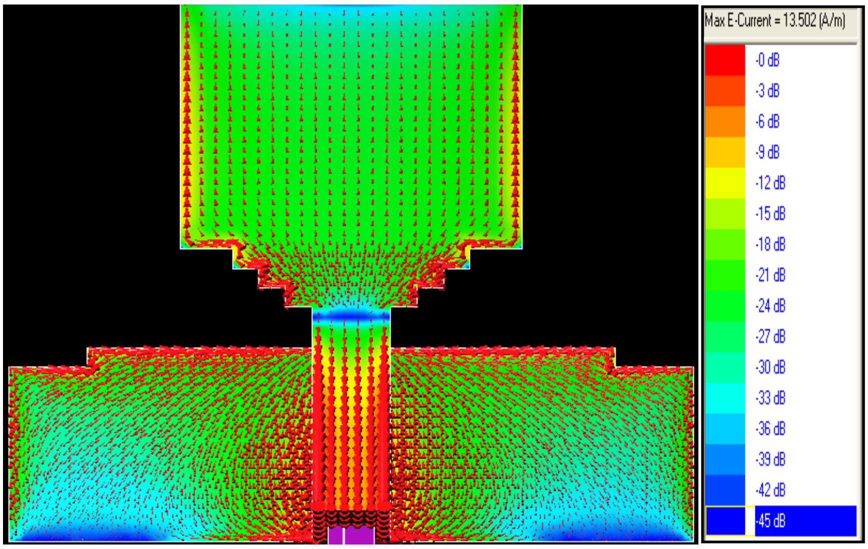
3.5 MODAL ANALYSIS

3.5.1 Current Distribution

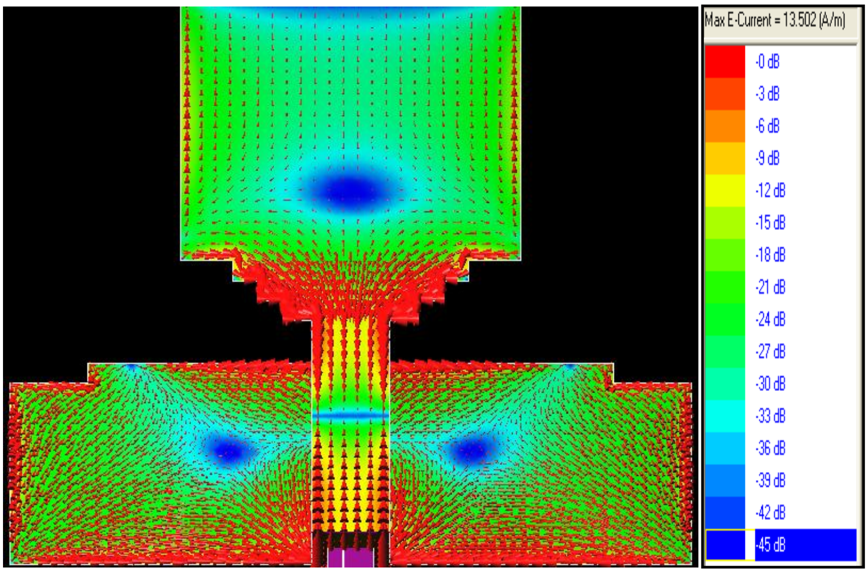
The simulated surface current distribution of proposed UWB antenna-3 is shown in Figure 3.14, at three different frequencies (a) 3.5GHz (b) 5.5GHz (c) 7GHz. It is evident that the surface current distribution is more dominant near the periphery of patch radiator and all the current vectors are in the same direction. Therefore, the antenna radiates at 3.5GHz, 5.5GHz and 7GHz. But the strength of current vector decreases at the upper frequencies. Therefore, the radiation patterns at upper frequencies become distorted.



(a) 3.5GHz



(b) 5.5GHz

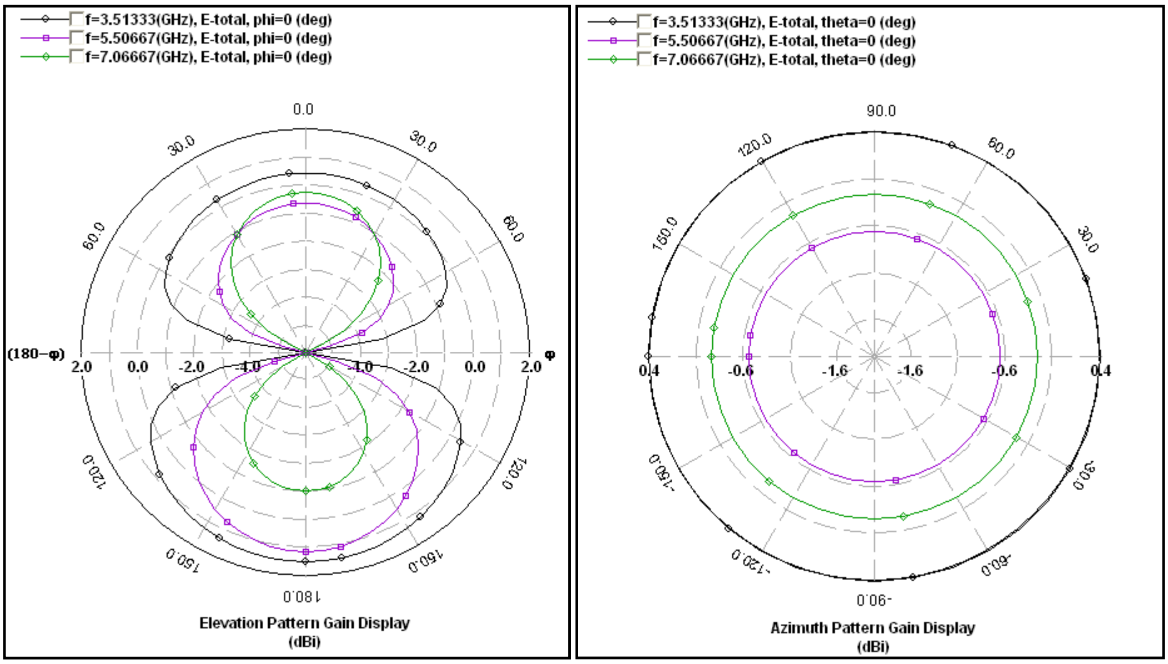


(c) 7GHz

Figure 3.14 Surface current distribution of UWB antenna-3 at (a) 3.5GHz (b) 5.5GHz and (c) 7GHz

3.5.2 Radiation Patterns

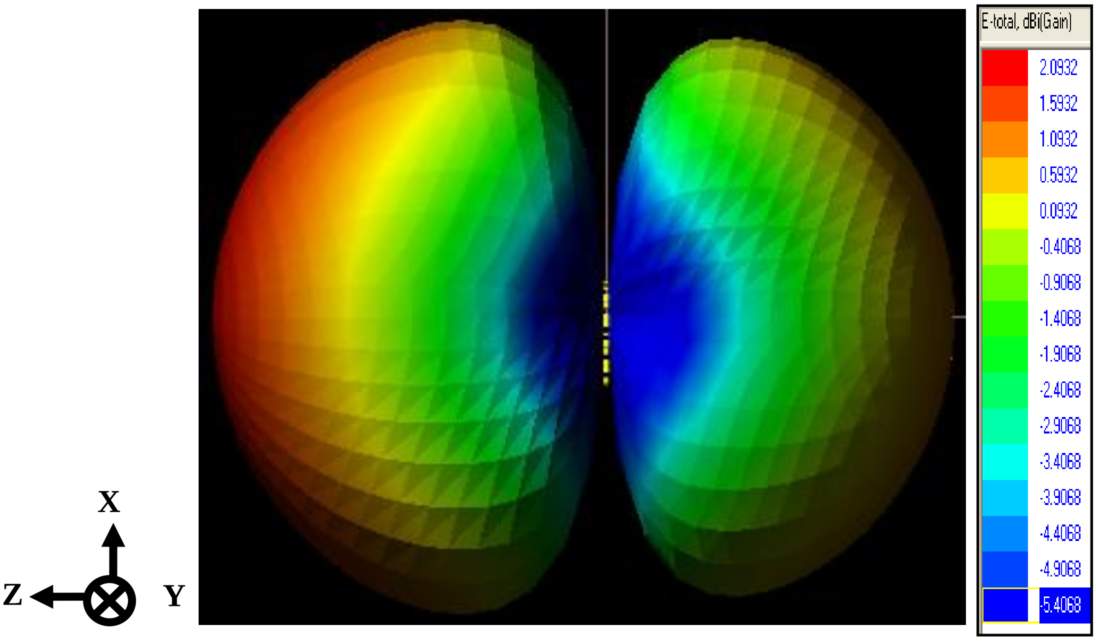
The 2-D radiation pattern of proposed UWB antenna-3 is illustrated in Figures 3.15 E-plane (Y-Z) and H-plane (X-Z) at 3.5GHz, 5.5GHz and 7GHz. Figure 3.15 (a) shows the E-plane (Y-Z) pattern which is similar to the dipole antenna pattern like Figure-of-Eight in vertical plane at frequencies of 3.5GHz, 5.5GHz and 7GHz, but the lobe width is reduced at the upper frequencies. The beam width of the antenna gets reduced as the frequency is increased from 3.5GHz to 7GHz. 2-D radiation pattern in H-plane (X-Z) is almost omnidirectional for all frequencies as illustrated in Figure 3.15 (b).



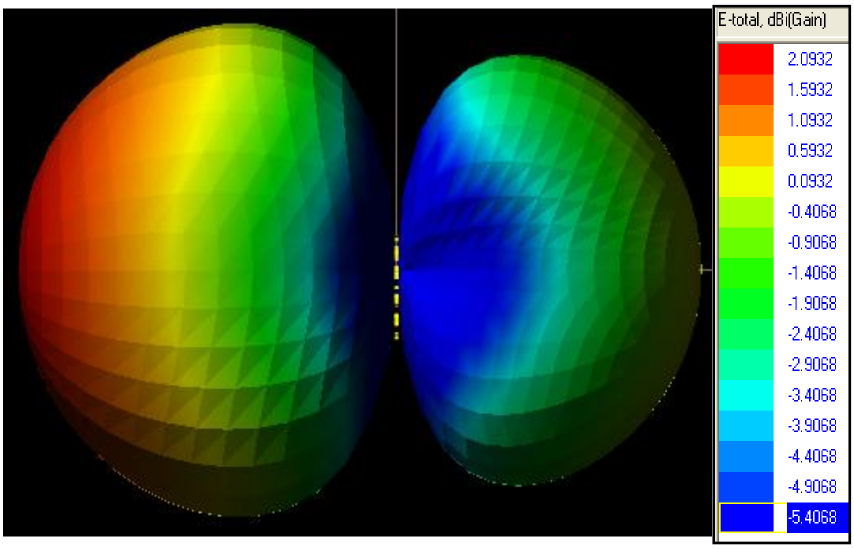
(a) Elevation pattern (Y-Z Plane) **(b) Azimuth pattern (X-Z Plane)**

Figure 3.15 2-D Radiation pattern of UWB antenna-3 at 3.5GHz, 5.5GHz and 7GHz

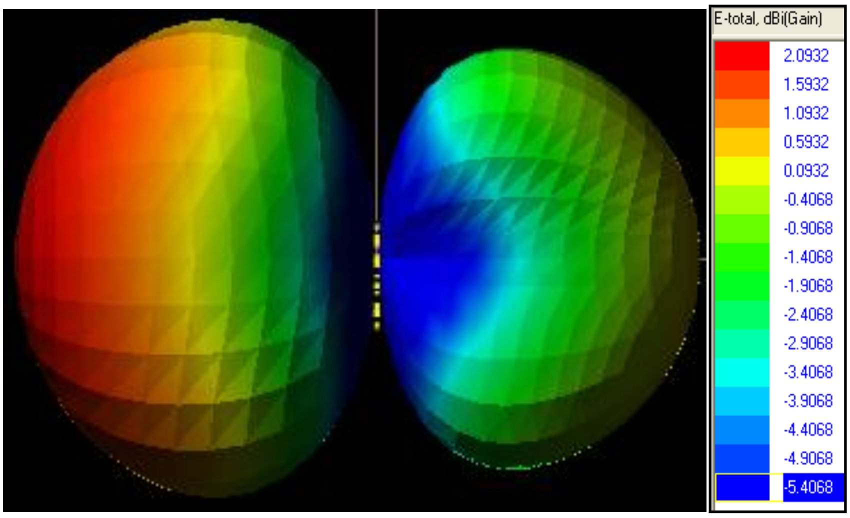
The 3-D radiation pattern of proposed UWB antenna-3 is shown in Figure 3.16 (a) 3.5GHz (b) 5.5GHz and (c) 7GHz. Figure 3.16 shows the 3-D radiation pattern which is analogous to the dipole antenna pattern in the vertical plane at the lower frequencies, but degradation at the upper frequencies.

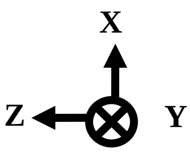


(a) 3.5GHz



(b) 5.5GHz





(c) 7GHz

Figure 3.16 3-D Radiation pattern of UWB Antenna-3 at (a) 3.5GHz (b) 5.5GHz (c) 7GHz

3.6 CONCLUSION

In this chapter, a new compact bevel slot patch antenna has been proposed for UWB applications. The proposed antenna has been designed from a rectangular patch antenna. Three bevel slots to the lower portion of radiator patch and a single bevel slot on the ground plane have been introduced in rectangular patch antenna. It is evident that the impedance bandwidth of the proposed antenna is considerably enhanced. Also, the proposed antenna gives a stable dipole radiation pattern over the entire UWB range and antenna design is simple.

CHAPTER 4

UWB ANTENNA WITH DUAL NOTCHED BAND

4.1 INTRODUCTION

Ultra wideband is one of the major technologies for huge data transmission speed in indoor communication system. Duo to the fast development and advancement of wireless technology, the frequency range of UWB system is coexisted with some other nearby indoor communication systems. Though, over the designed bandwidth of UWB system there exists nearby narrowband communication systems, which create interferences with UWB system. Thus, UWB antenna needs a notched band characteristics (a combination of band-pass and band-reject antenna) to avoid interference from these nearby narrowband communication systems. In this chapter we have taken WLAN and WiMAX narrow band communication systems.

A compact UWB patch antenna having a double band notched characteristic has been described in this chapter. To filter out the WiMAX and WLAN band, two resonating elements are etched on the radiating patch. By changing the size, and locations of resonating element, the proposed antenna can reject dual frequency bands of 3-3.9GHz and 5-5.9GHz from the UWB antenna. One of the most important features of the antenna is that it gives good gain suppressions at notched frequency bands.

Details of the proposed antenna design and the dimensions of U-shaped slots to create notched band are discussed in next section. For the analysis of antenna, an equivalent circuit model is developed. The electromagnetic software IE3D is used to design and simulate the proposed antenna. The proposed antenna has been fabricated and measurements are done to validate the design.

4.2 DUAL NOTCHED BAND UWB ANTENNA GEOMETRY

The antenna discussed in chapter 3 has been taken as initial antenna on which band notching circuits are printed out. Figure 4.1 illustrates the design and dimensions of the proposed UWB antenna. The proposed antenna has a very small size of W×L ($26\times27mm^2$) and printed on a substrate FR4 with $\varepsilon_r = 4.4$, thickness ht = 1.6mm and loss tangent tan δ = 0.02. The top and bottom patches printed on the substrate are radiating patch and ground plane. The width of the microstrip feed W_f = 3mm is set to attain 50Ω characteristic impedance to be matched to an SMA (Subminiature) connector [129].

By etching two uniform and symmetrical U shaped slots into the radiating patch of UWB antenna, a dual band notch can be realized. The dimensions of the notched frequency can be calculated as [82,128].

$$f_{Notch} = \frac{c}{2L_{Notch}\sqrt{\varepsilon_{eff}}} \quad (4.1)$$

$$\varepsilon_{eff} \approx \frac{\varepsilon_r + 1}{2} \quad (4.2)$$

$$L_{1Notch} \approx \frac{\lambda_{3.5}}{2} \approx 2n_1 + l_1 \quad (4.3)$$

$$L_{2Notch} \approx \frac{\lambda_{5.5}}{2} \approx 2n_2 + l_2 \quad (4.4)$$

Where L_{Notch} is the total length of U-shaped slot notching a frequency f_{Notch}, ε_{eff} is the effective dielectric constant, and c is the speed of light. To create rejection bands, at frequency of 3.5GHz and 5.5GHz, the effective length of resonating slots should be nearly half of operating wavelengths. For designing of the notch band antenna, an anti-resonance frequency is known, and then by using Equations (4.1-4.4) we calculate the preliminary dimension of U-shaped slot. Normally, by expanding the length of the slot, we can increase the value of inductance or capacitance of the slot. Therefore the center notched frequency can be decreased. The optimized dimension of designed antenna is summarized in Table 4.1.

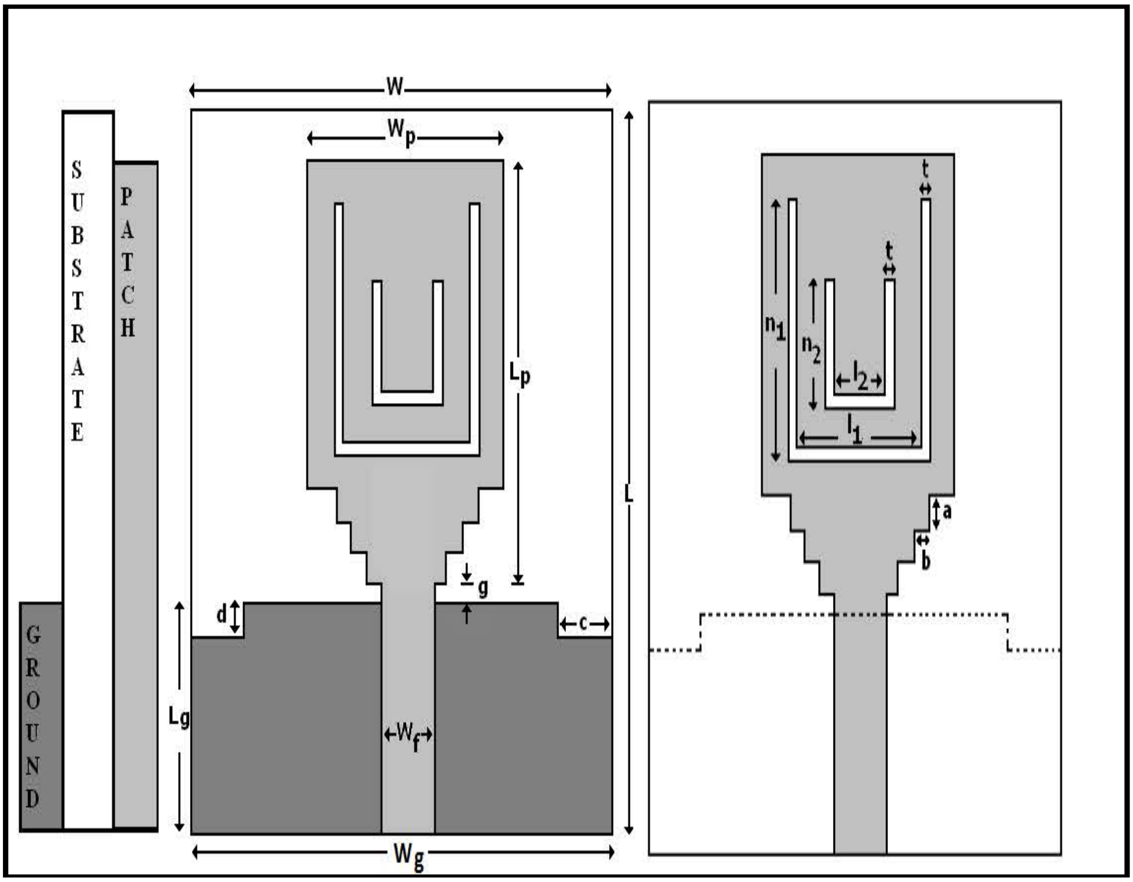


Figure 4.1 Geometry of dual notch band U-shape UWB antenna

Table 4.1 Parametric details of dual notch band UWB antenna

Parameter	Dimensions (mm)
W	26
L	27
W_P	13
L_P	16
W_g	26
L_g	10
W_f	3
g	0.5
a	1
b	1
c	3
d	1
n_1	9
l_1	9
n_2	4.7
l_2	6.7

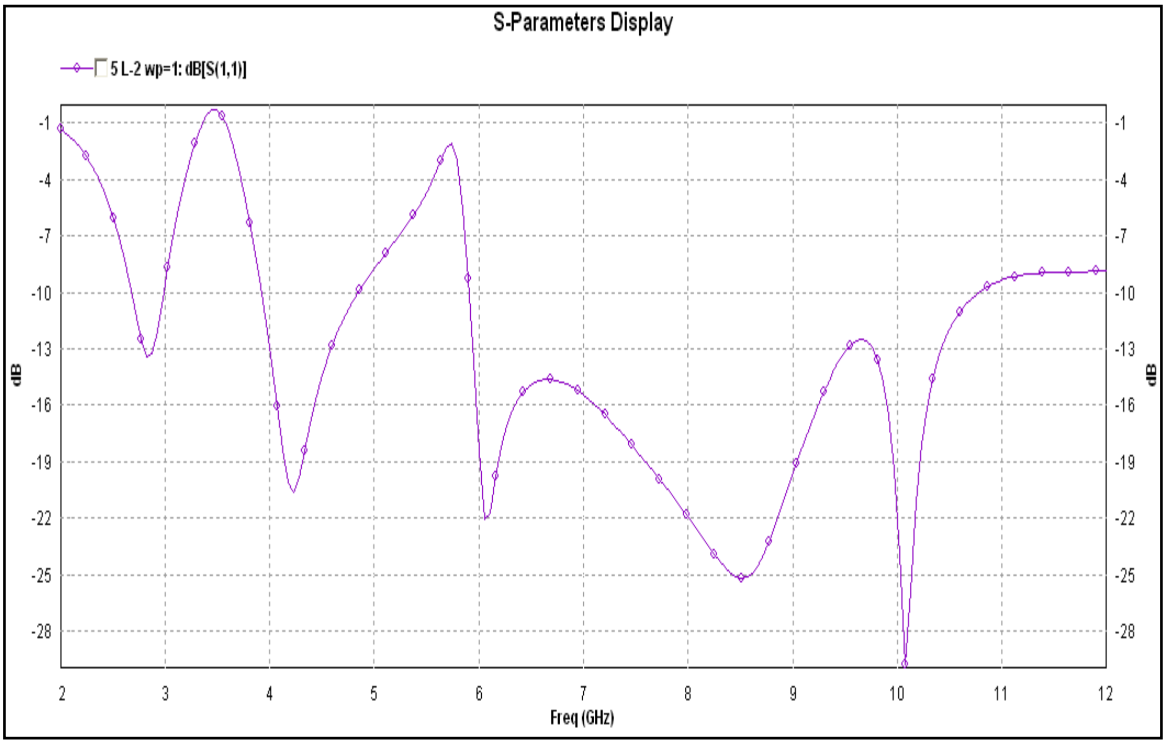


Figure 4.2 Simulated reflection coefficient S_{11}(dB) of dual notched band UWB antenna

The S_{11}(dB) results help in analyzing the set of frequencies radiated by the antenna for which antenna shows a reflection coefficient less than -10dB. Figure 4.2 illustrates the return loss of the proposed antenna, it is seen that an impedance bandwidth of 2.6-10.8GHz for

S_{11}<-10dB, cover the entire UWB range along with double notch bands of WiMAX with highest return loss of -0.8dB and WLAN with highest return loss of -2.1dB. Therefore, the proposed antenna is appropriate for UWB wireless application without interference from co-existing band of 3.3-3.7GHz WiMAX band and 5.15-5.75GHz WLAN band.

For maximum transfer of power from source to the antenna, the feed line must be matched in its impedance to the antenna connector, for which antenna shows a VSWR of less than 2. Figure 4.3 illustrates the VSWR plot of the proposed antenna. The proposed antenna has wideband performance of 2.6GHz to 10.8GHz for VSWR<2, cover the whole UWB range along with double notch bands of 3-3.9GHz and 4.9-5.9GHz having VSWR>2.

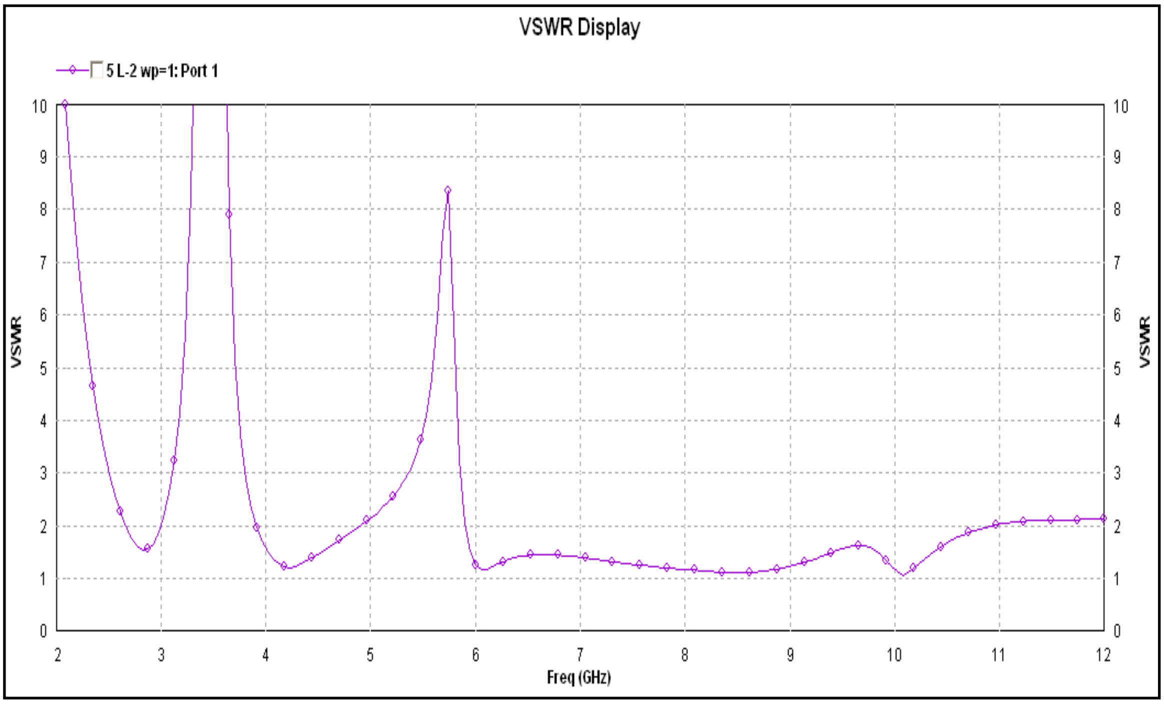


Figure 4.3 Simulated VSWR of dual notched band UWB antenna

The first notch frequency is decided by largest U-shaped slot. The center notch frequency gets shifted to lower value from 3.54GHz to 3.33GHz when L_{1Notch} is increased from 26mm to 28mm, as illustrated in Figure 4.4. In Table 4.2, the simulated (via IE3D) as and theoretical (via Equation (4.3)) calculation of notched band frequency for various total lengths (26-28mm) of U-shaped slot are compared. The maximum variation between simulated and theoretical frequency is on 0.07GHz, because of approximation is used in calculation of ε_{eff} in Equation (4.2). The similar concept is used for other U-shaped slot to achieve the preferred notched band frequency.

Table 4.2 Simulated and theoretical value of first center notch frequency

L_{1Notch} (mm)	Simulated Frequency (GHz)	Theoretical Frequency (GHz)	Difference (GHz)
26	3.54	3.51	0.03
27	3.40	3.38	0.02
28	3.33	3.26	0.07

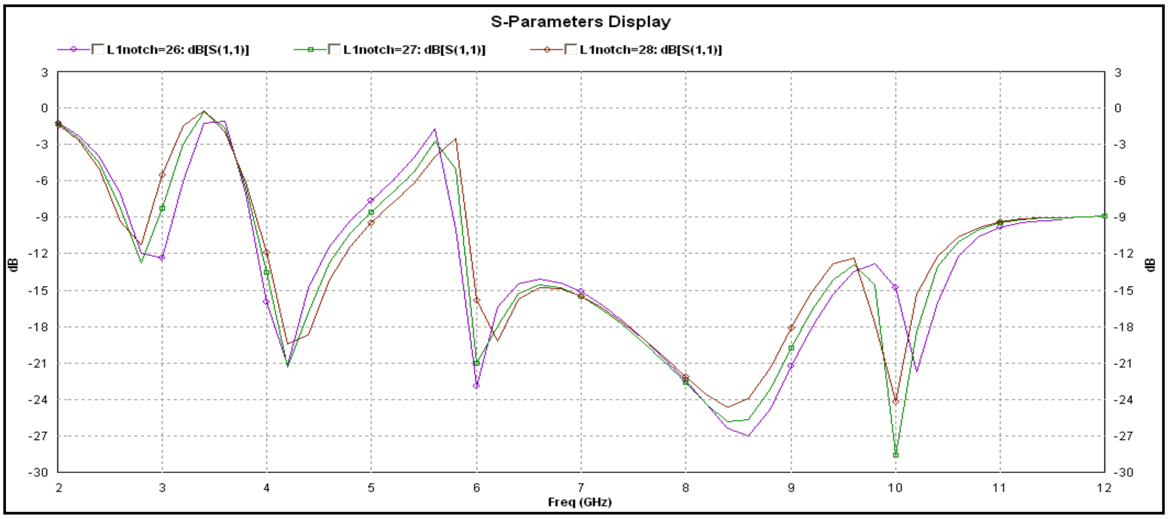


Figure 4.4 Simulated S_{11}(dB) of dual notched band UWB antenna with different L values

4.3 PARAMETRIC ANALYSIS OF THE ANTENNA

A microstrip feed patch antenna offers many parameters to the antenna designer that can be optimized to get a UWB antenna with notched bands to avoid interference. Each geometrical parameter of U-shaped structure is individually varied to see its effect on performance of proposed antenna in term of return loss, and impedance bandwidth is discussed in this section.

4.3.1 Effect of variation in U-shaped slot width (l_1)

In the proposed antenna, U-shaped slot width (l_1), was changed to see the affect of this variation on notch band of operation. It can be concluded from Figure 4.5 and Table 4.3 that the lower frequency of first notch (WiMAX) gets shifted to a lower value but very small variation on higher frequency of first notch by increasing the value of slot width (l_1) from 8.5mm to 9.5mm and the value of return loss at center frequency has been increased. Since the desired UWB wireless applications needs a notch band of 3.3-3.7GHz WiMAX, for the optimum value of slot width (l_1) 9mm, a notch band of 2.96-3.89GHz having S_{11}>-10dB and symmetrical notch band around centre frequency has been achieved.

Table 4.3 Effect of variation in U-shaped slot width (l_1)

Slot Width (l_1) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
8.5	3.07	3.86	0.79
9	2.96	3.89	0.93
9.5	2.84	3.92	1.08

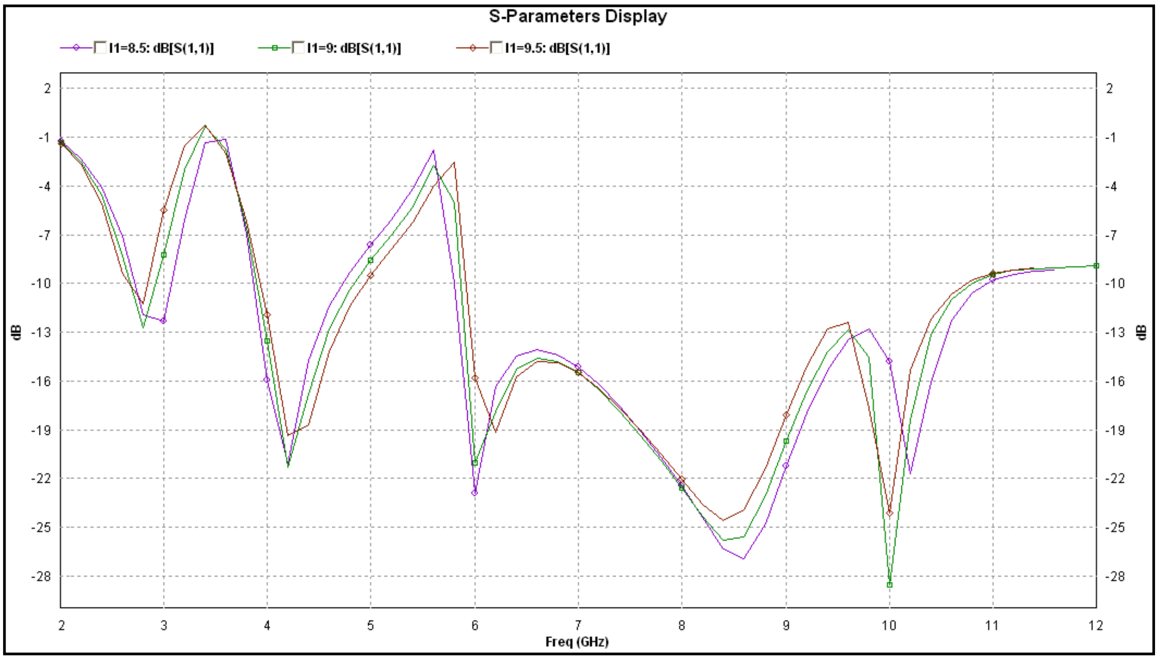


Figure 4.5 Simulated S_{11}(dB) of dual notch band U-shape UWB antenna for various l_1

4.3.2 Effect of variation in U-shaped slot length (n_1)

Figure 4.6 show that there is a variation in return loss value with variation in the U-shaped slot length (n_1). The WiMAX notch band frequency shifted to lower value side by increasing the value of slot length n_1 from 8.5mm to 9.5mm and center frequency also shifted to a lower value. From Table 4.4, it is observed that the best value of slot length (n_1) 9mm, a notch band of 2.96-3.89GHz having S_{11}>-10dB and getting a symmetrical notch band around centre frequency of 3.45GHz.

Table 4.4 Effect of variation in U-shaped slot length (n_1)

Slot Length (n_1) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
8.5	3.03	4.00	0.97
9	2.96	3.89	0.93
9.5	2.85	3.81	0.96

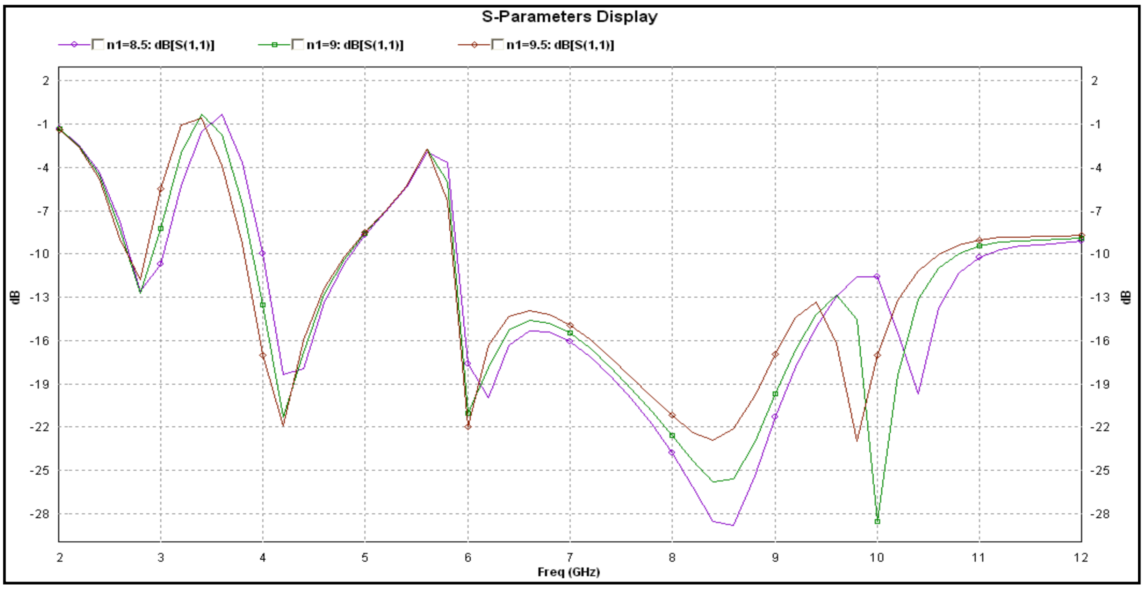


Figure 4.6 Simulated S_{11}(dB) of dual notch band U-shape UWB antenna for various n_1

4.3.3 Effect of variation in U-shaped slot width (l_2)

There is a variation in S_{11}(dB) value with change in the U-shaped slot width (l_2), as shown in Figure 4.7. The WLAN notch band frequency shifted to a lower value by increasing the value of slot width (l_2) from 6.2mm to 7.2mm and center frequency also shifted to a lower value with higher return loss value. Since the desired UWB wireless applications needs notch band of 5.15-5.75GHz for WLAN. It can be conclude from Table 4.5 that the optimum value of slot width (l_2) 6.7mm, a notch band of 4.83-5.86GHz having S_{11}>-10dB with center frequency of 5.6GHz has been achieved.

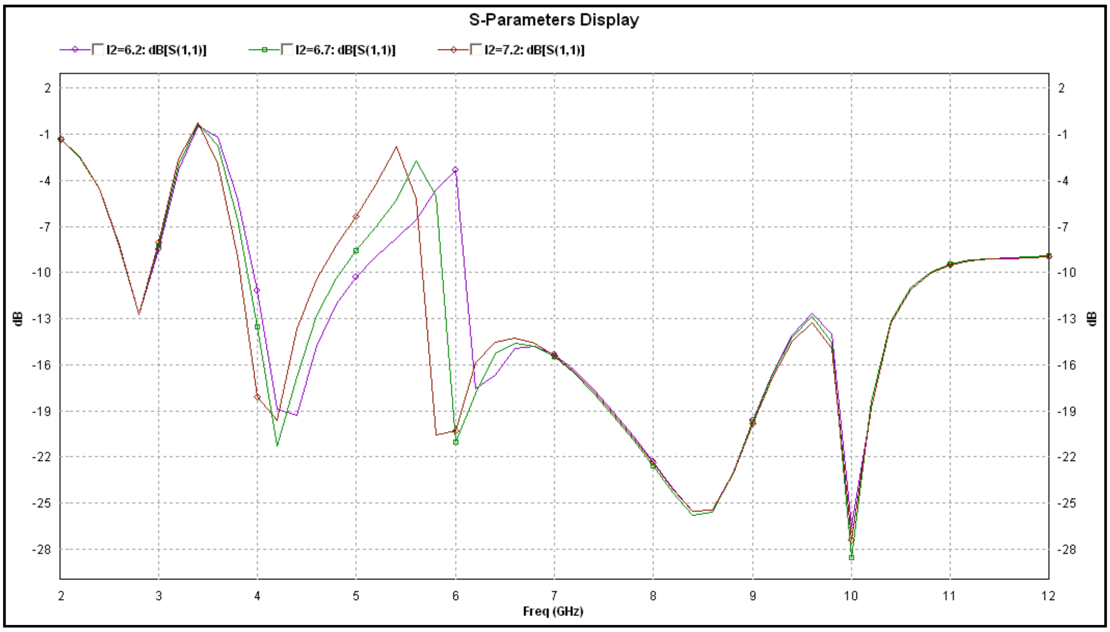


Figure 4.7 Simulated S_{11}(dB) of dual notch band U-shape UWB antenna for various l_2

Table 4.5 Effect of variation in U-shaped slot width (l_2)

Slot Width (l_2) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
6.2	5.03	6.08	1.05
6.7	4.83	5.86	1.03
7.2	4.61	5.66	1.05

4.3.4 Effect of variation in U-shaped slot length (n_2)

Figure 4.8 shows the variation of return loss with the change in U-shaped slot length (n_2). The WLAN notch band gets shifted to a lower value by increasing the value of slot length n_2 from 4.2mm to 5.2mm and the peak frequency also shifted to a lower value with higher return loss value. It can be concluded from Figure 4.8 and Table 4.6,the optimum value of slot length (n_2) 4.7mm, a notch band of 4.84-5.9GHz having S_{11}>-10dB.

Table 4.6 Effect of variation in U-shaped slot length (n_2)

Slot Length (n_2) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper(GHz)	Notch Bandwidth (GHz)
4.2	4.98	6.16	1.18
4.7	4.84	5.9	1.06
5.2	4.68	5.6	0.92

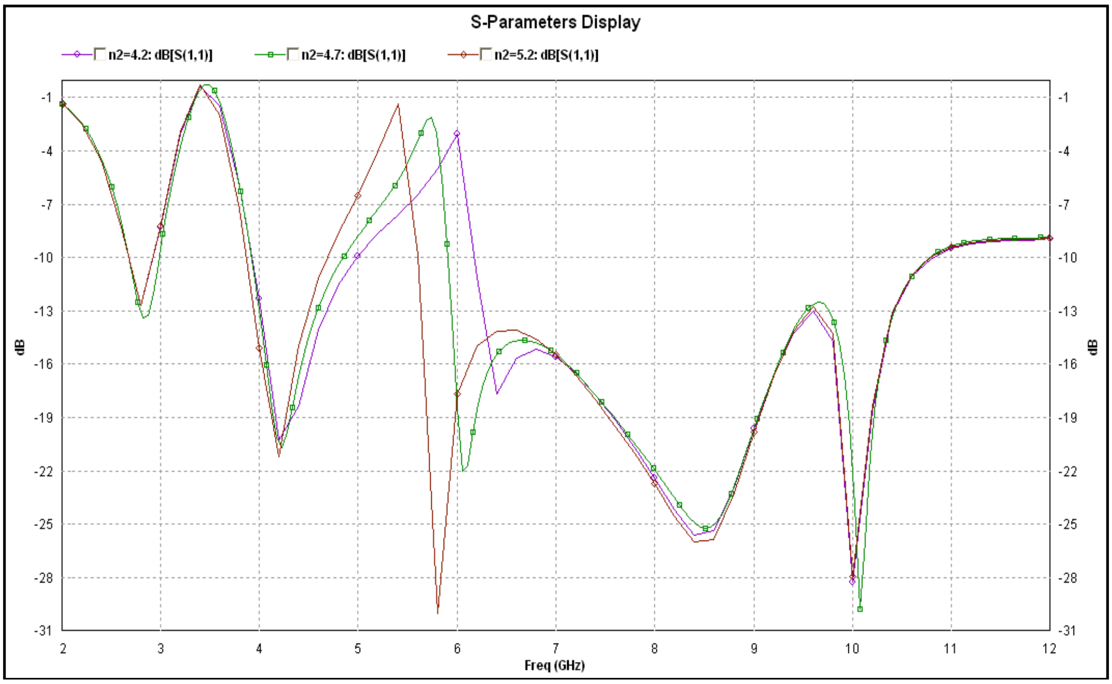


Figure 4.8 Simulated S_{11}(dB) of dual notch band U-shape UWB antenna for various n_2

4.4 FABRICATION AND TESTING OF DUAL NOTCH BAND UWB ANTENNA

Figure 4.10 shows the proposed fabricated antenna by using optimized parameters tabularized in Table 4.1. The various steps that are carried out in the fabrication process are highlighted in Figure 4.9, which shows the flow chart that is carried out to fabricate the final antenna.

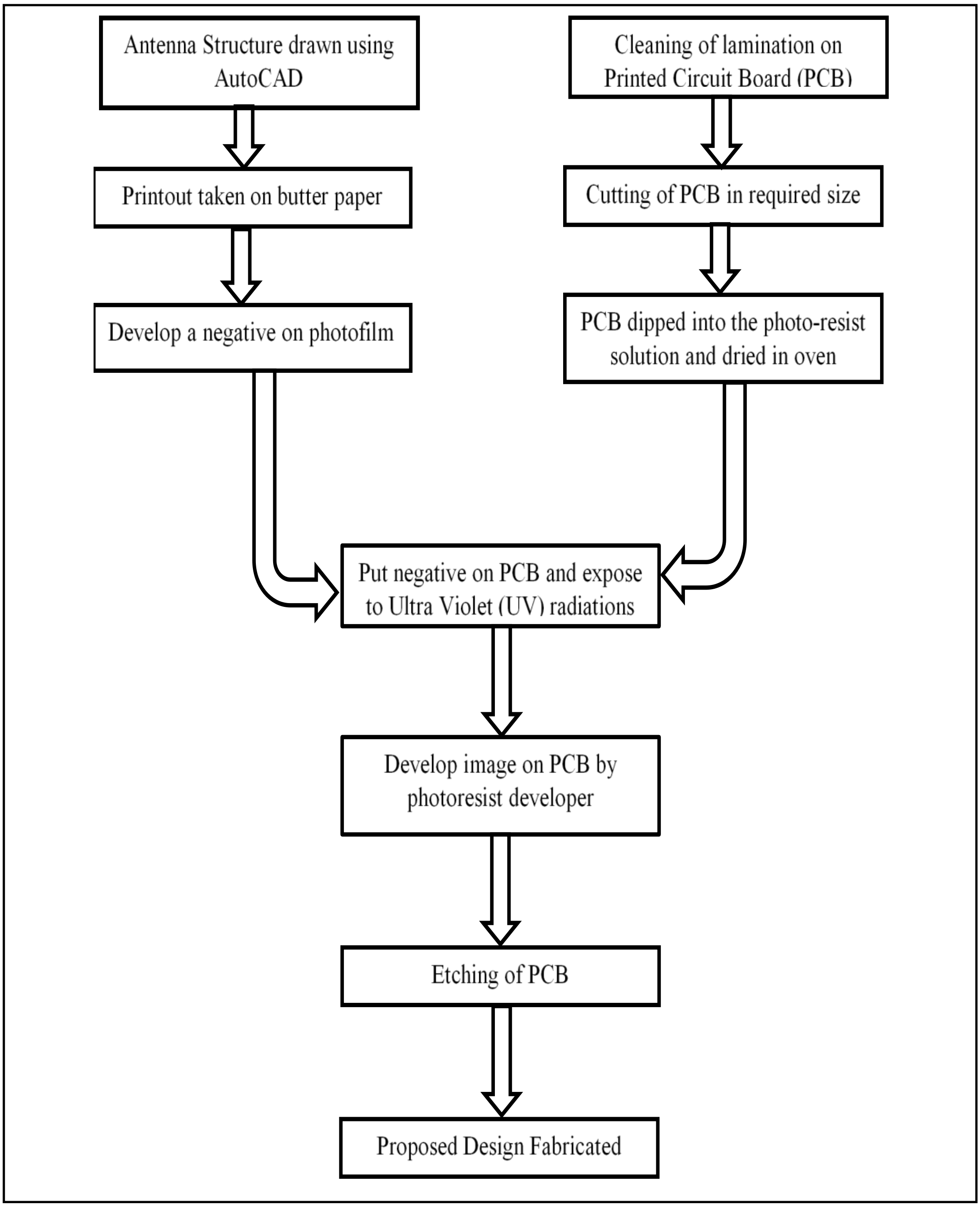
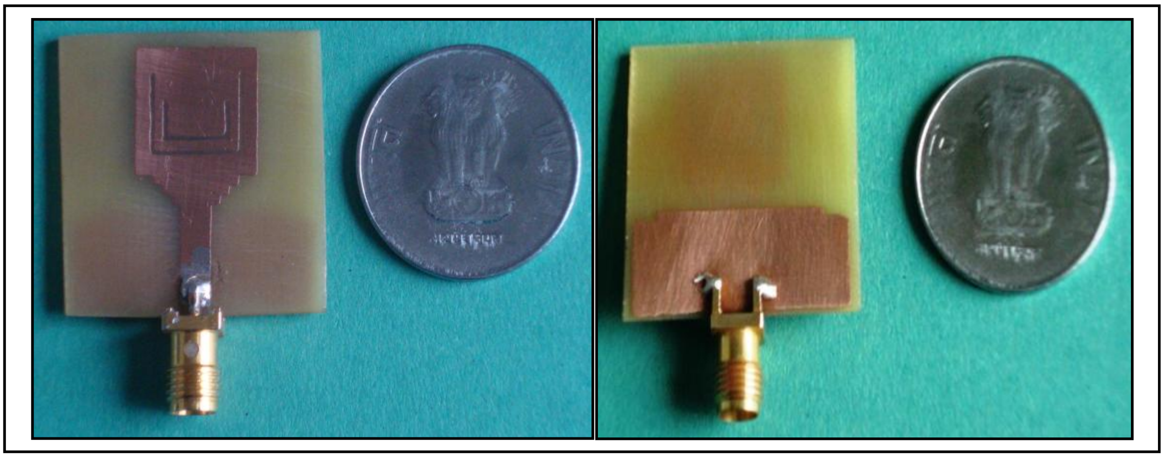


Figure 4.9 Fabrication process of projected antenna

Figures 4.10 (a) and (b) show the front view and back view of the fabricated antenna with feed line, and two U-shaped filter structure in the patch. The performance of fabricated antenna is evaluated in an anechoic room with Anritsu MS2028C vector network analyzer and far field antenna testing system



(a) Front View **(b) Back View**

Figure 4.10 Proposed fabricated dual notch band UWB antenna

Figure 4.11 illustrates the measured and simulated reflection coefficients of proposed dual notch band UWB antenna. The designed antenna has wideband performance of 2.6GHz to 10.8GHz for S_{11}<-10dB, cover up the whole UWB band with dual notch bands of 3-3.9GHz and 5-5.9GHz having S_{11}>-10dB. From Table 4.7, it is seen that here is a good agreement between simulated and measured results. Therefore, the proposed antenna is appropriate for UWB wireless application without interference with a co-existing band of WiMAX band and WLAN band [129].

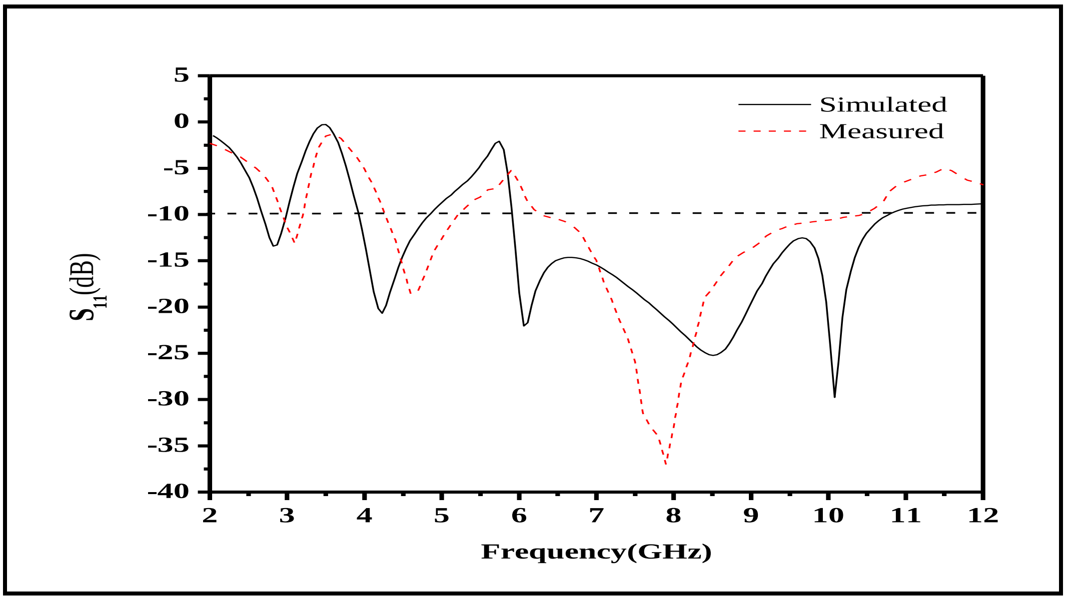


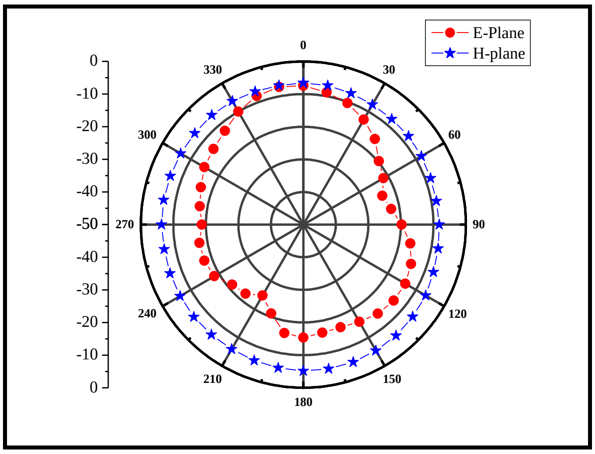
Figure 4.11 Simulated and measured S_{11}(dB) of dual notch band UWB antenna

Table 4.7 Comparison of simulated and measured return loss

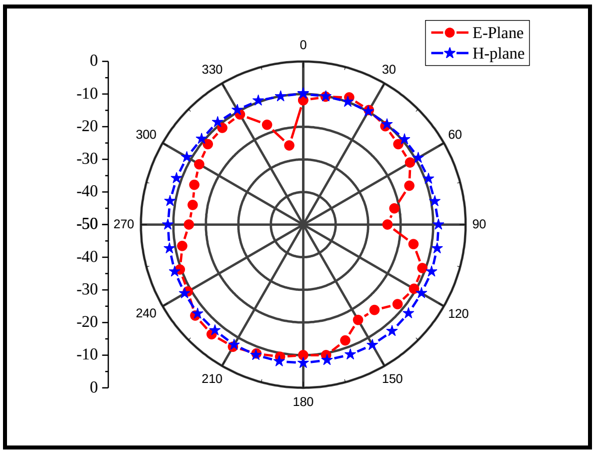
Notch band	Simulated Frequency at Peak S_{11} (GHz)	Measured Frequency at Peak S_{11} (GHz)	Error (GHz)
WiMAX	3.49	3.62	0.13
WLAN	5.61	5.78	0.17

The simulated return loss peak of notch band is slightly differing with the measured, because of the fabrication error that might be present while physically assembling it.

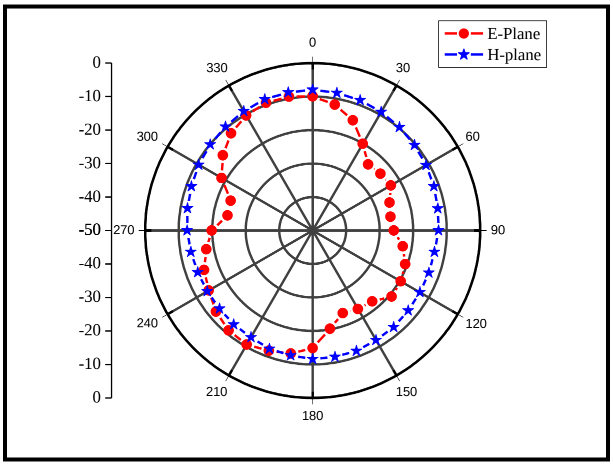
The measured radiation pattern of the proposed UWB antenna at 4.5GHz, 7GHz and 9.6GHz has been observed in Figure 4.12. The antenna is printed in X-Y plane, therefore Y-Z represents E-plane and X-Z represents an H-plane. It is observed from Figure 4.12 that the radiation pattern of E-plane (X-Z) is similar to monopole antenna and the radiation pattern of H-plane (Y-Z) is almost omnidirectional for all frequencies.



(a) 4.5GHz



(b) 7GHz



(c) 9.6GHz

Figure 4.12 Measured radiation pattern of double notch band UWB antenna at (a) 4.5GHz (b) 7GHz (c) 9.6GHz

The gain of the antenna has been tested in an anechoic chamber. This chamber has a standard horn antenna. It provides an ideal environment that is free of reflections for the testing of antennas. Figure 4.13 shows simulated and measured gain of the proposed antenna. At notch frequency band, the gain of antenna decreases sharply. The simulated gain of proposed antenna is 5.4dBi and its measured gain is about 4.1dBi over the UWB frequency range, except in a notched frequency band of WiMAX and WLAN as shown in Table 4.8. The dip in gain for notches can be increased by using following methods:

(a) By using high permittivity and low dielectric loss substrate [111]

(b) By varying the position of notch structure

(c) BY using DGS structure.

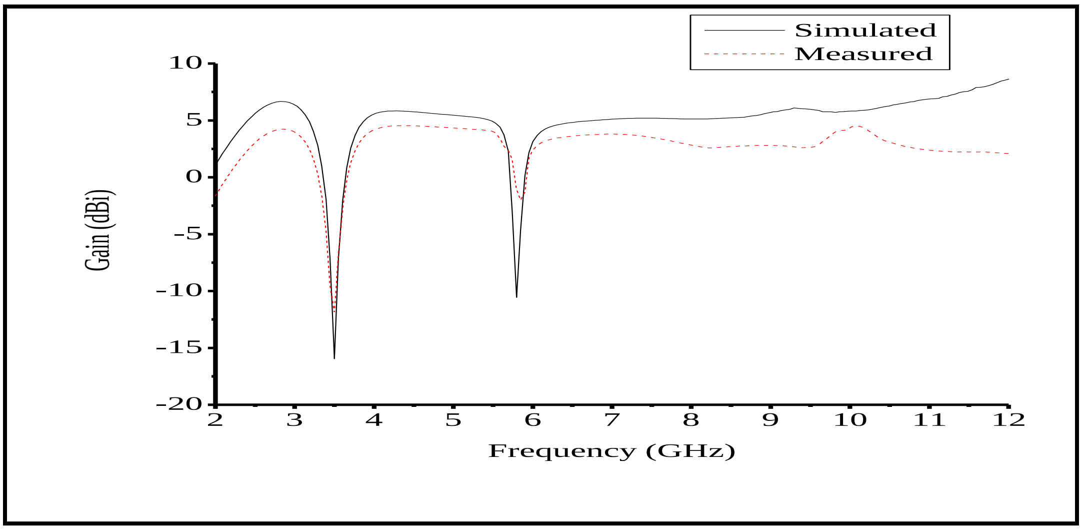


Figure 4.13 Gain of double notch band UWB antenna

Table 4.8 Gain suppression at various notch band

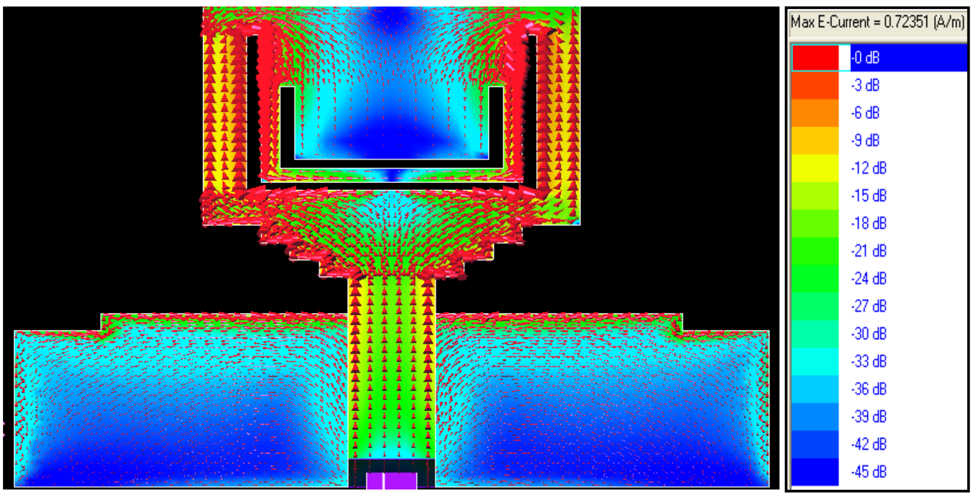
Notch band	**Simulated Maximum gain suppression (dBi)**	**Measured Maximum gain suppression (dBi)**
WiMAX	-15.95	-11.8
WLAN	-10.56	-1.7

4.5 MODAL ANALYSIS

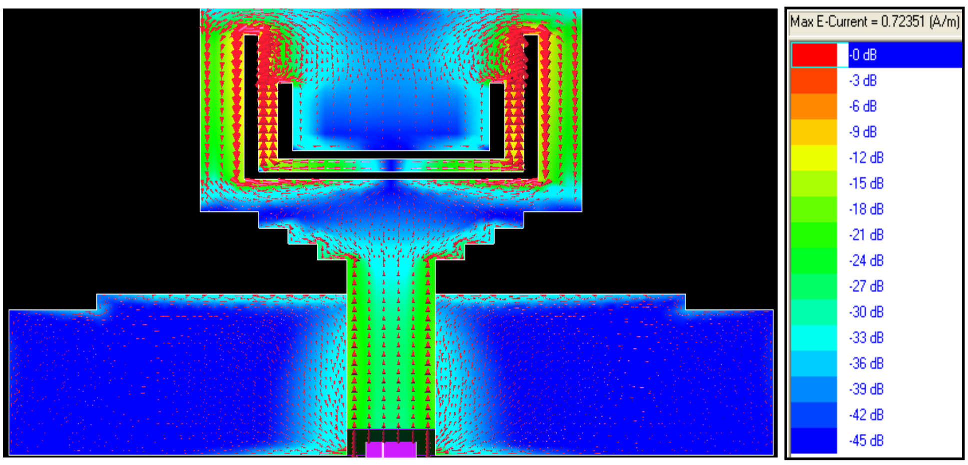
4.5.1 Current Distribution

The microstrip fed UWB antenna structure was excited using the feed network to see the distribution of energy over its various structural parts. This helps in analyzing that in what capacity, a specific part of the antenna is responsible for the given resonant frequency of antenna operation.

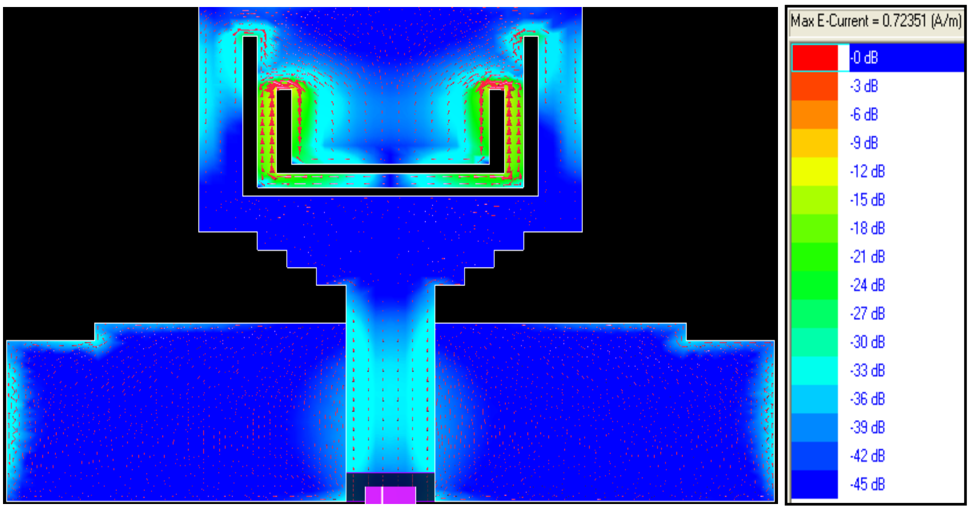
Figure 4.14 illustrates the simulated surface current distribution at a frequency of 2.9GHz, 3.5GHz, 5.5GHz and 10GHz. It has been observed in Figures 4.14 (a) and (d), the surface current distribution is more dominant near the periphery of patch radiator and all the current vectors are in the same direction, therefore the antenna radiates at 2.9GHz and 10GHz. But in Figures 4.14 (b) and (c), the surface current distribution is more dominant around the U-shaped filter structure at a frequency of 3.5GHz and 5.5GHz and the current vectors are in opposite direction and cancel each other, which acts as a short circuit resonator [128]. This suggests that the U-shaped filter structure has a major effect on UWB antenna performance for elimination of the frequency band. Therefore the antenna does not radiate at 3.5GHz and 5.5GHz and a frequency notch bands are created around these frequencies. Thus, from the current distributions, it is confirmed that the U-shaped filter structure causes the frequency notch functions [82, 100, 129].



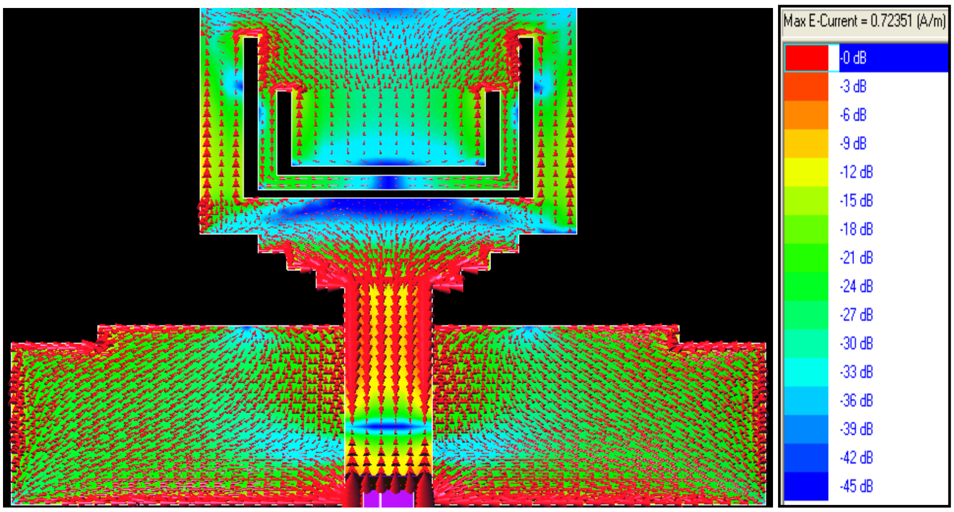
(a) 2.9GHz



(b) 3.5GHz



(c) 5.5GHz

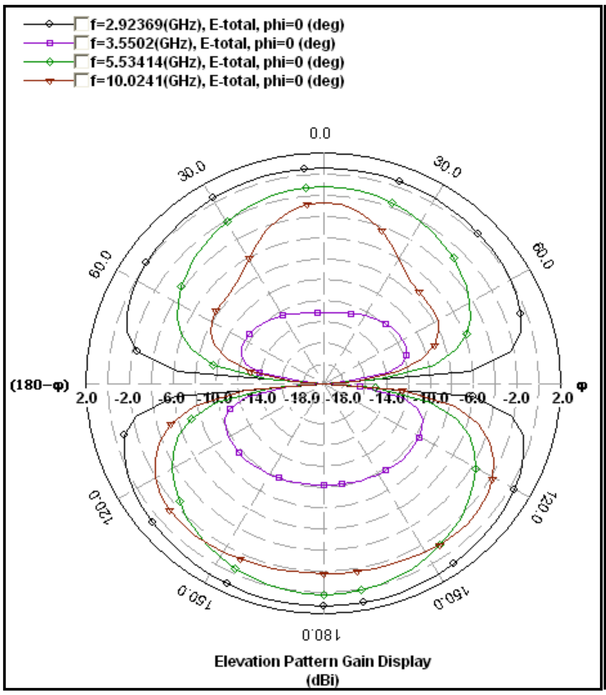


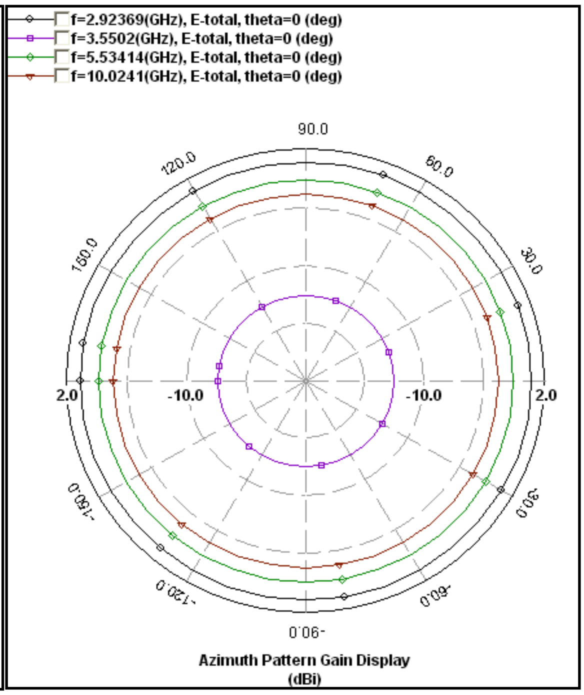
(d) 10GHz

Figure 4.14 Surface current distribution of dual notched band UWB antenna at (a) 2.9GHz (b) 3.5GHz (c) 5.5GHz (d) 10GHz

4.5.2 Radiation Patterns

The 2-D radiation pattern of the proposed double notched band UWB antenna, is illustrated in Figures 4.15 E-plane (Y-Z) and H-plane (X-Z) at 2.9GHz, 3.5GHz, 5.5GHz, and 10GHz. Figure 4.15(a) shows the E-plane (Y-Z) pattern which is similar to the dipole antenna pattern like Figure-of-Eight in vertical plane at the lower frequency of 2.9GHz, but lobe width is reduced at higher frequencies. Therefore, the radiation patterns at higher frequencies become slightly distorted form the Figure-of-Eight shape. Also, the radiation pattern gain at 3.5GHz and 5.5GHz is small as compared to other frequencies as illustrated in Figure 4.15 (a) and antenna does not radiate at these frequencies. The 2-D radiation pattern in H-plane (X-Z) is almost omnidirectional for all the frequencies as illustrated in Figure 4.15 (b).

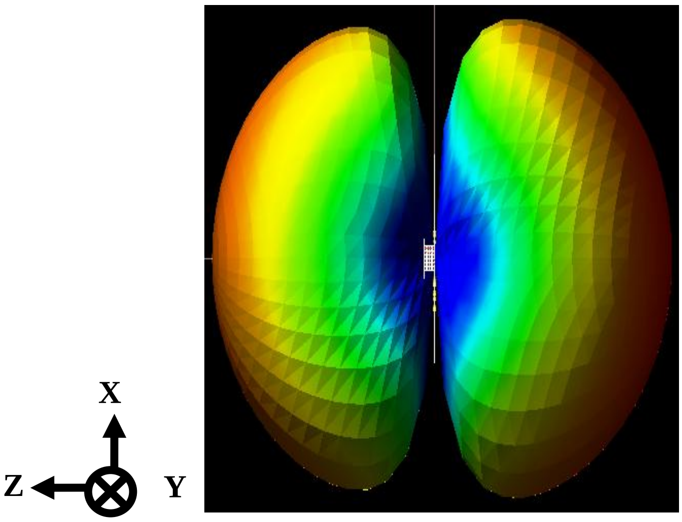


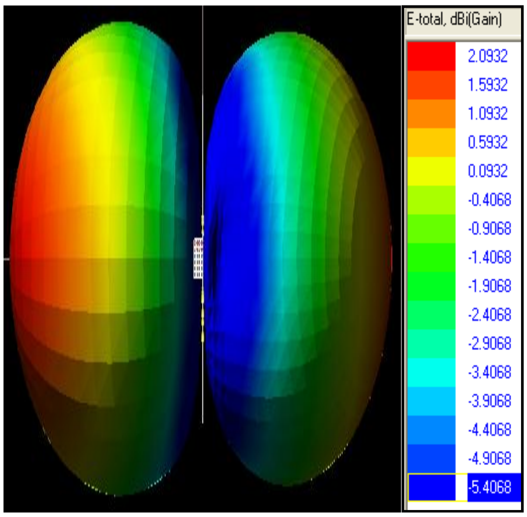


(b) Elevation pattern (Y-Z Plane) (b) Azimuth pattern (X-Z Plane)

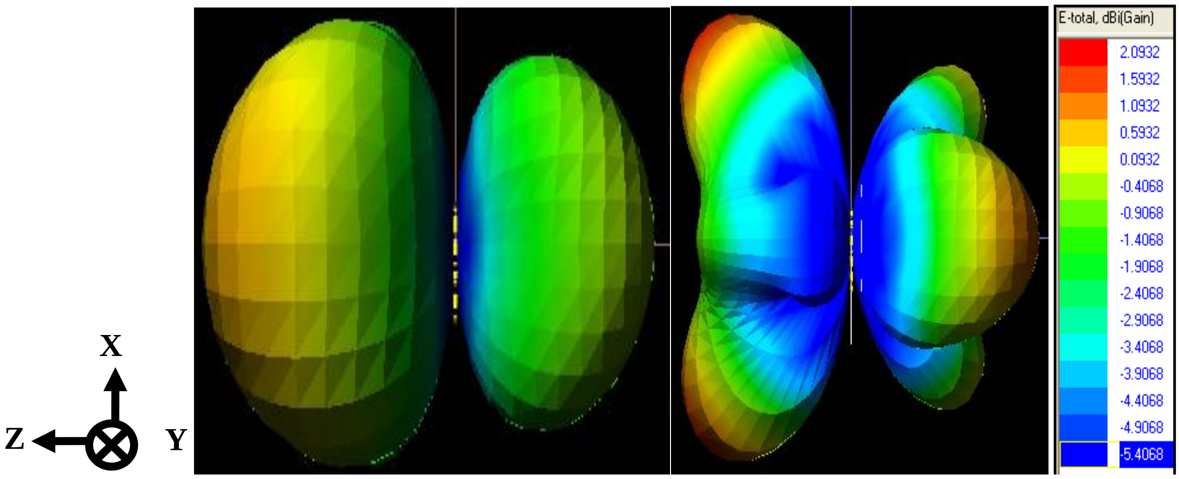
Figure 4.15 2-D radiation pattern of double notched band UWB antenna at 2.9GHz, 3.5GHz, 5.5GHz, and 10GHz

The 3-D radiation pattern of proposed double notched band UWB antenna is illustrated in Figures 4.16 at 2.9GHz, 3.5GHz, 5.5GHz and 10GHz. Figure 4.16 shows the 3-D radiation pattern which is similar to the dipole antenna pattern at the lower frequencies, but degradation at the upper frequencies. Therefore, the 3-D radiation pattern at higher frequencies become distorted and splits into minor lobes. It can also be observed from Figure 4.16 (b) and (d) that the radiation patterns gain at 3.5GHz and 5.5GHz is small as compared to other frequency, these shows that at these frequencies the antenna does not radiate.





(a)2.9GHz (b) 3.5GHz



(c) 5.5GHz (d) 10GHz

Figure 4.16 3-D radiation pattern of double notched band UWB antenna at (a) 2.9GHz (b) 3.5GHz (c) 5.5GHz (d) 10GHz

4.5.3 Equivalent Circuit

The analysis of proposed antenna can be done through an equivalent circuit and transmission line models. Theory of the notched band property can be explained with the help of an equivalent circuit model. Usually, the input impedance of UWB antenna is considered, as parallel RLC components. For the proposed dual notched band UWB antenna, notch band properties are attained by creating two resonant structures, consisting of two series RLC resonators.

Therefore, the input impedance is designed by parallel R, L and C for band-pass resonant frequencies. While for the two rejection bands, two extra R, L and C components in-series are included to describe the dual band-notched structures [125-127]. Figure 4.17shows the equivalent circuit model of proposed double notched band UWB antenna.

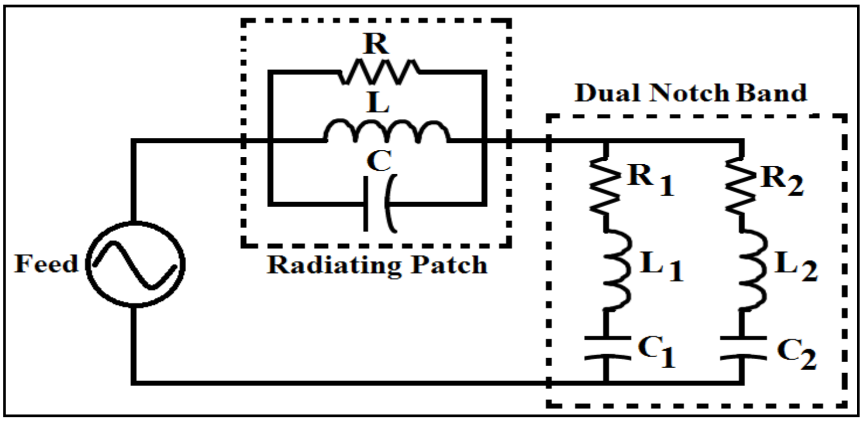


Figure 4.17 An approximated equivalent circuit model of proposed double notched band UWB antenna

Figure 4.18 shows the equivalent transmission line model of proposed double notched band UWB antenna, where Za is the impedance of an antenna and two parallel stubs acts like a half-wavelength resonator. The two stub ends are short circuited and modeled like $\lambda_{3.5}/2$ and $\lambda_{5.5}/2$ long for the total length about 27mm and 16.1mm which correspond to the rejection frequencies of 3.5GHz and 5.5GHz, respectively.

Figure 4.18 (a) shows, the band-pass frequency equivalent circuit. Figure 4.18 (b) shows, the first notch band, when $L_{1Notch} \approx \lambda_{3.5}/2$, the impedance at feed point is zero (short circuited) and the antenna become nonreactive; hence first notch band is produced. In a similar way, another notch band is created when $L_{2Notch} \approx \lambda_{5.5}/2$ and shown in Figure 4.18 (c).

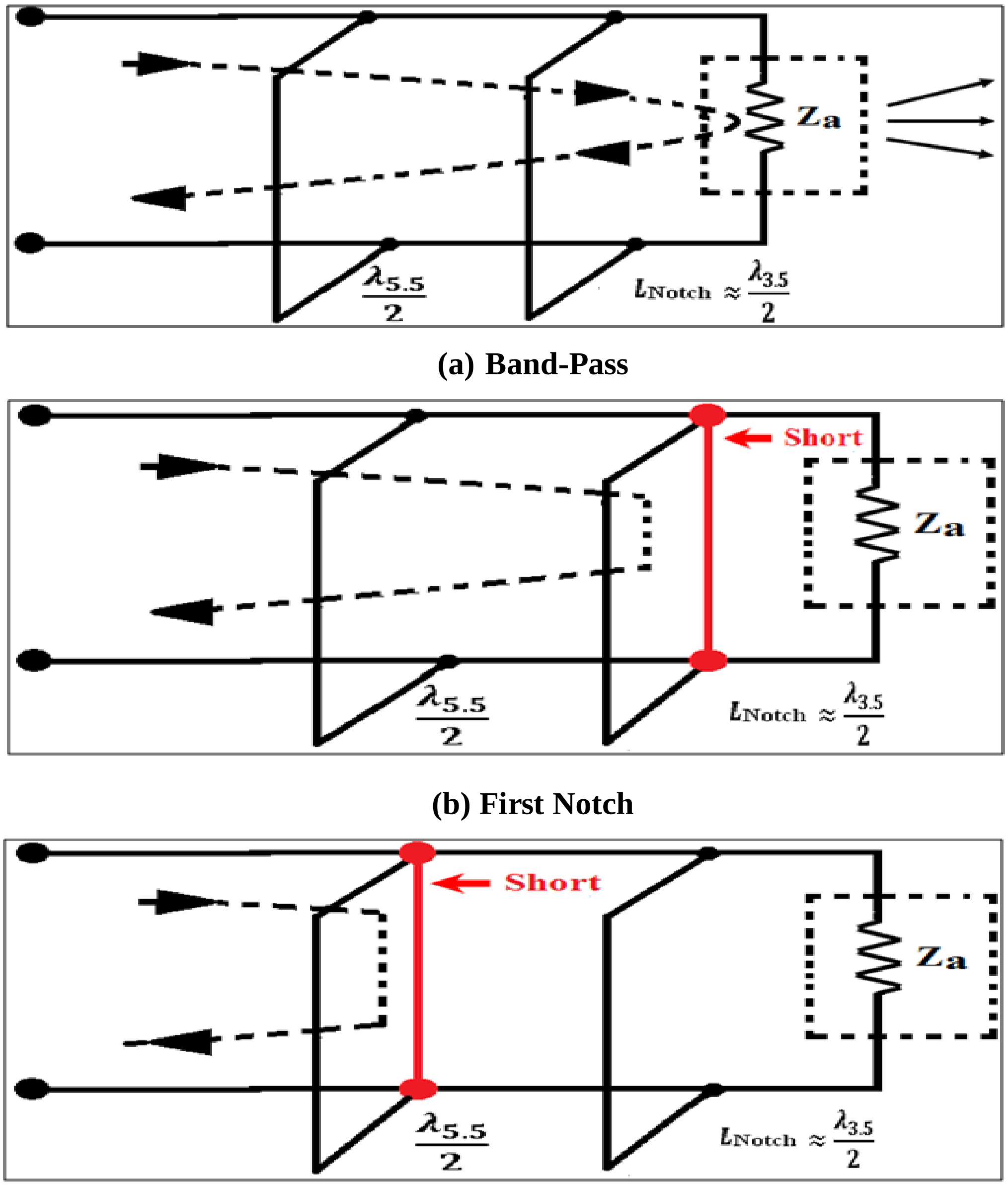


Figure 4.18 An equivalent transmission line model of dual notched band UWB antenna at (a) Band-pass (b) First notch (c) Second notch

4.6 CONCLUSION

This chapter concludes with microstrip fed planar UWB antenna with dual band notch characteristic to avoid interference of WiMAX and WLAN band with UWB band. Two U-shaped slots are etched into the patch of UWB monopole antenna to produce notch bands. The proposed antenna provides a return loss S_{11}<-10dB from 2.6GHz to 10.8GHz to cover UWB range, except a notch band 3GHz to 3.9GHz (WiMAX) band and 4.9GHz to 5.9GHz (WLAN) band. The proposed antenna gain is about 4.1dBi over the UWB frequency range, except in a notched frequency band of WiMAX and WLAN. The Radiation pattern is approximately omnidirectional over UWB range. The proposed antenna is compact, low cost, simple design techniques and easy to fabricate. The proposed double notched band UWB antenna is suitable for the UWB wireless applications without interference from coexisting bands of WiMAX and WLAN.

Table 4.9 Comparison with the design of [102]

Antenna	Techniques	Analyzed Parameters	Notch Bands (GHz)	Gain suppression (dBi)
Proposed	U-shaped slot strip Feed Rectangular	Size: 26×27 mm^2 BW: 2.6-10.8 GHz	3-3.9	-15.9
			4.9-5.9	-10.5
Reference [102]	W-shaped slot strip Feed Circular	Size: 20×30 mm^2 BW: 3-10.8 GHz	3.4-3.8	-7.2
			4.8-6.2	-9.4

Table 4.9 compares our proposed band-notched antenna with one comparable design as reported in [102], in terms of size, bandwidth (BW), number of notches and gain suppression. Both antennas have realized with two notches. However, the gain suppression of our design is better than the design reported in [102] and bandwidth of our antenna is also large.

CHAPTER 5

DESIGN AND ANALYSIS OF TRIPLE NOTCH BAND UWB ANTENNA

5.1 INTRODUCTION

In the previous chapter a dual notch band antenna has been designed to remove interference from two narrowband communication systems. But in practice there be can more than two communication system that can exist along with UWB antenna. To sort out this difficulty, many significant notched band techniques have already been discussed to overcome the interference difficulty for UWB antennas, for example, etching slots on radiating patch, C-shaped parasitic strips close to radiating patch or ground planes or along the feed line structure, L-shaped slots, T-shaped slots, H-shaped slots, metamaterial or electromagnetic band-gap (EBG) structure, and a split-ring resonator (SRR) slots. In this chapter a compact UWB patch antenna having triple notch band characteristics has been designed, simulated and fabricated.

To filter out, three interfering bands, three resonating elements are etched on the radiator patch. By changing the length, width and location of three resonating elements, the proposed antenna achieves UWB operation with a triple notched frequency band of 3.3-3.7GHz for WiMAX, 5.15-5.75GHz for WLAN and 8.02-8.4GHz for ITU. In addition, the proposed antenna achieved omnidirectional radiation patterns. The dimensions of U-shaped slots to create notched band have been optimized. For the analysis of antenna an equivalent circuit model is developed. The proposed antenna has been fabricated and the performance of fabricated antenna has been measured.

5.2 TRIPLE NOTCHED BAND UWB ANTENNA GEOMETRY

The antenna discussed in chapter 4 has been taken as initial antenna for design of triple notch band UWB antenna. Figure 5.1 illustrates the geometry and design of proposed triple notch band UWB antenna. In this design an additional U-shaped slot is created beneath the two U slots designed in chapter 4. The other parameters and overall dimensions of the antenna are kept same as discussed in chapter 4.

Table 5.1 Triple notch band UWB antenna dimensions

Parameter	Dimensions (mm)
W	26
L	27
W_P	13
L_P	16
W_g	26
L_g	10
W_f	3
g	0.5
a	1
b	1
c	3
d	1
n_1	9
l_1	9
n_2	4.7
l_2	6.7
n_3	5
l_3	1

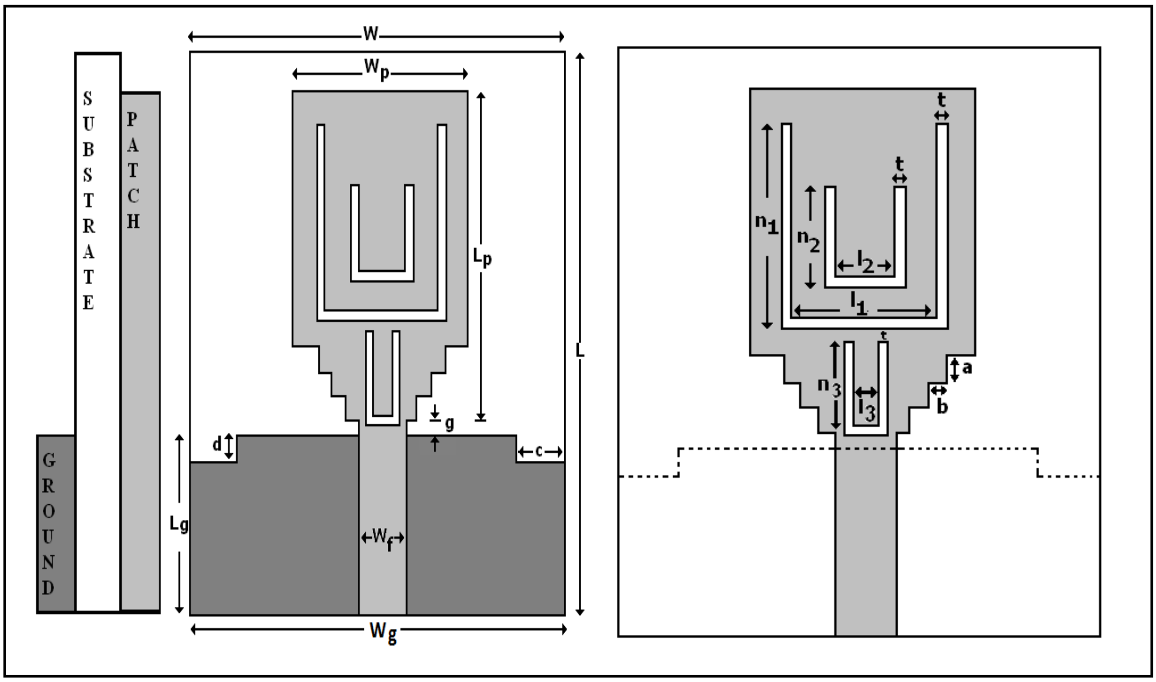


Figure 5.1Geometry of proposed triple notch band UWB antenna

By etching three U-shaped resonating slots into the radiating patch of UWB antenna, a triple band rejection can be realized. In this antenna the three notched frequencies 3.5GHz, 5.5GHz and 8.3GHz are present. The dimensions of the notched frequencies can be calculated by using equations 4.1 to 4.4, because the dimensions of L_{1Notch} and L_{2Notch} are already calculated in chapter 4. But the dimension of L_{3Notch} is calculated using equation 5.1.

$$L_{3Notch} \approx \frac{\lambda_{8.3}}{2} \approx 2n_3 + l_3 \quad (5.5)$$

Figure 5.2 shows the return loss of the proposed antenna, it is evident that an impedance bandwidth of 2.68-12GHz for S_{11}<-10dB, cover up the entire UWB range along with triple notch bands of 3-3.9GHz, 5-5.9GHz and 8-8.6GHz having S_{11}>-10dB. Therefore, the proposed antenna is appropriate for UWB wireless application with co-existing bands of the 3.3-3.7GHz (WiMAX), 5.15-5.75GHz (WLAN) and 8.04-8.4GHz (ITU) and without experiencing any interference from these bands.

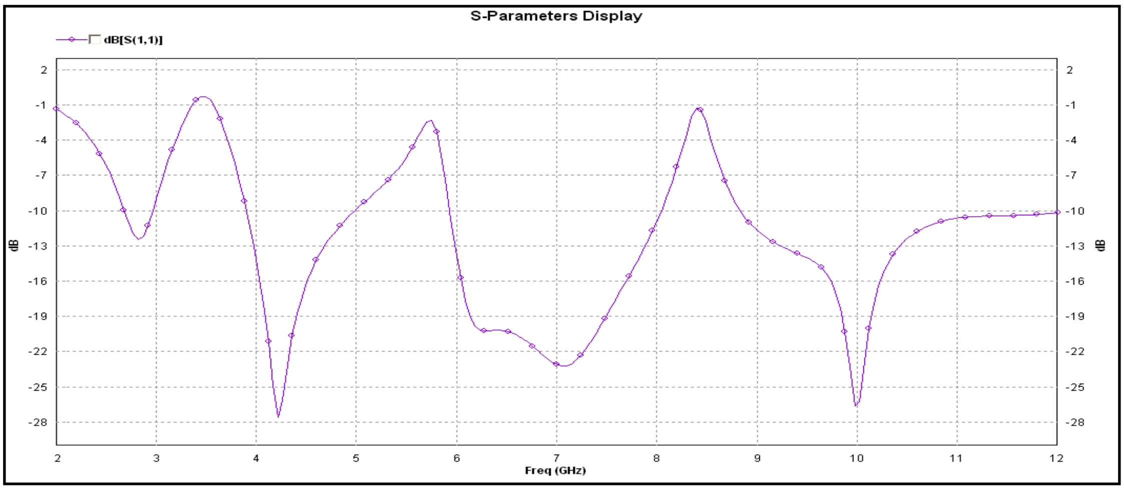


Figure 5.2 Simulated S_{11}(dB) of triple notch band U-shape UWB antenna

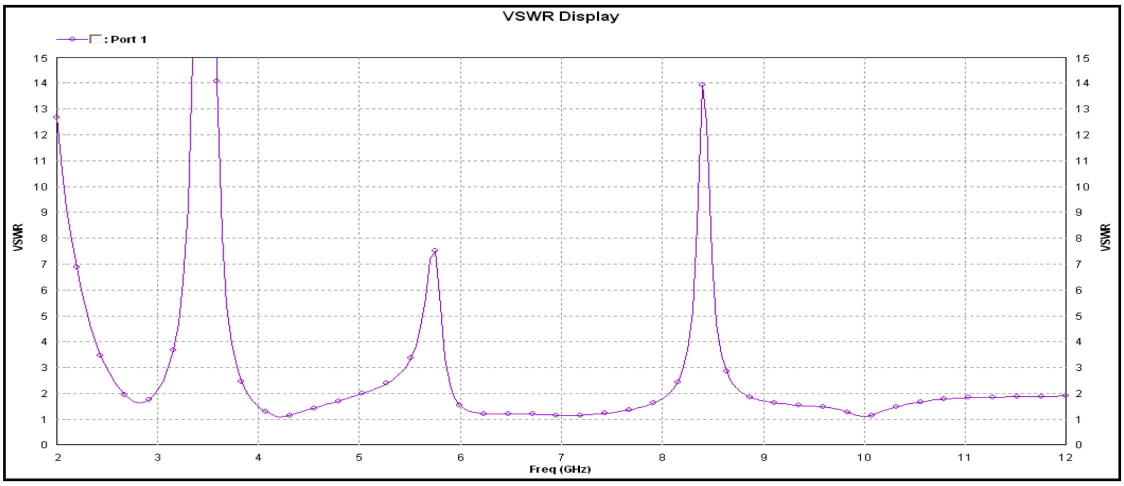


Figure 5.3 Simulated VSWR of triple notch band U-shape UWB antenna

Figure 5.3 illustrates the VSWR plot of anticipated antenna. The anticipated antenna has wideband performance of 2.68GHz to 12GHz for VSWR<2; cover up the whole UWB range along with triple notch bands of 3-3.9GHz, 5-5.9GHz and 8-8.6GHz having VSWR>2.

It is observed from Figure 5.4 and Table 5.2, the highest center notched frequency of 8.3GHz, which is determined in this section by smallest U-shaped slot. The center notched frequency gets shifted to lower value from 9.2GHz to 7.68GHz, while L_{3Notch} is increased from 10mm to 12mm, In Table 5.2, the simulated (via IE3D) and theoretical (via Equation (5.1)) calculation of notched band frequency for various L_{3Notch} lengths of U-shaped slot are compared. The maximum variation between simulated and theoretical frequency is about 0.09GHz, because of the approximation used in calculation of ε_{eff} in Equation (4.2). The U-shaped slots affect adjacent notch band peak frequency, but the effect is comparatively small as shown in Table 5.3.

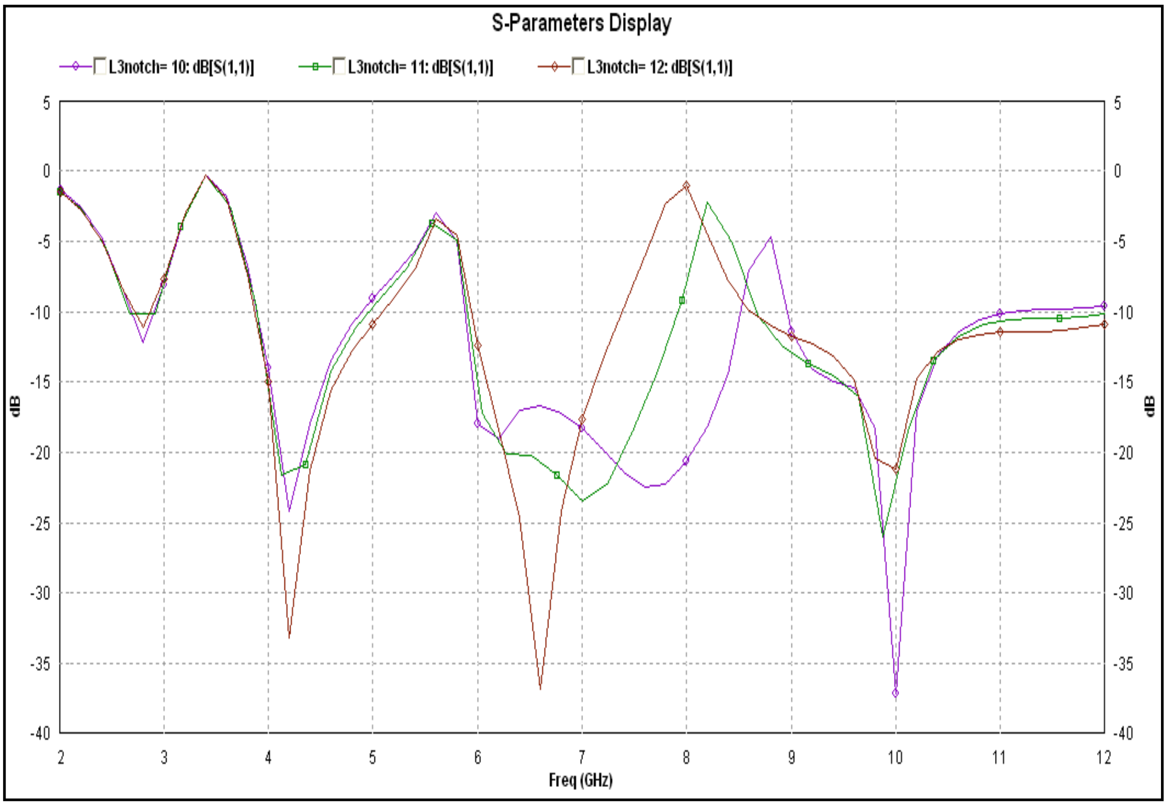


Figure 5.4 Simulated S_{11}(dB) of triple notch band antenna with different values of L_{3Notch}

Table 5.2 Simulated and theoretical value of third center notch frequency

L_{3Notch} (mm)	Simulated Frequency (GHz)	Theoretical Frequency (GHz)	Difference (GHz)
10	9.21	9.12	0.09
11	8.32	8.29	0.03
12	7.68	7.6	0.08

Table 5.3 Effect on notch band peak frequency by adjacent notch bands

Antenna	Lower notch band peak frequency	Difference in Lower notch band peak frequency	Middle notch band peak frequency	Difference in Middle notch band peak frequency
Dual Notch Antenna	3.498 GHz	0.002 GHz	5.743 GHz	0.009 GHz
Triple Notch Antenna	3.496 GHz		5.752 GHz	

5.3 PARAMETRIC ANALYSIS OF THE ANTENNA

A microstrip fed patch antenna offers many parameters to the antenna designer that can be optimized to get a UWB antenna with notched bands to avoid interference. Each parameter of U-shaped structure is individually varied to see its effect on performance of proposed antenna in term of return loss and impedance bandwidth is discussed in this section.

5.3.1 Effect of variation in U-shaped slot width (l_1)

The proposed notch band was analyzed for its operation by varying the dimensions of U-shaped slot. It can observed from Figure 5.5 and Table 5.4, the variation in S_{11}(dB) value with change in the U-shaped slot width (l_1). The lower notch frequency of first notch band gets shifted to left side by increasing the value of slot width (l_1) from 8.5mm to 9.5mm and higher notch frequency of first notch band have very small variation, and the value of return loss at center frequency has been increased. Since the desired UWB wireless applications needs a frequency notch band of 3.3-3.7GHz (WiMAX).Therefore the best value of slot width (l_1) 9mm, a notch band of 2.88-3.87GHz having S_{11}>-10dB and highest value of return loss at first center notch frequency has been achieved.

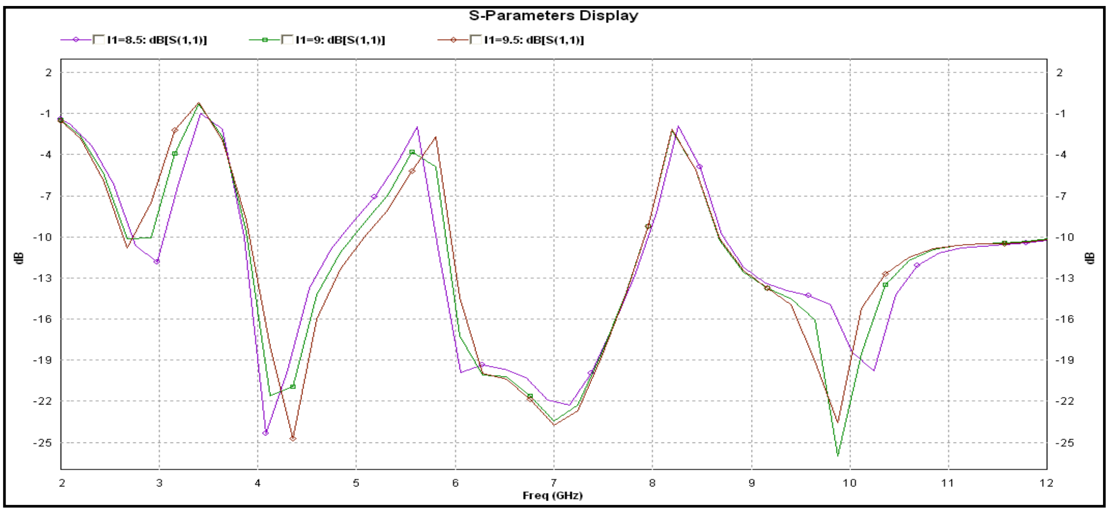


Figure 5.5 Simulated S_{11}(dB) of triple notch band U-shape UWB antenna for various l_1

Table 5.4 Effect of variation in U-shaped slot width (l_1)

Slot width (l_1) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
8.5	3.04	3.85	0.81
9	2.92	3.87	0.95
9.5	2.73	3.91	1.18

5.3.2 Effect of variation in U-shaped slot length (n_1)

From Figure 5.6 and Table 5.5, it is observed that, both the lower and higher notch frequency of first notch band shifted left side by increasing the value of slot length (n_1) from 8.5mm to 9.5mm and center frequency also gets to a lower value. For the optimum value of slot length (n_1) 9mm, a notch band of 2.92-3.87GHz having S_{11}>-10dB and symmetrical notch frequency band around center frequency has been achieved.

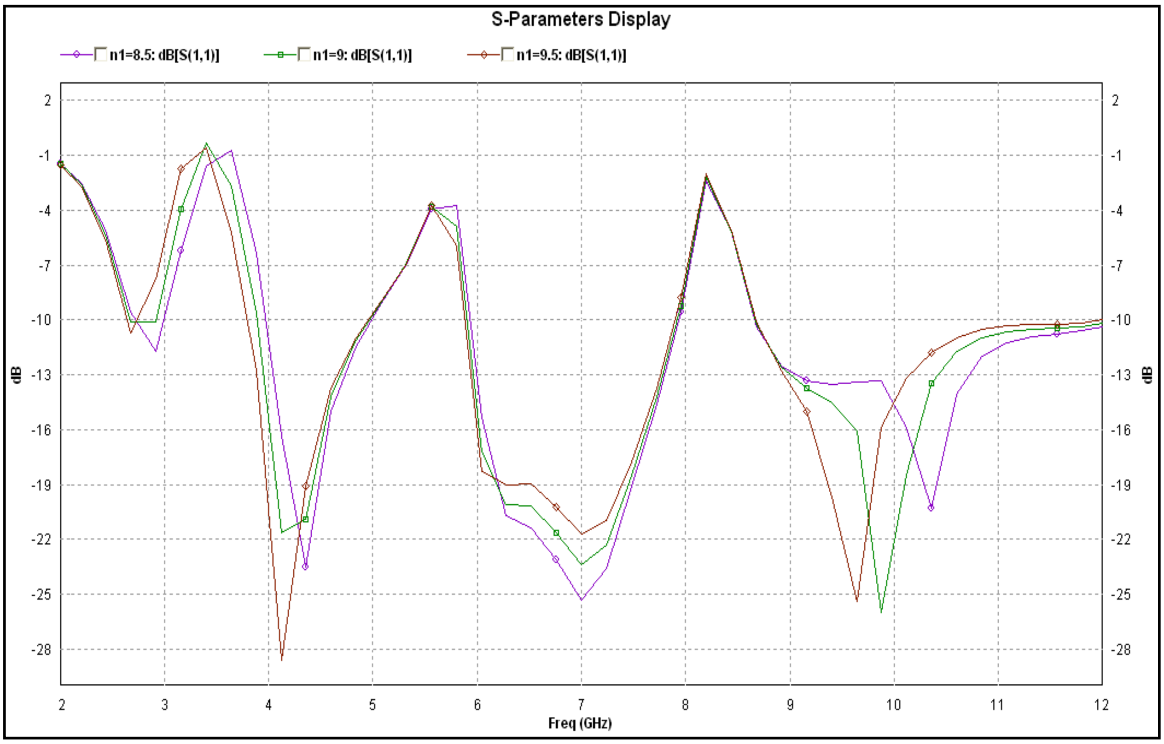


Figure 5.6 Simulated S_{11}(dB) of triple notch band U-shape UWB antenna for various n_1

Table 5.5 Effect of variation in U-shaped slot length (n_1)

Slot Length (n_1) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
8.5	2.99	3.96	0.97
9	2.92	3.87	0.95
9.5	2.73	3.81	1.08

5.3.3 Effect of variation in U-shaped slot width (l_2)

From Figure 5.7, it is seen that the middle notch frequency band gets shifted to lower frequency value by increasing the value of slot width (l_2) from 6.2mm to7.2mm and center frequency also gets to a lower value. For WLAN notch band, the optimum value of slot width (l_2) 6.5mm, a notch band of 4.95-5.88GHz having S_{11}>-10dB with center frequency of 5.5GHz has been achieved.

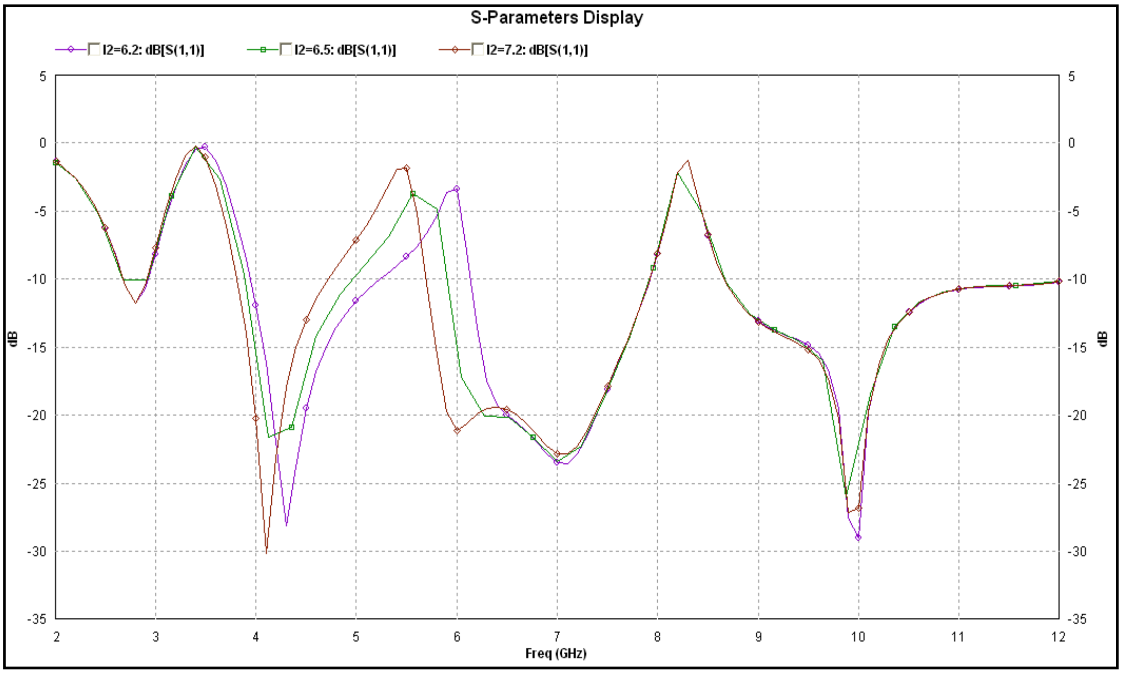


Figure 5.7 Simulated S_{11}(dB) of triple notch band U-shape UWB antenna for various l_2

Table 5.6 Effect of variation in U-shaped slot width (l_2)

Slot width (l_2) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
6.2	5.22	6.13	0.91
6.5	4.95	5.88	0.93
7.2	4.74	5.68	0.94

5.3.4 Effect of variation in U-shaped slot length (n_2)

From Figure 5.8 and Table 5.7, it can be concluded that, the middle notch frequency band gets shifted to lower frequency value by increasing the value of slot length (n_2) from 4.2mm to 5.2mm and center frequency also gets to a lower value. For the optimum value of slot length (n_2) 4.7mm, a notch band of 4.95-5.88GHz having S_{11}>-10dB to cover the WLAN notch behavior.

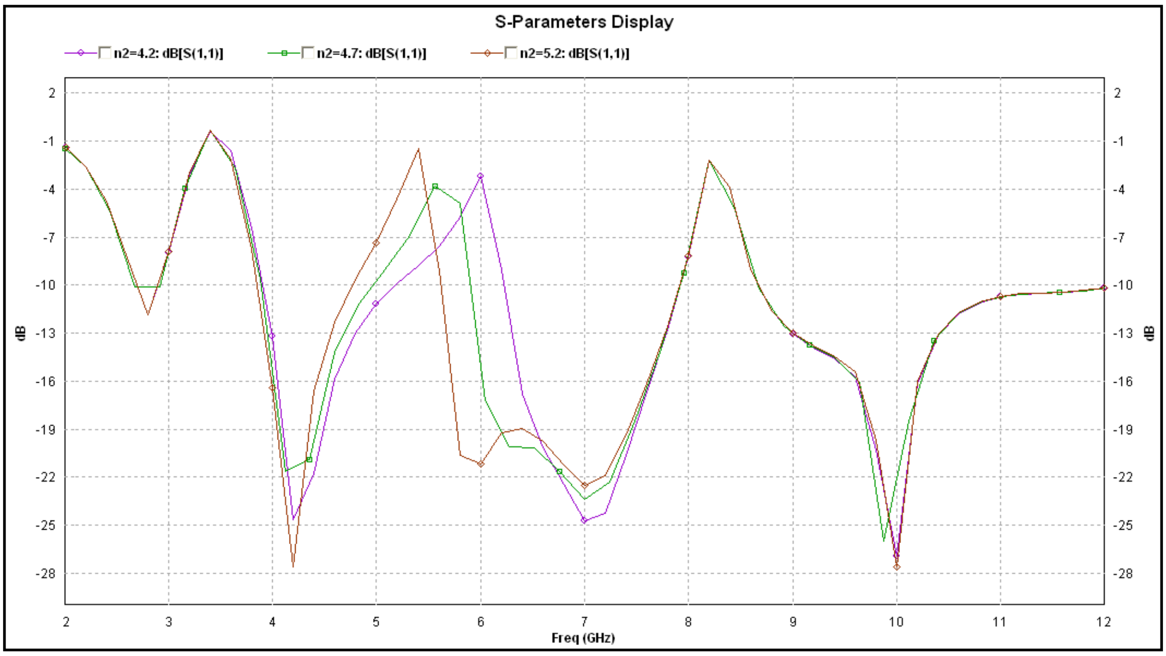


Figure 5.8 Simulated S_{11}(dB) of triple notch band U-shape UWB antenna for various n_2

Table 5.7 Effect of variation in U-shaped slot length (n_2)

Slot Length (n_2) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
4.2	5.17	6.21	1.04
4.7	4.95	5.88	0.93
5.2	4.76	5.61	0.85

5.3.5 Effect of variation in U-shaped slot width (l_3)

From Figure 5.9 we can observed that the upper notch frequency band shifted to lower side by increasing the value of slot width (l_3) from 0.5mm to 1.5mm and the value of return loss at center frequency has been increased. Since the desired UWB wireless applications needs a frequency notch band of 8.02-8.4GHz (ITU band) for satellite communication. From Table 5.8, the optimum value of slot width (l_3) 1mm, a notch band of 7.91-8.67GHz having S_{11}>-10dB has been achieved.

Table 5.8 Effect of variation in U-shaped slot width (l_3)

Slot width (l_3) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
0.5	8.5	8.96	0.46
1	7.91	8.67	0.76
1.5	7.36	8.61	1.25

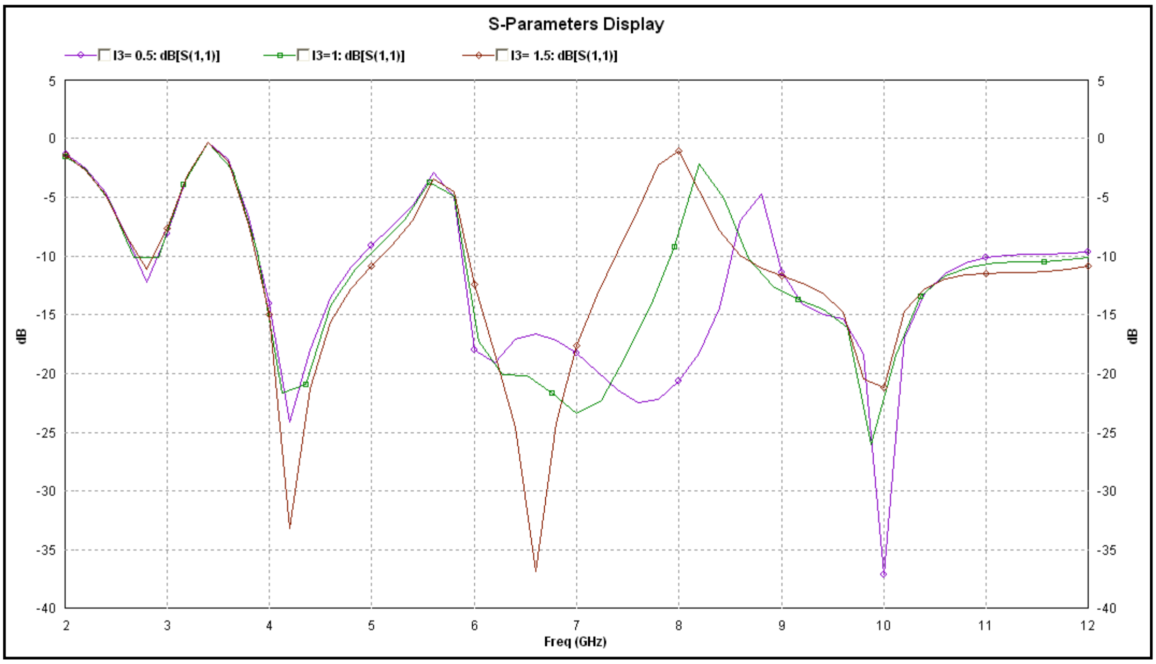


Figure 5.9 Simulated S_{11}(dB) of triple notch band U-shape UWB antenna for various l_3

5.3.6 Effect of variation in U-shaped slot length (n_3)

There is a large variation in return loss value with change in the U-shaped slot length (n_3), shown in Figure 5.10. The upper notch frequency band shifted to lower value side by increasing the value of slot length (n_3) from 4.5mm to 5.5mm and the value of return loss at center frequency has no major change. From Table 5.9, the optimum value of slot length (n_3) 5mm, a notch band of 7.91-8.67GHz having S_{11}>-10dB has been achieved.

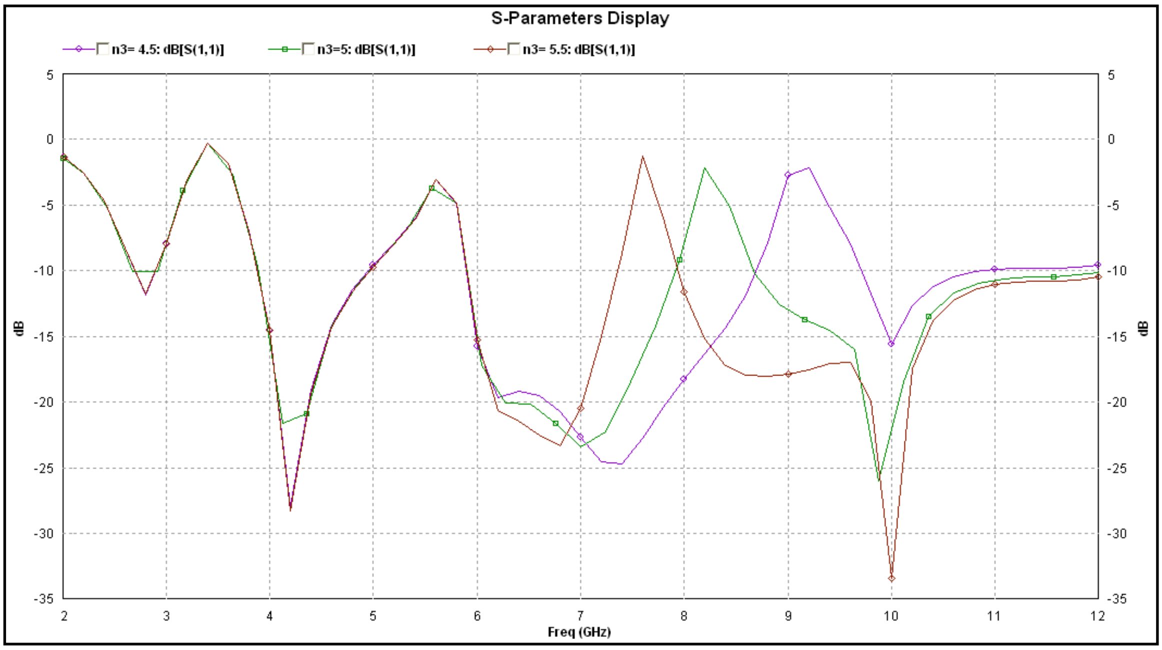


Figure 5.10 Simulated S_{11}(dB) of triple notch band U-shape UWB antenna for various n_3

Table 5.9 Effect of variation in U-shaped slot length (n_3)

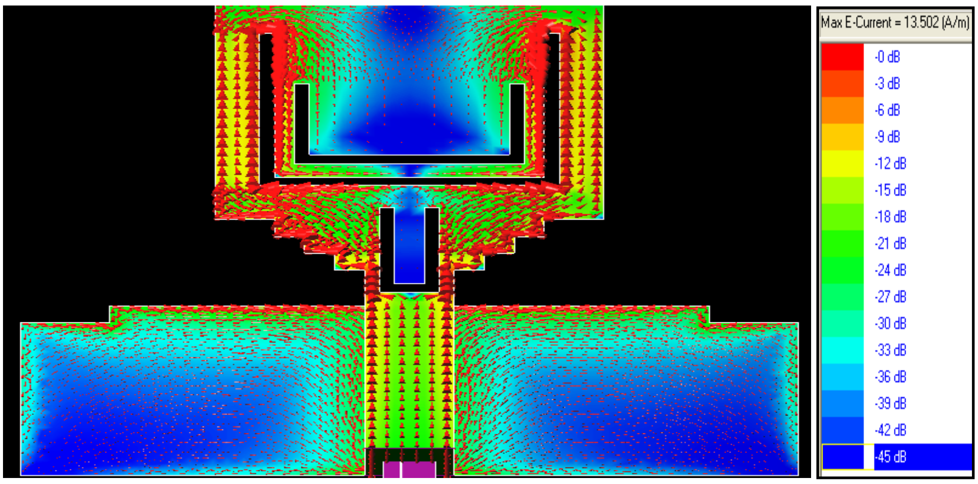
Slot Length (n_3) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
4.5	8.6	9.7	1.1
5	7.91	8.67	0.76
5.5	7.35	7.94	0.59

5.4 MODAL ANALYSIS

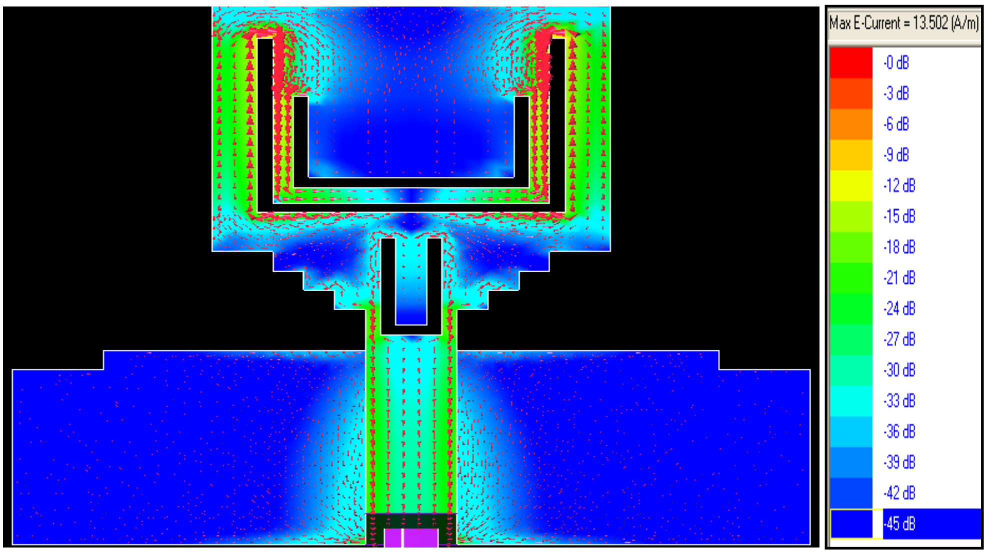
5.4.1 Current Distribution

The microstrip fed UWB antenna structure was excited using the feed network to see the distribution of energy over its various structural parts. This helps in analyzing that in what capacity, a specific part of the antenna is responsible for giving the resonant frequency of antenna operation.

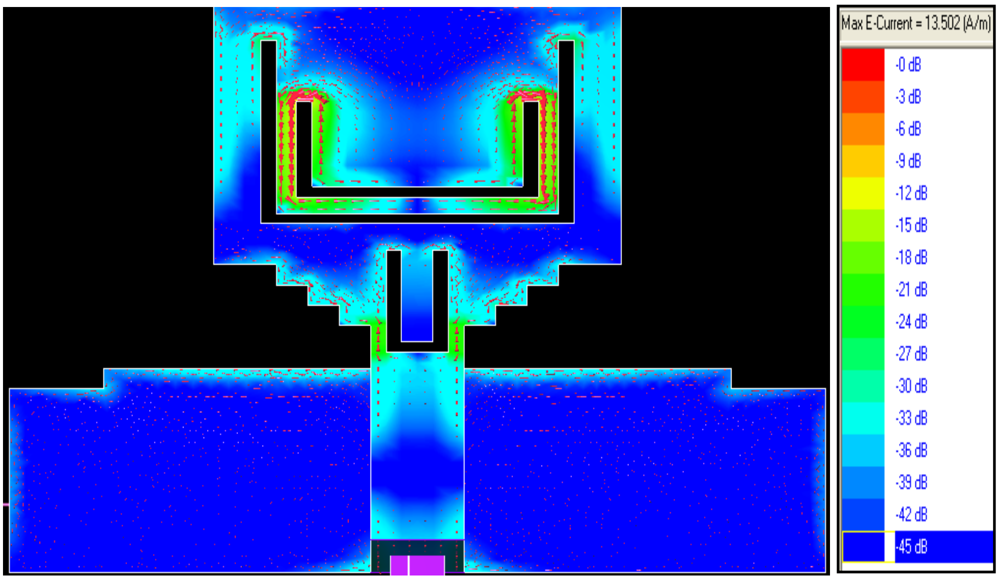
Figure 5.11 illustrates the simulated surface current distribution at a frequency of 2.8GHz, 3.5GHz, 5.5GHz, 8.3GHz and 10GHz. It has been observed in Figures 5.11 (a) and (e), that the surface current distribution is more dominant near the periphery of patch radiator and all the current vectors are in the same direction, therefore the antenna radiates at 2.8GHz and 10GHz. But in Figure 5.11 (b), (c) and (d) at frequency of 3.5GHz, 5.5GHz and 8.3GHz, the surface current distribution is more dominant around U-shape filter structure and current vectors are in opposite direction and they cancel each other, which acts as a short circuit resonator [128]. This suggests that the U-shaped filter structure has a major effect on UWB antenna performance for elimination of a frequency band. Therefore, the antenna does not radiate at 3.5GHz, 5.5GHz and 8.3GHz and a frequency notch bands are created around these frequencies. Thus, from the current distributions, it is confirmed that the U-shaped filter structure causes the frequency notch functions [82, 100, 130].



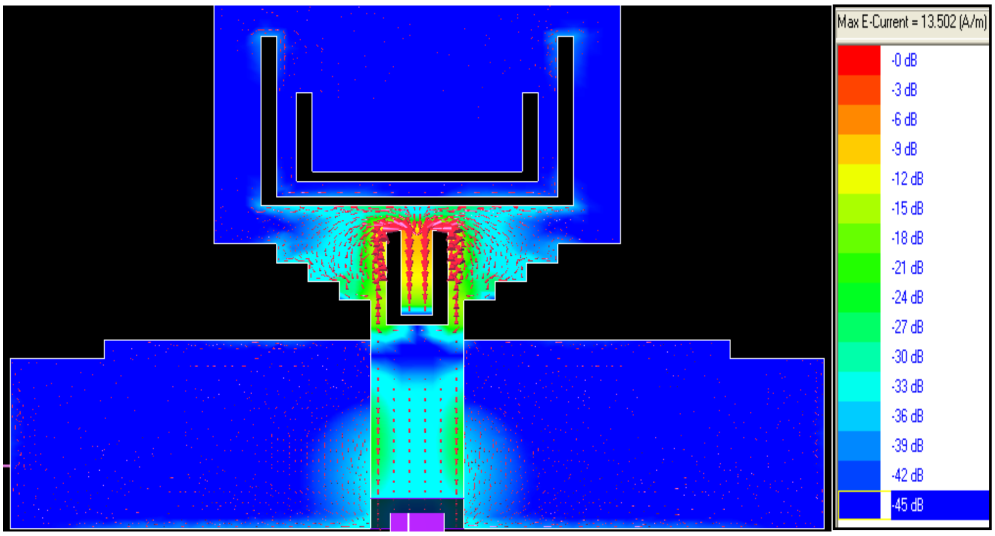
(a) 2.8GHz



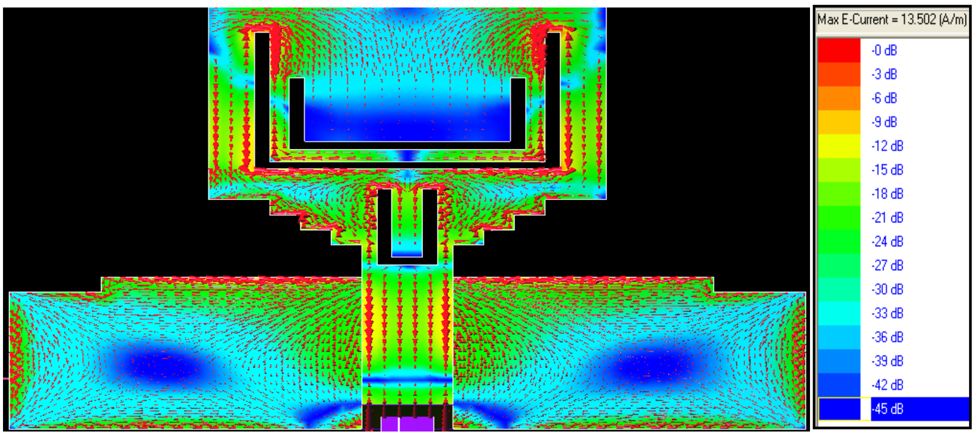
(b) 3.5GHz



(c) 5.5GHz



(d) 8.3GHz

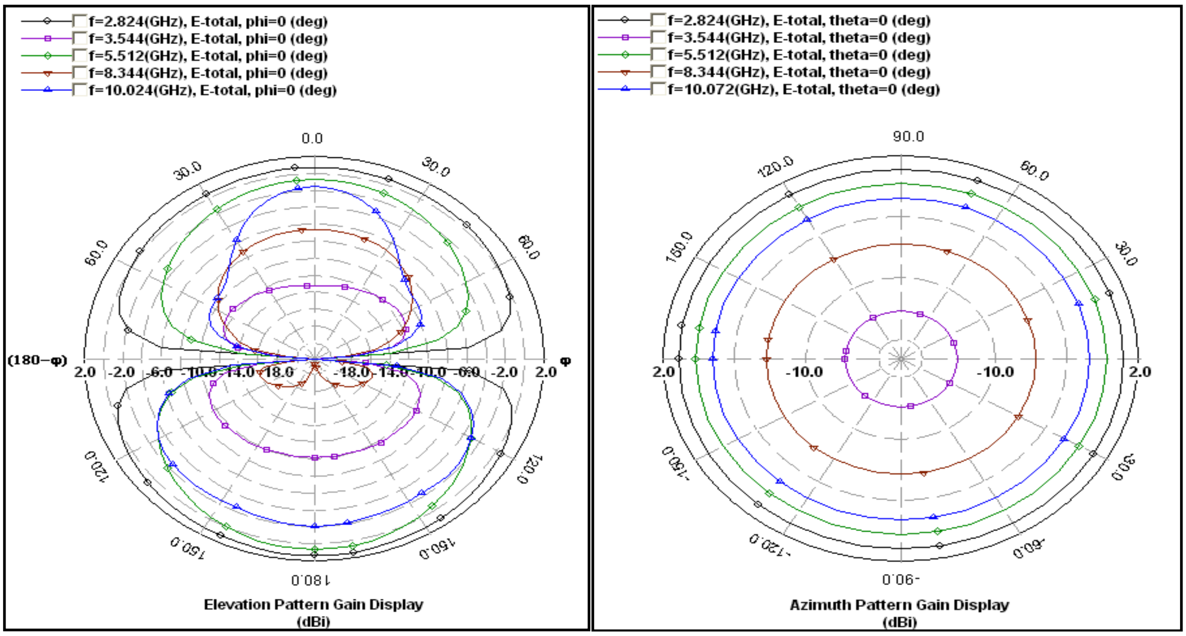


(e) 10GHz

Figure 5.11 Surface current distribution of triple notch band UWB antenna at (a) 2.8GHz (b) 3.5GHz (c) 5.5GHz (d) 8.3GHz (e) 10GHz

5.4.2 Radiation Patterns

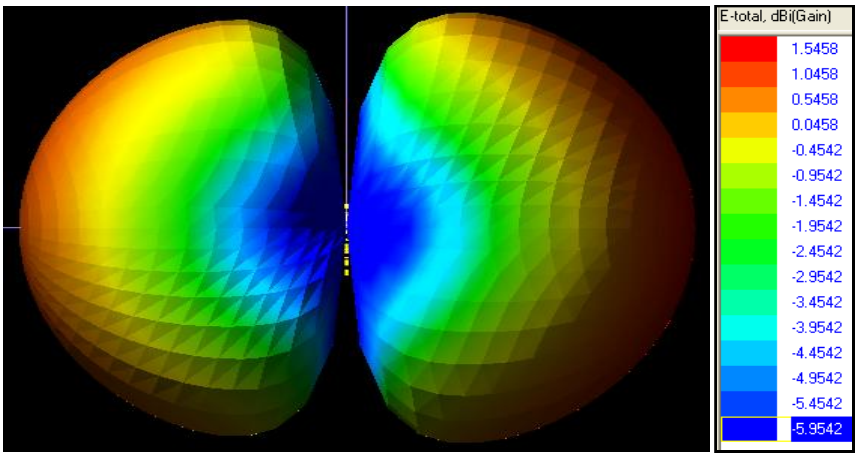
The 2-D radiation pattern of the designed triple notched band UWB antenna is illustrated in Figures 5.12 E-plane (Y-Z) and H-plane (X-Z) at 2.8GHz, 3.5GHz, 5.5GHz, 8.3GHz and 10GHz. Figure 5.12 (a) shows the E-plane (Y-Z) pattern which is similar to the dipole antenna pattern like Figure-of-Eight in vertical plane at the lower frequencies, but with reduced lobe width at higher frequencies. Therefore, the radiation patterns at higher frequencies become slightly distorted form Figure-of-Eight shape. Figure 5.12 (b) shows the 2-D radiation pattern in H-plane (X-Z) which is almost omnidirectional.



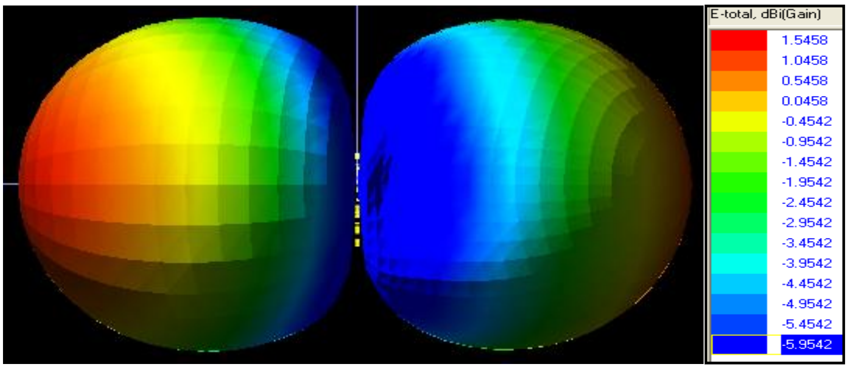
(a) Elevation pattern (Y-Z Plane) **(b) Azimuth pattern (X-Z Plane)**

Figure 5.12 2-D radiation pattern of triple notched band UWB antenna at 2.8GHz, 3.5GHz, 5.5GHz, 8.3GHz and 10GHz

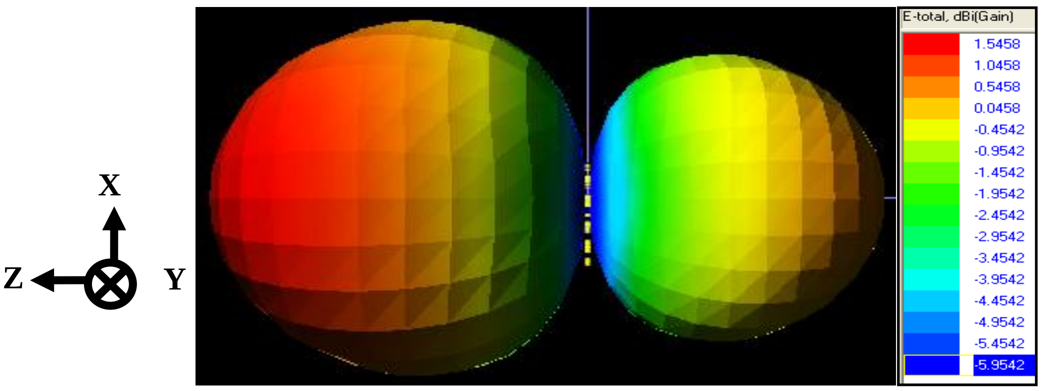
The 3-D radiation pattern of proposed triple notched band UWB antenna is illustrated in Figures 5.13 at 2.8GHz, 3.5GHz, 5.5GHz, 8.3GHz, and 10GHz. Figure 5.13 (a) shows the 3-D radiation pattern which is similar to the dipole antenna pattern in the vertical plane at the lower frequencies, but degradation at the upper frequencies is shown in Figure 5.13 (e).Therefore, the 3-D radiation pattern at higher frequencies become distorted and splits into minor lobes. It can also be observed from Figure 5.13 (b), (d) and (e) that the radiation pattern gain at 3.5GHz, 5.5GHz and 8.3GHz is small as compared to other frequency, these shows that at these frequencies the antenna does not radiate.



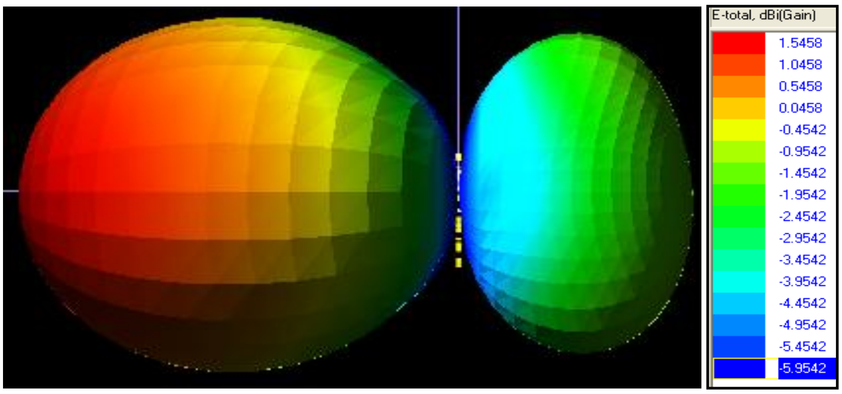
(a) 2.8GHz



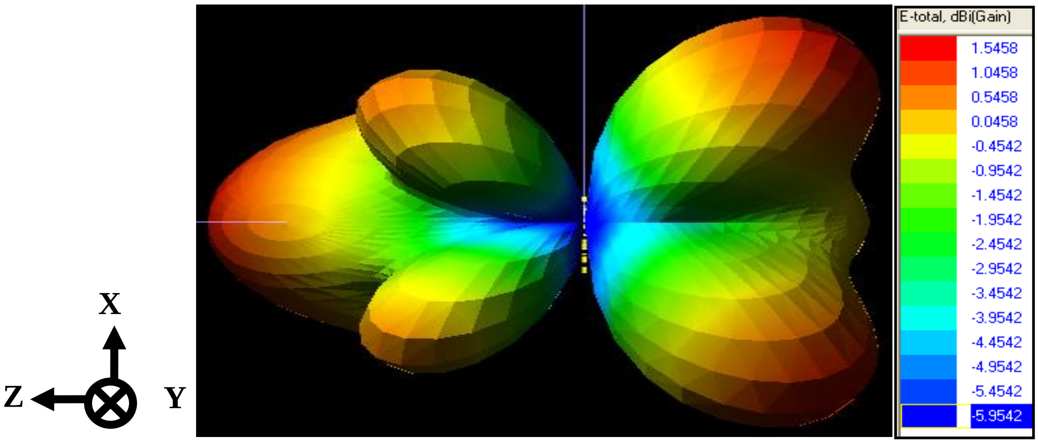
(b) 3.5GHz



(c) 5.5GHz



(d) 8.3GHz



(e) 10GHz

Figure 5.13 3-D radiation pattern of triple notched band UWB antenna at (a) 2.8GHz (b) 3.5GHz (c) 5.5GHz (d) 8.3GHz (e) 10GHz

5.4.3 Equivalent Circuit

For the proposed triple notched band UWB antenna, notch band properties are attained by creating three resonant structures, consisting of three series RLC resonators.

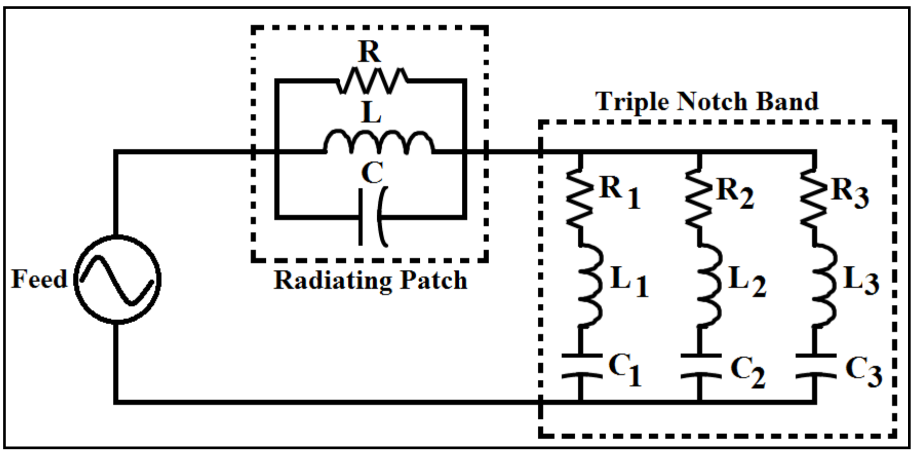
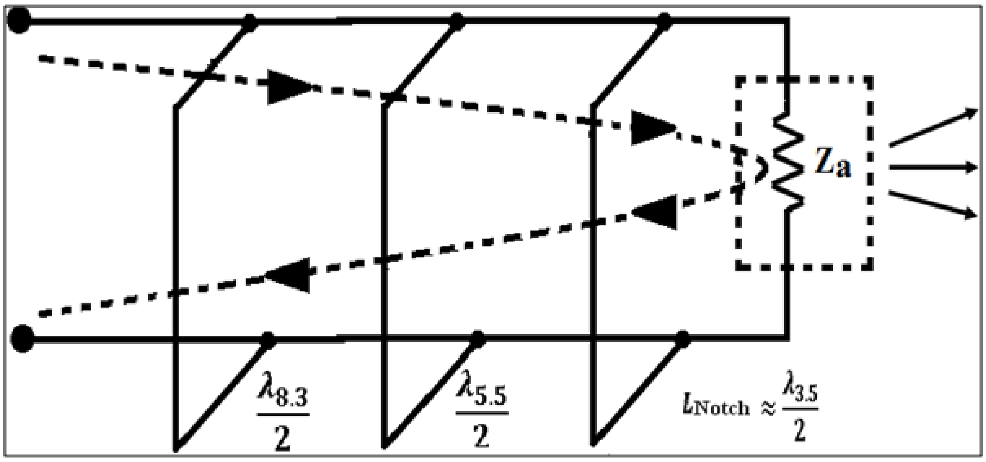


Figure 5.14 An approximated equivalent circuit model of triple notched band UWB antenna

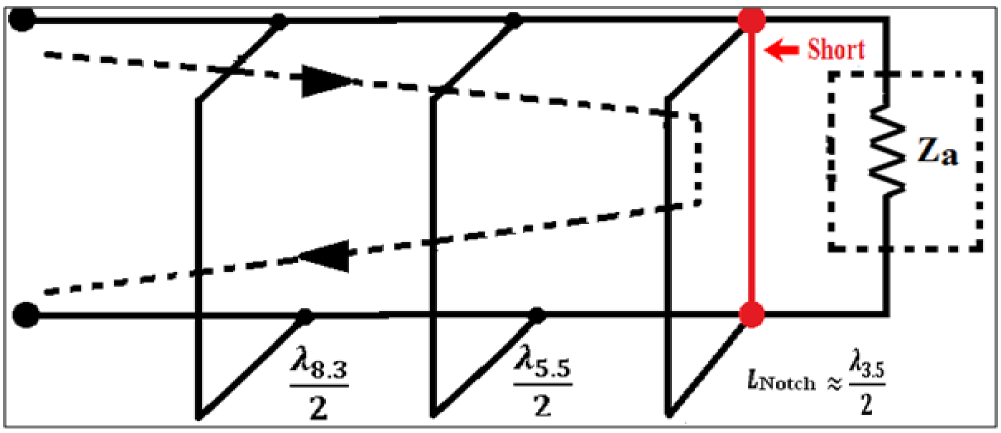
Therefore, the input impedance is designed by parallel R, L and C for band pass resonant frequencies. While for the three rejection bands, three extra R, L and C components in-series are included to describe the triple band-notched structures [125-127]. Figure 5.14illustrates the equivalent circuit model of designed triple notched band UWB antenna.

Figure 5.15 shows the equivalent transmission line model of proposed triple notched bands UWB antenna, where, Za is the impedance of the antenna and three parallel stubs acts like half-wavelength resonator. The three stub ends are short circuited and modeled like $\lambda_{3.5}/2$, $\lambda_{5.5}/2$, and $\lambda_{8.3}/2$ long for the total length about 27mm, 16.1mm and 11mm which correspond to the rejection frequencies of 3.5GHz, 5.5GHz and 8.3GHz, respectively.

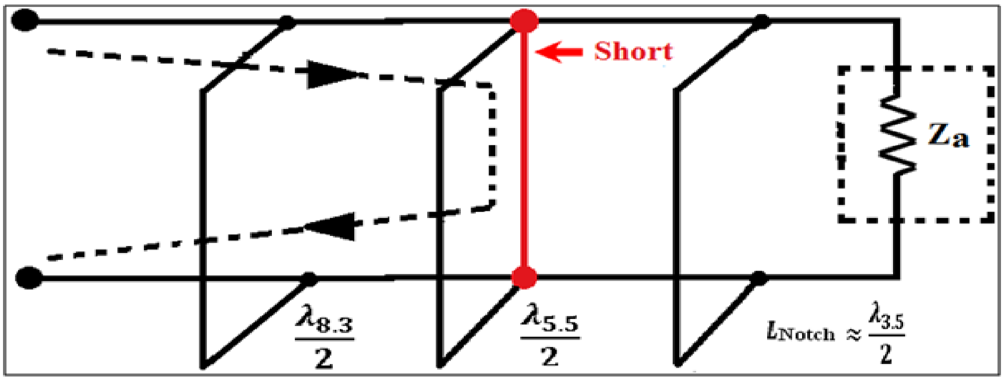
Figure 5.15(a) the band-pass frequency equivalent circuit. Figure 5.15(b) shows, the WiMAX notch band, when $L_{1Notch} \approx \lambda_{3.5}/2$, the impedance at feed point is zero (short circuited) and antenna become nonreactive; hence WiMAX notched band is produced. In a similar way, another notch band for WLAN and ITU are created when $L_{2Notch} \approx \lambda_{5.5}/2$, and $L_{3Notch} \approx \lambda_{8.3}/2$as illustrated in Figure 5.15(c) and (d).



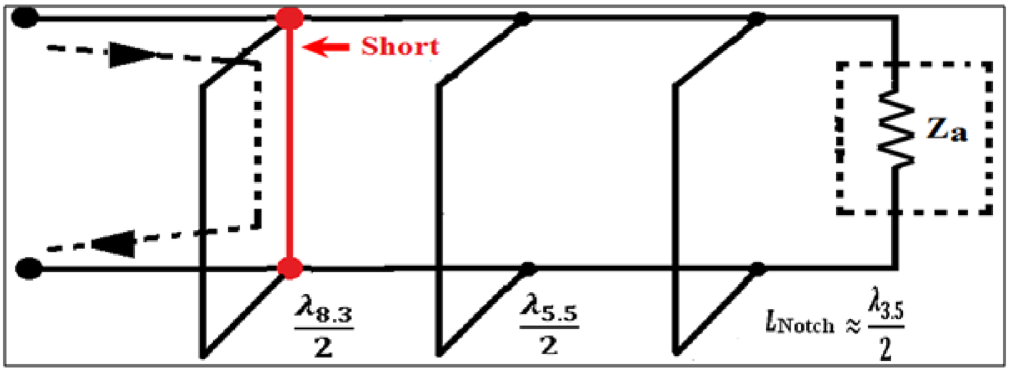
(a) Band-Pass



(b) WiMAX Notch



(c) WLAN Notch

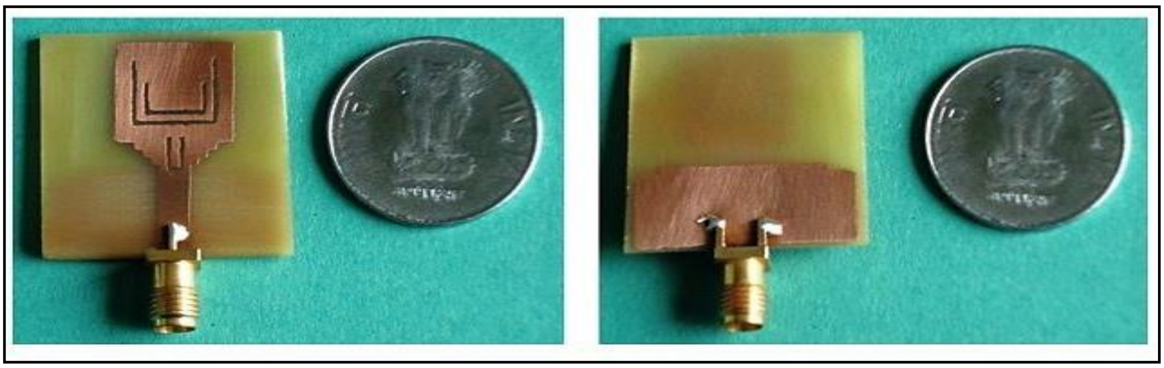


(d) ITU Notch

Figure 5.15 An equivalent transmission line model of triple notched band UWB antenna at (a) Band-pass (b) WiMAX notch (c) WLAN notch and (d) ITU notch

5.5 FABRICATION AND TESTING OF PROPOSED ANTENNA

Figure 5.16 shows the proposed fabricated antenna by using optimized parameters summarized in Table 5.1. The various steps that are carried out in the fabrication process are highlighted in Figure 4.9 of chapter 4, which shows the flow chart of steps that are carried out to fabricate the final antenna.



(a) Front View (b) Back View

Figure 5.16 Proposed fabricated triple notch band UWB antenna

Figure 5.17 shows the measured and simulated reflection coefficients of projected triple notch band UWB antenna. It is observed that here is a good agreement between simulated and measured results. The designed antenna has wideband performance of 2.9 to 10.7GHz for S_{11}<-10dB, cover up the entire UWB range with triple notch bands of 3.1-4GHz, 5-6.3GHz and 8.1-9GHz having S_{11}>-10dB. Therefore, the proposed antenna is appropriate for UWB wireless application without interfering with co-existing bands of the 3-3.7GHz (WiMAX) and the 5.15-5.75GHz (WLAN) and 8-8.4 (ITU) [130].

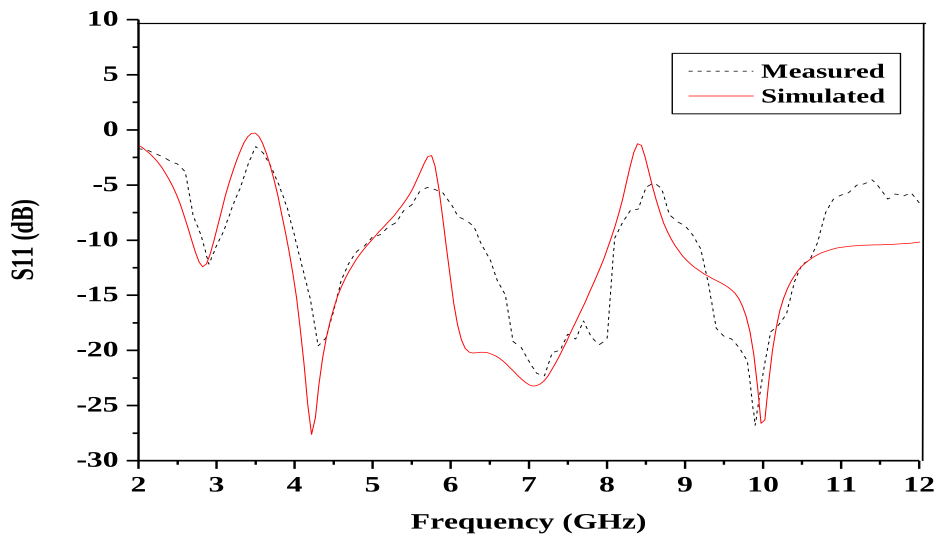


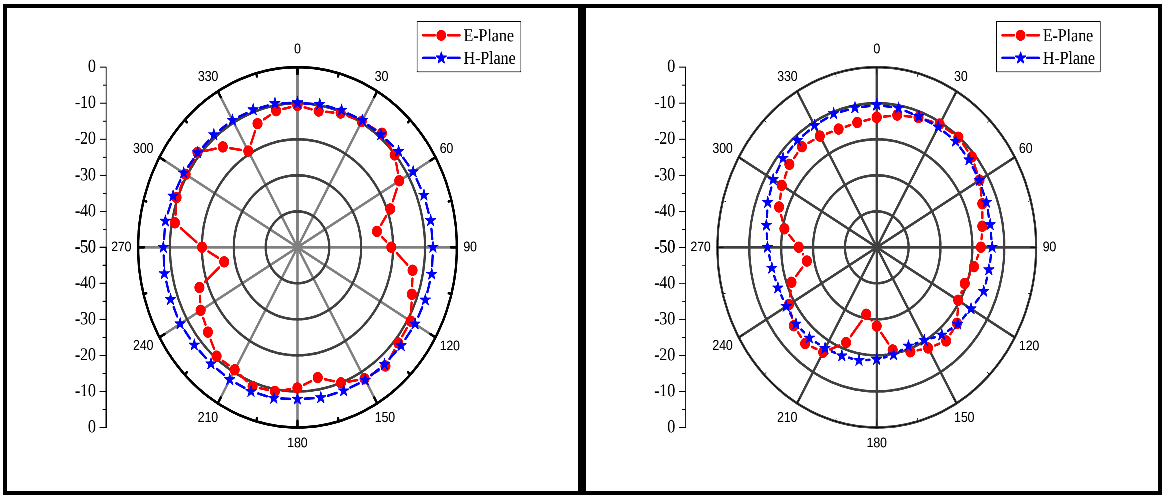
Figure 5.17 Simulated and measured S_{11}(dB) of triple notched band UWB antenna

Table 5.10 Comparison of simulated and measured return loss

Notch band	Simulated Frequency at Peak S_{11} (GHz)	Measured Frequency at Peak S_{11} (GHz)	Error (GHz)
WiMAX	3.49	3.52	0.03
WLAN	5.75	5.71	0.04
ITU	8.34	8.46	0.12

The simulated return loss peak of notch band is slightly differed with the measured, because of the fabrication error that might be present while physically assembling it.

The measured radiation pattern of the proposed UWB antenna at 4.56GHz, 7.08GHz and 9.64GHz has been illustrated in Figure 5.18. The antenna is printed in X-Y plane, therefore Y-Z represents E- plane and X-Z represents an H-plane. It is seen from Figure 5.18 that the radiation pattern of E-plane (X-Z) is similar to monopole antenna and radiation pattern of H-plane (Y-Z) is almost omnidirectional for all frequencies.



(a) **4.56GHz** **(b) 7.08GHz**

(c) 9.64GHz

Figure 5.18 Measured radiation pattern of triple notch band UWB antenna at (a) 4.56GHz (b) 7.08GHz (c) 9.64GHz

The gain of the antenna has been tested in an anechoic chamber. Figure 5.19 shows simulated and measured gain of the proposed antenna.

Table 5.11 Gain suppression at various notch band

Notch band	Simulated Maximum gain suppression (dBi)	Measured Maximum gain suppression (dBi)
WiMAX	-15.99	-10.8
WLAN	-9.48	-3.1
ITU	-4.68	-2.3

At notch frequency band, the gain of the antenna decreases sharply. The simulated gain of proposed antenna is 5.1dBi and its measured gain is about 3.8dBi over the complete UWB range, except in a notched frequency band of WiMAX, WLAN and ITU service band as shown in Table 5.11.

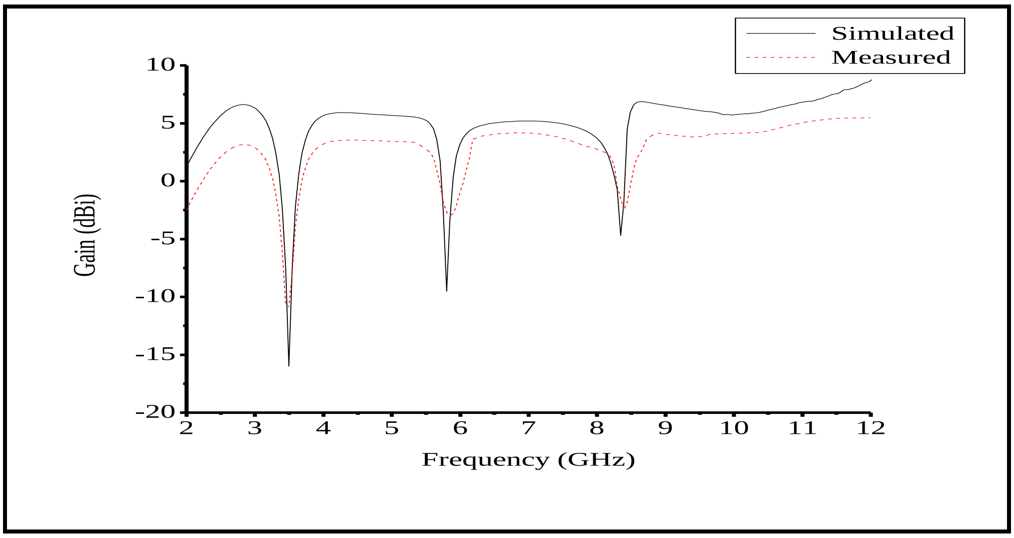


Figure 5.19 Gain of triple notch band UWB antenna

5.6 CONCLUSION

This chapter concludes with a microstrip fed planar UWB antenna with the triple notch band characteristic to avoid interference of WiMAX, WLAN and ITU service band with UWB band. Three U-shaped slots are etched into the patch of UWB monopole antenna to produce notch bands. The proposed antenna provides a return loss S_{11}<-10dB from 2.68 to 12GHz to cover UWB range, except notched bands in the 3-3.9GHz (WiMAX), 5-5.9GHz (WLAN) and 8-8.6GHz (ITU). The proposed antenna gain is about 3.8dBi over complete UWB frequency range, except in a notched frequency band. The Radiation patterns are approximately omnidirectional over UWB range. The designed antenna is compact, low cost, simple design techniques and easy to fabricate. The proposed triple notched band UWB antenna is suitable for the UWB wireless applications without interference from coexisting bands of WiMAX, WLAN and ITU.

Table 5.12 Comparison with the design of [112]

Antenna	Techniques	Analyzed Parameters	Notch Bands (GHz)	Gain suppression (dBi)
Proposed	U-shaped slot strip Feed Rectangular	Size: 26×27 mm^2 BW: 2.68-12 GHz	3-3.9	-15.9
			5-5.9	-9.5
			8-8.6	-4.7
Reference [112]	SRRs slot strip Feed Semi-Circular	Size: 35×35 mm^2 BW: 2.2-12.8 GHz	2.95-3.7	-5.8
			5.12-6.02	-1
			8.04-8.65	-3.1

Table 5.12 compares our proposed band-notched antenna with one comparable design as reported in [112], in terms of size, bandwidth (BW), number of notches and gain suppression. Both antennas have realized with three notches. However, the gain suppression of our design is better than the design reported in [112] and size of our antenna is also small.

CHAPTER 6

DESIGN OF CPW FED FIVE NOTCH BAND UWB ANTENNA FOR WIRELESS APPLICATIONS

6.1 INTRODUCTION

In recent years, coplanar waveguide (CPW) fed antenna has received much attention because of its attributes, like large bandwidth, planar structure and easy installation with RF devices. High-performance UWB antenna requires good impedance bandwidth, stable radiation patterns and high efficiency within the specified frequency bands.

In chapter 4 and chapter 5 two and three interferences were rejected from the UWB antenna. But sometimes, within the intended bandwidth of UWB system, there can exist more than three narrow band services for wireless communication, which create interference with UWB system. In this chapter a new CPW fed UWB antenna has been proposed in which five interferences sources have been filtered out. Five narrow interference bands like WiMAX, WLAN (lower and upper), downlink of X-band and ITU are notched, having a center frequency of 3.5GHz, 5.2GHz, 5.8GHz, 7.5GHz and 8.2GHz.

Details of the antenna design and the dimensions of U-shaped slots to create notched band are studied. For the analysis of antenna an equivalent circuit model is developed. The proposed antenna has been fabricated and the performance of fabricated antenna has been measured.

6.2 INITIAL RECTANGULAR CPW FED UWB ANTENNA DESIGN

A rectangular CPW fed antenna is selected as a fundamental structure due to its wide operating bandwidth. Figure 6.1 illustrates the geometry and drawing of the proposed CPW fed UWB antenna. The proposed antenna has a very small size of W×L ($30\times32mm^2$) and printed on a substrate FR4 with $\varepsilon_r = 4.4$, thickness ht = 1.6mm and loss tangent tan $\delta = 0.02$. The proposed antenna has been designed with optimal parameters tabulated in Table 6.1. The electromagnetic software IE3D is used for designing and simulation of antenna. Figure 6.2 and Figure 6.3 shows the simulated return loss and VSWR results of the designed CPW fed UWB antenna.

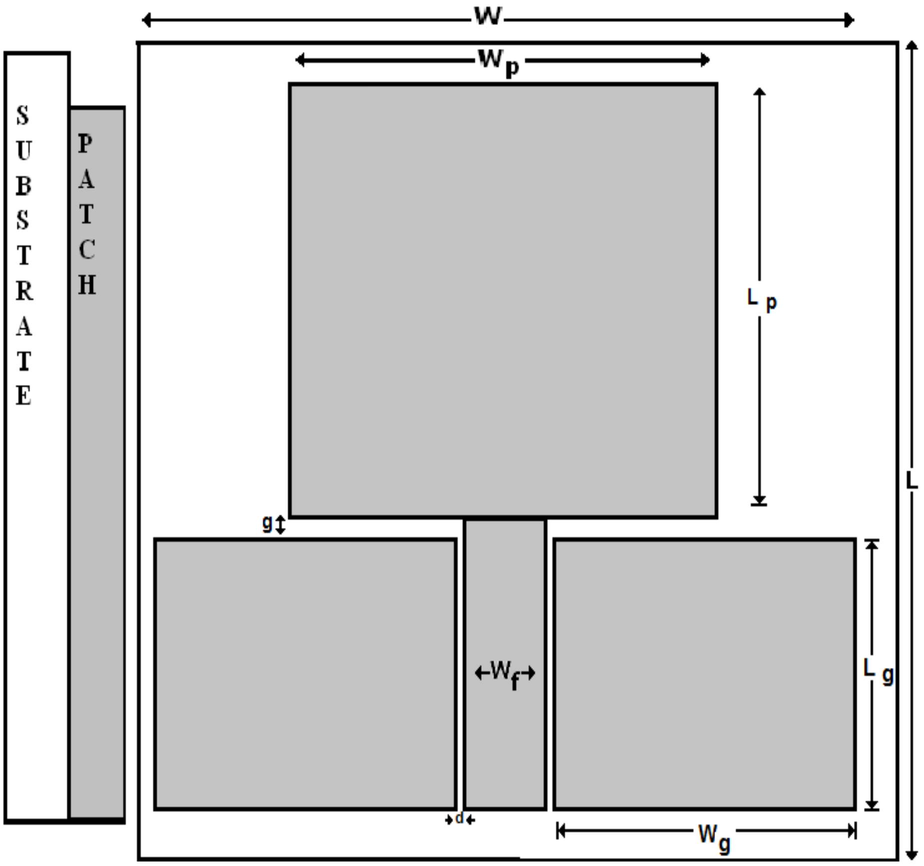


Figure 6.1 Geometry of proposed CPW fed UWB antenna

Table 6.1 Proposed CPW Fed UWB antenna dimensions

Parameter	Dimensions (mm)
W	30
L	32
W_P	13
L_P	18
W_g	13
L_g	13
W_f	3
g	0.8
d	0.3

Figure 6.2 illustrates the simulated reflection coefficients of the designed UWB antenna. It is evident from the return loss curve that the projected antenna has wideband performance of 3.15GHz to11.14GHz for S_{11}<-10dB, covering the whole UWB band. The antenna covers a bandwidth of 7.99GHz. Figure 6.3 illustrates the simulated VSWR of projected UWB antenna. The VSWR curve also shows a satisfactory performance of the antenna over the entire UWB band.

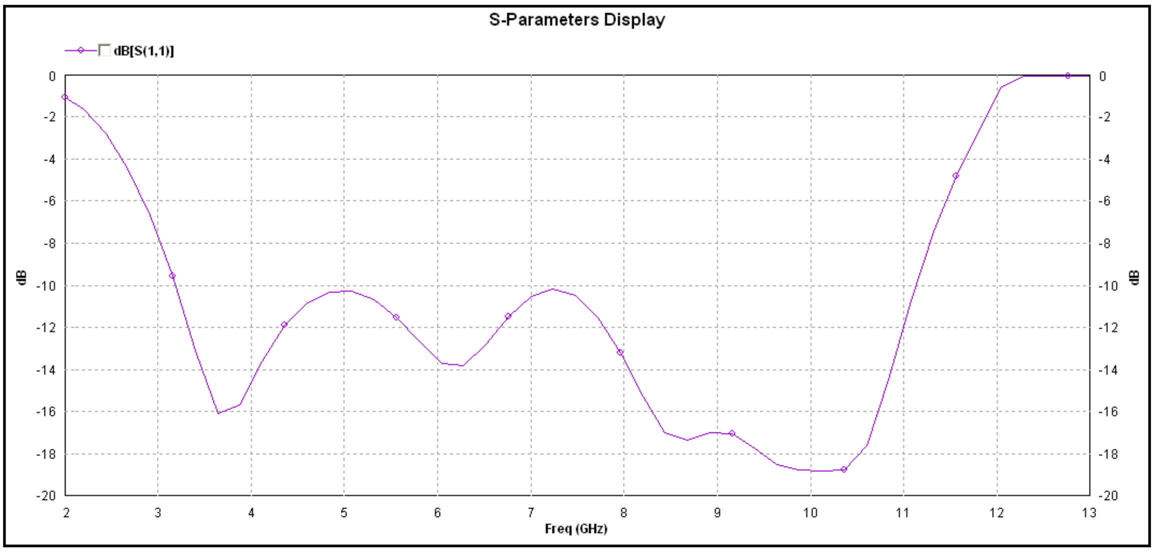


Figure 6.2 Simulated reflection coefficient S_{11}(dB) of rectangular CPW fed antenna

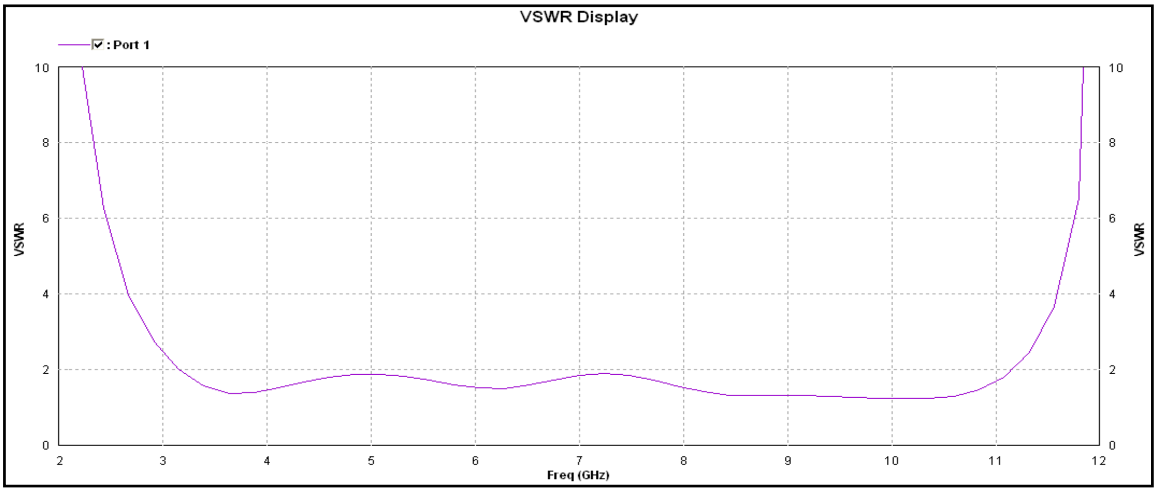


Figure 6.3 Simulated VSWR of rectangular CPW fed antenna

6.3 FIVE NOTCHED BAND UWB ANTENNA GEOMETRY

UWB antenna with multiple notch band characteristic has been designed by etching U-shape slots on initial rectangular CPW fed UWB antenna radiating patch designed in previous section. The U- shape slots are generating anti-resonance at the definite frequency by which notched band properties have been developed in antenna. By using this principle, the antenna having five notched bands has been projected. Figure 6.4 illustrates the geometry and design of anticipated five notch band UWB antenna. The proposed antenna has a very small size of W×L (30×32mm^2) and printed on a substrate FR4 with ε_r = 4.4, thickness ht = 1.6mm and loss tangent tan δ = 0.02. The width of the microstrip feed W_f = 3mm is set to attain 50Ω characteristic impedance to be matched to an SMA connector [131].

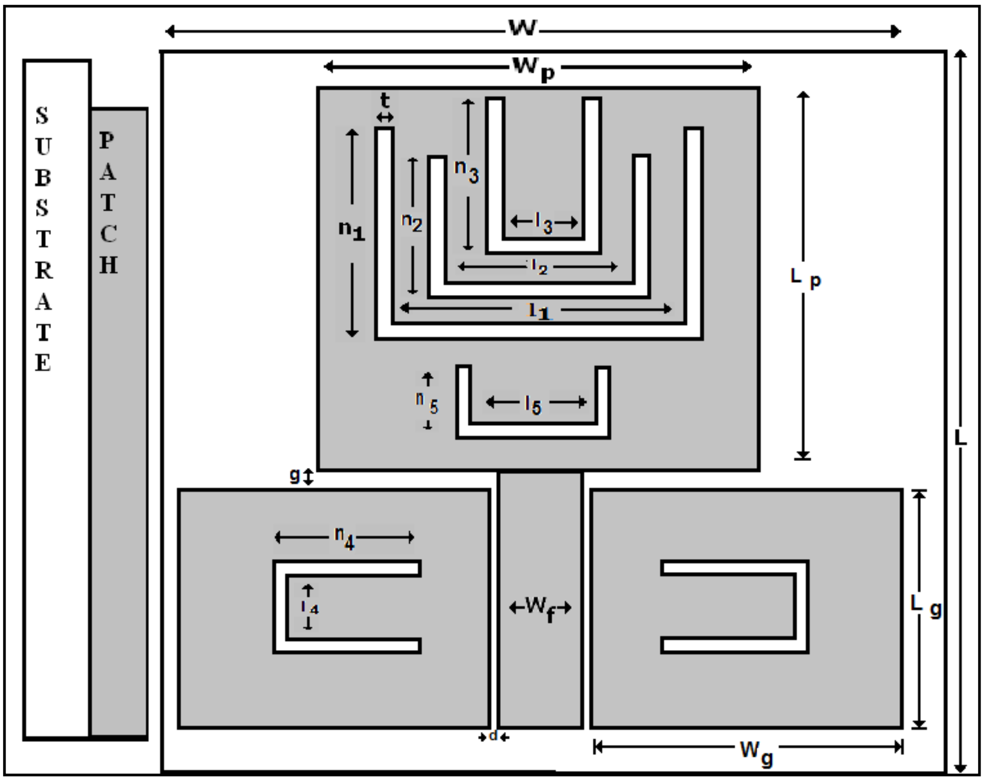


Figure 6.4 Geometry of projected five notched band U-shape UWB antenna

Table 6.2 Present the five notch band UWB antenna dimensions

Parameter	Dimensions (mm)
W	30
L	32
W_P	13
L_P	18
W_g	13
L_g	13
W_f	3
g	0.8
d	0.3
n_1	8.8
l_1	8.6
n_2	6
l_2	5
n_3	6.7
l_3	2.4
n_4	4.7
l_4	2.8
n_5	4.58
l_5	2.4

By etching four U-shaped anti-resonating slots into the radiating patch of UWB antenna, a four-band rejection has been achieved. To get the fifth notch band, two similar slots are etched on the ground planes of the CPW fed. These two slots are symmetrically placed in the ground planes. The dimensions of the notch frequency can be calculated as:

$$f_{Notch} = \frac{c}{2L_{Notch}\sqrt{\varepsilon_{eff}}} \quad (6.1)$$

$$\varepsilon_{eff} \approx \frac{\varepsilon_r + 1}{2} \quad (6.2)$$

$$L_{1Notch} \approx \frac{\lambda_{3.5}}{2} \approx 2n_1 + l_1 \quad (6.3)$$

$$L_{2Notch} \approx \frac{\lambda_{5.2}}{2} \approx 2n_2 + l_2 \quad (6.4)$$

$$L_{3Notch} \approx \frac{\lambda_{5.8}}{2} \approx 2n_3 + l_3 \quad (6.5)$$

$$L_{4Notch} \approx \frac{\lambda_{7.5}}{2} \approx 2n_4 + l_4 \quad (6.5)$$

$$L_{5Notch} \approx \frac{\lambda_{8.2}}{2} \approx 2n_5 + l_5 \quad (6.7)$$

Where, L_{Notch} is the total length of U-shaped slot, ε_{eff} is the effective dielectric constant, and c is the speed of light. To create rejection bands, the effective length of resonating slot is nearly half of wavelengths.

Figure 6.5 shows the return loss plot of the antenna, it is seen that the antenna shows an impedance bandwidth of 2.8-11.6GHz for S_{11}<-10dB, cover up the whole UWB range with five notch bands of 3.1-4GHz, 5-5.4GHz, 5.7-5.9GHz, 7.2-7.75GHz and 8-8.4GHz having S_{11}>-10dB. This allows the antenna to be appropriate for the UWB wireless application with co-existing bands of 3.3-3.7GHz for WiMAX, 5.15-5.35GHz and 5.725-5.825GHz for WLAN, 7.25-7.75GHz for X-band downlink and 8-8.4GHz for satellite communication band (ITU) system without experiencing any interference from these bands.

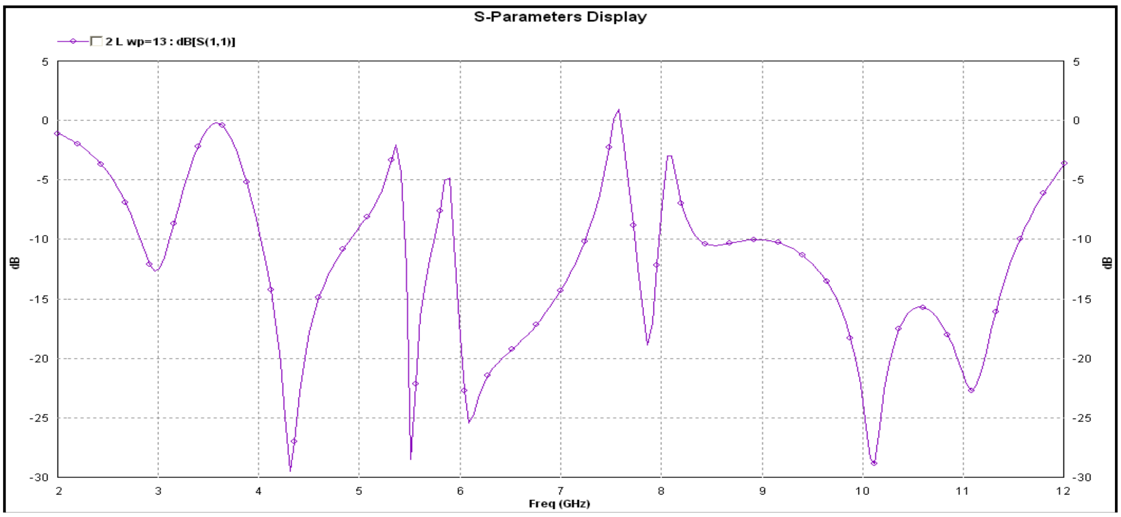


Figure 6.5 Simulated S_{11}(dB) of five notched band U-shape UWB antenna

Figure 6.6 illustrates the VSWR plot of the projected antenna. The projected antenna has wideband performance of 2.8GHz to 11.6GHz for VSWR<2; cover up the complete UWB range along with five notch bands of 3.1-4GHz, 5-5.4GHz, 5.7-5.9GHz, 7.2-7.75GHz and 8-8.4GHz having VSWR>2.

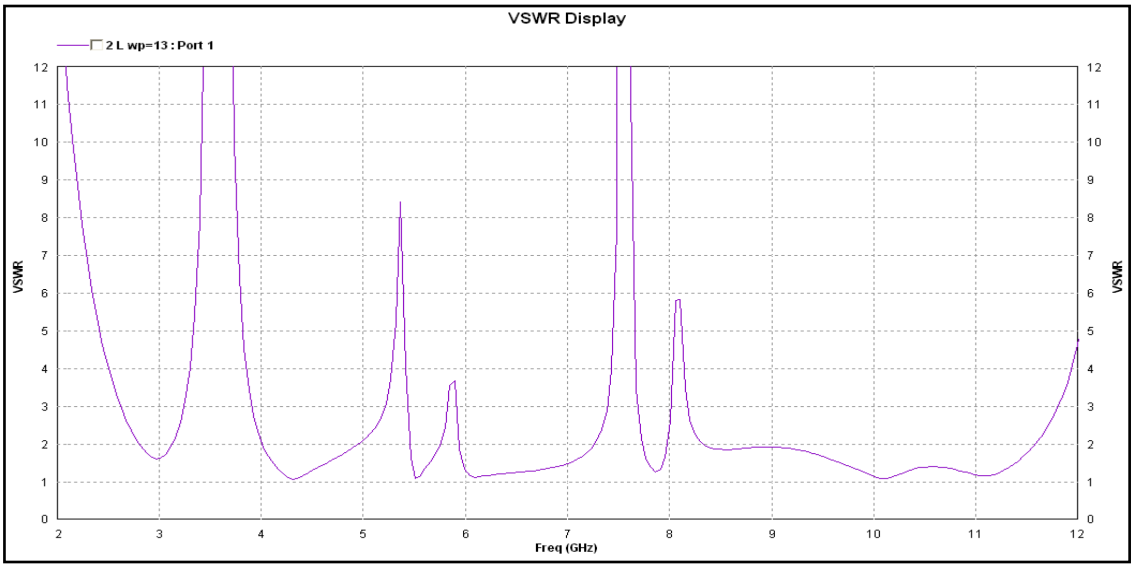


Figure 6.6 Simulated VSWR of five notched band U-shape UWB antenna

For the highest notched frequency of 8.2GHz, which is determined by smallest U-shaped slot; the center notched frequency gets shifted to lower value from 9GHz to 7.5GHz while $L_{5Notch}$is increased from 10.56 to 12.56mm, as illustrated in Figure 6.7 and Table 6.3.

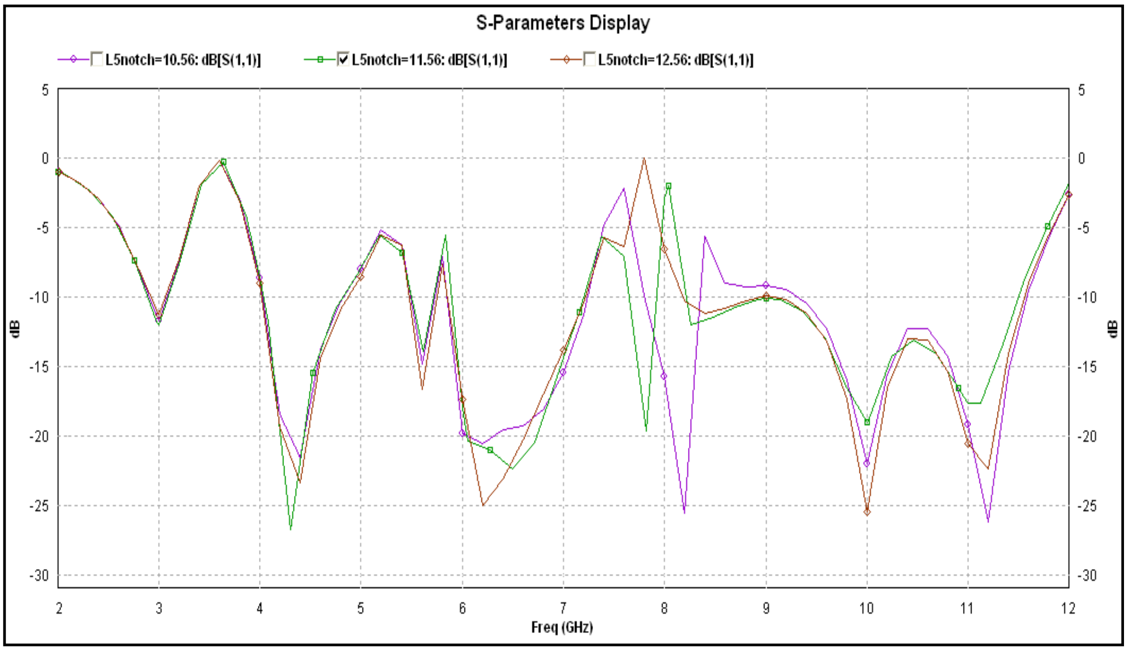


Figure 6.7 Simulated S_{11}(dB) of five notched band UWB antenna with different L_{5Notch}values

Table 6.3 Simulated and theoretical value of fifth center notch frequency

L_{5Notch} (mm)	Simulated Frequency (GHz)	Theoretical Frequency (GHz)	Difference (GHz)
10.56	8.91	8.64	0.27
11.56	8.15	7.89	0.26
12.56	7.5	7.26	0.24

The simulated (via IE3D) and theoretical (via Equation (6.7)) values of center notch frequency for various L_{5Notch} (10.56mm-12.56mm) of U-shaped slot are compared in Table 6.3. The maximum variation between simulated and theoretical frequency is about 0.27GHz. This variation is due to the approximation used in calculation of ε_{eff} in Equation (6.2) and the influence of adjacent notch bands as already shown in section 5.2. The similar concept is used for other U-shaped slots to achieve the preferred notched band frequencies.

6.4 PARAMETRIC ANALYSIS OF THE ANTENNA

A CPW fed patch antenna offers many parameters to the antenna designer that can be optimized to get a UWB antenna with notched bands to avoid interference. In this section, each parameter of U-shaped structure is individually varied to see its effect on notch band performance of proposed antenna in parameters of return loss and impedance bandwidth.

6.4.1 Effect of variation in U-shaped slot width (l_1)

It can be concluded from Figure 6.8 and Table 6.4 that the lower frequency of first notch band gets shifted to a lower value by increasing the value of slot width (l_1) from 8.1mm to 9.1mm and very small variation in higher frequency of first notch band and the value of return loss at center frequency is highest at slot width (l_1) 8.6mm. Since the desired UWB wireless applications needs a notch band of 3.3-3.7GHz (WiMAX), therefore the optimum value of slot width (l_1) 8.6mm, a notch band of 3.11-4.02GHz having S_{11}>-10dB with first center notch frequency of 3.5GHz has been achieved.

Table 6.4 Effect of variation in U-shaped slot width (l_1)

Slot Width (l_1) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
8.1	3.22	4.03	0.81
8.6	3.11	4.02	0.91
9.1	2.98	4.04	1.06

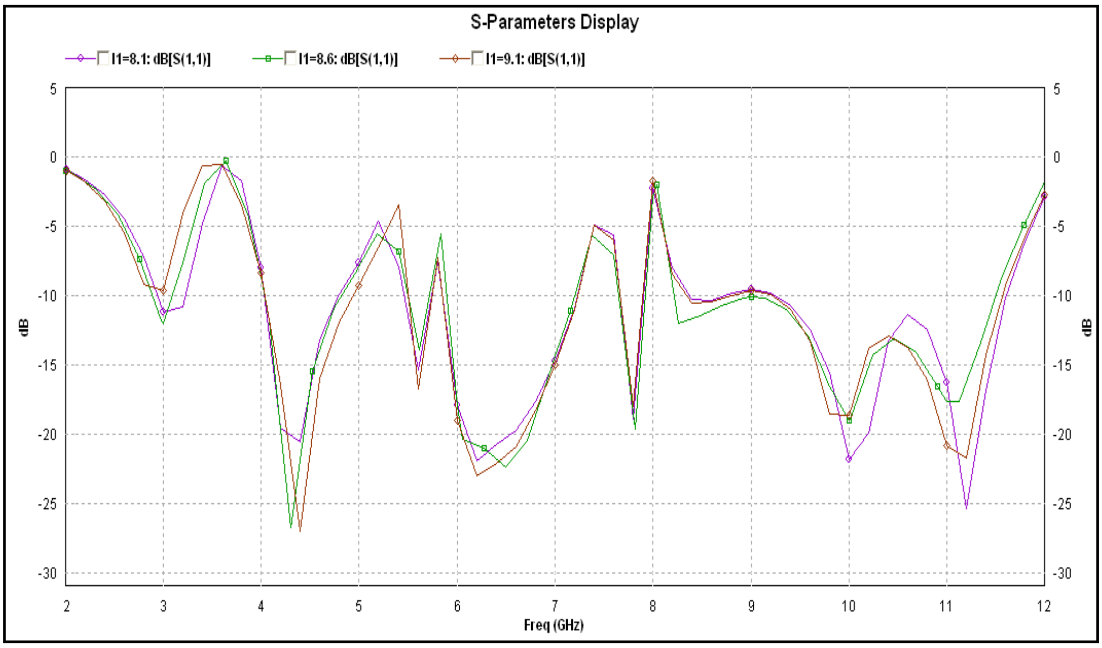


Figure 6.8 Simulated S_{11}(dB) of five notch band U-shape UWB antenna for various l_1

6.4.2 Effect of variation in U-shaped slot length (n_1)

There is a variation in return loss value with change in the slot length (n_1), shown in Figure 6.9. The first notch band gets shifted to lower value frequency by increasing the value of slot length (n_1) from 8.3mm to 9.3mm and the value of return loss at center frequency is highest at slot width (n_1) 8.8mm. From Table 6.5, the optimum value of slot length (n_1) 8.8mm, a notch band of 3.11-4.02GHz having S_{11}>-10dB with center frequency of 3.5GHz has been achieved.

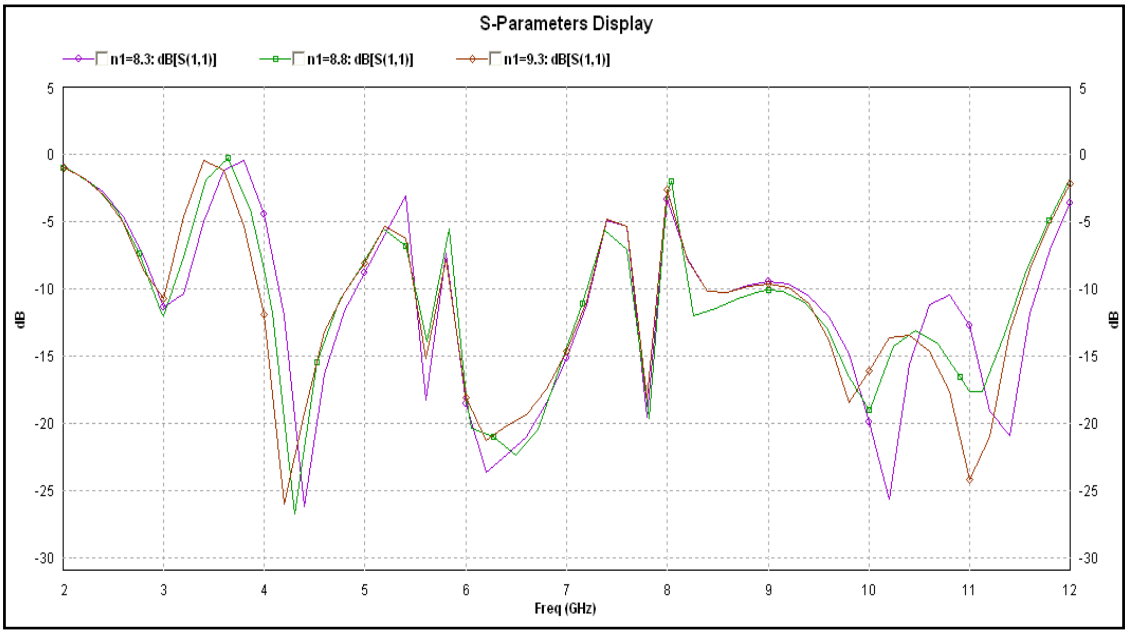


Figure 6.9 Simulated S_{11}(dB) of five notch band U-shape UWB antenna for various n_1

Table 6.5 Effect of variation in U-shaped slot length (n_1)

Slot Length (n_1) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
8.3	3.21	4.4	0.93
8.8	3.11	4.02	0.91
9.3	3.02	3.93	0.91

6.4.3 Effect of variation in U-shaped slot width (l_2)

It can be observed from Figure 6.10 and Table 6.6 that the second notch frequency band of operation gets shifted to lower value by increasing the value of slot width (l_2) from 4.5mm to 5.5mm and center frequency also shifted to lower value with higher value of return loss. Since the desired UWB wireless applications needs a notch band of 5.15-5.35GHz WLAN (lower). For the optimum value of slot width (l_2) 5mm, a notch band of 4.9-5.44GHz having S_{11}>-10dB with center frequency of 5.2GHz has been achieved.

Table 6.6 Effect of variation in U-shaped slot width (l_2)

Slot Width (l_2) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
4.5	5	5.5	0.5
5	4.9	5.44	0.54
5.5	4.71	5.22	0.56

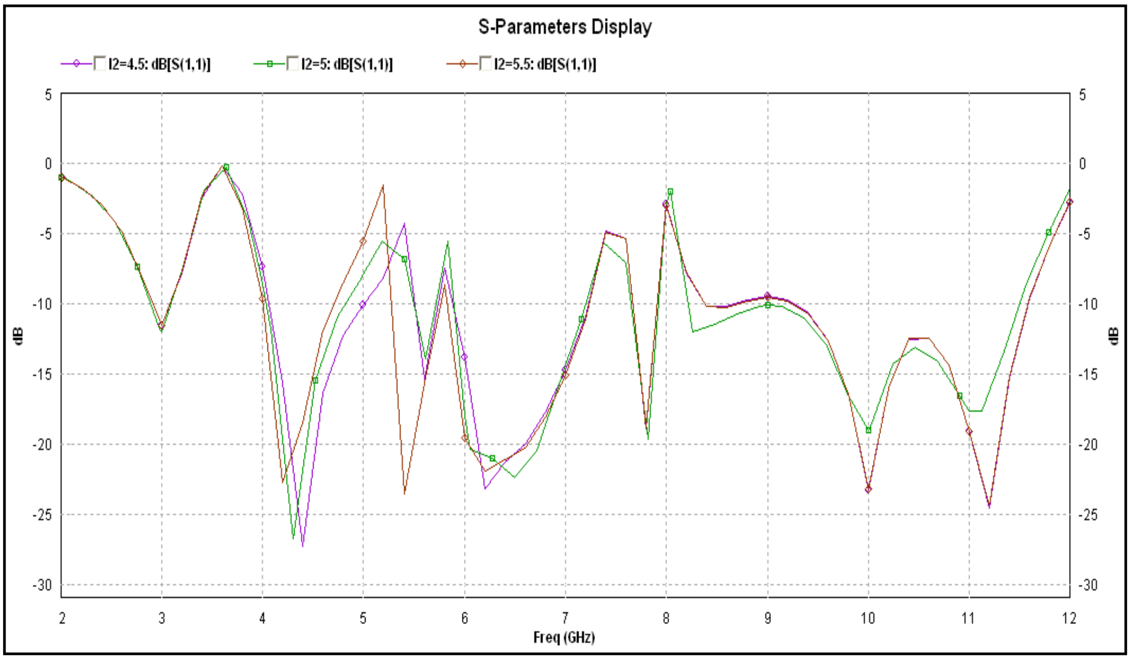


Figure 6.10 Simulated S_{11}(dB) of five notch band U-shape UWB antenna for various l_2

6.4.4 Effect of variation in U-shaped slot length (n_2)

From Figure 6.11and Table 6.7, it can be observed that the second notch frequency band gets shifted to lower value by increasing the value of slot length (n_2) from 5.5mm to 6.5mm and center frequency also shifted to a lower value and return loss is maximum at slot length (n_2) of 6mm. From Table 6.7, the optimum value of slot length (n_2) 6mm, a notch band of 4.99-5.44GHz having S_{11}>-10dB with highest value of S_{11}(dB) at center frequency has been achieved.

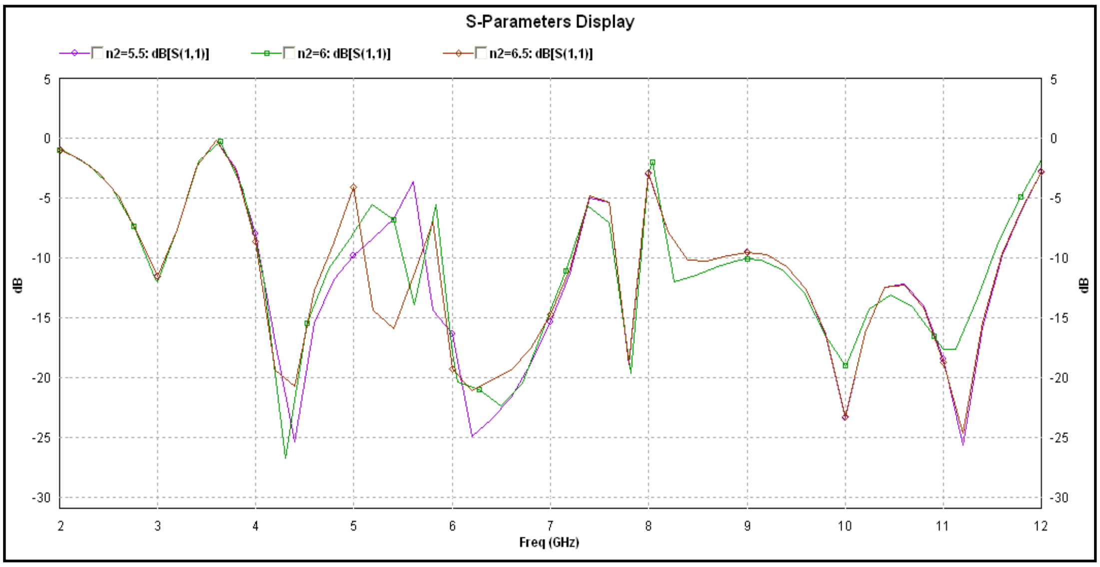


Figure 6.11 Simulated S_{11}(dB) of five notch band U-shape UWB antenna for various n_2

Table 6.7 Effect of variation in U-shaped slot length (n_2)

Slot Length (n_2) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
5.5	4.97	5.72	0.75
6	4.9	5.44	0.54
6.5	4.73	5.11	0.38

6.4.5 Effect of variation in U-shaped slot width (l_3)

Figure 6.12 and Table 6.8 shows that the third notch frequency band shifted to lower value by increasing the value of slot width (l_3) from 1.9mm to 2.9mm and center frequency also shifted to a lower value and return loss is maximum at slot width (l_3) of 2.4mm. For UWB wireless applications needs a notch band of 5.725-5.825GHz WLAN (upper), therefore the optimum value of slot width (l_3) 2.4mm, a notch band of 5.7-5.9GHz having S_{11}>-10dB with highest value of S_{11}(dB) at center frequency has been achieved.

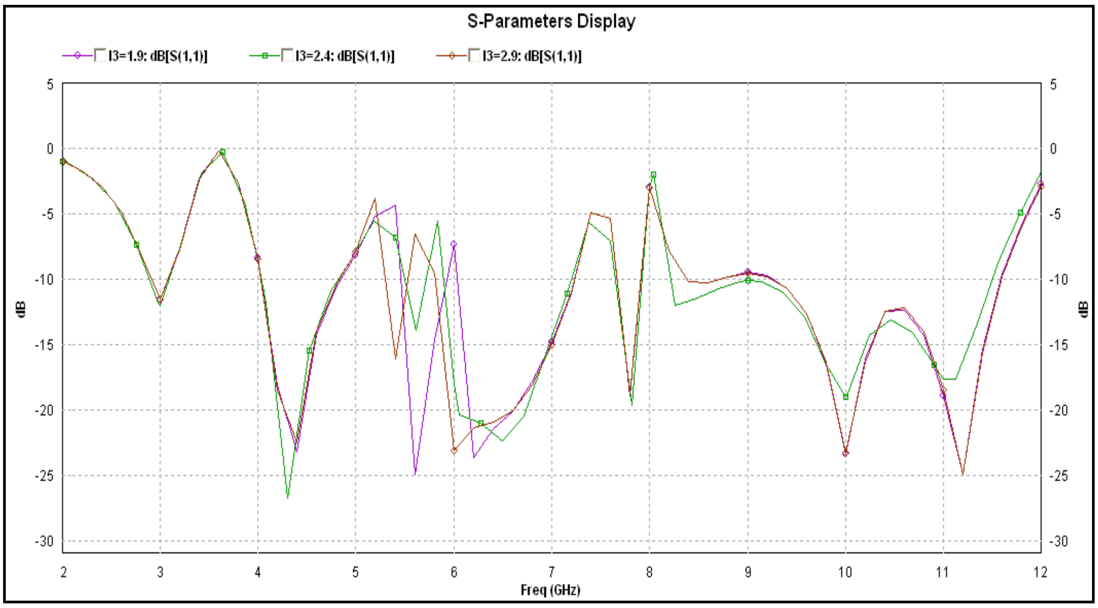


Figure 6.12 Simulated S_{11}(dB) of five notch band U-shape UWB antenna for various l_3

Table 6.8 Effect of variation in U-shaped slot width (l_3)

Slot Width (l_3) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
1.9	5.92	6.03	0.11
2.4	5.7	5.94	0.21
2.9	5.52	5.8	0.28

6.4.6 Effect of variation in U-shaped slot length (n_3)

There is a variation in return loss value with change in the U-shaped slot length (n_3), shown in Figure 6.13. The third notch frequency band gets shifted to lower value by increasing the value of slot length (n_3) from 6.2mm to 7.2mm and center frequency also shifted to lower value. When slot length (n_3) is equal to 7.2mm, the second and third notch band overlap and form a single notch band. Therefore, we get only four notch band shown in Figure 6.13. From Table 6.9, the optimum value of slot length (n_3) 6.7mm, a notch band of 5.7-5.9GHz having S_{11}>-10dB with highest value of S_{11}(dB) at center frequency has been achieved.

Table 6.9 Effect of variation in U-shaped slot length (n_3)

Slot Length (n_3) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
6.2	6.12	6.24	0.12
6.7	5.73	5.94	0.21
7.2	4.83	5.47	0.64

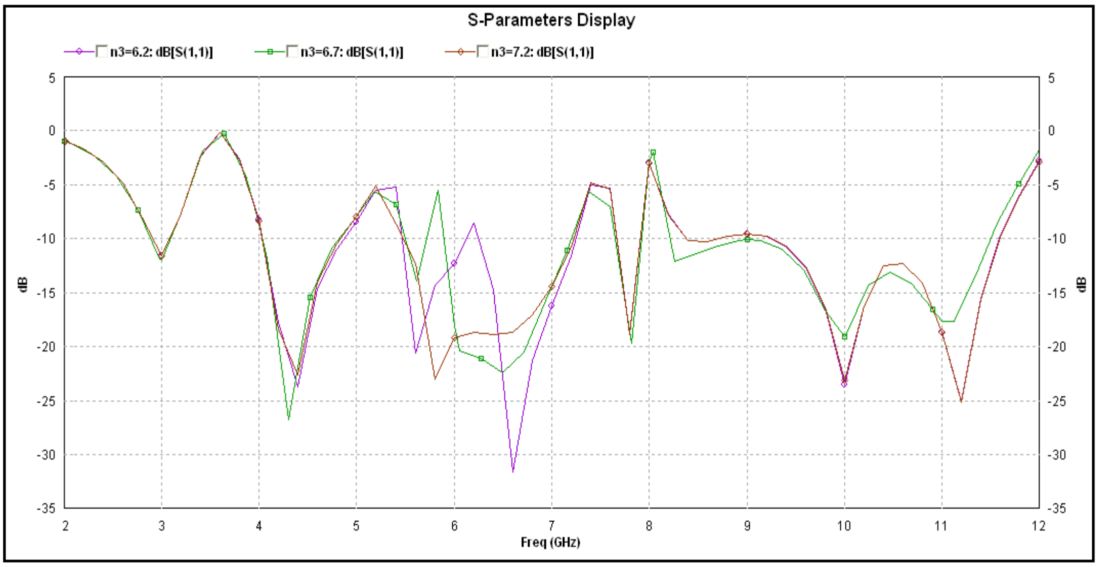


Figure 6.13 Simulated S_{11}(dB) of five notch band U-shape UWB antenna for various n_3

6.4.7 Effect of variation in U-shaped slot width (l_4)

It can be concluded from Figure 6.14 and Table 6.10 that the fourth notch frequency band of operation gets shifted to lower value by increasing the value of slot width (l_4) from 2.3mm to 3.3mm and center frequency also shifted to lower value. But when slot width (l_4) is equal to 2.3mm, the fourth and fifth notch bands overlap each other and form a single notch band. Therefore, we get only four notch band as shown in Figure 6.14. Since the desired UWB wireless applications needs a notch band of 7.25-7.75GHz (X-band down link). Therefore, from Table 6.10, the optimum value of slot width (l_4) 2.8mm, a notch band of 7.22-7.74GHz having S_{11}>-10dB with highest value of S_{11}(dB) at center frequency of 7.5GHz has been achieved.

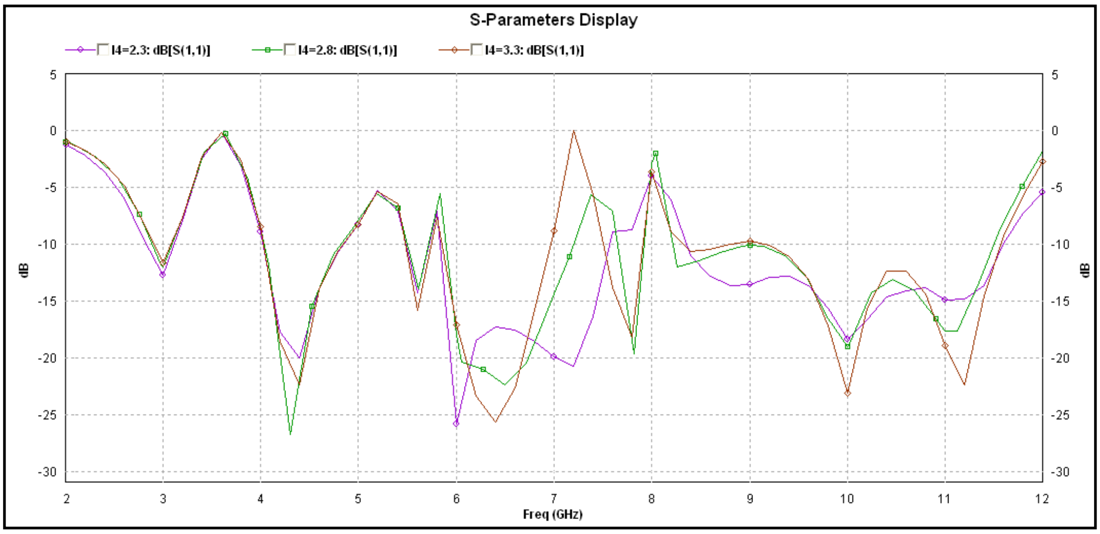


Figure 6.14 Simulated S_{11}(dB) of five notch band U-shape UWB antenna for various l_4

Table 6.10Effect of variation in U-shaped slot width (l_4)

Slot Width (l_4) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
2.3	7.56	8.35	0.79
2.8	7.22	7.74	0.37
3.3	6.95	7.49	0.41

6.4.8 Effect of variation in U-shaped slot length (n_4)

Figure 6.15 illustrated that the fourth notch frequency band gets shifted to lower value by increasing the value of slot length (n_4) from 4.2mm to 5.2mm and center frequency also shifted to a lower value. But when slot length (n_4) is equal to 4.2mm, the fourth and fifth notch bands overlap each other and form a single notch band. Therefore, we get only four notch band as shown in Figure 6.15. From Table 6.11, the optimum value of slot length (n_4) 4.7mm, a notch band of 7.22-7.74GHz having S_{11}>-10dB with highest value of S_{11}(dB) at center frequency has been achieved.

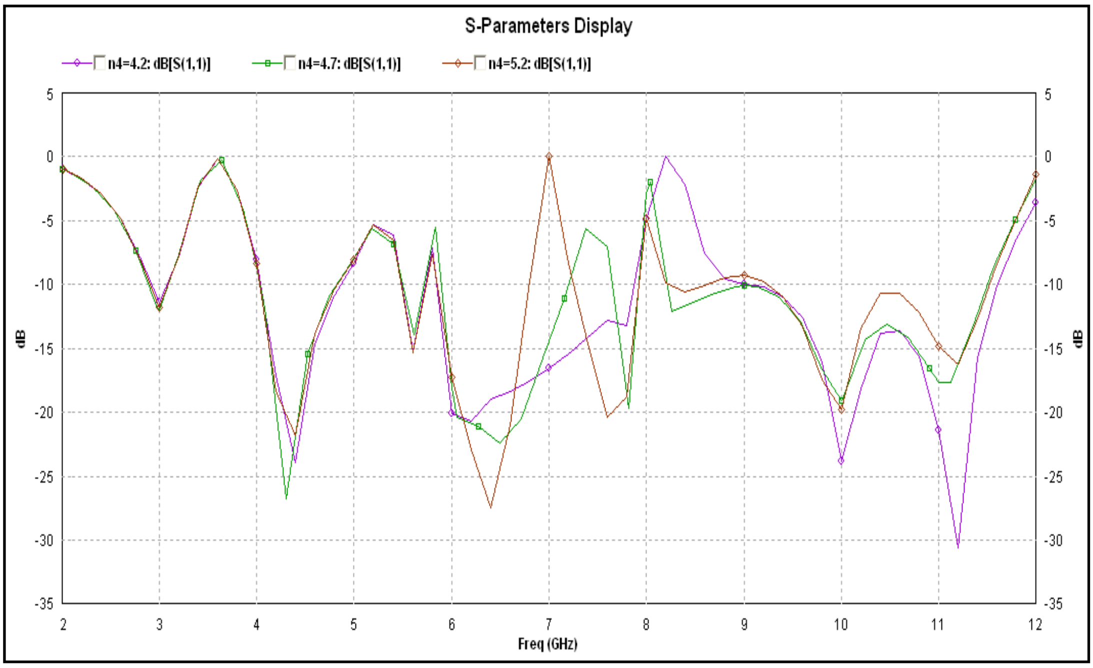


Figure 6.15 Simulated S_{11}(dB) of five notch band U-shape UWB antenna for various n_4

Table 6.11 Effect of variation in U-shaped slot length (n_4)

Slot Length (n_4) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
4.2	7.87	9	1.13
4.7	7.22	7.74	0.4
5.2	6.7	7.25	0.3

6.4.9 Effect of variation in U-shaped slot width (l_5)

From figure 6.16 it can be observed that the fifth notch frequency band shifted to lower value by increasing the value of slot width (l_5) from 1.9mm to 2.9mm and center frequency gets a lower value with higher value of return loss. But when slot width (l_5) is equal to 2.9mm, the fourth and fifth notch bands overlap each other and form a single notch band. Therefore, we get only four notch band as shown in Figure 6.16. Since the desired UWB wireless applications needs a notch band of 8.02-8.4GHz (ITU-band). Therefore, from Table 6.12, the optimum value of slot width (l_5) 2.4mm, a notch band of 7.97-8.4GHz having S_{11}>-10dB has been achieved.

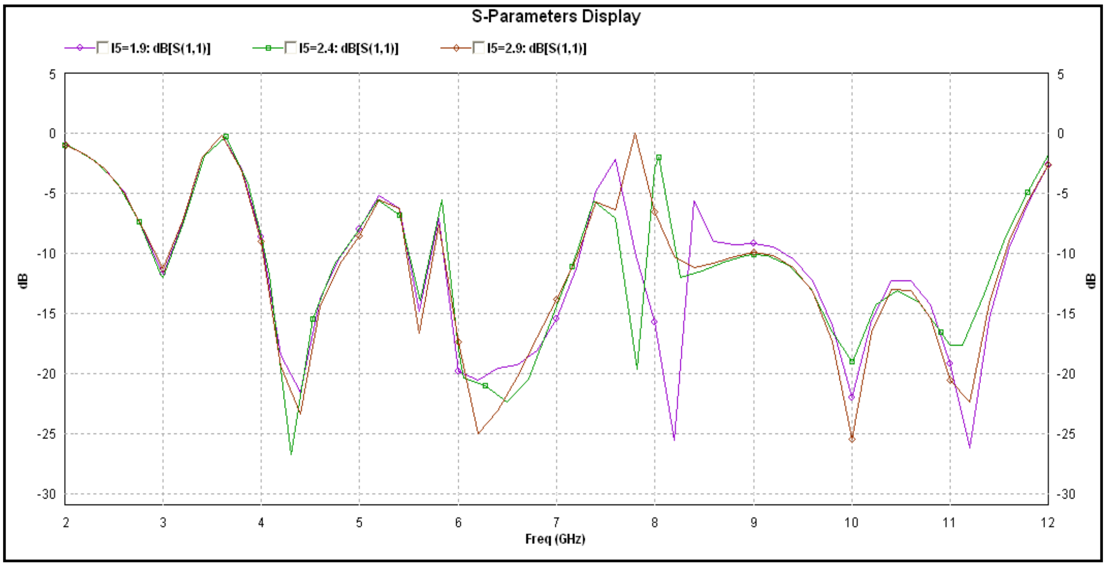


Figure 6.16 Simulated S_{11}(dB) of five notch band U-shape UWB antenna for various l_5

Table 6.12 Effect of variation in U-shaped slot width (l_5)

Slot Width (l_5) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
1.9	8.35	9.3	0.95
2.4	7.97	8.4	0.43
2.9	7.22	8.18	0.96

6.4.10 Effect of variation in U-shaped slot length (n_5)

There is a variation in return loss value with change in the U-shaped slot length (n_5), shown in Figure 6.17. The fifth notch frequency band gets shifted to lower value by increasing the value of slot length (n_5) from 4.08mm to 5.08mm and center frequency also shifted to lower value. But when slot length (n_5) is equal to 5.08mm, the fifth notch band gets overlap with fourth notch band and form a single notch band. Therefore, we get only four notch band as shown in Figure 6.17. Therefore, from Table 6.13, the optimum value of slot length (n_5) 4.58mm, a notch band of 7.97-8.4GHz having S_{11}>-10dB has been achieved.

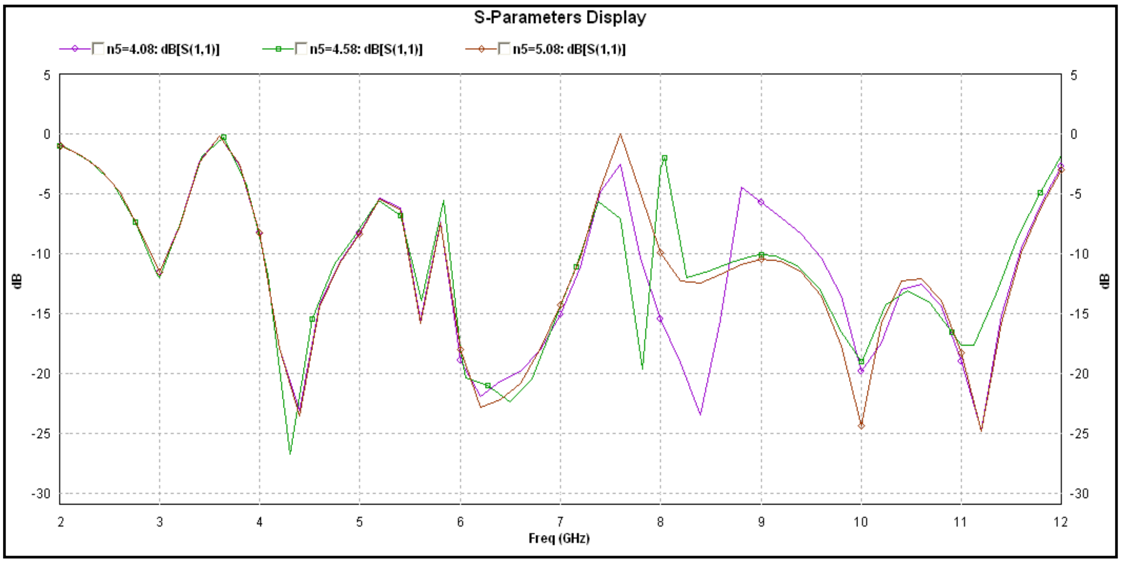


Figure 6.17 Simulated S_{11}(dB) of five notch band U-shape UWB antenna for various n_5

Table 6.13 Effect of variation in U-shaped slot length (n_5)

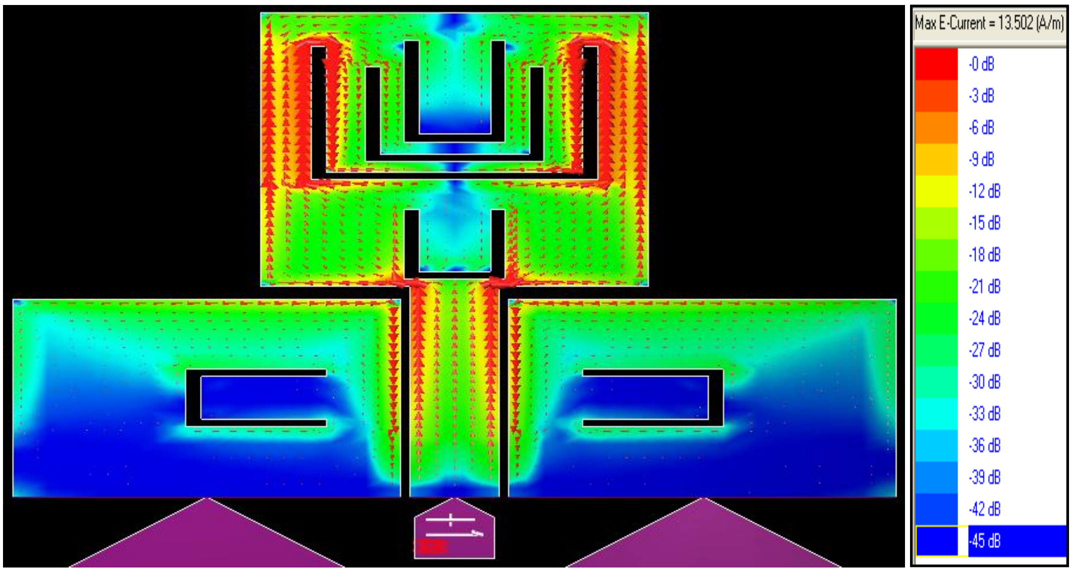
Slot Length (n_5) (mm)	Notch Frequency Lower (GHz)	Notch Frequency Upper (GHz)	Notch Bandwidth (GHz)
4.08	8.7	9.55	0.85
4.58	7.97	8.4	0.43
5.08	7.2	8	0.8

6.5 MODAL ANALYSIS

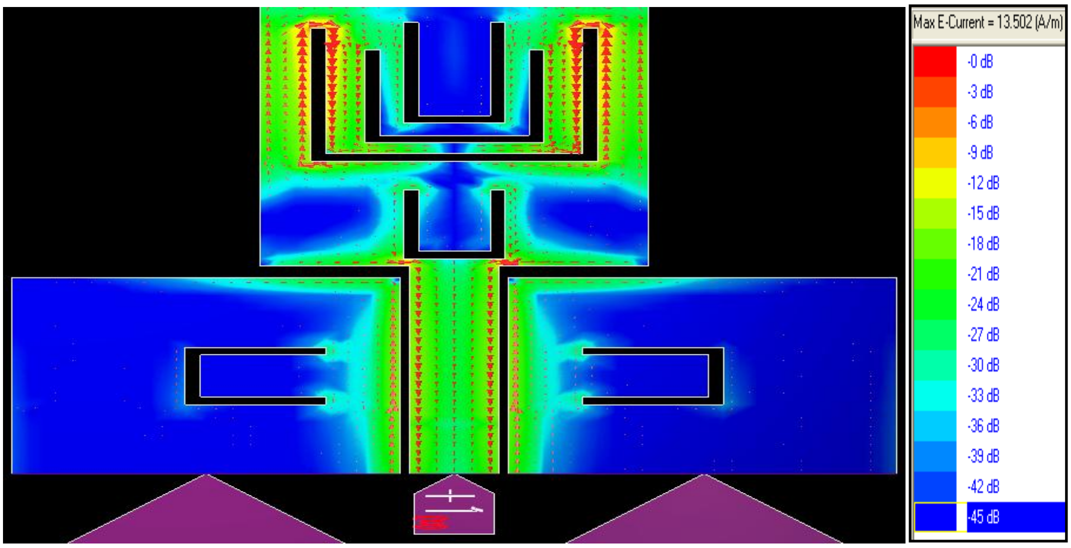
6.5.1 Current Distribution

A CPW fed UWB antenna structure was excited using the feed network to see the distribution of energy over its various structural parts. This helps in understanding the function of each slot in creating an anti-resonant band and also which specific part of the antenna is responsible for the given resonant frequency of antenna operation.

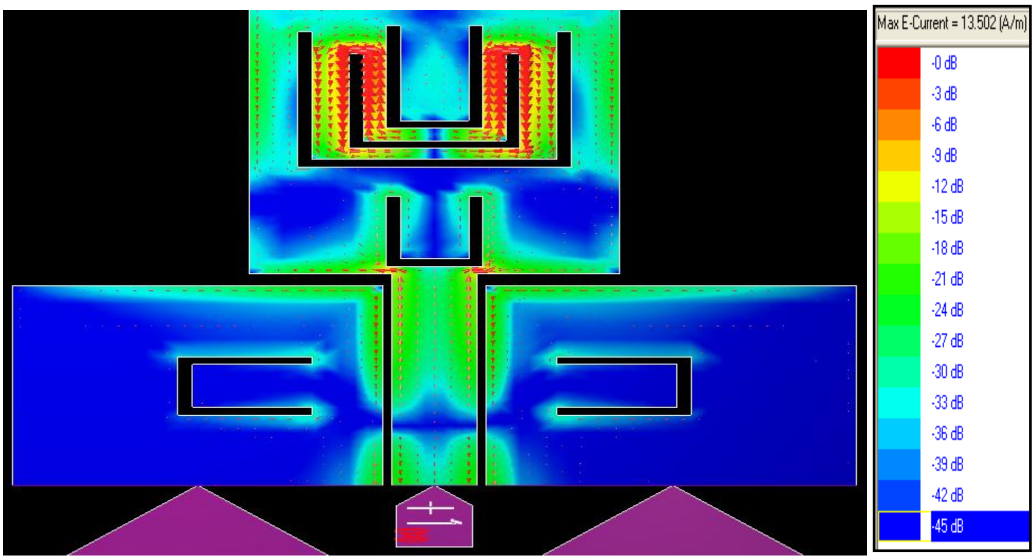
Figure 6.18 illustrates simulated surface current distribution at a frequency of 2.9GHz, 3.5GHz, 5.2GHz, 5.8GHz, 7.5GHz, 8.2GHz and 10.1GHz. It has been observed in Figures6.18 (a) and (g), the surface current distribution is more dominant near the periphery of patch radiator and all the current vectors are in the same direction therefore the antenna radiates at 2.9GHz and 10.1GHz. But in Figures 6.18 (b), (c), (d), (e) and (f) the surface current distributions are more dominant around U-shaped filter structure at a frequency of3.5GHz, 5.2GHz, 5.8GHz, 7.5GHz and 8.2GHz, and current vectors are in the opposite direction and cancel each other which acts as a short circuit resonator [128]. This suggests that the U-shaped filter structure has a major effect on UWB antenna performance for elimination of the frequency band. Therefore, the antenna does not radiate at 3.5GHz, 5.2GHz, 5.8GHz, 7.5GHz and 8.2GHz and frequency notched bands are created around these frequencies. Thus, from the current distributions it is confirmed that the U-shaped filter structure causes the frequency notch functions [82, 100, 131].



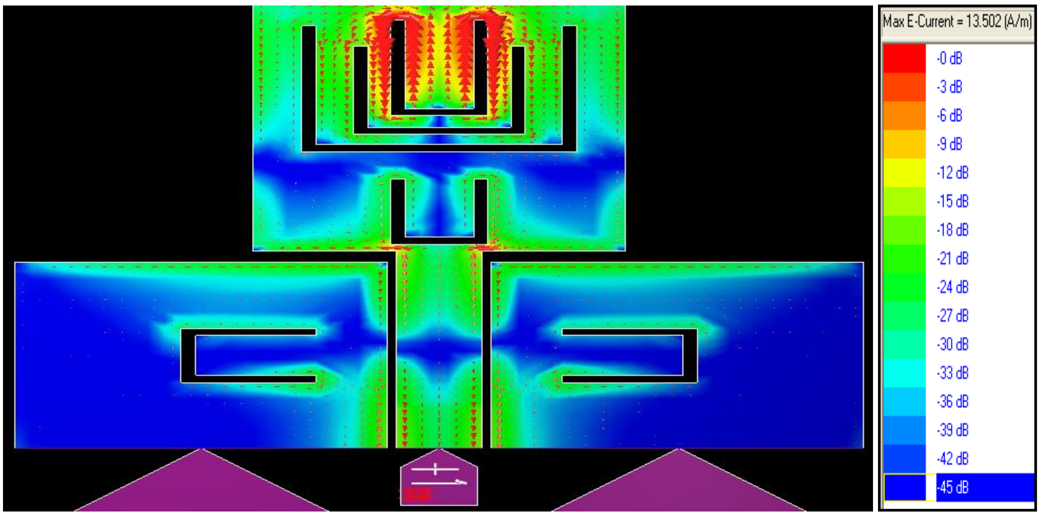
(a) 2.9GHz



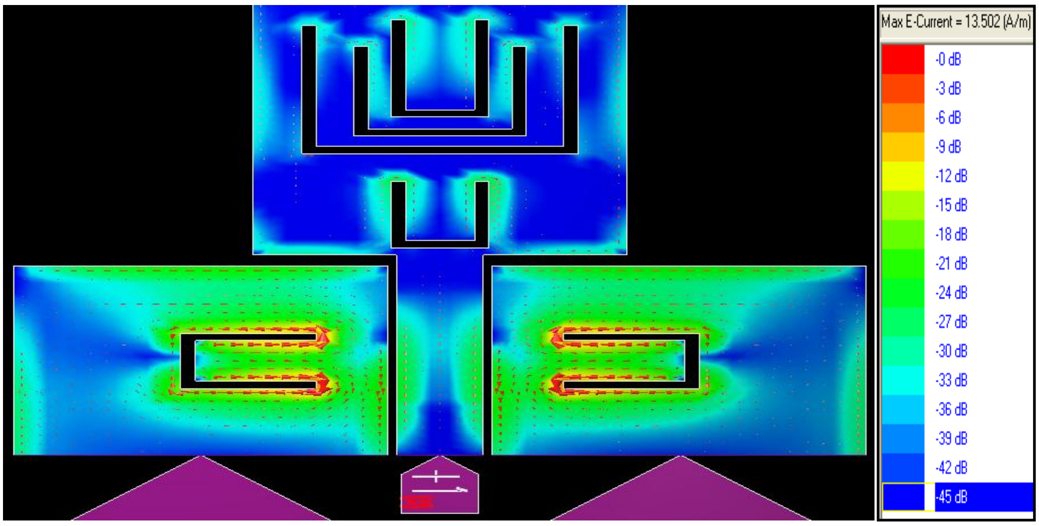
(b) 3.5GHz



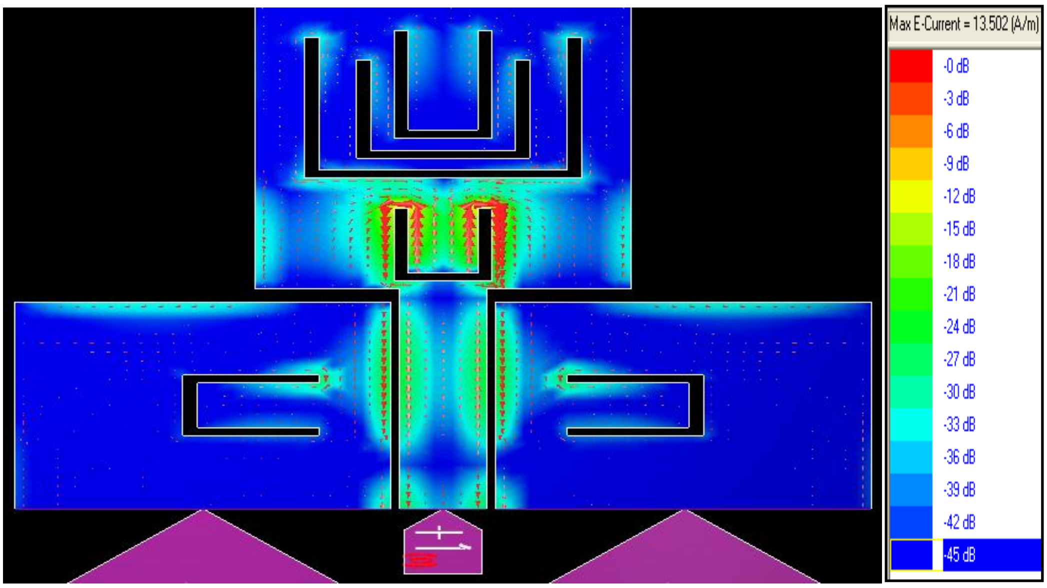
(c) 5.2GHz



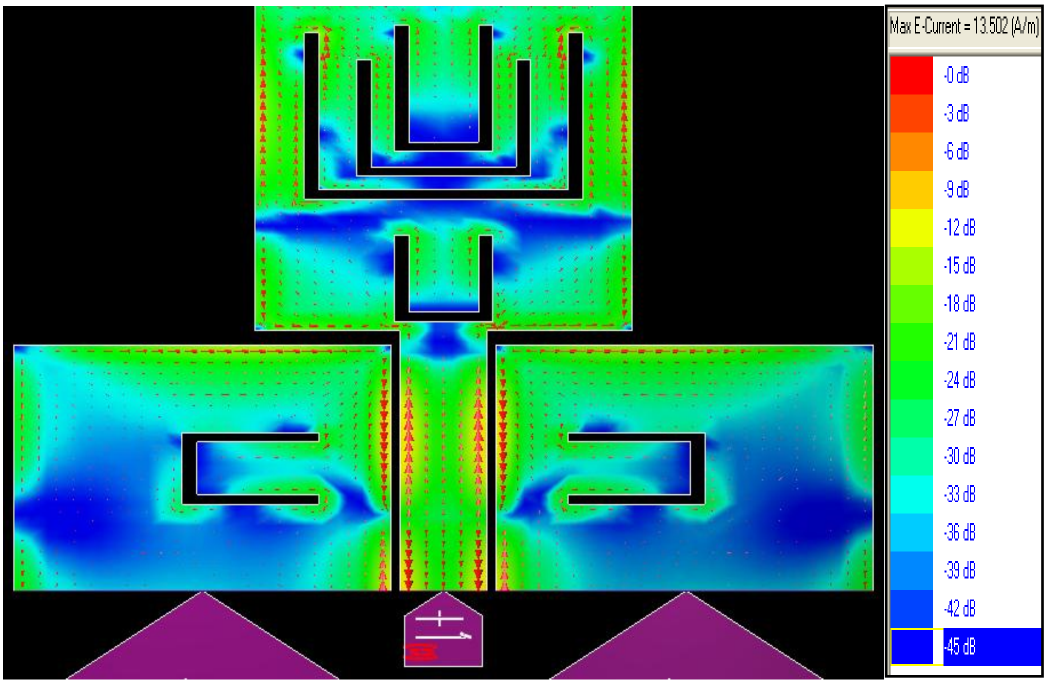
(d) 5.8GHz



(e) 7.5GHz



(f) 8.2GHz

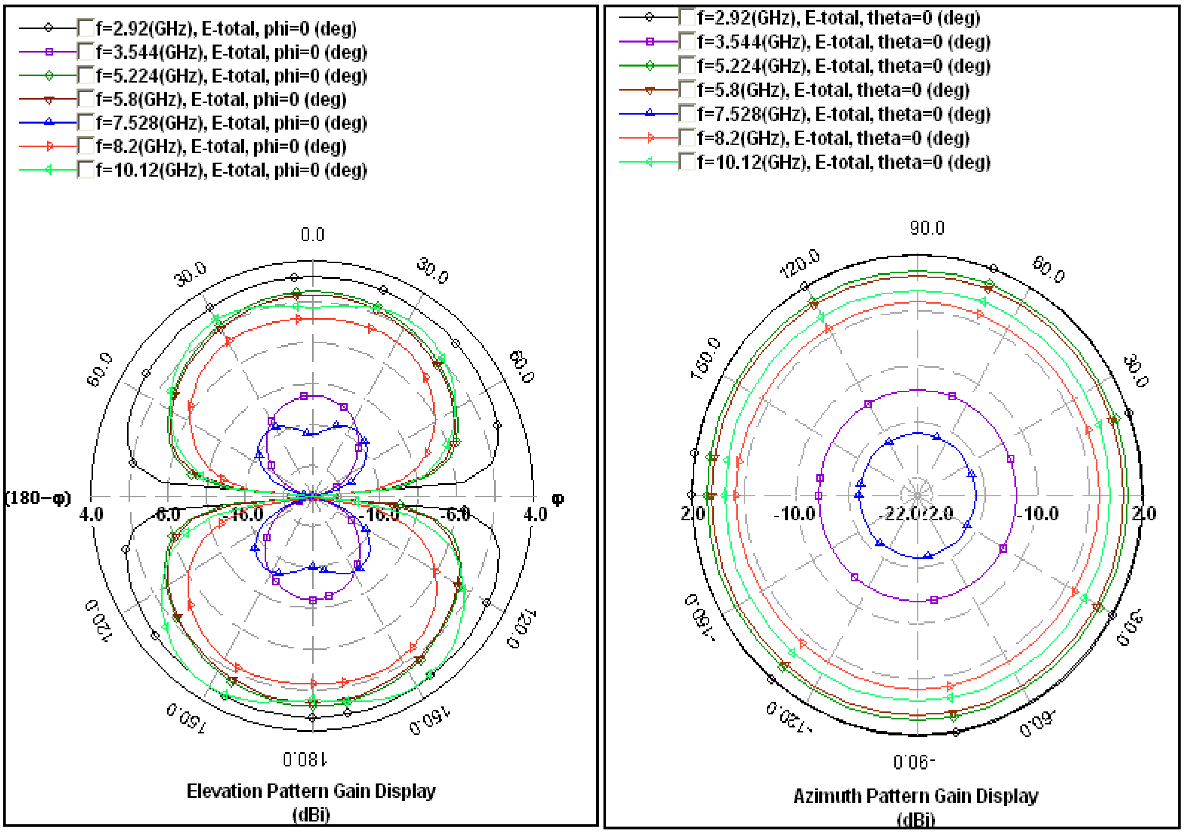


(g) 10.1GHz

Figure 6.18 Surface current distribution of five notch band UWB antenna at (a) 2.9GHz (b) 3.5GHz (c) 5.2GHz (d) 5.8GHz (e) 7.5GHz (f) 8.2GHz (g) 10.1GHz

6.5.2 Radiation Patterns

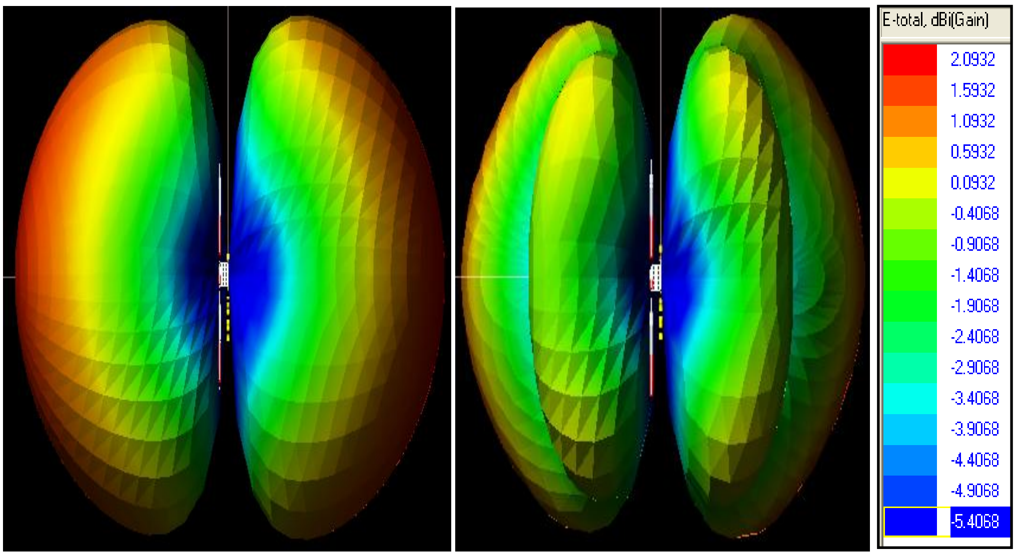
Figures 6.19 illustrates the 2-D radiation pattern of the projected five notch band UWB antenna, the E-plane (Y-Z) and H-plane (X-Z) at 2.92GHz, 3.54GHz, 5.22GHz, 5.8GHz, 7.52GHz, 8.20GHz and 10.12GHz. Figure 6.19 (a) shows the E-plane (YZ-plane) pattern which is similar to the dipole antenna pattern like Figure-of-Eight in the vertical plane at lower frequencies, but beam width is reduced at higher frequencies. Therefore, the radiation patterns at higher frequencies slightly distorted form the Figure-of-Eight shape. Also, the radiation pattern gain at 3.54GHz, 5.22GHz, 5.80GHz, 7.52GHz and 8.20GHz is small as compared to other frequencies, as illustrated in Figure 6.19 (a) and antenna does not radiate at these frequencies. 2-D radiation pattern in H-plane (X-Z) is almost omnidirectional for the all frequencies are shown in Figure 6.19 (b).



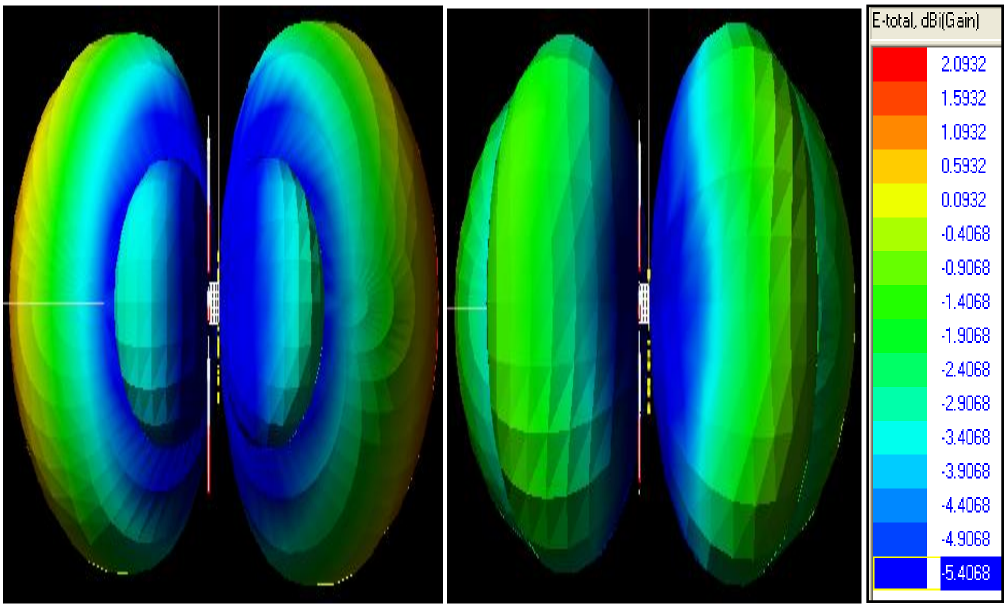
(a) Elevation pattern (Y-Z Plane) **(b) Azimuth pattern (X-Z Plane)**

Figure 6.19 2-D radiation pattern of five notched band UWB antenna at 2.9GHz, 3.5GHz, 5.2GHz, 5.8GHz, 7.5GHz, 8.2GHz, and 10.1GHz

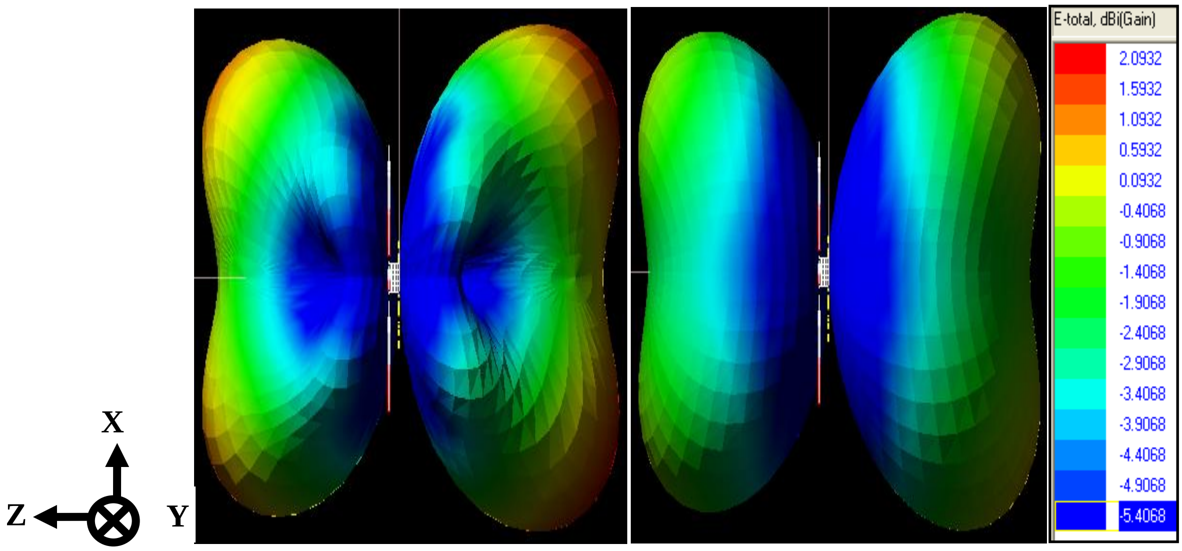
Figures 6.20 shows the 3-D radiation pattern of projected five notch bands UWB antenna at (a) 2.9GHz (b) 3.5GHz (c) 5.2GHz (d) 5.8GHz (e) 7.5GHz (f) 8.2GHz (g) 10.1GHz. Figures 6.20 show the 3-D radiation pattern which is similar to the dipole antenna pattern in the vertical plane at the lower frequencies, but degradation at the upper frequencies. The 3-D radiation pattern at higher frequencies become distorted and splits into minor lobes. We can also observe from Figures 6.20 (b), (c), (d), (e) and (f) that the radiation patterns gain at 3.5GHz, 5.2GHz, 5.8GHz, 7.5GHz and 8.2GHz is small as compared to other frequency, these shows that at these frequencies the antenna does not radiate.



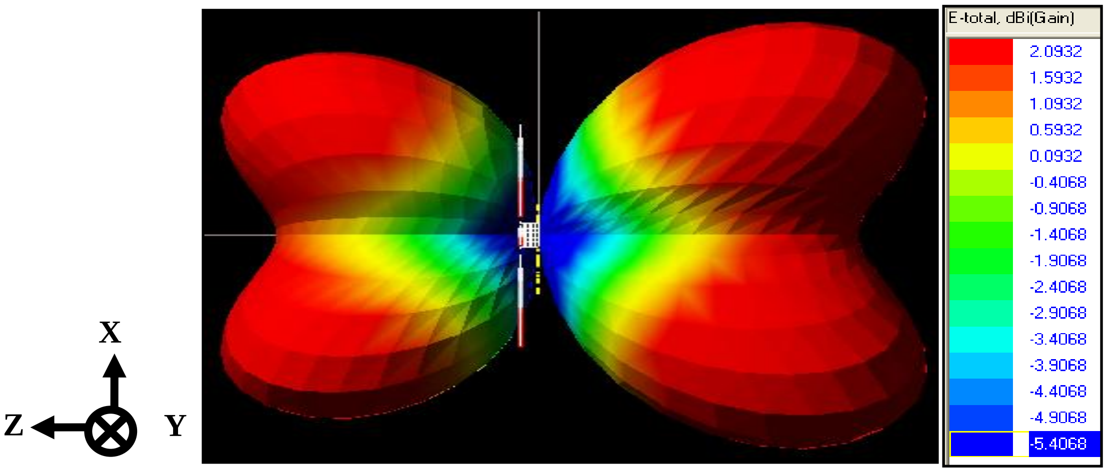
(a) 2.9GHz **(b) 3.5GHz**



(c) 5.2GHz **(d) 5.8GHz**



(e) 7.5GHz **(f) 8.2GHz**



(g) 10.1GHz

Figure 6.20 3-D radiation pattern of the five notched band UWB antenna at (a) 2.9GHz (b) 3.5GHz (c) 5.2GHz (d) 5.8GHz (e) 7.5GHz (f) 8.2GHz (g) 10.1GHz

6.5.3 Equivalent Circuit

For the proposed five notched band UWB antenna, notch band properties are attained by creating five resonant structures, consisting of five extra series RLC resonators.

Therefore, the input impedance is designed by parallel R, L and C for band-pass resonant frequencies. While for five rejection bands, five extra R, L, and C components in-series are included to describe the five notched band structures [125-127]. Figure 6.21, illustrated the equivalent circuit model of anticipated five notch band UWB antenna.

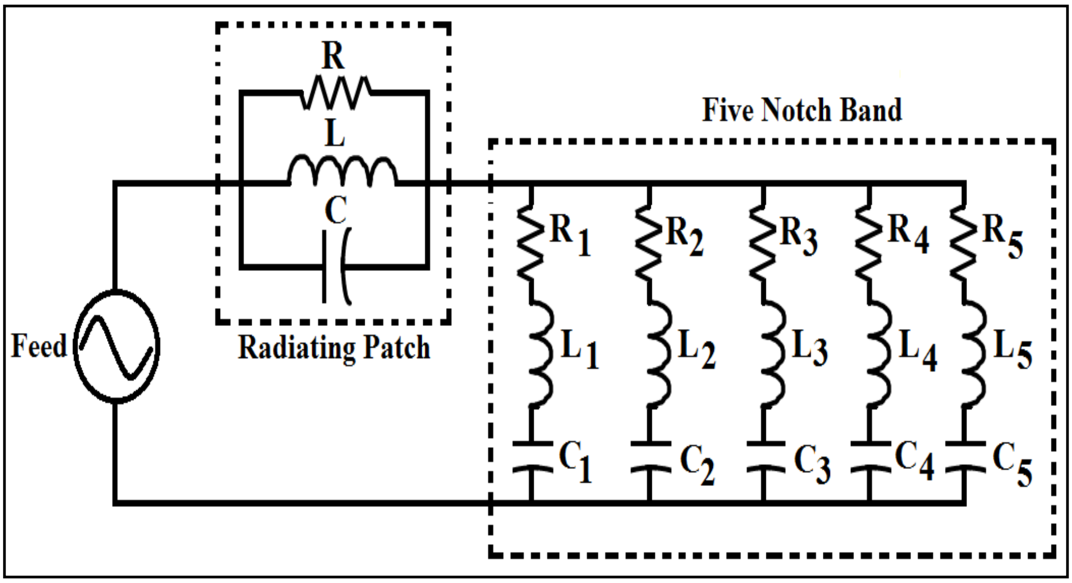
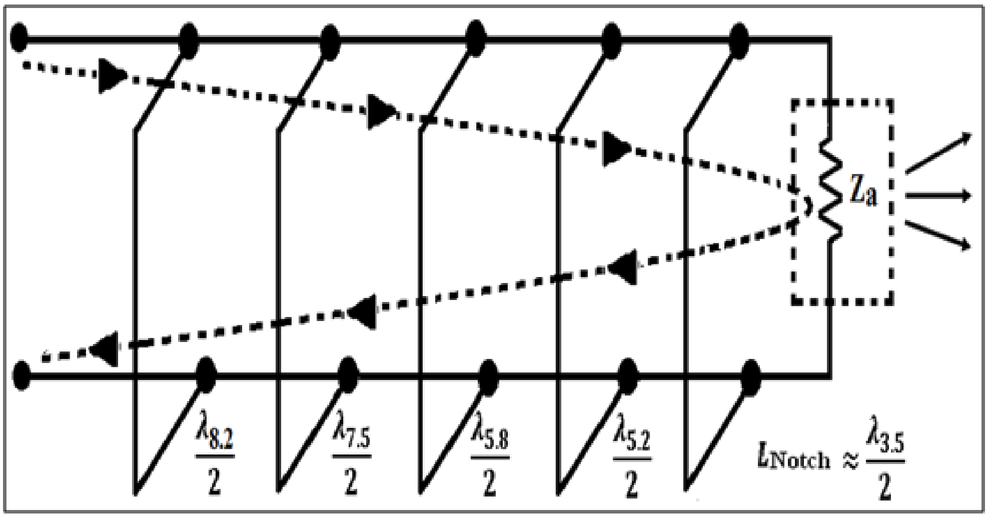


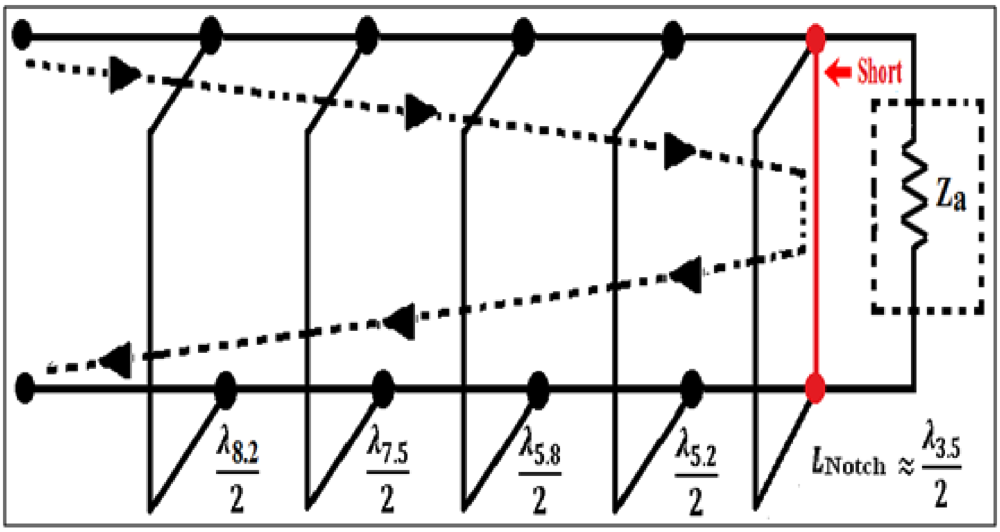
Figure 6.21 An approximate equivalent circuit model of five notch band UWB antenna

Figure 6.22 shows the equivalent transmission line model of a proposed five notched band UWB antenna, where, Za is the impedance of antenna and five parallel stubs acts like a half-wavelength resonator. The five stubs ends are short circuited and modeled like $\lambda_{3.5}/2$, $\lambda_{5.2}/2$, $\lambda_{5.8}/2$, $\lambda_{7.5}/2$ and $\lambda_{8.2}/2$ long for L_{Notch} about 26.2mm, 17mm, 15.8mm, 12.2mm and 11.56mm which corresponds to the rejection frequencies of 3.5GHz, 5.2GHz, 5.8GHz, 7.5GHz and 8.2GHz, respectively.

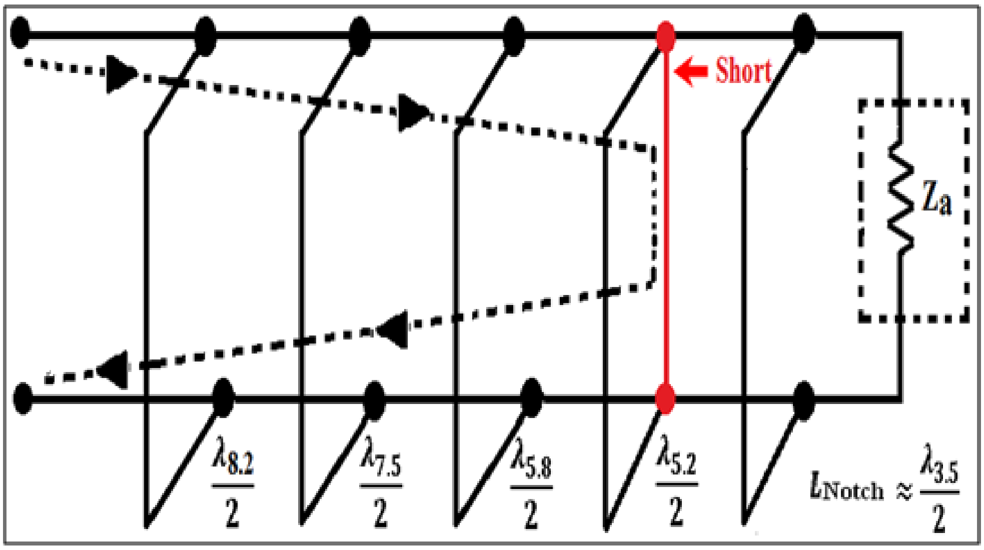
Figure 6.22 (a) shows, the band-pass frequency equivalent circuit. Figure 6.22 (b) shows, the first notch band, when $L_{Notch} \approx \lambda_{3.5}/2$, the impedance at the feed point is zero (short circuited) and antenna become nonreactive; hence the first notch band is produced. In a similar way, another notch band is produced when $L_{Notch} \approx \lambda_{5.2}/2$, $\lambda_{5.8}/2$, $\lambda_{7.5}/2$ and $\lambda_{8.2}/2$ and given in Figures 6.22 (c), (d), (e), (f) respectively.



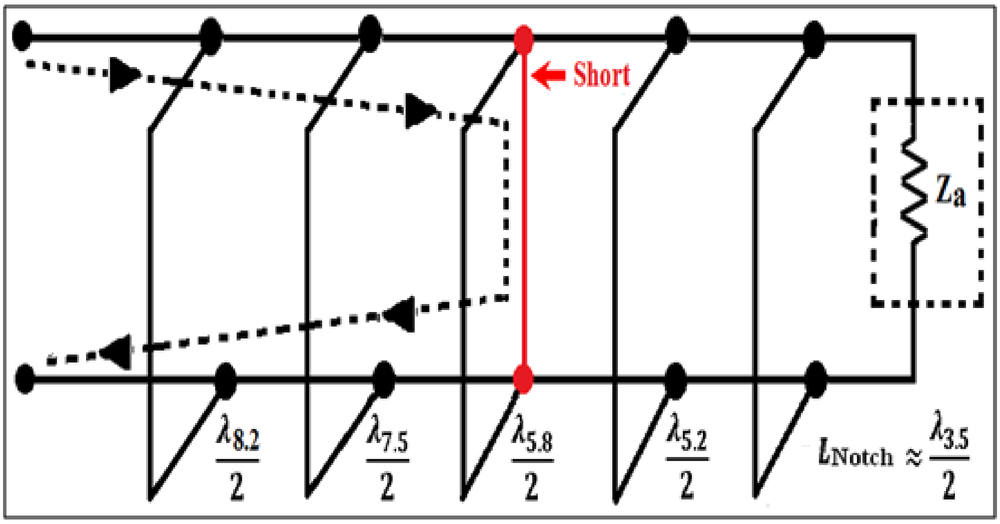
(a) Band-Pass



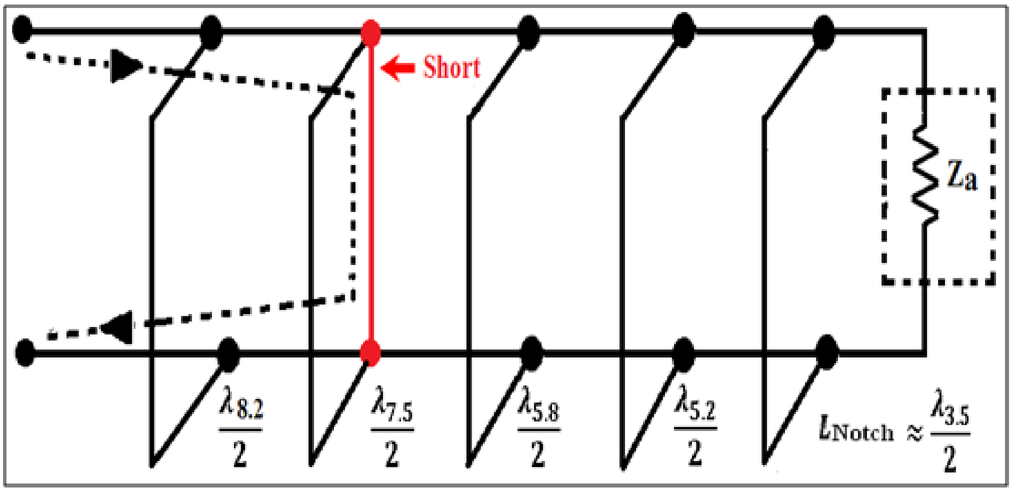
(b) First Notch



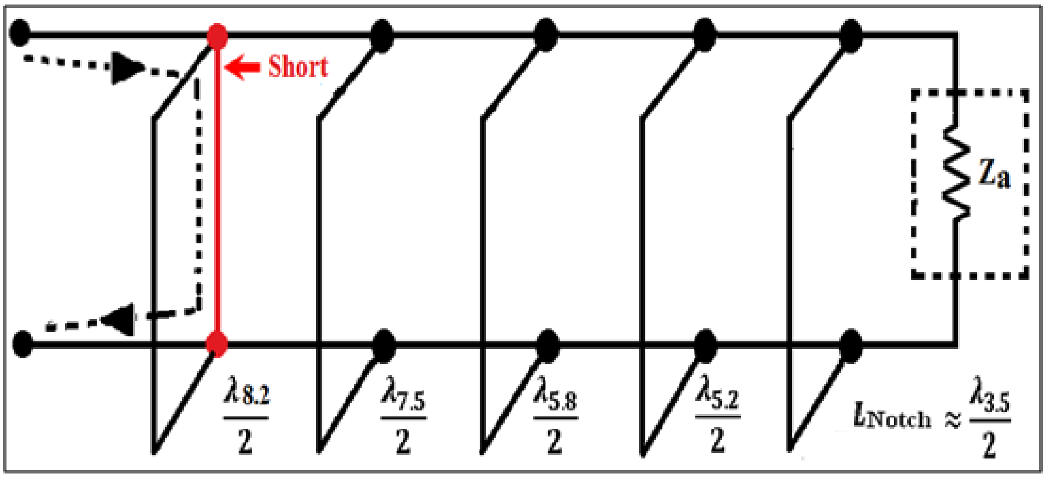
(c) Second Notch



(d) Third Notch



(e) Forth Notch



(f) Fifth Notch

Figure 6.22 An equivalent transmission line model of five notch band UWB antenna at (a) Band-pass (b) first notch (c) second notch (d) third notch (e) forth notch (f) fifth notch

6.6 FABRICATION AND TESTING OF FIVE NOTCH BAND UWBANTENNA

Figure 6.23 shows the proposed fabricated antenna by using optimized parameters summarized in Table 6.2. The various steps that are carried out in the fabrication process are highlighted in Figure 4.9 of chapter 4, which shows the flow chart that is carried out to fabricate the final antenna.

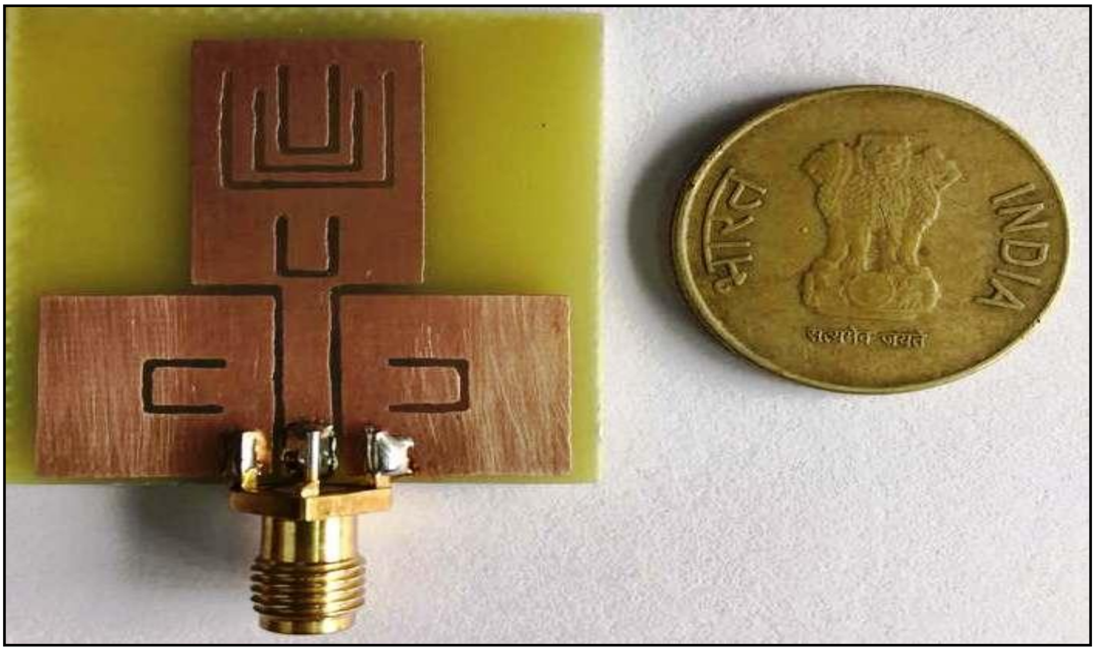


Figure 6.23 Photograph of proposed five notch band UWB antenna

Figure 6.24 illustrates the measured and simulated return loss of projected five notch bands UWB antenna. It is observed that here is a good agreement between simulated and measured results. The designed antenna has wideband performance of 3.06GHz to 11.08GHz for S_{11}<-10dB, cover up the whole UWB range with five notch bands of 3.2-4.12GHz, 5.03-5.37GHz, 5.56-5.9GHz, 7.19-7.65GHz and 7.8-8.35GHz having S_{11}>-10dB. Therefore, the proposed antenna is appropriate for UWB wireless application without interfering with co-existing bands of WiMAX, WLAN (lower and upper), downlink of X-band and ITU.

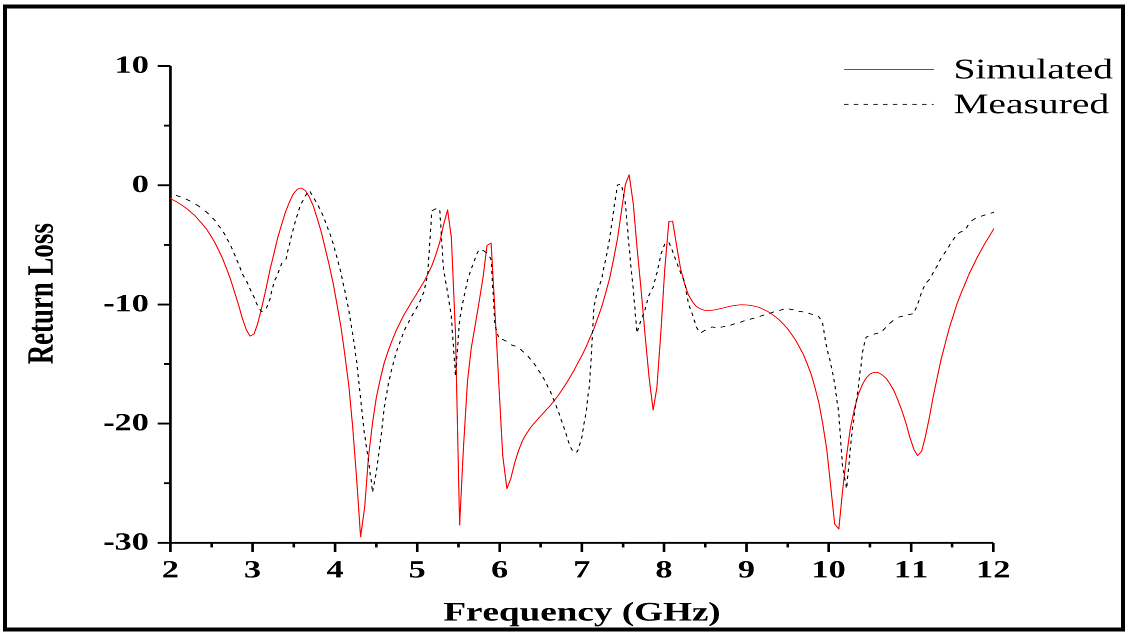
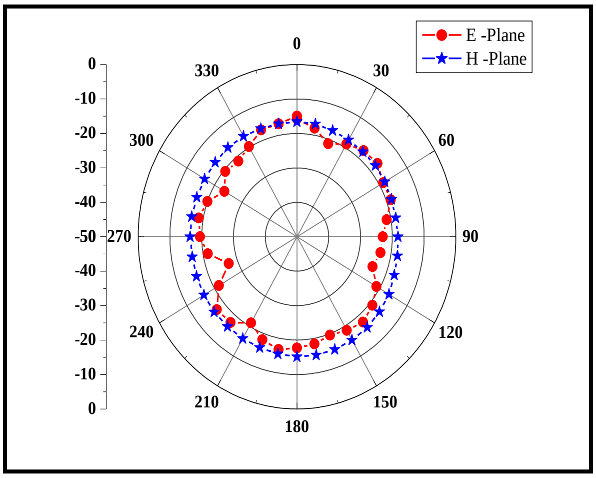


Figure 6.24 Simulated and measured S_{11}(dB) of five notch band UWB antenna

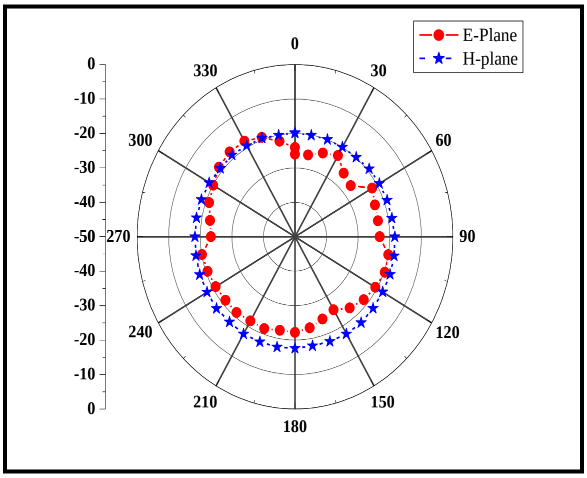
Table 6.14 Comparison of simulated and measured return loss

Notch band	Simulated Frequency at Peak S_{11} (GHz)	Measured Frequency at Peak S_{11} (GHz)	Error (GHz)
WiMAX	3.59	3.68	0.09
WLAN (Lower)	5.36	5.22	0.14
WLAN (Upper)	5.89	5.75	0.14
X-band (Down link)	7.52	7.48	0.04
ITU	8.10	8.05	0.05

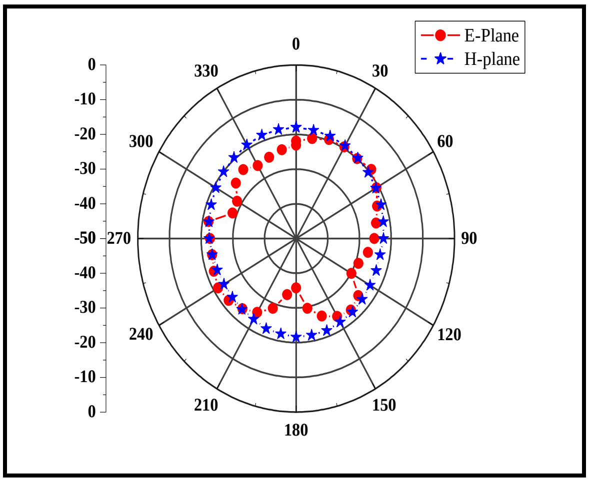
This makes the antenna is practically suitable for the suggested wireless applications. The simulated return loss peak of notch band is slightly differing with the measured, because of the fabrication error that might be present while physically assembling it.



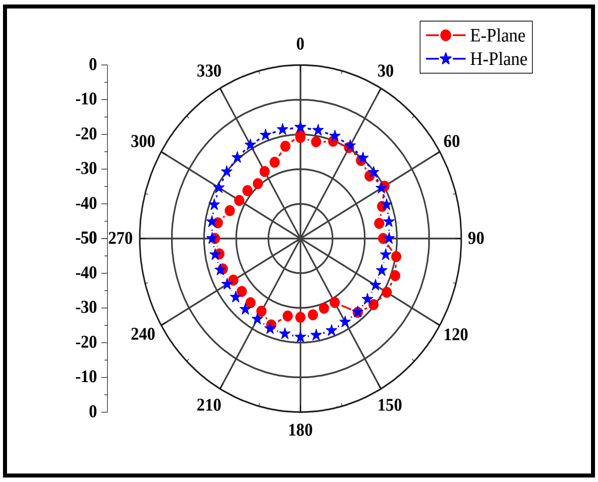
(a) 4.5GHz



(b) 5.5GHz



(c) 6.5GHz



(d) 9.5GHz

Figure 6.25 Measured radiation pattern of five notch band UWB antenna at (a) 4.5GHz (b) 5.5GHz(c) 6.5GHz (d) 9.5GHz

The measured radiation pattern of the projected UWB antenna at 4.5GHz, 5.5GHz, 6.5GHz and 9.5GHz, with E-plane and H-plane has been illustrated in Figure 6.25. The antenna is printed in X-Y plane, therefore Y-Z represents E- plane and X-Z represents an H - plane. It is observed from Figure 6.25 that the radiation pattern of E-plane is similar to monopole antenna and radiation pattern of H-plane is almost omnidirectional.

The antenna was also tested for gain measurements in an anechoic chamber. Figure 6.26 shows simulated and measured gain of the proposed antenna. At notch frequency, gain of antenna decreases sharply. The simulated gain of proposed antenna is 4.2dBi and its measured gain of about 3.1dBi over UWB frequency range, except in a notched frequency band of WiMAX, WLAN (lower and upper), X-band downlink and ITU service band as shown in Table 6.15.

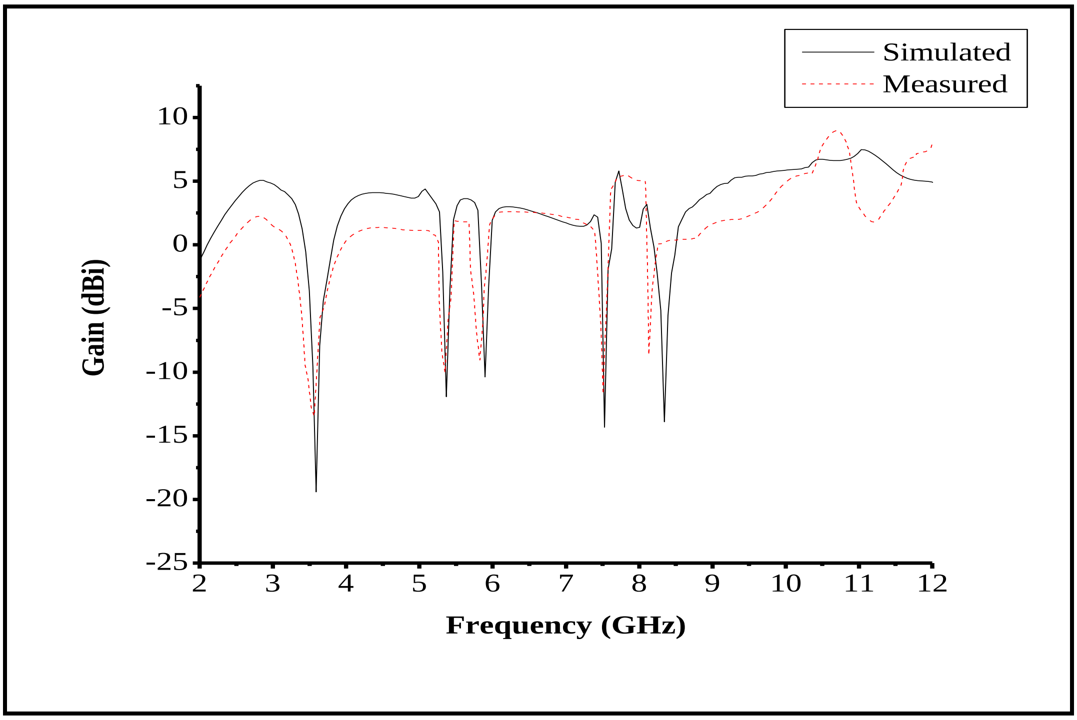


Figure 6.26 Gain of five notch band UWB antenna

Table 6.15 Gain suppression at various notch band

Notch band	Simulated Maximum gain suppression (dBi)	Measured Maximum gain suppression (dBi)
WiMAX	-19.4	-13.45
WLAN (Lower)	-11.9	-10.01
WLAN (Upper)	-10.37	-9.05
X-band (Down link)	-14.33	-11.7
ITU	-13.89	-8.62

6.7 CONCLUSION

In this present chapter, a CPW fed UWB antenna with five notch bands for wireless communication has been designed and analyzed. Five U-shaped structures are etched into the radiating patch and ground of UWB antenna to avoid interference of the UWB band with WiMAX, WLAN, X-band downlink and ITU service band. The designed antenna offers S_{11}<-10dB from 2.8GHz to 11.6GHz to cover UWB range, except notch bands WiMAX (3.1-4GHz), WLAN (5-5.4GHz and 5.7-5.9GHz), X-band downlink (7.2-7.75GHz), and ITU service band (8-8.4GHz). The designed antenna has a gain of about 3.1dBi over UWB frequency range, except at notched frequency bands. Over the entire UWB band, omnidirectional radiation patterns are obtained. The presented antenna is simple and useful for many UWB applications without interference from co-existing bands of WiMAX, WLAN (lower and upper), X-band downlink and ITU.

Table 6.16 Comparison with the design of [123]

Antenna	**Techniques**	**Analyzed Parameters**	**Notch Bands (GHz)**	**Gain suppression (dBi)**
Proposed	U-shaped slot, CPW Feed Rectangular	Size: 30×32 mm^2 BW: 2.8-11.6 GHz	3.1-4	-19.4
			5-5.4	-11.9
			5.7-5.9	-10.37
			7.2-7.75	-14.33
			8-8.4	-13.89
Reference [123]	C-shaped slot CPW Feed Circular	Size: 26×31.8 mm^2 BW: 2.45-12 GHz	3.27-3.57	-1.9
			5.01-5.45	-2.6
			5.55-6.05	-2
			7.05-7.45	+1
			7.83-8.19	-1.3

Table 6.16 compares our proposed band-notched antenna with one comparable design as reported in [123], in terms of size, bandwidth (BW), number of notches and gain suppression. Both antennas have realized with five notches. However, the gain suppression of our design is better than the design reported in [123].

CHAPTER 7
CONCLUSION AND FUTURE SCOPE

7.1 CONCLUSIONS

Ultra wideband technology is the most important technology used in wireless communications for applications which require high data transmission rates, such as imaging systems and high accuracy radars. UWB antenna has an extremely wide bandwidth and carrier free features. Because of these exclusive features, conventional narrowband antennas are insufficient. Therefore, in this thesis a complete study of unique UWB antenna has been presented. However, in the designed bandwidth of UWB system, there also exist some narrow band services for other communication systems, like 3.4-3.69 GHz for WiMAX, 5.15-5.35 GHz and 5.725-5.825 GHz for WLAN, 7.25-7.75 GHz for downlink of X-band and 8.02-8.4 GHz for satellite communication band (ITU) system, which creates interference with UWB system. Thus, it is essential for UWB antenna to have notched band function in the above mentioned frequency bands can be removed to avoid interference. In order to attain the desired uniqueness from the UWB microstrip antennas, bevel slots on the patch and the ground plane both are implemented in initial proposed UWB antenna.

In this thesis, four compact antennas have been designed, simulated, fabricated and tested for the current research work to be carried out effectively. Accordingly, these UWB antennas are the best candidates for wireless communication systems which operate in UWB region.

In Chapter 3, a compact UWB planar antenna, for current and future wireless communication applications has been presented. A simple planar UWB rectangular patch antenna with microstrip feed has been initially designed to explore the characteristic of UWB antenna. It is observed that the impedance bandwidth of the rectangular UWB antenna is mainly affected by the dimensions of the patch, feeding gap and dimensions of the ground plane. The impedance bandwidth of the proposed antenna has been considerably enhanced by etching three bevel slots on the lower portion of radiator patch and a single bevel slot on ground plane, as compared to a conventional rectangular UWB antenna. Moreover, the proposed antenna has a stable radiation pattern over the whole UWB bandwidth. The proposed antenna has a simple configuration.

In chapter 4, a compact ultra wideband (UWB) antenna with microstrip feed has dual notch band characteristic is presented. The antenna has two U-shaped slots on the radiating patch. The two integrated slots can provide different desired notch frequency band. The proposed antenna is capable to reduce the interference between UWB and WiMAX / WLAN. The propose antenna has a compact size of 26×27 mm^2. The proposed antenna has an operating bandwidth (S_{11}<-10dB) from 2.6 GHz to 10.8 GHz, with an excellent notched frequency band of 3-3.9GHz (WiMAX) and 5-5.9GHz (WLAN). The gain of proposed antenna is about 4.1dBi over the UWB frequency range, except in a notched frequency band of WiMAX and WLAN. The proposed UWB antenna exhibits an omnidirectional radiation pattern. Also, the surface current distributions and equivalent circuit models are discussed. Excellent radiation patterns and high gain values are achieved which make it suitable for UWB applications.

In chapter 5, a microstrip feed ultra wideband (UWB) antenna having triple notch band characteristic has been proposed. The proposed antenna has three U- shaped slots on the radiating patch. The three integrated slots can provide different desired notch frequency band. The proposed antenna reduces the interference between UWB and WiMAX/WLAN/ITU. The proposed antenna has an operating bandwidth (S_{11}<-10dB) from 2.68GHz to 12GHz except notch band 3-3.85GHz (WiMAX), 5-5.9GHz (WLAN) and 8-8.8GHz (ITU). The gain of proposed antenna is about 3.8dBi over the complete UWB range, except in a notched frequency band of WiMAX, WLAN and ITU. The proposed antenna exhibits omnidirectional radiation patterns. Also, the surface current distributions and equivalent circuit models are analyzed.

In chapter 6, a novel small CPW fed UWB antenna having five notch bands is projected to suppress the potential interferences in ultra wideband systems. The five integrated stubs can provide different desired notch frequency band. This projected antenna has small dimensions of 30×32×1.6mm^3 an operating bandwidth (S_{11}<-10dB) from 2.8GHz to 11.6GHz. By introducing five U-shaped slots, five notches are achieved in WiMAX (3.1-4GHz), WLAN (5.2-5.4GHz and 5.7-5.9GHz), X-band downlink (7.2-7.75GHz), and ITU service band (8-8.4GHz). The designed antenna possess a good gain of about 3.1dBi over UWB frequency range and it is nearly constant, except in notched frequency band of WiMAX, WLAN (lower and upper), X-band downlink and ITU service band. The antenna is fabricated and simulated. The proposed antenna exhibits omnidirectional radiation patterns. Measured results show a good agreement with simulated results. In addition, the surface current distributions and transmission line models are analyzed.

7.2 FUTURE WORK

The current research work presents a detailed study and analysis of UWB microstrip patch antenna with multiple notched bands. A variety of case studies have been included in the research work to understand the working of UWB antenna with multiple notched bands, with different structures, namely H-shaped slots, C-shaped slots, L-shaped slots, T-shaped slots, π-shaped slots, metamaterial, electromagnetic band-gap (EBG), split-ring resonator (SRR) slots and CSRR slots. With the increasing requirements of wireless communication systems, there is a large space for development in the field of antenna design. The following points discuss some possible future research directions for the work reported in this thesis.

i. Novel techniques should be developed to further reduce the size of the UWB antennas to match practical applications. Metamaterial is a good candidate, since it can reduce the antenna size significantly. Though most of current metamaterial antennas are used in narrow bandwidth application, this technique can be developed for wideband operation in the coming future.

ii. The antennas can be designed with Electromagnetic band gap structures (EBG) that can be used to design antennas with specific pass bands and stop bands.

iii. Because of the low power requirements of UWB systems, a UWB receiver needs a low noise amplifier. Integration of antenna with low-noise amplifier may be explored in future.

iv. Software defined radio and cognitive radio concepts, which are some of the future radio systems, produce significant challenges for the present antenna design and especially for re-configurable antennas.

REFERENCES

[1] Federal Communications Commission, "Revision of Part 15 of the commission's rules regarding ultra-wideband transmission systems, first report and order", ET Docket 98-153, FCC 02-48, pp. 1-118, Feb.14, 2002.

[2] N. P. Agrawall, G. Kumar, and K. P. Ray, "Wide-band planar monopole antennas", *IEEE Trans. on Antennas and Propagation,* vol. 46, pp. 294-295, 1998.

[3] E. S. Angelopoulos, A. Z. Anastopoulos, D. I. Kaklamani, A. A. Alexandridis, F. Lazarakis, and K. Dangakis, "Circular and elliptical CPW-fed slot and microstrip-fed antennas for ultra-wideband applications," *IEEE Antennas and Wireless Propagation* Letters, vol. 5, pp. 294-297, 2006.

[4] H. D. Chen and H. T. Chen, "A CPW-fed dual-frequency monopole antenna," *IEEE Trans. on Antennas and Propagation,* vol. 52, pp. 978-982, 2004.

[5] Y. Lu, Y. Huang, Y. C. Shen, and H. T. Chattha, "A further study of planar UWB monopole antennas," *Antennas & Propagation Conference, 2009. LAPC.* Loughborough, pp. 353-356, 2009.

[6] L. Paulsen, J. B. West, W. F. Perger, and J. Kraus, "Recent investigations on the volcano smoke antenna," *IEEE Antennas and Propagation Society International Symposium,* vol. 3, pp. 845-848, 2003.

[7] P. Cao, Y. Huang, J. W. Zhang, and Y. Lu, "A comparison of planar monopole antennas for UWB applications," *Antennas and Propagation Conference (LAPC),* Loughborough, pp. 1-4, 2011.

[8] K. C. L. Chan; Y. Huang, and X. Zhu, "A planar elliptical monopole antenna for UWB applications," *IEEE/ACES Inter. Conference on Wireless Communications and Applied Computational Elec.*, Hawaii, U.S.A., pp. 182-185, Apr. 2005.

[9] J. X. Liang, C. C. Chian, X. D. Chen, and C. G. Parini, "Study of CPW-fed circular disc monopole antenna for ultra-wideband applications," *IEEE Proc. Microwaves Antennas and Propagation*, pp. 520-526, Dec.2005.

[10] Z. N. Chen, et al, “Planar antennas”, *IEEE Microwave Magazine*, vol. 7, issue 6, pp. 63-73, Dec. 2006.

[11] Y. Huang and Kevin Boyle, “Antennas from theory to practice”, John Wiley and Sons, 2008.

[12] T. W. Barrett, “History of ultra wideband (UWB) radar & communications: Pioneers and Innovators,” *The Progress in Electromagnetics Symposium 2000 (PIERS2000)*, Cambridge, Jul. 2000.

[13] G. F. Ross, “Transmission and Reception System for Generating and Receiving Base-band Duration Pulse Signals without Distortion for Short Base-band Pulse Communication System,” U.S. Patent 3728632, Apr. 1973.

[14] H. F. Harmuth, “Synthetic-Aperture Radar Based on Non sinusoidal Functions: I-Moving Radar and Stationary Arrays in One or Two Dimensions,” *IEEE Transactions on Electromagnetic Compatibility,* vol. EMC-20, pp. 426-435, 1978.

[15] H. F. Harmuth, *Radiation of Non sinusoidal Electromagnetic Waves*. New York: Academic Press, 1990.

[16] Assessment of Ultra-Wideband (UWB) Technology, *OSD/DARPA,* Ultra-Wideband Radar Review Panel, R-6280, July 13, 1990.

[17] FCC, “First Report and Order: Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems,” Apr. 2002.

[18] M. F. Hasan, M. A. Islam and A. Z. M. S. Muttalib, “ A Miniaturization of the Quasi-Self-Complementary Antenna With a Wearable Leather Substrate and the Use of Specific Ultra- Wide-Band Frequency Range for On-Body Communications, ” *IEEE International Conference on Informatics, Electronics & Vision,* 2012.

[19] S. Zafar, G. Sinan and G. Ismail, “Ultra-wideband positioning systems: theoretical limits,” *Ranging Algorithms, and Protocols,* Cambridge University Press, 2008.

[20] Available: http://www.usb.org/developers/wusb/

[21] Available: http://web.mst.edu/~mobildat/wusb/index.html

[22] Available:http://en.wikipedia.org/wiki/ultra_wideband?&lang=en_us&output=json

[23] Available: http://www.cwins.wpi.edu/geolocation/uwbmrn.shtml

[24] C. Meissner, "The Next Generation of Medical Diagnostic Devices".

[25] C.A. Balanis, "Antenna Theory Analysis and Design," Third Edition. Wiley inter science. John Wiley & Sons, Inc., Hoboken, New Jersey, 2005.

[26] H.-K. Jang, W.-J. Lee and C.-G. Kim, "Design and fabrication of a microstrip patch antenna with a low radar cross section in the X-band," *Smart Materials and Structures*, Dec. 2010.

[27] C. U. Ndujiuba1, A. O. Oloyede, "Selecting Best Feeding Technique of a Rectangular Patch Antenna for an Application," *International Journal of Electromagnetics and Applications*, pp. 99- 107, 2015.

[28] R. Garg, P. Bhartia, I. Bahl, and A. Ittipiboon, "Microstrip Antenna Design Handbook," Artech House, Boston, London, 2001.

[29] RSA Raja Abdullah, D. Yoharaaj, and Alyani Ismail, "Bandwidth Enhancement Technique in Microstrip antenna for Wireless Applications," *PIERS online*, vol. 2, no. 6, pp. 633-635, 2006.

[30] Indrasen Singh, Dr. V. S. Tripathi, "Micro strip Patch Antenna and its Applications: aSurvey," *International Journal of Comp. Tech. Applications*, vol. 2 (5), pp. 1595-1599, 2011.

[31] Adnan Kaya, S. Kilinc, E. Yesim Yuksel, and U. Cam, "Bandwidth Enhancement of a Microstrip Antenna Using Negative Inductance as Impedance Matching Device," *Microwave Optical Technology letters*, vol. 42, pp. 476-478, 2004.

[32] Kathleen L. Virga and Yahya Rahmat-Samii, "Low-Profile Enhanced-Bandwidth PIFA Antennas for Wireless Communications Packaging," *IEEE Transactions on Microwave Theory and Techniques*, vol. 45, no. 10, pp. 1879-1888, Oct. 1997.

[33] W. Ren, "Compact Dual-band Slot Antenna For 2.4/5GHZ WLAN Applications," *Progress in Electromagnetics Research B*, vol. 8, pp. 319-327, 2008.

[34] Girish Kumar, K. P. Ray, “Broadband Microstrip Antennas,” Archtech House Boston, London 2003.

[35] R. Bancroft, “Microstrip and Printed Antenna Design,” Prentice-Hall of India, New Delhi, 2006, USA 2004.

[36] A. Sahu, V. DevabhaktunHouse, Boston en, “ A Slot Antenna Designed in Ridge Gap Waveguide Technology for V-Band Applications,” *IEEE MTT-S International Microwave and RF Conference (IMaRC)* Hyderabad, pp. 385-387, 2015.

[37] J. Malik and M. V. Kartikeyan, “A Stacked Equilateral Triangular Patch Antenna with Sierpinski Gasket Fractal for WLAN Applications,” *Progress in Electromagnetics Research Letters*, vol.22, pp. 71-81, 2011.

[38] V. Rumsey, “Frequency independent antennas,” Academic Press. New York, 1966.

[39] O. Lodge, “Electric telegraphy,” U. S. Patent No. 609, 154 Aug. 16, 1898.

[40] P. S. Carter, “Wide band short wave antenna and transmission line system,” U. S. Patent 2, 181, 870, Dec. 1939.

[41] S. A. Schelkunoff, “Ultra short wave radio system,” U.S. Patent 2, 235, 506, March 18, 1941.

[42] S. A. Schelkunoff, “Advanced antenna theory,” New York: John Wiley and Sons, pp. 160, 1952.

[43] L. N. Brillouin, “Broad band antenna,” U. S. Patent 2,454,766, Nov. 1948.

[44] S. S. Zhong, X. R. Yan and X. L. Liang, “UWB planar antenna technology,” *Frontiers of Electric and Electronic Engineering in China*, *3 (2)*, pp. 136-144, 2008.

[45] G. Dubost and S. Zisler. “Antennas a large band,” *New York: Masson,* pp. 128-129, 1976.

[46] N. P. Agrawall, G. Kumar, and K. P. Ray, “Wide-band planar monopole antennas,” *IEEE Trans. on Antennas and Propagation,* vol. 46, pp. 294-295, 1998.

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

[48] S. Y. Suh, W. L. Stutaman and W. A. Davis, “A new ultra-wideband printed monopole antenna: the planar inverted cone antenna (PICA),” *IEEE Trans. on Antennas and Propagation,* vol. 52, no. 5, pp. 1361-1364, May 2004.

[49] X. F. Bai, S. S. Zhong, and X. -L. Liang, “Leaf-shaped monopole antenna with extremely wide bandwidth,” *Microwave and Optical Technology Letters,* vol. 48, pp. 1247-1250, 2006.

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

[51] E. Antonino-Daviu, M. Cabedo-Fabres, M. Ferrando-Bataller, and A. Valero-Nogueira, “Wideband double-fed planar monopole antennas,” *Electronics Letters,* vol. 39, pp. 1635-6, 2003.

[52] M. J. Ammann and C. Zhi-Ning, “A wide-band shorted planar monopole with bevel,” *IEEE Trans. on Antennas and Propagation,* vol. 51, pp. 901-903, 2003.

[53] D. C. Chang, J. C. Liu and M. Y. Liu, “Improved U-shaped stub rectangular slot antenna with tuning pad for UWB applications,” *Electronics Letters,* vol. 41, pp. 1095-1097, 2005.

[54] S. Cheng, P. Halbjorner and A. Rydberg, “Printed slot planar inverted cone antenna for ultra-wideband Applications,” *IEEE Antennas and Wireless Propagation Letters,* vol. 7, pp. 18-21, 2008.

[55] E. S. Angelopoulos, A. Z. Anastopoulos, D. I. Kaklamani, et al., “Circular and elliptical CPW-fed slot and microstrip-fed antennas for ultra-wideband applications,” *IEEE Antennas and Wireless Propagation Letters,* vol. 5, no. 1, pp. 294-297, Dec. 2006.

[56] S. Singh and R. K. Sarin, “Enhanced Performance of Microstrip-fed Wide Slot Antenna using Periodic Gaps in Dielectric Substrate,” 11th WSEAS International Conference on Communications, Agios Nikolaos, Crete Island, Greece, , pp. 127-129, July, 2007.

[57] E. Gazit, “Improved design of the Vivaldi antenna,” *Microwaves, Antennas and Propagation, IEE Proceedings H*, vol. 135, pp. 89-92, 1988.

[58] J. D. S. Langley, P. S. Hall, and P. Newham, “Novel ultra-wide-bandwidth Vivaldi antenna with low cross polarization,” *Electronics Letters,* vol. 29, pp. 2004-2005, 1993.

[59] J. Jung, W. Choi, and J. Choi, “A Small Wideband Microstrip-fed Monopole Antenna, ”*IEEE Microwave and Wireless Components Letters,* vol. 15, no. 10, pp. 703-705, October 2005.

[60] J. Jung, K. Seol, W. Choi and J. Choi, “Wideband monopole antenna for various mobile communication applications,” *Electronics Letters,* vol. 41 no. 24, November 2005.

[61] S. Barbarino and F. Consoli, “Study on super-wideband planar asymmetrical dipole antennas of circular shape,” *IEEE Trans. on Antennas and Propagation,* vol. 58, pp. 4074-4078, 2010.

[62] H. Oraizi and S. Hedayati, “Wideband monopole fractal antenna with Hilbert fractal slot patterned ground plane,” *41st European Microwave Conference (EuMC)*, pp. 242-245, 2011.

[63] M. A. Dorostkar, M. T. Islam, and R. Azim, “Design of a novel superwide band circular-hexagonal fractal antenna,” *Progress in Electromagnetics Research,* vol. 139, pp. 229-245, 2013.

[64] C. Ke-Ren, C. Sim, and R. Jeen-Sheen, “A compact monopole antenna for super wideband applications,” *IEEE Antennas and Wireless Propagation Letters,* vol. 10, pp. 488-491, 2011.

[65] M. Almalkawi, M. Westrick, and V. Devabhaktuni, “Compact super wideband monopole antenna with switchable dual band-notched characteristics,” *Microwave Conference Proceedings (APMC)*, Asia-Pacific, pp. 723-725, 2012.

[66] M. H. Rabah, D. Seetharamdoo, R. Addaci, and M. Berbineau, “Novel Miniature Extremely-Wide-Band Antenna with Stable Radiation Pattern for Spectrum Sensing Applications,” *IEEE Antennas and Wireless Propagation Letters,* vol. 14, pp. 1634-1637, 2015.

[67] 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, pp. 1481-1483, 2011.

[68] D. Tran, A. Szilagyi, I. E. Lager, P. Aubry, L. P. Ligthart, and A. Yarovoy, “A super wideband antenna,” *5th European Conference on Antennas and Propagation (EuCAP)*, Rome, pp. 2656-2660, 2011.

[69] P. Li, J. Liang, and X. Chen, “Study of Printed Elliptical/Circular Slot Antennas for Ultra wideband Applications,” *IEEE Trans. on Antennas and Propagation*, vol. 54, no. 10, pp. 1670-1675, 2006.

[70] A. K. Gautam, S. Yadav and B. K. Kanaujia, “A CPW-fed compact UWB microstrip antenna,” *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 151-154, 2013.

[71] E. Pancera, D. Modotto, A. Locatelli, F. M. Pigozzo, and C. De Angelis, “Novel design of UWB antenna with band-Notch capability,” *European Conference on Wireless Technologies*, pp. 48-50, 2007.

[72] S. Nikolaou, B. Kim, Y. S. Kim, J. Papapolymerou, and M. M. Tentzeris, “CPW-fed ultra-wideband (UWB) monopoles with band rejection characteristic on ultra-thin organic substrate,” *Proceedings of APMC2006*, pp. 12-15, Dec. 2006.

[73] T. Dissanayake and K. P. Esselle, “Prediction of the notch frequency of slot loaded printed UWB antennas,” *IEEE Trans. on Antennas and Propagation*, vol. 55, pp. 3320-3325, 2007.

[74] Z. A. Zheng, and Q. X. Chu, “A CPW-Fed ultrawideband antenna with dual notched bands,” *IEEE International Conference on Ultra-Wideband ICUWB 2009*, pp. 645-648, 2009.

[75] E. Antonino-Daviu, et al., “Modal analysis and design of band-notched UWB planar monopole antennas,” *IEEE Trans. on Antennas and Propagation*, vol. 58, pp. 1457-1467, 2010.

[76] C. Qing-Xin and Y. Ying-Ying, “A compact ultra-wideband antenna with 3.4/5.5 GHz dual band-notched characteristics,” *IEEE Trans. on Antennas and Propagation*, vol. 56, pp. 3637-3644, 2008.

[77] Y. Kim and D. H. Kwon, “CPW-fed planar ultra wideband antenna having a frequency band notch functions,” *Electronics Letters,* vol. 40, pp. 403-405, 2004.

[78] L. Liu, Y. F. Weng, S. W. Cheung, T. I. Yuk, and T. Peter, “Deep band-notched characteristic using meander lines for UWB monopole antennas,” *PIERS Proceedings,* Kuala Lumpur, Malaysia, pp. 27-30, March, 2012.

[79] S. W. Qu, et al., “A band-notched ultra-wideband printed monopole antenna,” *IEEE Antennas and Wireless Propagation Letters*, vol. 5, pp. 495-498, 2006.

[80] A. M. Abbosh and M. E. Bialkowski, “Design of UWB planar band-notched antenna using parasitic elements,” *IEEE Trans. on Antennas and Propagation,* vol. 57, pp. 796-799, 2009.

[81] S. Nikolaou, N. D. Kingsley, G. E. Ponchak, J. Papapolymerou, M. M. Tentzeris, “UWB elliptical monopoles with a reconfigurable band notch using MEMS switches actuated without bias lines,” *IEEE Trans. on Antennas and Propagation*, vol. 57, no. 8, pp. 2242-2251, Aug. 2009.

[82] K. S. Ryu and A. A. Kishk, “UWB antenna with single or dual band-notches for lower WLAN band and upper WLAN band,” *IEEE Trans. on Antennas and Propagation,* vol. 57, pp. 3942-3950, 2009.

[83] K. H. Kim, et al., “Band-notched UWB planar monopole antenna with two parasitic patches,” *Electronics Letters,* vol. 41, pp. 783-785, 2005.

[84] C. Y. Huang, W. C. Hsia, and J. -S. Kuo, “Planar ultra-wideband antenna with a band-notched characteristic,” *Microwave and Optical Technology Letters,* vol. 48, pp. 99-101, 2006.

[85] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, “Magnetism from conductors and enhanced nonlinear phenomena,” *IEEE Transactions on Microwave Theory and Techniques,* vol. 47, pp. 2075-2084, 1999.

[86] J. Kim, et al., "5.2 GHz notched ultra-wideband antenna using slot-type SRR," *Electronics Letters,* vol. 42, pp. 315-316, 2006.

[87] L. Li, Z. L. Zhou, J. S. Hong, and B. Z. Wang, "Compact dual-band-notched UWB planar monopole antenna with modified SRR," *Electronics Letters,* vol. 47, pp. 950-951, 2011.

[88] J. Nam-I, K. Dang-Oh, and K. Che-Young, "A compact band notched UWB antenna for mobile applications," *PIERS online,* vol. 6, no. 2, 2010.

[89] Chirag Arora, Shyam S. Pattnaik, and Rudra N. Baral, "SRR inspired microstrip patch antenna array," *Progress in Electromagnetics Research C*, vol. 58, pp. 89-96, 2015.

[90] J. R. Kelly, P. S. Hall, and P. Gardner, "Planar band-notched UWB antenna," *3rd European Conference on Antennas and Propagation (EuCAP),* Berlin, pp. 1636-1639, 2009.

[91] J. R. Kelly, P. S. Hall, P. Gardner, and F. Ghanem, "Integrated narrow/band-notched UWB," *Electronics Letters*, vol. 46, pp. 814-816, 2010.

[92] M. Yazdi and N. Komjani, "Design of a band-notched UWB monopole antenna by means of an EBG structure," *IEEE Antennas and Wireless Propagation Letters,* vol. 10, pp. 170-173, 2011.

[93] S. K. Mahto, A. Choubey and R. Kumar, "A Novel Compact Multi-Band Double Y-Slot Microstrip Antenna Using EBG Structure," *IEEE*, 2015.

[94] K. H. Kim and S. O. Park, "Analysis of the small band-rejected antenna with the parasitic strip for UWB," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 6, June 2006.

[95] K. Chung, S. Hong and J. Choi "Ultrawide-band printed monopole antenna with band-notch filters," *IET Microwave Antennas Propagation.*, vol. 1, no. 2, April 2007.

[96] H. A. Majid, M. K. A. Rahim, M. R. Hamid, N. A. Murad, N. A. Samsuri, M. F. M. Yusof and M. R. Kamarudin, "Band-notched reconfigurable CPW-fed UWB antenna," *Applied Physics A material Science &processing, Springer,* September 2016.

[97] M. Ojaroudi, G. Ghanbari, N. Ojaroudi and C. Ghobadi, “Small square monopole antenna for UWB applications with variable frequency band-notch function,” *IEEE Antennas and Wireless Propagation Letters,* vol. 8, 2009.

[98] K. G. Thomas and M. Sreenivasan, “A simple ultrawideband planar rectangular printed antenna with band dispensation,” *IEEE Transactions on Antennas and Propagation,* vol. 58, no. 1, January 2010.

[99] S. K. Koul, M. Kumar and A. Basu, “An ultra-wideband antenna with band rejects capability and its characterization in time domain,” *Progress in Electromagnetics Research C,* vol. 19, pp. 223-234, 2011.

[100] M. Abdollahvand, G. Dadashzadeh, D. Mostafa, “Compact dual band-notched printed monopole antenna for UWB application,” *IEEE Antennas and Wireless Propagation Letters,* vol. 9, pp. 1148-1151, 2010.

[101] K. S. Ryu and A. A. Kishk, “UWB antenna with single or dual band-notches for lower WLAN band and upper WLAN band,” *IEEE Trans. on Antennas and Propagation,* vol. 57, pp. 3942-3950, 2009.

[102] L.Y. Cai, Y. Li, G. Zeng and H.C. Yang, “Compact wideband antenna with double-fed structure having band-notched characteristics,” *Electronics Letters,* vol. 46 no. 23, November 2010.

[103] Q. X. Chu and Y. Y. Yang, “A compact ultra-wideband antenna with 3.4/5.5 GHz dual band-notched characteristics,” *IEEE Trans. on Antennas and Propagation,* vol. 56, pp. 3637-3644, 2008.

[104] W. S. Chen and K. Y. Ku, “Band-rejected design of the printed open slot antenna for WLAN/WiMAX Operation,” *IEEE Trans. on Antennas and Propagation,* vol. 56, pp. 1163-1169, 2008.

[105] J. Wen and C. Wenquan, “A novel UWB antenna with dual notched bands for WiMAX and WLAN Applications,” *IEEE Antennas and Wireless Propagation Letters,* vol. 11, pp. 293-296, 2012.

[106] Y. Sung, “UWB monopole antenna with two notched bands based on the folded stepped impedance resonator,” *IEEE Antennas and Wireless Propagation Letters,* vol. 11, pp. 500-502, 2012.

[107] L. Xiong and P. Gao, “Dual-band planar monopole antenna for Bluetooth and UWB applications with WIMAX and WLAN band-notched,” *Progress in Electromagnetics Research Letters,* vol. 28, pp. 183-194, 2012.

[108] D. Zhou, S. Gao, et al., “A simple and compact planar UWB antenna with single or dual-band-notched,” *Progress in Electromagnetics Research,* vol. 123, pp. 47-65, 2012.

[109] F. Zhu, S. Gao, J. Z. Li, and J. D. Xu, “Planar asymmetrical ultra-wideband antenna with improved multiple band-notched characteristics,” *Electronics Letters,* vol. 48, pp. 615-617, 2012.

[110] M.T. Islam, R. Azim and A. T. Mobashsher, “Triple band-notched planar UWB antenna using parasitic strips,” *Progress in Electromagnetic Research,* vol. 129, pp. 161-179, 2012.

[111] F. Zhu, S. Gao, A. TS Ho, R. A. A. Alhameed, C. H. See, T. WC Brown, J. Li, G. Wei, and J. Xu, “Multiple band-notched UWB antenna with band-rejected elements integrated in the feed line,” *IEEE Transactions on Antennas and Propagation,* vol. 61, no. 8, August 2013.

[112] D. Sarkar, K.V. Srivastava and K. Saurav, “A compact microstrip fed triple band-notched UWB monopole antenna,” *IEEE Antennas Wireless Propagation Letters,* vol. 13, pp. 396–399, 2014.

[113] Y. Zhang, W. Hong, C. Yu, Z. Q. Kuai, Y. D. Don, and J. Y. Zhou, “Planar ultra-wideband antennas With multiple notched bands based on etched slots on the patch and/or split ring resonators on the feed line,” *IEEE Trans. on Antennas and Propagation,* vol. 56, pp. 3063-3068, 2008.

[114] T. Ming-Chun, S. Q. Xiao; T. W. Deng, D. Wang, J. Guan; B. Z. Wang; G. Ding. Ge, “Compact UWB antenna with multiple band-notches for WiMAX and WLAN,” *IEEE Trans. on Antennas and Propagation,* vol. 59, no. 4, pp. 1372-1376, April 2011.

[115] Y. F. Weng, S. W. Cheung, and T. I. Yuk, "Triple band-notched UWB antenna using meandered ground stubs," *Antennas and Propagation Conference (LAPC), 2010,* Loughborough, pp. 341-344, 2010.

[116] M. Almalkawi and V. Devabhaktuni, "Ultra-wideband antenna with triple band-notched characteristics using closed-loop ring resonators," *IEEE Antennas and Wireless Propagation Letters,* vol. 10, pp. 959-962, 2011.

[117] L. Chia-Ching, J. Peng, and R. W. Ziolkowski, "Single, dual and tri-band-notched Ultra-wideband (UWB) antennas using capacitively Loaded Loop (CLL) Resonators," *IEEE Trans. on Antennas and Propagation,* vol. 60, pp. 102-109, 2012.

[118] D.O. Kim, N.I Jo, H.A. Jang, and C.Y. Kim, "Design of the ultrawideband antenna with a quadruple-band rejection characteristics using a combination of the complementary split ring resonators," *Progress in Electromagnetics Research,* vol. 112, pp. 93-107, 2011.

[119] Y. Q. Cao, J. X. Wu, H. C. Yang, "Design of CPW-fed monopole antenna with quadruple band-notched function for UWB application," *2011 International Conference on Computational Problem-Solving (ICCP),* pp. 353-356, 2011.

[120] X. Y. Li, L. S. Yan, W. Pan, and B. Luo, "A compact printed quadruple band-notched UWB antenna," *International Journal of Antennas and Propagation,* vol. 12, 2013.

[121] Z. H. Wu, F. Wei, X. W. Shi, and W. -T. Li, "A compact quad band-notched UWB monopole antenna loaded one lateral l-shaped slot," *Progress in Electromagnetics Research*, vol. 139, pp. 303-315, 2013.

[122] M. Islam, M.T. Islam, M. Samsuzzamanand, M. Rashed I. Faruque, "Five band-notched ultrawide band (UWB) antenna loaded with c-shaped slots," *Microwaves and Optical Technology Letters,* vol. 57, no. 6, 1470-1475, June 2015.

[123] J. Xu, D. Y. Shen, X. P. Zhang, and K. Wu, "A compact disc Ultra wideband (UWB) antenna with quintuple band rejections," *IEEE Antennas and Wireless Propagation Letters,* vol. 11, pp. 1517-1520,2012.

[124] B. Hammache, A. Messai, I. Messaoudene, M. A. Meriche, M. Belazzoug, and Y. B. Chaouche, "A compact ultra wideband monopole antenna with five rejected-

bands,"*7th IEEE Seminar on Detection Systems: Architectures and Technologies*, Feb.2017.

[125] F. Zhu, S. Gao, A. T. S. Ho, C. H. See, R. A. Abd-Alhameed, J. Li, and J. Xu, "Design and analysis of planar ultra-wideband antenna with dual band-notched function," *Progress in Electromagnetics Research*, vol. 127, pp. 523-536, 2012.

[126] M. Manohar, R. S. Kshetrimayum, and A. K. Gogoi, "Super wideband antenna with single band suppression," *International Journal of Microwave and Wireless Technologies*, April 2015.

[127] J. Wang, Y. Yin, and X. Liu, "Triple band-notched ultra wideband (UWB) Antenna using a novel modified capacitively loaded loop (CLL) resonator," *Progress In Electromagnetics Research Letters,* vol. 42, pp. 55-64, 2013.

[128] S. K. Mishra, and J. Mukherjee, "Compact printed dual band-notched U- shape UWB antenna," *Progress in Electromagnetics Research C,* vol. 27, pp. 169-181, 2012.

[129] *****Ajeet Pratap Singh, Rajesh Khanna, and Hardeep Singh, "UWB Antenna with Dual Notched Band for WiMAX and WLAN Applications," *Microwave and Optical Technology* Letters (MOTL), Volume 4, Issue 59, pp. 792-97, April 2017.

[130] *****Ajeet Pratap Singh, Rajesh Khanna, and Hardeep Singh, "A Strip Feed Compact UWB Antenna with Triple Band Notched," *Current Trends in Signal Processing (CTSP),* ISSN: 2277-6176 (Online), ISSN: 2321-4252 (Print), Volume 7, Issue 1, pp. 1-7, April 2017.

[131] *****Ajeet Pratap Singh, Rajesh Khanna, and Hardeep Singh, "A CPW Feed Compact UWB Antenna with Five Band Notches," *Journal of Communication Engineering & Systems (JoCES),* ISSN: 2249-8613 (Online), ISSN: 2321-5151 (Print), Volume 7, Issue 2, pp. 27-33, August 2017.

***Author Publication**

List of Publications

[1] Ajeet Pratap Singh, Rajesh Khanna, and Hardeep Singh, "UWB Antenna with Dual Notched Band for WiMAX and WLAN Applications," *Microwave and Optical Technology* Letters (MOTL), Volume 4, Issue 59, pp. 792-97, April 2017.

[2] Ajeet Pratap Singh, Rajesh Khanna, and Hardeep Singh, "A Strip Feed Compact UWB Antenna with Triple Band Notched," *Current Trends in Signal Processing (CTSP)*, ISSN: 2277-6176 (Online), ISSN: 2321-4252 (Print), Volume 7, Issue 1, pp. 1-7, April 2017.

[3] Ajeet Pratap Singh, Rajesh Khanna, and Hardeep Singh, "A CPW Feed Compact UWB Antenna with Five Band Notches," *Journal of Communication Engineering & Systems (JoCES)*, ISSN: 2249-8613 (Online), ISSN: 2321-5151 (Print), Volume 7, Issue 2, pp. 27-33, August 2017.