

Implementation of Multifrequency Antennas and Broadband Designs for Wireless Applications

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by

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Certificate

I, **Geetanjali**, hereby certify that the work which is being presented in this thesis entitled **“Implementation of Multi-Frequency Antennas and Broadband Designs for Wireless Applications”** in fulfillment of requirements for the award of degree of the Doctor of Philosophy in Electronics and Communication Engineering from Thapar Institute of Engineering and Technology, Patiala, Punjab is an authentic record of my own work carried under the supervision of **Dr. Rajesh Khanna**.

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

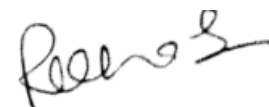
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Abstract

Wireless systems have highly revolutionized and replaced the wired communication systems in consumer as well as industrial applications. Advanced multifunctional wireless devices have evolved which are capable of supporting multiple systems, services and standards in a single device. For example, smart phones provide a number of applications to the user simultaneously such as audio, video, data transfer, radio, TV, NFC feature and access to different networks such as Bluetooth, GPS, WiFi, WLAN and GSM. The usefulness of wireless device depends on the effectiveness of the antenna used for the transmission and reception of information over the wireless media, as it ensures coverage, capacity and quality to the system. The performance characteristics of any communication system for a particular application are profoundly influenced by the type of antenna used. Its design and placement in the communication system also affect the application of the system. Different forms of antennas are employed in different systems. Some systems require directional antennas for transmitting information in a particular direction such as radars, whereas in some other systems, the omnidirectional antennas are used to broadcast the information equally in all directions as in WLAN access points. In some systems antennas for point-to-point communication are required. Thus antennas play an important role in formulating the characteristics of any communication system.

Next Generation wireless system devices needs high data rate for multimedia applications like VoIP, Video Conferencing, VBR (Variable Bit Rate) etc. These high data rate applications require large bandwidth. So the antenna used should have good characteristics over wide range of frequencies.

Thus the antennas should be designed in such a manner that these are able to sustain multi-functionality feature and multiband in homogeneous as well as heterogeneous bands with enhanced bandwidth at each band, in a single compact antenna system. Along with the multifunctional features, the wireless communication devices need to be compact and light weight such as mobiles and other handheld devices. Thus the antennas used in such devices should have low profile, light weight, cost effective, safe for human health, and able to transfer data at high data rate at different communication standards.

In this thesis, methods to develop Microstrip Patch Antennas (MPAs) that exhibit multi-frequency and wideband performance for different homogeneous and heterogeneous wireless applications like WLAN, UNII bands, WiMAX, LTE, aeronautical radionavigation and radiolocation standards are investigated.

In this research work different techniques have been used to design various multifrequency antennas with a goal of getting perfectly matched antenna with appreciable value of return loss, wide impedance bandwidth, increased gain, and reasonable antenna size. First two antenna designs are presented to cover various homogeneous bands of WLAN standard. In the first design, the use of multiple rings in the main patch is dictated along with the formation of DGS (Defected Ground Structure) in the CPW ground plane to obtain multibanding at 2.4 GHz WLAN band, lower/ middle UNII bands at 5.2/ 5.3 GHz. The second design presents an innovative antenna design in which a UWB antenna is experimented with EBG filter structure implemented at the input side, that is, on the microstripline to create a stopband from 5.9 GHz to 11.3 GHz and enabling its use in homogeneous WLAN bands.

The other two antenna designs are aimed at making multifrequency antennas for heterogeneous networks which are based on different topologies. The modification in the patch by means of slotting to form E-slot in the radiating patch and extending the Co-Planar waveguide (CPW) feed all around the patch is found effective in producing additional resonances beside the fundamental resonating frequency. The modifications in the patch cause the current distribution to change accordingly, generating multiband operation with wideband characteristics for heterogeneous networks. The design is able to cover several communication bands at LTE (3.4 to 3.6 GHz) and WiMAX (3.4– 3.694 GHz), aeronautical radionavigation radiolocation (2.7–2.9 GHz), radiolocation radionavigation (2.9–3.1 GHz), radiolocation earth exploration-satellite (active) mobile (3.1–3.3 GHz), radiolocation amateur mobile (3.3–3.41 GHz), mobile (3.41–3.6 GHz) standards. In the fourth design, rectangular rings along with parasitic strip and meandering are incorporated in a rectangular patch to obtain multiband operation for WLAN (2.4/5.2/5.8 GHz) and WiMAX (2.3/2.5/5.5 GHz) bands with enhanced impedance bandwidth in WLAN (from 2.26 GHz to 3.03 GHz) and WiMAX (from 4.48–6.85 GHz) bands.

On the whole, the antenna designs presented in this thesis, display multiband and wideband behavior. The goal of achieving seamlessly matched antenna with considerable reflection coefficient, desired radiation patterns and increased peak gain is accomplished. The simulation results are obtained on CST MWS V.10 and V.14, and IE3D software to judge their performance. On attaining the desired results the antenna structures are fabricated using photolithographic and wet etching method and tested practically on Vector Network Analyzer (VNA) and Anechoic Chamber, available in Microwave and Antenna Laboratory of Thapar Institute of Engg. & Tech., which validates the simulated results of the designed antennas.

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Acronyms and Abbreviations

1-D	One Dimensional
2D	Two Dimensional
2G	Second-generation
3D	Three Dimensional
3G	Third Generation
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
AMC	Artificial magnetic conducting
AP	Access Point
AR	Axial-ratio
AUT	Antenna Under Test
Auto- CAD	Autodesk Computer Aided Drafting
BW	Bandwidth
C2C	Car to Car
CM	Cavity model
CNT	Carbon nanotube
CP	Circularly polarized
CPW	Co Planar Waveguide
CSRR	Complementary Split Ring Resonator
CSRR	Complementary Split Ring Resonator
CST V10.0	Computer Simulation Technology Version 2010.
dB	Decibel
dBi	decibels relative to isotropic
DBS	Direct Broadcast Service
DCS	Digital Cellular Service
DGS	Defected Ground Structure
DSL	Digital subscriber loop
DVB-H	Digital Video Broadcasting - Handheld
EBG	Electromagnetic Band Gap

ECED	Electronics and Communication Engineering
EDGE	Enhanced Data for GSM Evolution
EM	Electromagnetic
EMI/EMC	Electromagnetic compatibility / Electromagnetic interference
FCC	Federal Communications Commission
FDM	Frequency Division Multiplexing
FIT Technique	Finite Integration Technique
FM	Frequency modulation
FPQHA	Folded printed quadrifilar helical antenna
FR4	Flame Retardant
FW	Full Wave
GHz	Giga hertz
GPS	Global Positioning System
GSM	Global System for Mobile Communication
HF	High frequency
HFSS	High Frequency Structure Simulator
HIPERLAN	High Performance Radio LAN
HIS	High Impedance Surface
HPBW	Half power beam width
ICs	Integrated Circuits
IDCLLRs	Inter-digital capacitance loaded loop resonators
IE3D	Integral Equation 3 Dimension
IEEE	Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications
IP	Internet Protocol
ISM	Industrial Scientific and Medical
ISP	Internet Service Provider
ITU	International Telecommunication Union
KHz	Kilo Hertz
LTE	Long Term Evolution

Mbps	megabits per second
MBSFN	Multicast-Broadcast Single Frequency Network
MHz	Mega Hertz
MIMO	Multiple-Input Multiple-Output Antennas
MMIC	Microwave and Millimeter-Wave Integrated Circuit
MMMC	Micro-metal mesh conductive
MoM	Method of Moments
MP3	MPEG-1 or MPEG-2 Audio Layer III
MPA	Microstrip Patch Antenna
MSA	Microstrip Patch Antenna
MWS	Microwave Studio
NFC	Near-field communication
PBA	Perfect Boundary Approximation
PBG	Photonic Band Gap
PBG	Photonic Band Gap
PC	Personal Computer
PC	Personal Computer
PCB	Printed Circuit Board
PCB	Printed Circuit Board
PCS	Personal Communications Service
PEC	Perfect Electric Conductor
PIFA	Planar Inverted-F Antenna
PIN	p-type semiconductor intrinsic n-type semiconductor
PSO	Particle Swarm Optimization
RF	Radio Frequency
RFID	Radio Frequency identification
RL	Return Loss
S11 parameter	Scattering parameter
SAR	Specific absorption rate
SDM	Space Division Multiplexing
SMA	Sub Miniature version A

TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TEM	Transverse Electric Magnetic
TLM	Transmission line model
TM	Transverse Magnetic
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunication Systems
UNII	Unlicensed National Information Infrastructure
UWB	Ultra Wide Band
v/s	versus
VWSR	Voltage Standing Wave Ratio GHz Giga-Hertz
W-CDMA	Wideband Code Division Multiple Access
WiFi	Wireless Fidelity
WiMAX	Wireless Interoperability for Microwave Access
WLAN	Wireless Local Area Networks
WMAN	Wireless Metropolitan Area Network
WPAN	Wireless Personal Area Network
WRAN	Wireless Regional Area Network
WWAN	Wireless Wide Area Network

CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

Late 20th and 21st century is known as ‘information age’ due to the huge amount of information accessible to our generation. From verbal and written forms of communication, we have progressed to wired and wireless communication. But the future trend is to shift towards all wireless connectivity through IP based mobile radio networks [1]. In the history of wireless communication, this is considered as the fastest growth period due to technological improvements in wireless systems, services and standards, which permit its widespread deployment. The Bell Laboratories empowered wireless communications by introducing the cellular concept, in the year 1960 and 1970’s end, enabling its extensive use globally [1]. The advancements in cellular radio and wireless communication standards at microwave frequencies have led to the development of highly miniaturized and robust hardware design. The significant modifications in the hardware design signal handling, network access methods and link setup capacities have marked the progress of mobile radios and personal communication systems. The electromagnetic spectrum is used for different forms of communication. The regulatory authority of radio spectrum allocate different frequencies to existing standards or services and add new services for federal and non-federal communications [1, 2].

Antenna has been one of the critical components used in every electric or electronic communication device. It acts as a radiator of electromagnetic waves in a transmitting system or receiver of electromagnetic waves in a receiving system. However small and efficient communication system we may design, its efficiency is limited by the capability of the antenna at the transmitting or receiving side. Antennas can be broadly classified as wire antennas, microstrip antennas, aperture antennas, array antennas, lens antennas and reflector antennas [3]. Today’s advanced communication devices draw the need for development of antennas with low cost, low profile, multiband and wideband functionalities. It is critical for mobile devices to minimize the overall volume, to meet the severe physical space constraints, and to save the cost

[4, 5]. As the wireless devices have undergone a major reduction in their size, so the antennas used for them should also be small enough to get incorporated in the device. These design requirements are all the more intensified by growing demand for better efficiency, enhanced bandwidth, and multi frequency coverage. In the quest for low cost, small volume and multiband operations, the design of multiband antennas has acquired much attention in academic and industrial field. A multiband antenna can simultaneously operate at different frequency bands, and reduces the need to employ different number of antennas and also avoids the use of bandpass filters required in a multiband wireless system [4,5].

Microstrip antennas are compact and low profile antennas used at microwave frequencies, which are compliant with the planar as well as non-planar surfaces. They are cost effective and can be fabricated with the help of modernized printed-circuit technology [4]. In wireless systems with low power transmission, solid state devices are used whereas for high power transmission, gyrotron is used [5]. In the present work multi-banding and wide banding of microstrip antennas for wireless communication systems has been taken as topic of research. The motivation for considering the proposed research area is presented next.

1.2 MOTIVATION FOR RESEARCH

Today's mobile terminals are now required to handle multi-standard services such as voice, data, video, digital multimedia, global roaming and need to operate in more than one standards. Some of these standards are (GSM850/900/1800/1900), Bluetooth, FM radio and LTE, W-CDMA and WLAN/WiMAX, Digital TV (DVB-H), Global Positioning System (GPS), WRAN [6-12][13]. This requirement has led to the development of Dual-band and Tri-band phones, featuring dual band and triple band antennas. Various cellular and non-cellular wireless standards used for wireless communication are summarized below:

1.2.1 GSM (Global System for Mobile Communications)

In the first-generation systems, GSM networks operated in 400 and 450 MHz frequency bands. Then it got segregated into two different frequency ranges – one for 2G GSM system functional in the 900 MHz or 1800 MHz bands and other for UMTS frequency bands which formed 3G system. In places, where these bands were already assigned to different operations, like Canada and USA, the 850 MHz and 1900 MHz bands were used [6]. In Europe, they mostly worked over 2100 MHz frequency band. In GSM, whatever frequency band of

operation is selected by the operator, it is shared by individual phones on the basis of timeslots in which eight full-rate voice channels are allowed for each radio frequency. These eight time slots form a TDMA frame. The data rate for all eight channels is 270.833 kbps, and the duration of the frame is 4.615 ms. The power transmitted by the phone is restricted to a maximum of 2 watts in GSM 850/900 and 1 watt in GSM 1800/1900 [6].

1.2.2 UMTS (Universal Mobile Telecommunication Systems)

UMTS (Universal Mobile Telecommunications System) is a third generation (3G) mobile broadband cellular technology for networks based on the GSM standard. It is packet-based transmission of digitized voice, text, video and multimedia at data rates up to 2 megabits per second (Mbps). UMTS is an element of the ITU standard IMT-2000, developed by 3GPP (3rd Generation Partnership Project), which relates to CDMA 2000. UMTS provides larger bandwidth and better spectral efficiency to mobile users by using WCDMA (wideband code division multiple access) technology. UMTS uses a bandwidth of 5 MHz, which means it can accommodate a large number of users at the same time [7].

1.2.3 IMT (International Mobile Telecommunications)

It defines the transition from the existing 2G systems to 3G competent systems using the multiband/ multi-mode mobile equipment. Mobile radio technologies are providing cost-effective method to make telecom services accessible to underserved areas in evolving countries using radio spectrum below 1 GHz and make the mobile usage globally popular. In advanced countries, which are already nearing fullness in mobile usage, they are exploring spectrum above 2 GHz to satisfy “broadband” services using enhanced IMT-2000 (3G) and IMT-Advanced (4G) [8].

1.2.4 LTE (Long Term Evolution)

It is basically an up gradation of the 3G UMTS to 4G mobile technology. It is basically a simplification of the architectural transition from the present circuit and packet switched UMTS to an all-IP based architecture. It can support data rates up to 299.6 Mbps in downlink and 75.4 Mbps in uplink. It can support different services up to 20 MHz bandwidth with better mobility depending on the frequency band. It has greater spectrum flexibility and each 5 MHz cell can support minimum 200 active customers. Due to simple architecture, and MBSFN

(Multicast-Broadcast Single Frequency Network) feature, it can provide services like Mobile TV as in case of TV broadcast using DVB-H. It is capable of interoperating with the existing standards like UMTS, GSM/EDGE and CDMA2000. The different frequency bands planned for use with LTE standard are 700 and 1700 MHz in North America, 1800 and 2600 MHz in Asia and 800, 1800, 2600 MHz in Europe and 1800 MHz in Australia [8].

1.2.5 WLAN (Wireless Local Area Network)

IEEE (Institutes of Electrical and Electronic Engineers) developed a series of standards for WPAN, WLAN, WMAN and WWAN referred to as 'IEEE 802.x' standards. 802.11 is the standard for wireless LAN operating at ISM (Industrial Scientific and Medical) frequency bands viz. 2.4/ 5.2/ 5.8 GHz. WLAN standard provides high-speed data transfer rate of 11 Mbps (approximately) which upsurges the popularity of the system and the progress of multiband antenna. There are three different wireless standards like 802.11a, 802.11b and 802.11g. As 802.11b and 802.11g are operating at 2.4 GHz frequency band and 802.11a uses 5 GHz frequency band so multi band antenna is necessary for WLAN applications. The popularity of WLAN has increased due to high-speed transfer rate, which has increased the need of development of broadband and multiband microstrip antennas [9].

1.2.6 WiMAX (Wireless Interoperability for Microwave Access)

IEEE developed 802.16 standards to encourage interoperability and conformity of the standard so named it WiMAX. It is also known as Broadband Wireless Access technology as it enables the provision of last mile wireless broadband access in place of cable and DSL. WiMAX operates in 2.5/ 3.5/ 5.5 GHz bands with data rates upto 70 Mbps over a radius of 5–15 km for mobile station and 50 km for fixed station. IEEE 802.16-2004 has no support for mobility, therefore known as "fixed WiMAX". IEEE introduced 802.16e standard with mobility support referred to as "mobile WiMAX". WiMAX is the future-generation of wireless systems which provides high-speed internet access to the variety of devices like smart phones, laptops, and electronic gadgets. Mobile WiMAX devices typically require omni-directional antenna. [11].

1.2.7 UWB (Ultra Wide Band)

As the name suggests, this technology provides ultra-wide bandwidth ranging from 3.6 to 10 GHz. It is a low cost, low power technology similar to Bluetooth as it provides access to

short distance communication over the range of approximately 10 meters. But it has very high data rate 100 times greater than provided by Bluetooth. Although it is capable of sharing the band with other communication standards but interference might degrade its performance. Hence interference rejection techniques are explored from the literature and work related to band rejection in UWB is presented in the research work [12]

A summary of different wireless standards, along with their operating frequency bands and minimum bandwidth required for its operation over that specific frequency band is specified in table 1.1.

Table 1.1 Wireless Standards and their Frequency Bands [6-13].

Wireless Applications	Frequency Band (MHz)	Bandwidth (MHz)
GSM 900	890 - 960 MHz	70
DCS 1800	1710 -1805 MHz	95
PCS 1900	1850 -1990 MHz	140
UMTS 2000	1920-2170 MHz	250
IMT	2300-2400 MHz	100
	2700-2900 MHz	200
	3400-4200 MHz	800
	4400-4900 MHz	500
Bluetooth	2400-2500 MHz	100
WLAN	2400-2484 MHz	84
	5150-5350 MHz	200
	5725-5825 MHz	100
UNII-1	5150 - 5250 MHz	100
UNII-2	5250 - 5350 MHz	100
WiMAX	2500-2690 MHz	190
	3400-3690 MHz	290
	5250-5850 MHz	600

GPS	1227 -1575 MHz,	348
	1565-1585 MHz	20
RFID	865-868 MHz	03
	2.446-2.454 GHz	08
DVB-H	470-702 MHz	232

In coming generations, the terminals will have an integrated antenna to provide indoor portability to the devices. Also, a web access through a Wireless Local Area Network (WLAN) could provide assured on-demand services. All these services require antenna to operate in different wireless bands. Therefore, modern communication devices call for the use of a single antenna which can cover different wireless frequency bands at the same time. The antennas are no longer an external extension to the system, but are embedded extensively in the mobile or portable devices like mobile phones, laptops, video game consoles, personal computers and digital audio players. Thus antennas are required to deliver a variety of services like voice, video, data, internet and multimedia contents [1-4]. Therefore, bandwidth enhancement of the antenna needs to be addressed.

Another challenge in front of antenna designer is the size of portable and hand held devices, that is drastically shrinking with diversified domain of services and features to be provided by them. Physically and electrically small antennas are required for multiband and diversity antennas to operate within a very limited space in the devices, [3-5]. To maintain the conformability with the advanced multifunctional portable devices, with wireless connectivity to different standards, antenna used should also be capable of efficient transmission and reception with desirable features such as simple fabrication, multiband behavior with high-efficiency, low profile, simple structure, low cost, and ease of integration with RF front end [3-5].

All these developments have put many technical challenges for wireless system designer to design a wireless device which should be small in size, compact, lightweight with low power capability, must incorporate multiband and multiple mode of operation to support the different applications.

Based on the study of existing literature, there are certain issues which need to be resolved for future wireless antennas.

1.3 PROBLEM STATEMENT

This thesis aims to design and develop multi-frequency antennas versatile enough to cover homogeneous bands of WLAN and heterogeneous bands of different standards like WLAN/ WiMAX/ LTE/ mobile satellite and aviation services. Also, it resolves the issue of interference rejection to discard the unwanted bands in a wideband antenna. It demonstrates the use of several methods like slotting, meandering, use of parasitic strips, Defected Ground Structure (DGS) and Electromagnetic Band Gap (EBG) structures to design different antenna configurations for different applications. Following investigations on multibanding and broadbanding of antenna carried out to solve the identified problem of microstrip antenna for homogenous and heterogeneous bands.

- Investigation of return loss, radiation pattern characteristic for multiband operation in homogeneous bands of a WLAN wireless standard with enhanced bandwidth of patch antennas using (i) multiple rings with parasitic strips, (ii) CPW feeding with DGS in its ground plane and (iii) EBG filter structure by modulating the microstripline and creating circular defects in the ground.
- Investigation of S_{11} parameter, radiation characteristics of heterogeneous structures with bandwidth enhancement of multifrequency microstrip antennas using coplanar waveguide and (i) modified patch shape (ii) use of rings and (iii) use of parasitic strips, meandering in rectangular radiating patch.

1.4 RESEARCH OBJECTIVES:

As discussed above, the main objective of this thesis is to simulate, design, optimize and fabricate and test various multifrequency antennas for homogenous and heterogeneous wireless communication system with enhanced bandwidth. In this thesis work, microstrip line fed and CPW fed multiband antennas have been proposed. This thesis focuses on the design of rectangular geometries, suitable for multifunctional and small antenna for heterogeneous wireless communication systems. Based upon the literature review and identified research gaps, the following objectives were proposed:-

1. Design of new multi frequency antenna for WLAN Standard.
 - Parametric studies on the proposed antenna.
 - Fabrication and testing of the above mentioned proposed antenna.
2. Design of new multi frequency antenna for Heterogeneous wireless standards.

- Parametric studies on the proposed antenna.
 - Implementation of above proposed antenna for Heterogeneous Wireless Standards.
3. Comparison of simulated and measured results for both the design objectives to obtain multi-frequency antennas with enhanced bandwidth.

Extensive study of various techniques has been done to implement the above mentioned objectives and prove the potential efficacy of the proposed multi-frequency wideband Microstrip Patch Antennas (MPAs) at the desired bands for wireless applications.

Two antenna structures are designed to cover objective 1:

- In the first design, an asymmetrically split rectangular ring is incorporated to the single ringed patch and DGS is formed in the CPW ground to achieve dual band at 2.4/ 5.2 GHz WLAN bands.
- In the second design, a modified UWB antenna is presented with modulated microstripline and EBG structure beneath it to reject higher bands and allow its extensive use in 2.4/ 5.2/ 5.75 GHz WLAN bands

Two antennas are implemented for second objective:

- A rectangular patch antenna with modified CPW feed and rotated 'E' slot is designed and simulated to cover heterogeneous bands at 1.5/ 3.4 for Mobile satellite/ LTE and WiMAX applications.
- A double ring microstrip antenna with parasitic strip and meandering is designed and simulated to cover 2.4/ 5.2/ 5.8 GHz WLAN bands and 2.3/ 2.5/ 5.5 GHz WiMAX bands.

The antennas are then fabricated and tested to practically verify the simulated and measured results.

1.5 THEORY OF MICROSTRIP RADIATORS

1.5.1 Background

The first perception of microstrip antenna was considered long back in 1950's. Englemann was the first person who anticipated the origination of the microstrip antennas, in 1952 [14]. The concept was further promoted by Deschamps [15-16]. In the year 1955, Deschamps along with Gluton and Bassinot [15-17] formed a simple radiator, which could be used in the UHF region. In 1960's, Collings experimented on microstrip radiators with different feeds, and also studied the radiations from the antenna [18]. In 1970's, the research on antennas became progressive

when new shapes of the patch, new materials for substrate were made available with low loss tangent values, improved fabrication techniques. Howell and Munson were the first persons to develop practical models of rectangular and circular shaped MPAs for military purposes [19, 20]. Mathematical modeling was carried out to better understand the fundamentals of microstrip antenna and verify their characteristics [21]. It was followed by extensive research in this field to create antennas with reduced size, better radiation characteristics. Design of ring antennas and tunable antennas for military applications, based on theoretical electromagnetic solution were presented by Lo et al [22]. The Cavity model and full wave method were developed [23, 24] which considered the use of thicker substrates and various shapes of patch. The first international workshop on Printed Circuit Antennas was held in New Mexico, in 1979 [20]. Hall & Wood and Bahl et al. published books on practical implementation of microstrip antennas [26, 27]. The microstrip antennas were initially used for satellite communications and aircraft. In 1980s, thicker substrates, new feeding methods such as proximity feed and aperture coupled feed and antenna arrays with different polarizations were explored to achieve enhanced bandwidth of microstrip patch antenna [28- 31]. In 1990s, advancement in the signal processors, simulation tools and rapid growth of wireless communications using mobiles and small handheld devices necessitated the developments of compact and light weight microstrip antennas [32]. Since then, extensive research is being carried out to achieve small sized MPAs with improved design parameters such as bandwidth, gain, radiation efficiency, polarization properties and array design by the use of various algorithms such as Particle swarm optimization, Genetic algorithm etc. [29, 33, 34]. Due to its numerous advantages and diversified application areas, MPAs has been established as a discrete topic of research in academia, industry and electronic system design.

1.5.2 Microstrip Patch Antenna Configurations

The Figure 1.1 illustrates the basic configuration of microstrip patch antenna which consists of a radiating metallic patch mounted on one side of the dielectric substrate and the ground plane on the other side. The microstrip feed connects the edge of the patch to the edge of the substrate where it is joined to the waveguide port for signal excitation.

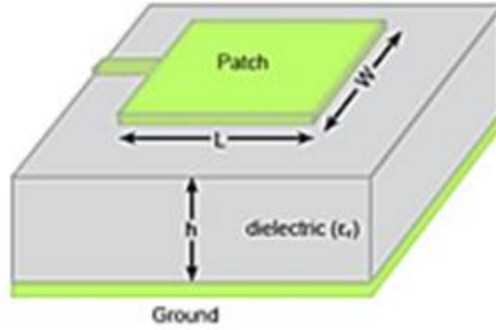


Figure 1.1 Geometry of Microstrip Patch Antenna [2]

As shown in Figure 1.2., the radiating patch, made up of copper or gold, can be of any shape such as rectangle, circle, triangle or any arbitrary shape, the most common being rectangular or circular due to their easy analysis. The length, width and thickness of the radiating patch determine the frequency at which the antenna resonates i.e. decide the resonant characteristics of the antenna. [2, 35].

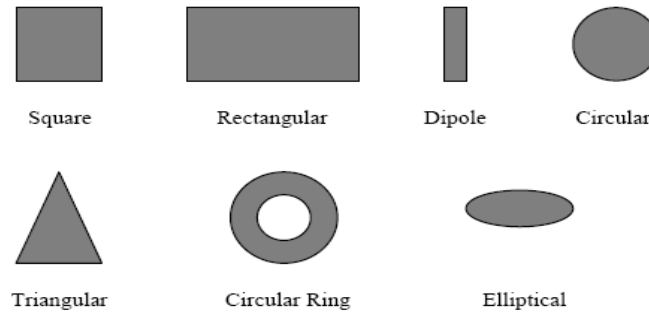


Figure 1.2 Various shapes of microstrip patch elements [35]

Various substrates with different dielectric constant ($2.2 < \epsilon_r < 10$) and loss tangent values are available in tube or sheet form. The thickness of substrate and the material used are also important in antenna design [2, 36]. Generally, low dielectric constant values are preferred but to design microstrip antenna with small size, substrate with higher dielectric constant is used. But it leads to lower bandwidth, gain and power handling capability [37]. Therefore, a tradeoff has to be made among various performance parameters to attain the optimum performance of the antenna for a specific application. Bandwidth enhancement of microstrip antennas is the major field of research which has been partially achieved by the researchers [38, 39]. Microstrip antennas are analyzed for their performance using various analysis techniques which are discussed later [40-43].

1.5.2 Advantages and Disadvantages of Microstrip Patch Antennas

Advantages of MPAs:

The microstrip antennas have gained much popularity nowadays, and surpassed the conventional microwave antennas due to the numerous advantages they offer [2, 32, 44]. Some of the main advantages are listed below:

- Compact, low profile, low power consumption.
- Conformable to non-planar and planar surfaces.
- Cost effective, as mass production is carried out due to PCB technology
- Designer flexibility which allows components to be added or removed from the PCB (Printed Circuit Board) and generate various patterns depending upon the shape of the radiating patch.
- Capable of multifrequency operation
- Capable of linear as well as circular polarization.
- Simple fabrication process
- Feed lines and the matching networks could be fabricated on the same plane as the patch.
- Compatible with MMICs
- Good radiation mechanism

Disadvantages of MPAs:

Microstrip patch antennas have some drawbacks as compared to conventional antennas, few of which are mentioned below [2, 44]:

- Low bandwidth, gain and efficiency
- Reduced power handling capability.
- High cross polarization with increase in frequency.
- Spurious radiations in the feed structure.
- For high performance antenna arrays, structures become complicated.
- Polarization purity is difficult to achieve.
- End-fire radiation which limits the performance in desired direction.
- Excitation of surface waves.

1.5.4 Applications of Microstrip Patch Antennas

Printed Microstrip patch antennas specifically work in the microwave region of frequencies in the electromagnetic spectrum [28]. Usually, the patch antennas find their applications in the frequency range of 1 GHz to 100 GHz [29], in several arenas such as aircrafts, missiles, rockets, in military systems, satellites and biomedical usage. These antennas are used in almost every field may it be communication or military or medical due to their low profile, low cost, simple fabrication and many advantages specified above [38] [45-46]. Some important application fields of MPAs are:

- Mobile and wireless communications.
- Military and Radars communications.
- Satellite communication such as Global Positioning Systems (GPS)/ Direct broadcast services (DBS)/ Remote sensing and environmental instrumentation.
- Radio Frequency Identification (RFID).
- Radio Altimeters.
- Biomedical applications.
- Telemetry/ Smart Weapon Systems/ Missiles.
- Intruder alarms/ Control and command systems.
- Feed elements in complex integrated antennas.
- Rectenna.

The operational characteristics of MPA depend on the feeding method also. The feeding methods commonly used in MPAs are discussed next.

1.5.5 Feeding Techniques of Microstrip Patch Antennas

There are several methods available to impart electromagnetic energy to the radiating patch mounted on the dielectric substrate. These techniques may be classified as contacting and non-contacting feeding techniques.

1.5.5.1 Contacting scheme:

It is one of the direct feeding scheme in which the RF energy is directly delivered to the radiating patch element through microstrip line. The following feeding methods fall in this category:

- Microstrip line feed
- Coaxial probe feed
- Coplanar waveguide feed

(a) Microstrip line feed

It is a signal strip of width much smaller than that of the patch. It is formed on the same side of the substrate as the microstrip patch to create a planar structure. The patch is connected directly to a conducting strip as shown in Figure 1.3. The width of feeding strip could be adjusted to provide proper impedance matching between the stripline and the patch. It could be radiating edge type, a gap space type or an inset feed. This feeding scheme is quite easy to fabricate and simple in modeling but it can cause spurious radiation. Hence, it is used in applications where the performance requirements are not stringent and the feed must lie in the same plane as that of the patch [2, 32, 38] [47-55].

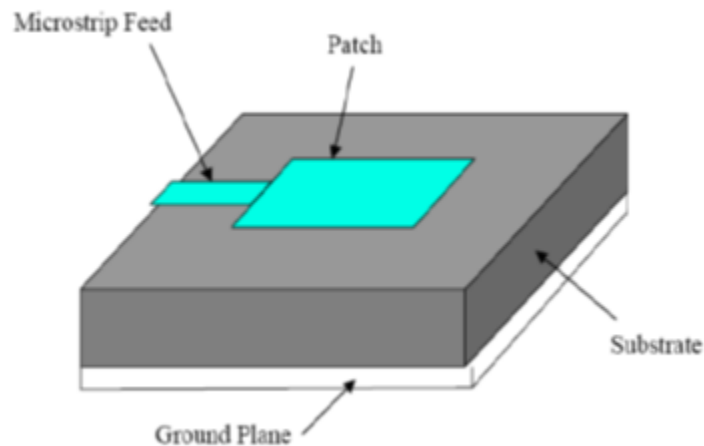


Figure 1.3 Microstripline feed [27]

(b) Coaxial feed

In this, the inner conductor of the coaxial feed is attached to the radiator patch whereas the outer conductor is connected to the ground plane as shown in Figure 1.4. It is easy to construct and match as it could be located at any suitable position inside the patch to cause proper impedance matching. It also has less spurious radiations but it offers small bandwidth and is somewhat difficult to model [2, 32, 38] [47-55].

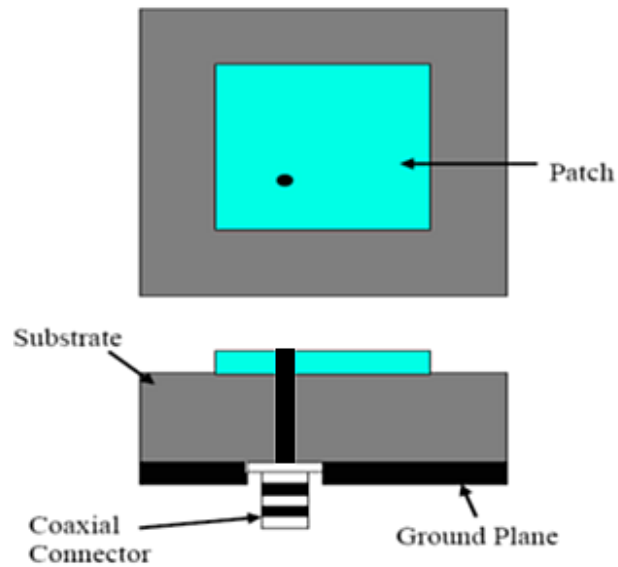


Figure 1.4 Coaxial feed [27]

(c) Coplanar waveguide (CPW) feed

CPW feed is a unilateral structure which consists of the radiating patch, the signal strip and the ground plane all on one side of the substrate, as shown in Figure 1.5. It comprises of a central conducting signal strip and two equal semi-infinite ground planes on either sides of the central signal strip to form CPW assembly. CPW feed provides better impedance matching, lower transmission losses, broader bandwidth, and easy integration with other active devices [2, 32, 38, 48- 55].

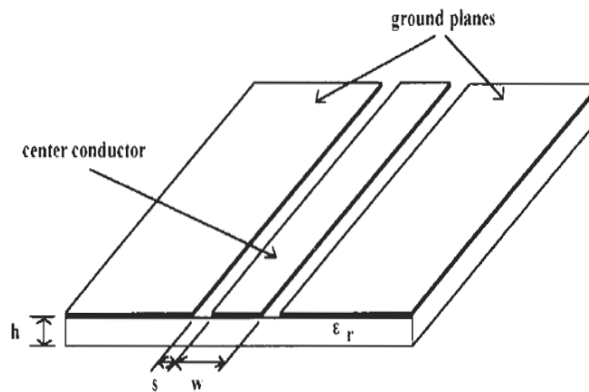


Figure 1.5 Coplanar waveguide feed [38]

The main drawback of CPW feed is its overall substantial physical size. Its complex arrangement limits the antenna's use.

The non-contacting feeding such as proximity coupled feed and aperture coupled feed resolve the issues confronted by the contacting schemes which are discussed and illustrated in the following section.

1.5.5.2 Non-contacting scheme:

In the non-contacting feeding method, the RF power is channelized to the patch through electromagnetic coupling [56, 5]. It includes:

- Aperture coupling feed
- Proximity coupling feed

(a) Aperture coupled microstrip feed

It is a type of non-contacting scheme which consists of two substrates separated by a ground plane. The feed lies on the bottom side of lower substrate and the patch on the top of upper substrate. A slot is cut in the ground plane, usually focused beneath the patch, which couples the feed line to the radiating patch as shown in Figure 1.6. The substrate parameters as well as the dimension and location of feed and the slot are important parameters to enhance coupling [38, 54]. It improves the polarization purity of the structure with low spurious radiations but the structure becomes complicated due to the use of many layers using the substrate, ground and the patch. It therefore increases the overall thickness of the antenna [2, 32, 38] [48-56].

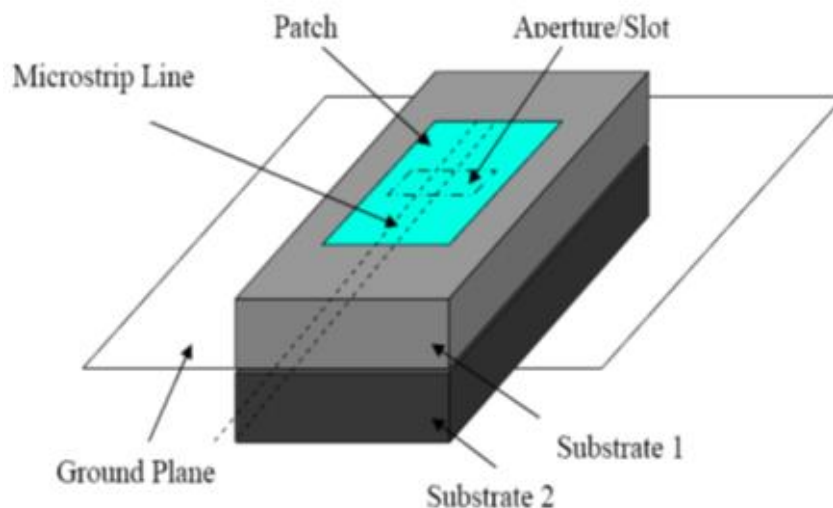


Figure 1.6 Aperture-coupled feed [27]

(b) Proximity (electromagnetic) coupled microstrip feed

In this technique, two different dielectric substrates are used. The radiating patch is mounted on top of the upper substrate and the feed line is placed between the two substrates, as illustrated in Figure 1.7. This feeding method provides wide bandwidth due to increased thickness of the structure and lessens the radiations from the feed [48-55]. But the two dielectric layers should be properly aligned, which makes its construction difficult.

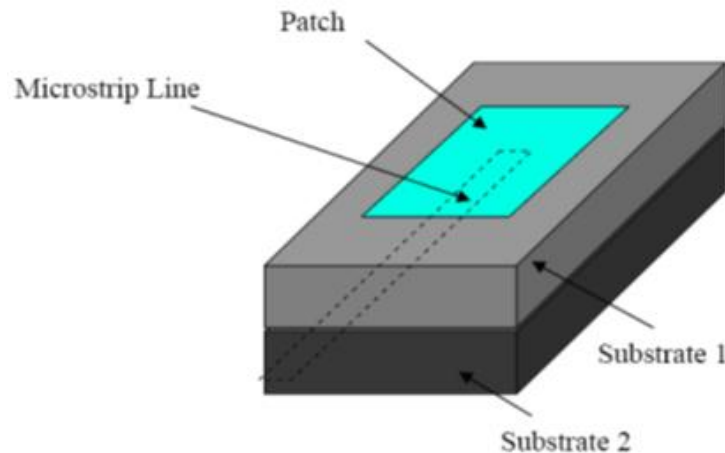


Figure 1.7 Proximity-coupled feed [27]

Table 2.1 tabulates a brief summary for the characteristics of the different types of feed structures for MPAs.

Table 1.2 Comparison of various types of feed structures for Microstrip Patch Antennas [27,38]

Feeding Technique → Characteristic ↓	Microstrip Feeding			Coaxial Feeding	Aperture Coupled Feeding	Proximity Coupled Feeding	Coplanar Waveguide (CPW) Feeding
	Radiating Edge coupled	Gap coupled	Inset cut				
Impedance matching	Poor	Simple	Simple	Simple	Simple	Simple	Simple
Polarization Purity	Decent	Poor	Poor	Poor	Good	Poor	Decent
Bandwidth	≈ 9-12%	≈ 2-5%	≈ 2-5%	≈ 2-5%	≈ 21%	≈ 13%	≈ 3%
Spurious feed	Less	More	More	More	More	More	Less

radiation							
Ease of Fabrication	Simple	Simple	Simple	needs Soldering	needs Alignment	needs Alignment	needs Alignment
Reliability	Better	Better	Better	Poor	Decent	Decent	Decent

1.5.6 Design Parameters of Microstrip Patch Antennas

While designing the antenna, certain performance parameters are fixed which must be fulfilled by the antenna to be functional for a particular application. In this thesis the performance of an antenna is investigated by representing the output of the antenna, in terms of impedance bandwidth, radiation pattern, current distribution, gain, efficiency, Voltage Standing Wave Ratio (VSWR), return loss etc. A few of the design parameters considered while designing antenna are mentioned below [52-55]:

1.5.6.1 Return loss

The return loss is the measure of signal power lost due to reflection from any discontinuity in the transmission line. Due to mismatch between the terminating load and the transmission line the wave gets reflected to form standing wave pattern [55, 57]. Due to this mismatch, the complete power from the source is not transferred to the load and hence there is a loss of the power which is expressed in terms of return loss which is represented in decibels (dB). The Return Loss (RL) is represented as:

$$RL = -20 \log_{10} \Gamma \text{ (dB)}, \quad (1.1)$$

Where,

Γ is the reflection coefficient, which represents the relative magnitude of reflected power to the incident power.

For $\Gamma = 0$, return loss, $RL = \infty$ dB, which represents no reflected power. For $\Gamma = 1$, the return loss, $RL = 0$ dB, which means that all incident power is reflected back to the source. For $\Gamma = 0.00001$, $RL = 100$ dB. Return Loss value of 10 dB is an agreeable value for realistic applications.

1.5.6.2 Voltage Standing Wave Ratio (VSWR)

As specified above, a standing wave pattern is formed in the transmission line when power is reflected back from the load. VSWR is defined as the ratio of the maximum value of voltage to

the minimum voltage level in the standing wave pattern. VSWR value of 1.0 is considered an ideal value which occurs when all incident power reaches the destination with no reflected power. An infinite value of VSWR means that no power is transmitted to load but all the power is reflected back. The VSWR is depicted by [58]

$$S = \frac{1+\Gamma}{1-\Gamma}, \quad (1.2)$$

Although an ideal value of VSWR is 0, but for all practical implementations, the value of VSWR should lie between 1 and 2.

1.5.6.3 Bandwidth

Antenna Bandwidth represents the range of frequencies over which the performance of an antenna does not degrade below a specified standard[54]. It clearly indicates the frequency bands across which the value of VSWR lies within a permissible limit. The bandwidth (BW) of a Microstrip Patch Antenna is given by [59]:

$$BW = \frac{f_H - f_L}{f_o}, \quad (1.3)$$

where,

f_H ; upper frequency

f_L ; lower frequency and

f_o ; resonant frequency of the patch.

1.5.6.4 Radiation pattern

The radiation pattern of an antenna is the graphical representation of the radiation properties of the antenna as a function of space coordinates. In most of the cases, the radiation pattern is determined in the far-field region and is represented as a function of different spatial coordinates which are represented in terms of elevation angle and the azimuth angle. Antenna radiate energy differently in different directions. It is expressed as a ratio of radiated power from the antenna structure per unit solid angle [2, 60].

1.5.6.5 Gain

It represents the ability the antenna to direct the radiated power in a specific or desired direction [2]. It is defined ratio of maximum radiation intensity from the AUT (antenna under test) to the reference antenna fed with the same amount of input power. The gain of an antenna is expressed in dBi.

The directivity indicates the ratio of energy centralized in the favorable direction to the radiation in other directions. The directivity and antenna gain become comparable when antenna efficiency is 1 and the antenna acts as an isotropic radiator. The gain can be represented in terms of directivity and efficiency of antenna as [2, 54]

$$G = e_t D , \quad (1.4)$$

where,

G ; the gain of antenna,

e_t ; total antenna efficiency

D ; the directivity of the antenna.

1.5.6.6 Radiation efficiency and antenna efficiency

The metallic elements of the antenna structure and other losses within the terminal are responsible for losses in antenna. Radiation efficiency is defined as the ratio of total radiated power to the total input power.

The antenna efficiency takes into consideration the losses occurring inside and at the ends of antenna. These losses are reflection losses which occur due to mismatch within the antenna and the transmitter and the other loss is the $I^2 R$ loss which is caused due to the dielectric and conductor. The overall antenna efficiency, e_t is given by [2]:

$$e_t = e_r e_c e_d , \quad (1.5)$$

where,

e_r ; reflection efficiency

e_c ; conduction efficiency

e_d ; dielectric efficiency.

After setting the design parameters, the antenna is simulated and analyzed for its performance using various methods discussed below:

1.5.7 Analysis of Microstrip Patch Antennas

There are several methods which are used to analyze the performance of microstrip antennas in terms of input impedance, its radiation pattern, bandwidth, gain and efficiency of antenna. The common models used for the analysis are:

- Transmission line model (TLM)
- Cavity model (CM)
- Full Wave (FW)

1.5.7.1 Transmission Line model

The transmission-line model is most basic of all the models and provides good understanding of the structure, but is difficult to model and lacks accuracy [52, 55]. In TLM, the microstrip patch antenna is represented by two slots, which are separated by a finite length transmission represented by 'L', as shown in Figure 1.8 (a) [52, 55]. It considers dielectric substrate and the ground plane to be infinite. Since the dimensions of the patch are finite, it causes fringing fields, most of which travel to the substrate and some part to the air, as shown in Figure 1.8 (b).

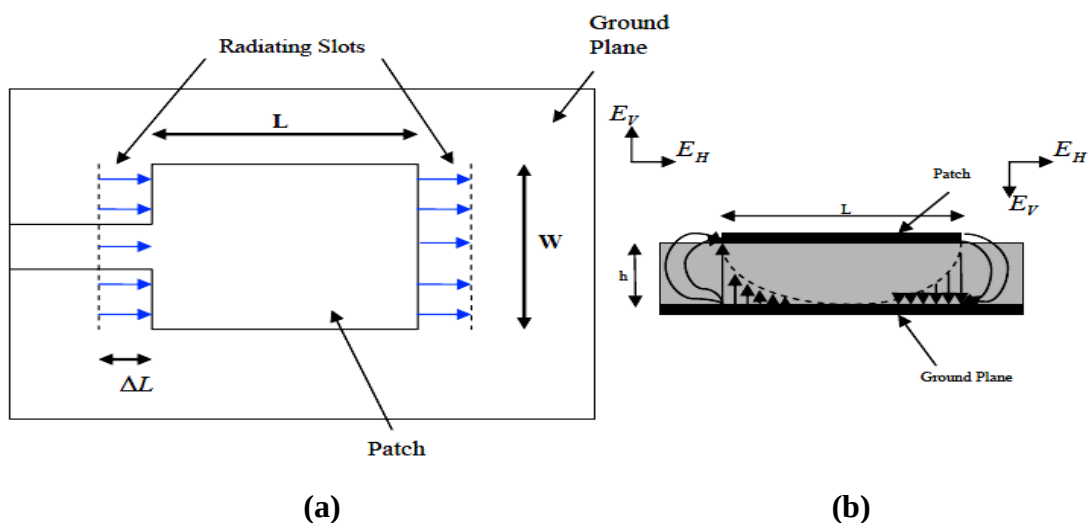


Figure 1.8 Formation of (a) radiating slots, (b) field lines in the microstrip antenna [55]

Hence the microstrip patch forms a non-homogeneous line of two dielectrics, one substrate and the other air. Therefore an effective dielectric constant value, ϵ_{reff} , is calculated

which is somewhat less than the dielectric constant of the substrate, ϵ_r . Generally, $1 < \epsilon_{\text{reff}} < \epsilon_r$. Due to this inhomogeneity, the quasi TEM modes propagate in it. CST MWS software uses transient solver and TLM for antenna analysis.

The value of effective dielectric constant, ϵ_{reff} can be calculated using expression (1.6) given below[2]:

$$\epsilon_{\text{reff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{W} \right]^{-\frac{1}{2}} \quad (1.6)$$

where

ϵ_r ; dielectric constant of substrate

W ; width of the patch

h ; height of the substrate

The microstrip patch antennas are designed to operate at a particular frequency, for a specific application. The dielectric constant and height of the substrate are chosen, followed by the calculation of the patch size formulated by length and width of the rectangular patch at given frequency of resonance. Generally, low loss substrates are considered useful for the antenna design. A higher dielectric constant value of the substrate is good to achieve the size reduction of the patch but it decreases the bandwidth of the antenna. The low cost FR4 is used in this thesis which is a flame resistant compound material made up of glass-reinforced epoxy laminate readily available in the market in sheet form [2]. The equations for finding width and length of rectangular microstrip patch are calculated using TLM as given below:

The width (W) of the patch of microstrip antenna is computed using the following equation [2]:

$$W = \frac{c}{2f_0 \sqrt{\frac{(\epsilon_r + 1)}{2}}} \quad (1.7)$$

where,

f_0 ; frequency of resonance,

ϵ_r ; dielectric constant of the substrate,

c ; speed of light.

The frequency of resonance, f_0 , for TM_{mn} mode is given by [26]:

$$f_0 = \frac{c}{2\sqrt{\epsilon_{\text{reff}}}} \left[\left(\frac{m}{L} \right)^2 + \left(\frac{n}{W} \right)^2 \right]^{\frac{1}{2}}, \quad (1.8)$$

where,

m and n are field modes propagating along L and W respectively.

The effective length of the patch antenna is found out using the following equation [2, 55]:

$$L_{\text{eff}} = \frac{c}{2f_o \sqrt{\epsilon_{\text{reff}}}}. \quad (1.9)$$

The fringing fields also increase the effective length of the patch on both radiating sides. The extension of length of the patch antenna due to fringing effects is found out using the following equation [2, 55]:

$$\Delta L = 0.412h \frac{(\epsilon_{\text{reff}} + 0.3) \left(\frac{W}{h} + 0.264\right)}{(\epsilon_{\text{reff}} - 0.258) \left(\frac{W}{h} + 0.8\right)}. \quad (1.10)$$

The actual length is formulated from the equation below:

$$L = L_{\text{eff}} - 2\Delta L \quad (1.11)$$

Although an infinite ground plane is presumed in the transmission line model, but for practical deliberations a finite value of ground plane is calculated using the equation given below [2,55]:

$$L_g = 6h + L, \quad (1.12)$$

$$W_g = 6h + W, \quad (1.13)$$

where,

h ; height of substrate,

L_g ; length of the ground plane,

W_g ; width of the ground plane.

1.5.7.2 Cavity model

The cavity model provides greater accuracy as compared to TLM, but its representation is more complex. However, it gives decent physical understanding of the microstrip antenna operation. The rectangular patch antenna can be very well considered as a cavity resonator which is formed by the patch on one side and the ground plane on the other both acting as electric walls, whereas the substrate lying in between the two forms magnetic walls on four sides. In

cavity model, the effective length of the patch is more than the calculated value due to fringing fields emerging from the periphery of the patch [53-55].

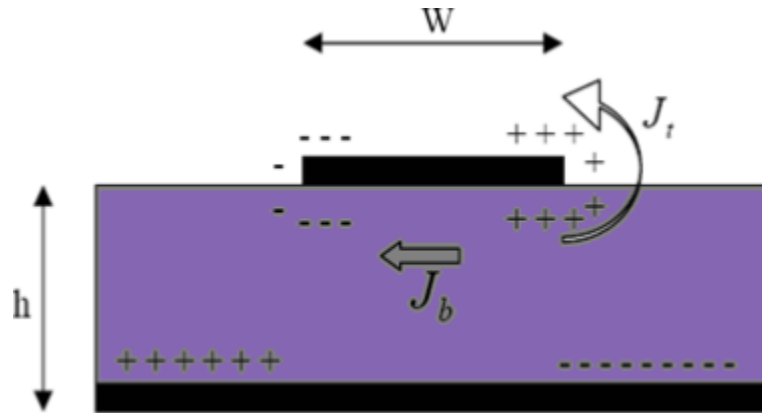


Figure 1.9 Charge distribution on the Microstrip Patch [55]

The operation of the microstrip patch can be well understood from Figure 1.9, which shows the distribution of charges around the lower and upper surface of the patch and also at the bottom of the ground plane on excitation of microstrip antenna by a source. Attractive mechanism and repulsive mechanism, acting on the microstrip patch, are responsible for the creation of different transverse magnetic (TM) field modes. The current flow is caused due to movement of charges at the bottom and the top surfaces of the patch [48, 53, 55] causing current densities, J_b and J_t .

If the cavity walls and the material inside it are considered lossless, then there won't be any radiation. For radiation to occur, which is the pre-requisite for an element to act as antenna, losses are introduced by considering radiation and conduction losses. The effective loss tangent specifies lossiness of the medium [53-55] and is given by:

$$\delta_{\text{eff}} = 1/Q_T \quad (1.14)$$

where Q_T is the total antenna quality factor.

1.5.7.3 Full Wave model

The full wave models are the most accurate ones and can be used for full wave analysis of single or multiple element antenna of any shape. The modeling is complex and difficult to understand but due to high level of accuracy, they are being used to analyze complex structures

such as antenna arrays [55]. It presents the solution to Maxwell's equations which are constricted by proper boundary conditions. It is of three types [61-63]. The MOM Full Wave model is used to provide solutions to the integral equations while the Full wave FEM and FDTD models are centered on differential equations. These equations can be transformed into matrix equations which are solved algebraically [48-55].

1.6 RESEARCH APPROACH

A planned approach is made towards the research work done over the years starting with the thought process, preparation of the proposal, conducting the research, writing the research papers, sharing the research outcomes with others and revising the research papers. The strategy followed to carry out to complete the task of designing various antennas presented in this thesis.

1.6.1 State of the art study

First of all keeping in view the state of the art technology in communication field, various wireless standards, their operating frequency bands and bandwidth required is studied. Then the electromagnetic spectrum is analyzed to find the application of different standards for upcoming wireless communication devices. The different standards are discussed in section 1.2 and their bandwidth requirements are specified in table 1.1.

Microstrip antennas are explored as a possible solution to work at microwave frequencies for portable and hand held devices. All the study material related to the basics of microstrip antennas, its advantages, disadvantages, their performance parameters and their applications at different wireless applications is explored from the books, journals, magazines, internet and thesis written by other people and formed a literature review.

1.6.2 Gap identification and problem formulation

The gaps in the previous research are identified and the problem statement is defined which is specified in detail in section 1.3. The scope of improvement of various parameters of microstrip antenna is studied in section 1.5.6 and the techniques which can create multifrequency antennas with enhanced bandwidth are explored in literature review in chapter 2. The methods which can be used for interference rejection of unwanted bands are also taken up in literature review.

Detailed study of multiple resonant structures employing different techniques is done and the effect of varying structural and dimensional parameters on return loss, radiation pattern and gain is worked out from the literature survey presented in detail in chapter 2.

1.6.3 Antenna design and simulation

For the design and simulation of the microstrip patch antennas with composite RF printed circuits and other electronic constituents at microwave frequencies, simulation tools based on electromagnetic field theory are used. A brief discussion of the simulation tools used in the research work is presented below:

CST MWS V.10 and V.14 have been used in my research work as the simulator software to model the designs of microstrip antennas for different applications [64]. The antenna structures are graphically modeled after setting the frequency of operation, boundary conditions, port assignment. Parametric adjustments are done to obtain an optimal design of antenna. It is then simulated using the transient solver by setting the hexahedral mesh using 20 lines per wavelength and fixing the accuracy level at -40 dB, whereby we can opt for the results which we want to see using the fields monitor option for calculating various electromagnetic quantities like electric and magnetic fields, surface current and power flow across the antenna structure and other farfield results like gain and 3D/2D radiation plots. It offers to export the simulated results to bmp format, ASCII file or touchstone files and saved as screen shot also [64].

Zeland IE3D is a standard development tool based on Method of Moment (MOM) principle, which makes possible the 3D simulation of high frequency components. It facilitates fast and precise analysis of high frequency (HF) planar and multiple layered structures such as antennas, couplers, filters etc. simulator is. The geometry of antenna is constructed in the layout editor which is then simulated to obtain simulation results. Various parameters of the designed antenna are calculated and displayed using post processor module which could be optimized using inbuilt optimizer. It has a user friendly interface and great flexibility available in solver techniques such as Time Domain solver and the Frequency Domain solver which gives a clear understanding of EM behavior of the high frequency designs over wide range of applications [65].

1.6.4 Parametric study of antenna

The comprehensive parametric study is carried out for all the simulated antennas by using the built-in “parameter sweep” tool in the transient solver window in CST MWS V10/ V14. It allows changing one parameter or multiple parameters at a time and seeing their effect on the antenna performance. Different sweep types are available in CST such as linear sweep, logarithmic sweep or sweep applied at arbitrary points. One can choose it according to the design type of the antenna. In this thesis, linear sweep is used in which we can define the lower and upper bounds of the parameter to be varied along with the number of samples for each variation or the step size. The result of each parametric sweep is stored in a table which is available in the navigation tree of CST [66].

1.6.5 Empirical Relations

The design parameters W , L and ϵ_r of the microstrip patch antenna affect the resonance frequency and bandwidth of the antenna by the following relation [2, 26, 35]:

$$f_o = \frac{c}{2\sqrt{\epsilon_{\text{reff}}}} \left[\left(\frac{m}{L} \right)^2 + \left(\frac{n}{W} \right)^2 \right]^{\frac{1}{2}} \quad 1.15$$

$$BW = \frac{16}{3\sqrt{2}} \frac{p}{L\epsilon_r} \frac{1}{\epsilon_r} \frac{h}{\lambda_o} \frac{W}{L} q \quad 1.19$$

Where,

$$\text{Radiation efficeincy} = e_r = \frac{P_r}{P_i} \quad 1.20$$

$$p = 1 - \frac{0.16605}{20} (k_o W)^2 + \frac{0.02283}{560} (k_o W)^4 - 0.009142 (k_o L)^2 \quad 1.21$$

$$q = 1 - \frac{1}{\epsilon_r} + \frac{2}{5\epsilon_r^2} \quad 1.22$$

So by varying various dimensions of the antenna, the bandwidth as well as resonant frequency can be optimized

1.6.6 Antenna Fabrication

After the simulated results are obtained over desired frequency bands with desired performance parameters, the antenna pattern is projected on the FR-4 (Fiber-glass Reinforced epoxy), which is used as substrate material, using the photolithographic and wet etching technique described below:

The simulated microstrip patch antenna configuration is exported as the DXF file. The file is decoded using Auto-CAD software and a print out of this image is taken on a butter paper. This image is used to form a negative mask of the geometry to be produced. This blue print is aligned and taken down on the substrate sheet of specified thickness.

The substrate sheet is properly cleaned using soap solution and acetone solution and then microwaved at 100°C for approximately 10 minutes. A negative photo resist solution is then applied uniformly over the dry surface of the substrate in a dark room with the help of spin controller and dried once again in the microwave oven by exposing the substrate to ultraviolet radiations for 2 minutes.

The substrate is dipped in the developer solution which is then cleaned with water and then soaked in FeCl_3 (hot etching solution) which generates the antenna pattern on the copper plate. Wet etching is done after completing the photolithographic process, and the etched substrate is cleaned and dried out.

The soldering of 50 ohm SMA (Sub Miniature version A) connector is done at the appropriate location on the antenna feed and measurements are taken for the fabricated antenna structure using various instruments which are discussed next.

1.6.7 Antenna Measurements

The various characteristics of microstrip antenna such as impedance bandwidth, return loss, gain and radiation pattern are measured with the help of Vector Network Analyzer (VNA) and anechoic chamber available at Microwave and Antenna Laboratory, ECED in THAPAR INSTITUTE OF ENGG. & TECH., Patiala. The brief description of the measuring equipments and procedures are specified below:

1.6.7.1 Measurements using Vector Network Analyzer (VNA)

VNA is a sophisticated instrument which is used to measure the bandwidth, return loss and VSWR generated by the antenna (Figure 1.10). VNA is based on signal processing algorithm that evaluates the data transmitted and received by the antenna and the corresponding results are measured and displayed on the screen of VNA which can be saved in suitable graphical format. The standard VNA has the ability to operate in time domain and frequency domain. It can provide very accurate measurements of two port network parameters such as S_{11} , S_{12} , S_{21} and S_{22}

[67]. In this research work, ENA series of vector network analyzer of Agilent technologies, VNA E5071C, has been used to test the antennas within a frequency range of 9 KHz to 8.5 GHz.

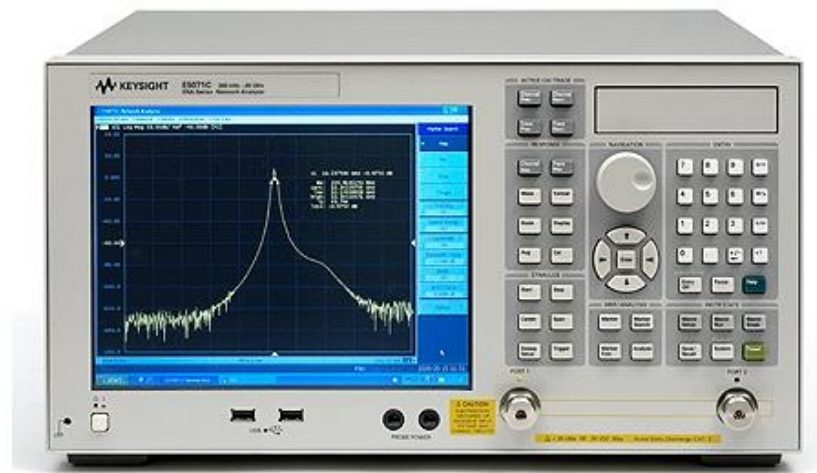


Figure 1.10 Vector Network Analyzer (VNA) [67]

The Antenna Under Test (AUT) is connected to one of the ports of VNA through the connector and the coaxial cable. First of all, VNA is set in S11/S22 mode and the port is calibrated to known standards of short, open and matched termination loads over the desired range of frequencies. The single port calibration technique is employed to portray the different parameters of microstrip antenna like bandwidth, return loss, input impedance and VSWR [67]. The frequency at which the value of return loss is minimum is taken to be the frequency of resonance of the antenna. The bandwidth of the antenna is calculated by identifying the range of frequencies for which the return loss is below- 10 dB.

1.6.7.2 Measurements using anechoic chamber

The anechoic chamber, shown in Figure 1.11, is indoor test equipment, used to measure the radiation pattern of AUT. It consists of two anechoic boxes connected through horn like extensions. The complete length of the chamber is 9.0 meter and tapered anechoic boxes are of 1.2m x 1.2m cross section. Two windows are provided, one at transmitter end and the other at AUT end. The chamber can overcome weather limitations, EMI/EMC disturbances and ground effects and offers a 'quiet zone' to the AUT. To absorb the electromagnetic reflections and provide impedance matching, it has tapered shaped microwave absorbers all around, in the

chamber [68]. The aluminum sheets conceal the roof and the walls to elude the neighboring EM interventions.

It works over a frequency range of 800 MHz to 12 GHz with the size of quiet zone to be 20cm x 20cm x 20cm. The AUT is placed at distance of 7.2 m to be in far field even at 12 GHz from a standard Horn antenna at the transmitter side. The gain of AUT is measured with respect to the standard horn antenna which has 12 dBi calibrated gain value. Then graph is plotted using gain substitution/ transfer technique. The validation of its results is done on Agilent's E5071C vector network analyzer (VNA) operating in the frequency range of 9 KHz to 8.5 GHz [68-69].

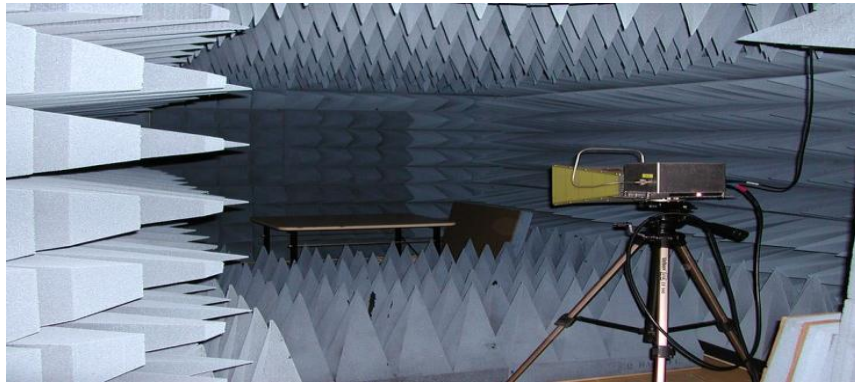


Figure 1.11 Anechoic chamber [68]

A transmitting antenna, a signal generator, a rotating motor and a vector network analyzer are used to measure the radiation pattern. The radiation pattern is measured manually by following a standard procedure. The AUT is kept in the quiet zone of the anechoic chamber and suitably positioned on a rotary table. It is attached to port 1 of the VNA. The horn antenna is used as the transmitting antenna which is attached to the port 2 of VNA.

The VNA is set in S_{21}/S_{12} mode to ascertain the radiation pattern of the AUT. The numbers of samples of frequency are fixed according to the suitability. Then, the 'THRU' calibration is executed for the specified band of frequency and it is then saved in 'CAL' set. This setup procedure is carried out manually to find the measured radiation pattern which is then compared with the simulated results obtained on the CST MWS software [68-69].

1.7 ORGANIZATION OF THE THESIS

The aim of this thesis is to study the different aspects and parameters of microstrip antenna at microwave frequencies, make use of their advantages and work upon the drawbacks to improve their performance. Various techniques have been used to design different antenna

configurations for attaining multi-frequency behavior with wideband response at each resonance band and also to obtain overall size reduction of the antenna. It also takes into consideration the interference rejection capability of antenna to reject unwanted bands. In this thesis, study, design and simulation of different geometries of microstrip patch antennas is done to get multifrequency antennas to cover homogeneous bands of WLAN standard and heterogeneous bands of WLAN, WiMAX and LTE standards. The antennas are then fabricated and tested for their actual performance in the required bands. This thesis consists of seven chapters and their overview is given below:

Chapter 1 gives an introduction about the existing cellular and non-cellular wireless technologies, different services, standards and systems to implement these technologies to make the devices associated as compact and efficient as possible. This chapter also discusses the role of antenna in wireless communication, particularly microstrip antennas for microwave frequency applications. It also explains their basic principle of operation, their advantages and disadvantages, feeding techniques and various antenna parameters and its applications.

Chapter 2 presents the comprehensive literature survey carried out in the area of multiband microstrip antenna and broadband designs. The techniques of designing a modified antenna with band rejection capability from the original wideband antenna using different methods are also presented. It discusses the results obtained for various structures implemented by different authors to get multi-frequency microstrip antenna.

Chapter 3 presents a compact sized, rectangular ring Microstrip Patch Antenna with Co Planar Waveguide (CPW) feed to operate for WLAN bands. It consists of a single ring structure with CPW ground evenly placed on FR4 substrate. The effect of incorporating an asymmetrically split rectangular ring to the single ringed structure and etching DGS in CPW feed is studied in the proposed antenna which can operate in dual band from 2.2 to 2.5GHz and 5.1GHz to 5.35 GHz covering the both WLAN bands at 2.4 and 5.1 GHz standards. The prototype of the proposed antenna is designed and fabricated. The experimental results show good return loss characteristics and stable field pattern over the desired frequency bands.

Chapter 4 In this chapter, an ultra-wideband antenna comprising of a planar circular patch element with microstrip line feed on FR4 substrate generating a bandwidth of 6.8 GHz is taken as reference antenna. To modify the antenna for WLAN (Wireless Local Area Network) applications, a stopband filter, rejecting frequencies higher than 5.9 GHz, is formed by modulating the microstrip line. The holes are etched on ground plane of antenna to form an

Electromagnetic Band Gap (EBG) structure to improve the performance of filter. The final antenna structure resonates from 1.97 to 2.65 GHz and 3.12 to 5.86 GHz, suitable for WLAN (2.40-2.484/ 5.150-5.350/ 5.725-5.825 GHz) bands. The passband and stopband characteristics are plotted to verify the results. Return loss is plotted, which is well beyond -10dB for operating bands and nearly omni-directional field pattern is obtained over the passband.

Chapter 5 presents a rectangular microstrip patch element with modified Co-Planar waveguide (CPW) feed and rotated E-slot in the radiating patch to obtain multiband operation with wideband characteristics for heterogeneous networks. Good impedance matching is obtained over the three resonant modes, which cover several applications for Mobile satellite (1.5 to 1.7 GHz), aeronautical radionavigation radiolocation (2.7–2.9 GHz), radiolocation radionavigation (2.9–3.1 GHz), radiolocation earth exploration-satellite (active) mobile (3.1–3.3 GHz), radiolocation amateur mobile (3.3–3.41 GHz), mobile (3.41–3.6 GHz), LTE (3.4 to 3.6 GHz) and WiMAX (3.4– 3.694 GHz) standards. Effect of modifications in CPW ground slot length and width of E slot is studied. The simulated results are verified by comparing them with the measured ones.

Chapter 6 In this chapter, a novel design of compact, CPW fed, planar monopole antenna with enhanced bandwidth and multiband characteristics has been proposed for WLAN/WiMAX applications. Two rectangular rings are incorporated in a rectangular patch to obtain multiband operation for WLAN (2.4/5.2/5.8 GHz) and WiMAX (2.3/2.5/5.5 GHz) bands. A parasitic strip and meandering along with double ringed structure are used to achieve enhanced impedance bandwidth in WLAN (from 2.26 GHz to 3.03 GHz) and WiMAX (from 4.48–6.85 GHz) bands. The parametric analysis is carried out to study the effect of varying dimensions on antenna performance. The proposed antenna is optimized and prototype is designed and fabricated. Simulated and measured radiation patterns in elevation and azimuthal planes are also observed.

Chapter 7 Finally, this chapter presents the summary of conclusions drawn from research work reported in this thesis. The ideas for future work to obtain enhanced performance multifunctional microstrip antenna are also suggested.

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

There has been an increasing demand for multi-functional and compact wireless device with the introduction of new wireless services and standards [70]. Novel techniques for designing these devices have to be developed to meet various criteria like small size, light weight, low profile, low cost and conformability to different surfaces. To accomplish the performance enhancement of wireless mobile component these criteria become design challenges for a designer. Antenna is one of these wireless device that need to be designed and matched with these new challenges [71-75].

As discussed in chapter 1, MPAs which are planar patch antennas working in the microwave frequency range are considered as one of the best choice for such small devices. MPAs possess small size, low profile, light weight, and bulk production possibility. However, all these parameters still need improvement along with creation of multiband and multimode MPAs. In literature numerous techniques of designing miniaturized MPA with multimode and multiband functionality have been implemented [76-77].

With multi frequency features being incorporated in new wireless systems and standards the need for multibanding of MPAs has become one of the major research issue. Designing antennas that are conformable, efficient, and compact with low profile and cost, multiband and with wideband support for various bands, has become new challenging task for antenna engineers. Multifrequency MPAs with wide bandwidth need to be developed in order to fulfill the bandwidth requirements of different standards [78-84].

The demand of broadband wireless systems has also increased with the introduction of new compact and multi-functional wireless systems [85-89]. The antenna size is inversely proportional to the square of frequency. Also, while using a wideband antenna like UWB (Ultra Wide Band) interference rejection capability of antenna need to be taken care of to avoid interference from the nearby resonating bands.

In this chapter, different techniques used to design multiband and broadband antennas in different wireless standards with interference rejection capability is presented in the literature review. In general, the various issues and theoretical concept related to design of multifrequency antennas have been presented briefly. For the illustration purpose some design examples, published in literature are discussed. The major sources referred for this review are books, papers published in journals and conferences, the internet sources, IEEE Standards and other dissertations.

2.2 LITERATURE REVIEW

New and innovative antenna designs with multiband and wideband geometry have emerged recently by the efforts of several researchers around the world. This section presents an exhaustive survey of various methods adopted by researchers for designing compact, multiband planar antennas with sufficient bandwidth. The review is divided into three parts. First, the survey on multiband antenna design for homogenous networks is presented. Then the survey on multiband antenna design for heterogeneous networks is discussed and finally the review concludes with interference rejections techniques and filter design in a wideband antenna.

2.3 LITERATURE SURVEY ON VARIOUS MULTIBAND ANTENNA DESIGNS

There are numerous papers published on the design and testing of the multiband antenna. The antenna designed might cover different operating frequencies for the same standard i.e. homogeneous multibanding for example 2.45/ 5.2/ 5.8 GHz bands for WLAN. It might be heterogeneous multibanding whereby an antenna covers different standards of different network like WLAN/ WiMAX/ LTE etc. The designer has to keep in mind the constraint on the device size in which the antenna has to be embedded. This section reports different multibanding techniques so far employed by the antenna designers across the world.

2.3.1 Multifrequency Microstrip Antenna Designs for homogeneous bands of WLAN Standard

In [90], the authors have proposed a rectangular monopole antenna with CPW fed used for WLAN bands. It has a cross shaped slot implanted in it which affects only the lower frequency band due to increasing in the path length of the surface current. The proposed

antenna's prototype is fabricated and tested. The simulated S11 parameter result show that the impedance bandwidth at the lower frequency and upper frequency band is 13.7% and 28.3% respectively. The only drawback of the design is its large size.

In [91], authors presented a dualband antenna design for WLAN standard operating at 2.4/5 GHz bands. The design is in the shape of a horse-shoe with multiple L-shaped slots embedded in it. It creates two resonating bands: lower frequency band from 2.38 GHz to 2.51 GHz and upper frequency band from 5.1 GHz to 5.88 GHz. The proposed antenna shows a small overall gain value of 2 dBi approximately.

In [92], the authors designed a microstrip antenna using HFSS (High Frequency Structure Simulator) software for WLAN standards including IEEE 802.11, Bluetooth and 2.4 GHz ISM bands. An H-shaped defect is created in the ground plane forming Defected Ground Structure. The dimensions of the slot are optimized to obtain enhanced bandwidth and size reduction in the microstrip antenna.

A dual-frequency broadband monopolar stacked patch antenna composed of a via-loaded ring is on the bottom layer and a circular patch on the top layer is proposed for WLAN applications [93]. A lower band ranging from 2.28 to 2.55 GHz and upper band from 5.15 to 5.9 GHz is generated. The maximum gain of antenna is found to be 5 and 6 dBi at lower and upper bands respectively.

In [94] wideband rectangular microstrip slot antenna is presented to work for wireless applications. The antenna consists of H shaped patch embedded with a U shaped slot. The dimensions of the U- slot, namely, its width, its side arm length and the base arm length are optimized to obtain the desired resonant bands for the operation of antenna. The same results are obtained by optimizing the width of parasitic H shaped patch and the length of the notch and the distance between the two patches. The results showed that the antenna acquires an impedance Bandwidth of 44.5%.

The authors presented an obtuse pie-shaped radiating patch suitable for WLAN applications [95]. The patch is fed by a 1.5 mm wide microstrip line and its corresponding metallic structure is coupled to the ground plane which creates dual banding in the proposed antenna structure in the WLAN bands extending from 2.24 GHz to 2.532 GHz in the lower frequency band and 4.62 GHz to 6.16 GHz in the higher frequency band with the requisite bandwidth in both the bands.

In [96], authors considered the use of stacked, U shaped, slotted microstrip patch antenna which uses two feeds; coaxial feed and CPW feed. Particle swarm optimization is used to optimize the designed antenna parameters. The results show that the antenna effectively covers the IEEE 802.11a/ IEEE 802.11b WLAN bands at 2.4 GHz and 5.8 GHz respectively. The impedance bandwidths of the bands covered at are found to be around 135 MHz and 270 MHz. The measured gain of the proposed antenna at 2.4 GHz and 5.8 GHz represent significant values of 8.668 dB and 8.694 dB respectively.

A compact and novel printed antenna with extended bandwidth is proposed for 2.4-GHz WLAN/Zigbee/Bluetooth applications [97]. The antenna combines strip slot mode to generate dual band. The antenna is folded to reduce the overall size also. The antenna has a 122 MHz bandwidth at 2.397 GHz (5.09% fractional bandwidth). The antenna has got good radiation performance.

A slotted antenna with L-shaped electromagnetically coupled microstrip line feed is presented in [98]. The authors have incorporated two slots in the middle of the ground plane: one circular ring slot and another square ring slot which produces the dual band effect. The designed antenna resonates at 2.4 GHz and 5 GHz bands for WLAN ISM applications. The impedance bandwidth for the lower frequency band at 2.4 GHz of WLAN standard ranges from 2.3 GHz to 2.6 GHz and the impedance bandwidth for the upper frequency band ranges from 5.15 GHz to 5.9 GHz. The size of designed antenna is 1.6 cm^3 which is quite large.

An optically transparent dual symmetric meandered monopole with strip feed is presented for WLAN applications. A micro-metal mesh conductive (MMMC) film is used for designing the MIMO antenna. The antenna has got very high efficiency of more than 40% at 2.4–2.48 and 5.15–5.8 GHz bands. The gain of antenna is also found to be high as compared to others transparent antennas [99].

The authors investigated the design of microstrip patch antenna with a partial U shaped slot with shorting wall. The dimensions of groove and the notch considerably affect the performance parameters of the antenna. The impedance bandwidth of the designed antenna is 21.59% at the central operation frequency. The half power beam width (HPBW) of the antenna is 90° at the center frequency of operation at 2.6 GHz [100].

A dual-polarized H-shaped CPW fed slot antenna with high port isolation is designed, fabricated and tested [101]. To have dual polarization two side slots are fed with a strip feed. The main slot has electric field node in the middle, and two side slots have 90° phase difference. The

isolation between two ports is increased by connecting a conductor strip over the non-fed side slot. The prototype of the antenna is fabricated and tested for WLAN band at 2.4 GHz. It achieves 2.24 to 2.60 GHz band (17% relative bandwidth) with 32 dB isolation over the entire band.

In [102], the author has used closely placed parasitic strips to attain multiband and wideband behavior in compact monopole antenna. It uses a horizontal strip with hook shaped strips on either side of it. Each hook shaped strip is loaded with a T-shaped strip on its upper end. The hooked arrangement of strips generates resonant bands suitable for WLAN system with wide bandwidth in the lower (2.1-2.52 GHz) as well as upper (5.07-6.62 GHz) frequency band. The peak gain of the antenna in the lower band is 1.95 dBi which is quite small.

A two element made of rectangular patch antennas with reduced mutual coupling for WLAN MIMO application is designed. To reduce mutual coupling six parallel metal strips, are used between the feed lines of the two antennas. The antenna resonates at 5.8 GHz with -42 dB of mutual coupling. Without parallel metal strips the mutual coupling is degraded by 30 dB, but the radiation pattern is not affected by addition of the metal strips [103].

In [104], the authors have presented a novel design of a compact microstrip antenna with multiband and wideband characteristics covering WLAN bands. It uses a combination two strips; one straight strip and the other C-shaped strip to generate two distinct resonant paths with different geometric measurements which help to accomplish dual banding in the designed antenna at 2.4 and 5 GHz, respectively. The impedance bandwidth of the implemented structure ranges from 2.38 GHz to 2.52 GHz at the lower band and from 4.86 to 6.87 GHz at the upper frequency band hence is suitable for WLAN applications at the 2.4/5.2/5.8 GHz ISM bands. But it has the drawback that the geometric size of the structure is 2.24 cm³ approx., which is relatively large.

A printed cross-dipole antenna having high gain, directivity and efficiency for WLAN applications is proposed in this paper [105]. The efficiency and directivity are improved by using slow-wave parasitic elements. The designed antenna has dual-orthogonal polarization and can operate for WLAN band from 5.15–5.85 GHz. The measured results show that the antenna has radiation efficiency of 76% and very low side-lobe level.

A compact CPW-fed, folded slot antenna is demonstrated in [106] for WLAN applications. A pair of dissimilar shaped slots is implanted in the folded slot antenna to create dualband at 2.4/3.6 GHz. The third resonant mode is generated at 5.5 GHz by the use of two

inverted L-shaped strips in the structure of designed antenna. The antenna printed on only one side of the substrate has somewhat complex geometry.

A small sized ($24 \times 25 \text{ mm}^2$), dual-band, two-element MIMO antenna for WLAN applications is presented by [107]. Two stepped microstrip feeds having 50 ohms impedances are used for feeding the antennas. Two open-ended quarter-wavelength slots of different lengths, are used for generating resonances at 2.5 and 5.6 GHz. The isolation more than 20 dB is provided by using a wide slot and two narrow slots. The envelope correlation coefficient is also found to be in the acceptable range.

The authors presented a circular slotted patch antenna with multiple arc shaped metallic strips loaded in the circular patch [108]. The 30 strips implanted into the circular patch, create multiband and wideband effect over all bands of WLAN standard useful at ISM bands. The size of the designed antenna is 1.3 cm^3 approx., which is somewhat large.

In this paper authors [109] present a planar monopole dual-band circularly polarized antenna. Two strips of “C” and “L” shaped are etched out on the main radiator for upper and lower band. The impedance and broadside direction axial-ratio (AR) bandwidths of fabricated antenna is tested and found to be 380 MHz and 180 MHz for lower band from 2.32 to 2.70 GHz and 2.39–2.57 GHz respectively and 1.24 GHz and 870 MHz for upper band from 4.76–6 GHz and 5.13–6 GHz respectively. The antenna has bidirectional radiation patterns with good gain in the resonating bands.

In this paper [110] authors have proposed a microstrip array consisting of an active monopole and two parasitic elements for high gain in the main lobe direction. The structure has a complex feeding structure but is able to provide gain of 6 dB. The main lobe direction can be tuned by varying the meanders inserted in feed lines and thereby the phases of the feed currents. The monopoles are printed on upper side of FR4 substrate, and parasitic elements on the back of the same substrate. The proposed design was compact and was fabricated and tested for WLAN applications.

In this paper authors have presented a wideband equilateral triangular patch antenna with a V-shaped slot and coaxial feed for WLAN (5.15–5.752 GHz) and C2C from 5.85 to 5.925 GHz (Car to Car) communications. Shorting pins are added to improve the impedance bandwidth of the antenna. Shorting pins on an equilateral triangular patch and V-shaped slot generate three resonances. Three resonances generate a wideband characteristic from 4.82 to 6.67 GHz. The antenna exhibits an omnidirectional radiation pattern with a gain of 5 dB [111].

In this paper [112], a compact three-element consisting of one chamfered-edge square patch and two printed dipole antennas MIMO antenna for 5.8 GHz WLAN application. The antenna can have both pattern and linear/circular polarization diversity. Without any decoupling structure the designed antenna is able to provide a high isolation of more than 15 dB. The antenna was fabricated and tested for diversity and return loss characterization. Both measured and simulated results were found to be closely matching.

In [113], low profile rhombus patch with CPW feed has been designed and inspected for WiMAX applications. The proposed antenna uses a two inverted L-shaped slits in the rhombus shaped patch to provide wideband operation. A pair of slits and three notches are introduced in the ground of the antenna to generate three bands with wide impedance bandwidth from 2.25 to 2.9 GHz, 3.3 to 3.9 GHz and 5.1 to 6 GHz, respectively.

A compact and low profile dual-circularly polarized printed ring-slot antenna with unidirectional radiation pattern is designed, fabricated and tested [114]. The radiator is placed close to an artificial magnetic conducting (AMC) acting as reflector. Two T-shaped capacitive two port feed structure with 4% isolation between ports provide circular polarization. The WLAN antenna operating at 2.4 GHz found to be having peak gain of 6.8dBi. Without reflector a gain loss of 3 dB is observed.

A triband rectangular microstrip antenna with CPW feed is proposed in [115] to fulfill the requirements for WiMAX applications. The proposed rectangular microstrip antenna considered the use of two thin slits on either side of the metallic patch whose dimensions are varied to suppress the in between frequencies of the WiMAX bands. It also reduces the interference amid the lower and the middle frequency band and results in triple band operation for WiMAX systems.

A multiband four helix-shaped radiating elements multiband and tuneable antenna is proposed for WLAN, LTE and WiMAX applications is proposed [116]. A simple technique slot etching on the arms of folded printed quadrifilar helical antenna (FPQHA) is a simple approach for creating multiband antenna. The antenna can be tuned by varying geometrical dimensions of the slot. The fabricated and tested antenna resonates at five frequency bands with a bandwidth of 19%, 4%, 5%, 4.5% and 9.5% at centre frequencies of 1.6 GHz, 2.45 GHz, 3.5 GHz, 4.5 GHz and 5.25 GHz (9.5%) respectively with stable CP radiation pattern.

A new design technique is investigated in [117], whereby, a meandered slit is used in a rectangular shaped monopole antenna to achieve wide operating bandwidth and notched band

operation appropriate for WiMAX systems. It explores the use of two I-shaped slots in the CPW feed line to reject bands from 3.96 - 4.9 GHz. The designed rectangular shaped monopole excites three resonant bands from 2.3 - 2.99 GHz, 3.2 - 4 GHz and 5.2 - 6 GHz respectively, which is suitable to cover the WiMAX bands with requisite bandwidth. The approximate size of the fabricated antenna is 2.52 cm^3 .

All the designed antennas conferred in this part of literature are able to cover one band or the other for homogeneous coverage of a single standard but not all the bands of a desired application standard simultaneously. Although the antenna in some cases cover all the WLAN bands but the impedance bandwidth attained at different bands is very small with poor return loss characteristics. Some of the proposed antenna designs show inadequate gain at the covered bands and have substantially large antenna size.

2.3.2 Multifrequency Antenna Designs for Heterogeneous bands of different Standards

Nowadays mobile terminals and other hand held devices require to operate in different bands of different networks provide worldwide mobility to users. The different countries operate on various standards of heterogeneous networks; therefore, the device should be so designed to operate in one or more bands of different standards prevalent worldwide.

A circular, compact sized, multiband antenna with V slit, and loaded with stub and slot for UMTS, WiMAX and WLAN is discussed [118]. The probe-fed antenna's UMTS band has circular polarisation while WLAN and WiMAX have linear polarizations. The antenna resonates at 2, 3.5 and 5.6 GHz with bandwidth and gains of (4.2%, 2%, 6.2%) and (4.4 dBi, 3.5 dBi and 2.8 dBi) respectively. The antenna has got omnidirectional pattern for WLAN band and direction for WiMAX band. The simulation and tested results are in good agreement.

Variable shapes of the monopole are experimented and tested in [119] to achieve multiband and widebanding operation over the heterogeneous networks. A U-shaped monopole and a triangular shaped monopole antenna with CPW feed are coupled in such a manner that they cover entire range of WLAN/WiMAX standard. The U- shaped monopole creates resonance at 2.5 GHz and the triangular monopole generates resonance at 3.6 GHz. The coupling between the two monopoles causes the merging of upper bands to produce wideband operation covering all the higher frequency bands of WLAN/WiMAX standard.

A compact, square slot printed antenna with reconfigurability with respect to frequency of Bluetooth, WiMAX, and WLAN standards is designed, fabricated and tested [120]. The

antenna size is reduced by making changes and modifications in the ground plane of antenna. The antenna is made reconfigurable by using a p-i-n diode by in the antenna. The H plane radiation characteristics of the antenna are omnidirectional with frequency of resonances at 2.3–2.51 GHz, 3.35–3.75 GHz and 4.95–5.53 GHz for Bluetooth, WiMAX and WLAN standards respectively.

In [121], the authors illustrate the use of a microstrip line fed, fork shaped patch mounted on one side of the substrate. By optimizing the dimensions of the arms of the fork, the different resonances are generated with required bandwidth to cover the bands of Bluetooth, WiMAX, WLAN standards. An elliptical slot with T and L- shaped slits is incorporated in the ground plane of the fork shaped antenna which assists in multiband operation with wide impedance bandwidth.

A new planar loop antenna consisting of rectangular ringed loop with three slits, small split rectangular ring and a parasitic strip between inner and outer loops, covering all the bands, of WLAN/WiMAX is designed [122]. The parasitic strip is responsible for improving the matching and bandwidth of the antenna. The antenna is covering 2.37–3.78 GHz and 5.15–5.85 GHz suitable for WLAN/WiMAX applications. The antenna has got radiation pattern similar to a dipole, constant gain and excellent radiation efficiency.

In [123], the authors proposed a compact rectangular monopole antenna with microstrip feed designed for WLAN/USB applications. The dimensions of the metallic patch are so calculated that it causes the merging of the higher order modes to produce wideband operation aimed at USB standard. The radiating patch uses a meandered stub with three steps at the lower end of the patch for impedance matching. Moreover, inverted L-shaped slit is incorporated in the patch to form two extensions radiating at two modes, 2.45 GHz and 3.5 GHz respectively. A thin slot is scratched below the microstrip line feed in the ground to form DGS which produces the effect of improved impedance matching at the upper frequency band.

In [124], the authors have proposed a microstrip antenna for heterogeneous bands of WLAN/ WiMAX. It employs a rectangular ring with two inverted L-shaped strips connected to it to provide multiband operation at 2.4/5.2/5.8 GHz WLAN and 3.5/5.5 GHz WiMAX bands with requisite bandwidth in each band. The rectangular ring constructed creates single resonant band ranging from 3 - 4.49 GHz. The upper inverted L-shaped strip, along with the rectangular ring generates a dualband covering 2.39 - 2.56 GHz band and 3.37 -5.19 GHz band.

A reconfigurable monopole active integrated antenna with additional circuit tracks for WLAN and WiMAX applications proposed [125]. The antenna can support and switch between single and dual band operation. The antenna can cover 2.3–2.56 GHz and 3.3–3.59 GHz for WLAN and WiMAX bands respectively. The pattern of antenna is found to be omni-directional. The fabricated antenna is compact in size with gain enhancement of 8.5 and 12.3 dB for WLAN and WIMAX respectively.

A novel design of l shaped antenna for PCS/WLAN/USB communication systems is presented in [126]. The main patch is embedded with U and H shaped slots to obtain the multiband operation in antenna. The H shaped slot in the trapezoidal patch generates resonance at PCS band and U-shaped slots result in the resonant modes at WLAN band respectively. A stub is used in the trapezoidal patch which generates the USB band.

In [127] authors present the design of CPW fed microstrip antenna with four L-shaped, two F-shaped, two U-shaped resonating arms to achieve multiband operation. The design dimensions are optimized using finite element method to enable the operation at 0.945 GHz, 2.50 GHz, 3.50 GHz, and 5.80 GHz suitable for RFID/WiMAX/WLAN application with considerable gain at desired frequencies.

In [128] A CPW fed planar monopole antenna is investigated using a novel technique in which the two corners of rectangular radiating patch are truncated to achieve wide impedance bandwidth and reduced size antenna. The truncated patch is embedded with two inverted L shaped to achieve multiband operation at 2.4/5.2/5.8 GHz and 3.5/5.5 GHz WLAN and WiMAX bands respectively.

A dual-antenna design comprising of two symmetric placed printed antenna elements for multiband and wideband operation for 2G/3G/4G mobile handsets is proposed in [129]. Each antenna element is an F-like monopole with two extensions to the ground. 50 ohm microstrip line is used to excite each F shaped element. The measured results show that the antenna is capable of multiband performance with wide impedance bandwidth at 1.8/1.9 GSM bands, UMTS, 2.3/2.5 GHz LTE bands, and 2.4 GHz WLAN bands.

A design of rectangular monopole antenna for integrated operation of different wireless standards is developed in [130]. Tuning of widths of asymmetric CPW ground plane results in bandwidth enhancement and excitation of resonance at 1.57 GHz. Furthermore, a grounded inverted-L parasitic strip in the patch is used to produce wide functional bandwidth from 1.37 - 2.82 GHz, for GPS, PCS, DCS, LTE, WLAN and IMT-2000 applications.

A new design of a printed monopole antenna for operation over multiple wireless communication systems is presented [131]. The antenna is designed and implemented using HFSS commercial software by combining different techniques like meandering, spiral line, and branched geometry fabricated on FR-4 substrate of thickness 1.6mm and dielectric permittivity of 4.4 which results in reduced size of the antenna. It uses a gap feeding technique and a shorting pin which further shrinks the antenna size to enable it to be mounted on the surface of the mobile device. This antenna measures $6 \times 30 \times 3.2 \text{ mm}^3$ which is small enough in size to be practically implanted in a mobile handset as an embedded antenna.

In [132], the authors presented a CPW fed slotted dipole antenna with frequency reconfiguration characteristics. The antenna comprises of three pairs of slots, placed in series which are then united into a rectangular case to attain improved, steady impedance matching over the desired band. Three pairs of pin diodes are incorporated into the arms of dipole. By changing the state of the three pin diode switches, the antenna can be operated for single, dual or tri band at 2.4/ 3.5/ 5.2 GHz. The antenna design is simulated in CST software. The antenna is then fabricated and tested to validate the results. The measured results showed that the average gain of the antenna at three bands is 1.54 dBi, 2.92 dBi and 1.89 dBi.

A new diamond shaped patch with several narrow strips is investigated in [133] for multiband operation. The inner portion of the main diamond shaped patch represents the notched region and the quarter wavelength strips create resonances at different frequencies leading to multiband operation at GSM/WLAN and UWB bands. The authors explore a different shaped antenna in the form of an egg using the standard ellipse equation to create multibanding at WLAN/ UWB standard the dimensions of the ground plane seem to have substantial effect on the impedance bandwidth of the antenna.

The authors have investigated the use of self-similar structures called fractals in the form of sectoral or Koch fractal geometry in designing multiband antenna in [134, 135] for dual or triple band performance with improved bandwidth. The number of iterations to the initial parameter has an impact on the number of bands covered and the impedance bandwidth obtained over the desired band. It also helps to reduce the size of the antenna. Serpinski or triangle shaped fractal antenna can also be used for the purpose.

In [136], the authors proposed the design of compact slotted rectangular microstrip antenna with multiband operation for WLAN, Mobile WiMAX, and WCDMA applications. Seven slots are etched in the main radiating patch which generates closely spaced resonances to

achieve an overall wideband in the range of 2-8 GHz which is suitable to cover numerous bands. It also studied the effect of defected ground structures on the performance of the antenna.

In [137] authors presented a dual-band strip fed slot antenna with a complimentary stub and high gain for WLAN and WiMAX standards. The antenna is made unidirectional by using a reflecting ground plane with a gain of 9.1 dBi and efficiency of 95%. The radiation properties of a prototype antenna were measured in a compact antenna range. Simulated and measured results are found to be in good agreement.

A novel dual-layer, single feed, E-shaped and U-slot patch based, linearly polarized, dual-band patch antenna is designed and tested [138]. The simulated antenna covers 2.40–2.4835 GHz and 3.40–3.61 GHz for WLAN and WiMAX bands respectively. The bandwidths and peak gains of the antenna are found to be 26.9% ,7.1% and 7.1, 7.4 dBi at central frequencies of 2.60 and 3.50 GHz respectively.

In the review it is found that various multiband structure for heterogeneous networks have designed and fabricated. All structures are unable to meet all the requirements of heterogeneous standards in all respects. Some could provide high gain but were unable to provide sufficient bandwidth. Some were not compact. New designs are needed for future wireless communication systems.

2.3.3 Interference rejection in microstrip antenna:

Ultra wideband antennas are a much sought after field in industry and research due to their operation in unlicensed frequency bands extending from 3.1 GHz to 10.6 GHz for commercial applications in the field of communication [139]. UWB systems are capable of providing a number of wireless services like digital voice services, video telephony, fast internet access etc. In UWB technology, the energy of the signals spread over wide range of frequencies and the power consumption of UWB antenna is quite low for the band. [140]. These characteristics make UWB a promising candidate for future communications.

A compact slotted UWB (ultra- wideband) rectangular microstrip antenna is presented in [141]. The antenna is designed on FR4 substrate with effective permittivity of 4.4 and thickness 1.6mm using rectangular patch with tapered geometry and microstripline feed. The ground plane is truncated to achieve broadband operation over the entire range of 4.1 GHz to 12 GHz.

A small sized inverted T slot based UWB antenna, printed on copper-cladded substrate for cognitive radio applications is proposed [142]. The antenna can produce adjustable,

independent band notches. The tuneable rejection bands are created using varactor diode inserted a split vertical rectangular strip and a U-shaped parasitic element on top and bottom side of the substrate respectively. The simulated and measured results, were found to be in good agreement.

In [143] the authors proposed design represented a uniplanar UWB (Ultra Wide Band) antenna fabricated on LCP substrate for rejecting 802.11a WLAN bands. The antenna is able to reject narrow bands spaced close to each other at 5.25 GHz and 5.775 GHz WLAN bands by means of two open circuited stubs. Lumped and distributed element circuit models verify the use of stubs for rejecting two closely spaced bands. The proposed antenna shows high selectivity and allows passing of the band between 5.35 GHz to 5.725 GHz for UWB applications.

A low profile triple band-reject UWB antenna is investigated in [144]. In order to check the problem of interference from neighboring communication standards inside operating frequency range of UWB, complementary co-directional SRR (Split Ring Resonator) structure is used. The proposed antenna rejects 3.3–3.6 GHz, 5.15–5.35 GHz and 5.725–5.825 GHz bands of WiMAX, lower WLAN and upper WLAN standard. The results show that the designed antenna covers a wide band from 3.03 - 11.4 GHz with three notched bands for UWB operation.

A slotted band-notched ultrawideband (UWB) antenna is examined in [145]. A rectangular patch is modified by embedding one circular slot and three rectangular slots in it. Also, ground plane of the antenna is modified by inserting two triangular slits in it, generating a wide band from 3.12–12.51 GHz. Two p-i-n diodes are connected across the circular slot to generate reconfigurable notched bands at 3.12–3.84 GHz, 4.9–6.06 GHz and 5–6.07 GHz.

A new strategy experimented on Microstrip Antenna is presented in [146] in which the slotted rectangular radiating element is used as a reference for two antenna designs. First design is constructed with conventional conducting ground plane and the second one uses perturbed ground plane which changes the path of current on the surface of the patch and generates two resonances at frequencies of 1.9 GHz and 2.4 GHz and rejecting the entire range lying within the two bands. The results simulated in HFSS software show 18.2% interference rejection bandwidth using perturbed ground as compared to 13.5% for conventional ground plane.

In [147], the authors proposed a small elliptical antenna with microstripline feed for UWB applications capable of rejecting WLAN and WiMAX bands. By introducing a C-shaped slit in the elliptical patch and a pair of quarter wavelength resonator placed around the microstrip feed, the antenna is capable of rejecting 3.3 GHz to 3.8 GHz WiMAX band and 5.15

GHz to 5.85 GHz WLAN bands. The antenna is able to produce an effective impedance bandwidth of 2.9 GHz to 9.3 GHz sufficient for UWB systems.

The authors proposed a reformed nine element FR4 based L-shaped resonator which acts as bandstop filter at microwave frequencies in [148]. Conventional L-shaped filter working at 2.45 GHz frequency is modified by altering the width of L-shaped resonator and connecting a series of filters of 9th order increases the rejection bandwidth from 2.4-2.48 GHz for 802.11b WLAN standard which is evident from the results obtained in ADS software.

A wide band microstrip antenna with bandstop filter with central frequency of 3.7 GHz is designed and simulated in [149]. A 2 pole band stop filter is fabricated on a FR-4 substrate with wide band reject property is implemented in IE3D using open circuited stubs for band rejection from S to C band in microwave range.

In [150], the authors have demonstrated the use of IDCLLRs (inter-digital capacitance loaded loop resonators) to project microstrip band-reject filter design on synthetic medium. IDCLLRs are coupled to conventional design of 50 ohm transmission line to generate a single stage, 3 stage and 9 stage band-reject multiple tuned filter. The use of synthetic medium with negative effective permeability and by altering the number and length of inter digital fingers rejection bandwidth can be controlled.

In [151], the design of two UWB antennas with band-notched characteristics is presented. In the first design, single patch is used without any coupling gaps and a square shaped notch on the upper side of the ground plane to generate a passband with enhanced bandwidth and reduced size antenna. In the second design, a new microstrip antenna is constructed for UWB operation having band rejection performance. A slot in the shape of triangle is cut from the patch and cross shaped feed is to obtain passband from 2-12 GHz with notched band from 4.2 and 6 GHz covering HIPERLAN/2, WLAN and C-band standards.

In [152], the authors have presented a low profile monopole microstrip antenna with single and multiple notched bands for operation in UWB systems. The antenna is fed by a microstrip line and the design is realized using DGS (Defected Ground Structure) in the ground plane in the form of two L shaped slots which generate proper impedance matching for the antenna over all the operating bands of UWB systems. The antenna is able to work in the heterogeneous bands of WLAN, Wi-MAX and C-band applications.

In [153], A. K. Arya, A. Patnaik and M. V. Kartikeyan proposed a new design of antenna based on the modifications made in the stacked design of microstrip antenna to achieve

broadband operation. The stacked patches are coupled to each other using proximity coupling technique. Also, a skew shaped defect is etched in the ground plane of the antenna and its dimensions are varied to see the effects of variation on the performance of antenna. The measured results showed an increase in impedance bandwidth of the antenna along with reduction in the overall size of antenna.

A new band-notched slotted microstrip antenna is designed and fabricated on RT/duroid 6006 substrate for UWB wireless communication systems [154]. In the design, ellipse shaped stub is used to excite another slot aperture of similar shape. Also, H-shaped slot is infused in the elliptical stub to cover the operational frequency range of UWB from 3.1 to 10.6 GHz with band rejection capability to remove the band of frequencies ranging from 5.15 to 5.825 GHz i.e. IEEE 802.11a and HIPERLAN/2 bands. The dimensions of the H-shaped slot are varied and its effect on the antenna performance is plotted in the results. The experimental results match well with the simulated ones. The antenna is made-up on 1.27 mm sheet of Duroid material with relative permittivity value of 6.15. The measured size of the fabricated antenna structure is approximately $50 \times 50 \text{ mm}^2$.

A small sized triple band notched microstrip antenna is investigated for its performance in UWB communication systems. 5.32 GHz, 8.45 GHz and 10.83 GHz [155]. The proposed design comprises of a rectangular shaped patch that is excited by a 50 ohm microstrip line feed. Two u-shaped slots are embedded in the main patch one above the other and it uses a reduced ground plane with a slit inserted in it. This creates stop band operation to remove any interference from WiMAX, WLAN and mobile Aeronautical bands and allow its usage over the UWB band ranging from 3.1 - 10.6 GHz. Time domain and Frequency domain results are obtained for the designed antenna which shows improved impedance matching and stable omnidirectional radiation pattern over the entire UWB band.

Split-ring resonators have been used to design a compact frequency tuneable filter structure in [156]. With a single p-i-n diode the response of the filter is varied between first and second harmonic. With double p-i-n diodes the response of the filter can be switched between bandpass and bandstop. To show the performance of filters an UWB antenna is designed with adjustable band notch filter.

A novel UWB MIMO antenna comprising of two orthogonal circular antenna elements and stripline feed is proposed for working range of 3.1-10.6 GHz [157]. Dual notched bands are created in the final response of the antenna using band-pass CSRR filter consisting of a three-line

coupled microstrip with short-circuited stubs. The notched bands are created at 3.35-3.55 GHz and 5.65-5.95 GHz frequencies. The fabricated antenna has an isolation of 20 dB. The antenna pattern is similar to that of a dipole.

2.4 SUMMARY OF THE CHAPTER

In this chapter, the research work undertaken for the multibanding, widebanding and rejection of interfering bands, using various methods, is discussed. A number of microstrip antenna topologies and designs are discussed. New techniques of making low profile and weight, and compact multiband antenna described. To achieve multiband operation with improved characteristics in microstrip antennas, various antenna elements and their correlation with unique geometrical properties is presented. Microstrip antennas still have been found to be promising paradigm for military and civilian wireless applications. New innovative and improved designs can be explored for homogenous and heterogeneous networks. Next four chapters present new and improved design for homogenous, heterogeneous bands and interference rejection techniques for UWB antennas.

CHAPTER 3

CPW FED RECTANGULAR RINGS BASED PATCH ANTENNA WITH DGS FOR WLAN APPLICATIONS

3.1. INTRODUCTION

Presently, devices are progressively working without cables, following the wireless approach to access any network. Wireless communications can be carried out using cellular mobile technology, microwave or satellite communication for long distance communication, while WLAN is a preferred technology for communication over short range. Wireless LANs use radio frequency signals, lasers or infrared light rays to interconnect the computer terminals, hubs or file servers. Each terminal device on a wireless network has a transmitting and receiving antenna to direct and collect information wirelessly. It enables laptops and remote terminals to connect to the LAN where it may be hard to install cables. At present, we are acknowledging rapid and wide acceptance of WLAN network as high-speed technology which can provide up to 216 Mbps data rate at low cost [158-159].

Together, 2.45 GHz and 5 GHz WLANs are license-free bands, particularly used for Industrial, Scientific and Medical (ISM) applications. The IEEE 802.11x based Wi-Fi equipment is working at 2.45 GHz band and is being widely used for domestic applications due to its wall - penetrating characteristics, considerable range and bandwidth required for mobile devices. IEEE 802.11b/g standard works at 2.45 GHz band with data rate 5.5 Mbps and 11 Mbps, respectively [9-11].

5 GHz band is more commonly allocated to industrial use, since it is less congested and has more number of channels with greater bandwidth which reduces the chances of interference. IEEE 802.11a/ac radios are intended for operation in 5 GHz band. IEEE 802.11n is functional at both 2.4 and 5 GHz bands available with dual-band chipset. It introduced the concept of MIMO (Multiple Inputs, Multiple Outputs) antenna which can encode many 'spatial streams' simultaneously with increased data rate of 216 Mbps [160].

FCC (Federal Communications Commission) has established three more sub bands in addition to 5.725 to 5.875 GHz ISM band known as UNII (Unlicensed National Information Infrastructure) bands which extend from: [160].

- 5.150 - 5.250 GHz (UNII-1/ lower band)
- 5.250 - 5.350 GHz (UNII-2/ middle band)
- 5.450 - 5.710 GHz (UNII-2 Extended band)

It forms a portion of the RF spectrum which can be used by IEEE-802.11a devices and various wireless Internet Service Providers (ISPs). The use of UNII-1/ lower band was initially limited to indoor use only, whereas UNII-2/ middle band could be used indoor as well as outdoors. UNII-2/ Extended band is used for alignment of standards in various countries.

Moreover, easy fabrication using PCB design technique and easy integration with other circuits makes microstrip antennas to find application in diverse fields such as ECM applications [161], as wearable antennas [162], in interferometric radiometer [163]etc.

In this chapter, bandwidth enhancement is kept as the goal while designing the proposed antenna for WLAN bands. This chapter illustrates the design of a novel, small sized, rectangular microstrip antenna with CPW feeding mechanism. A dual band WLAN antenna is designed and fabricated by incorporating rectangular rings and DGS in the CPW ground planes. The proposed antenna operates in two homogeneous bands of WLAN at 2.4GHz and 5.15 GHz. It is illustrated that use of multiple rings and DGS (Defected Ground Structure) in MPA geometry, helps to improve the performance of antenna in terms of operational resonant frequency and the impedance bandwidth at that particular frequency of resonance for homogeneous WLAN bands.

The antenna contains single ring rectangular patch element and CPW feed placed on FR4 substrate of 1.6 mm thickness and loss tangent value of 0.018. By integrating another asymmetrically split rectangular ring to the single ringed patch and cutting DGS in CPW feed, the proposed antenna can operate in dual band with enhanced bandwidth over the desired bands. The parametric analysis is carried out to study effect of adding various rectangular rings and DGS on antenna performance. The proposed antenna is optimized and prototype is designed and fabricated. The results show that the impedance bandwidth of the antenna at each band ranging from 2.20 GHz to 2.65 GHz and 5.0 GHz to 5.45 GHz is 450 MHz. The experimental results show good return loss characteristics and stable field pattern over the desired frequency bands. The design of the antenna is discussed next.

3.2. PARAMETRIC STUDY

The parametric study of the proposed antenna is carried on the basis of structural variations and geometrical variations. The basic structure of the antenna is designed in steps and for each step the performance of antenna is studied. The parametric study is executed for each geometrical change implemented which seem to have significant effect on the performance of antenna in terms of its return loss and bandwidth [181]. The basic rectangular ring with microstrip feed and CPW ground is taken as initial structure.

3.2.1 Initial Design of Antenna

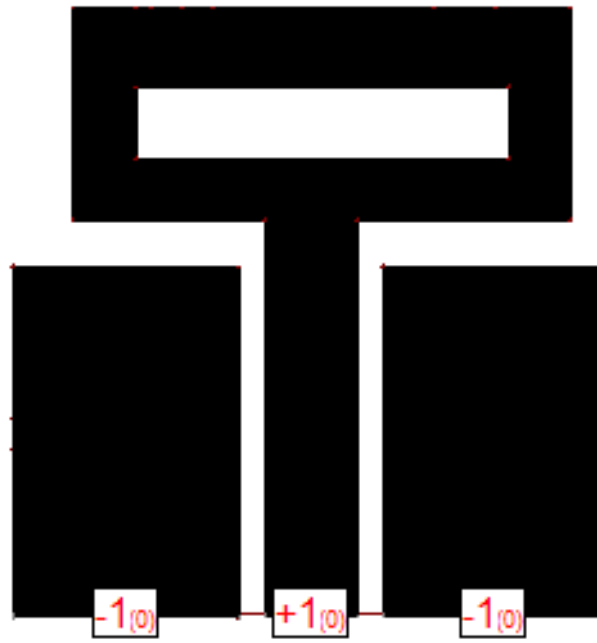


Figure 3.1 Basic antenna design with single ring

The basic antenna design of the proposed antenna consists of small rectangular ring shaped patch as illustrated in Figure 3.1. It is fed by a stripline surrounded by CPW ground plane on either side of it. The comparative return loss curve of the initial antenna structure and the final structure is depicted in Figure 3.2. The figure clearly indicates that the initial design of the antenna is able to provide single resonance at a frequency of 5.25 GHz, covering the band ranging from 5.1 to 5.5 GHz offering a bandwidth of 400 MHz for WLAN applications.

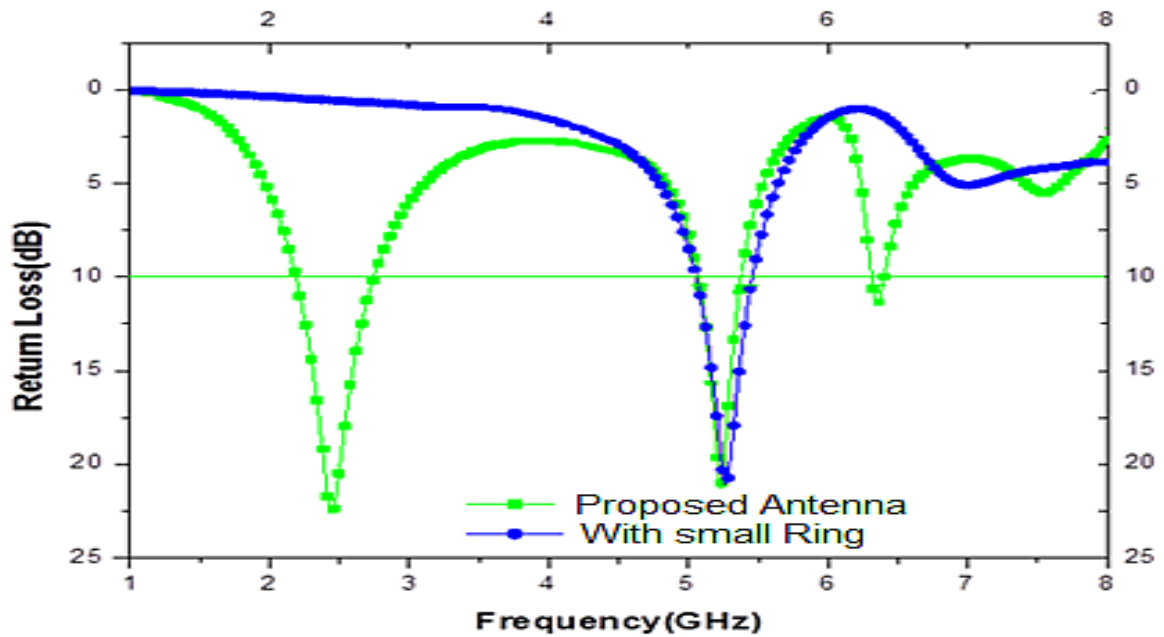


Figure 3.2 Return loss of initial antenna with small ring (compared with proposed antenna)

The table 3.1 summarizes the results obtained for the initial antenna structure implementing single rectangular ring antenna with CPW ground plane on either side of the stripline.

Table 3.1 Results obtained for initial design of antenna using single ring

Band	Frequency Range	Bandwidth	Peak Return Loss
5.25 GHz	5.1 to 5.5 GHz	400 MHz	-21.3 dB

3.2.2 Effect of addition of large upper ring

A large upper ring is added to the initial single ringed patch using two small parasitic strips as illustrated in Figure 3.3. The effect of addition of the large upper ring is examined in terms of return loss parameter

(S_{11}) of the antenna in Figure 3.4. Two effects can be observed from the simulation study on the performance of the antenna. It causes the antenna to display a multiband effect by generating two additional bands at 2.4 GHz and 6.4 GHz. The antenna indicates a return loss value of -26 dB at 2.4 GHz and significant bandwidth from 2.1 to 2.5 GHz as required for WLAN operation at this band. But, it causes a considerable fall in the value of return loss from -21 dB to -10 dB at 5.25 GHz band obtained previously using a single ring antenna. The resonance at 6.4 GHz does not show any significant return loss. Table 3.2 summarizes the results obtained for antenna using small ring and large upper ring.



Figure 3.3 Modified antenna after addition of large upper ring

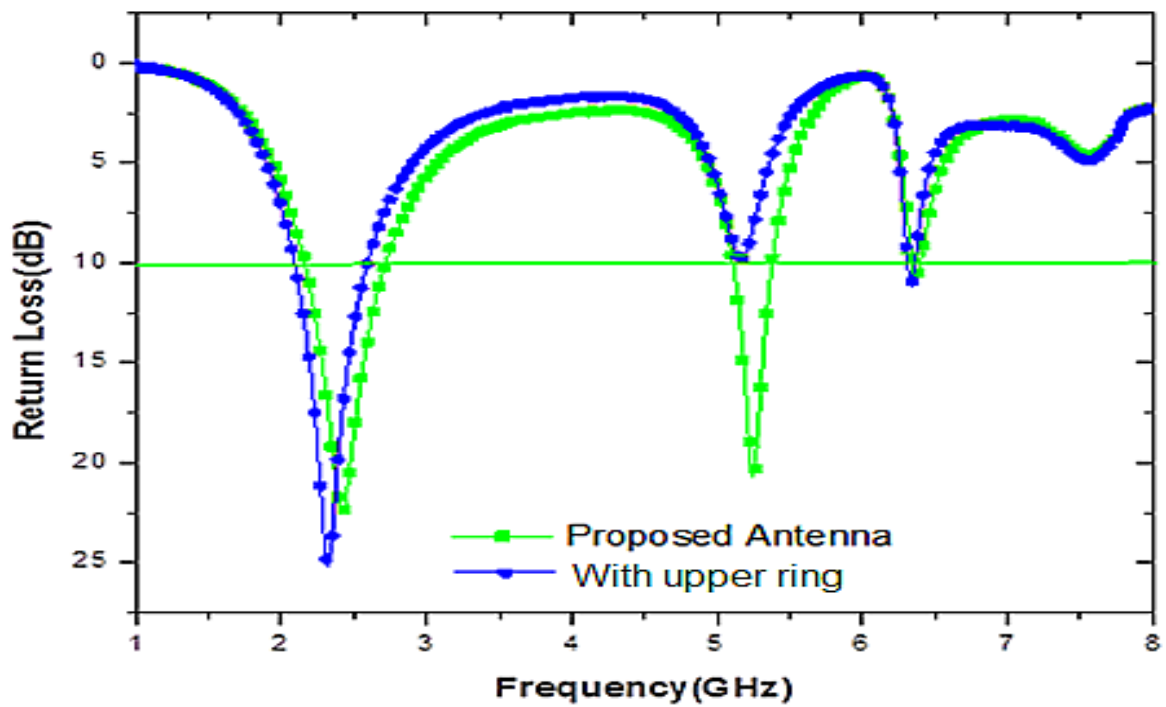


Figure 3.4 Return loss obtained after the addition of large upper ring (compared with the proposed antenna)

Table 3.2 Results obtained for antenna using small ring and large upper ring.

Band	Frequency Range	Bandwidth	Peak Return Loss
2.4 GHz	2.1 to 2.5 GHz	400 MHz	-26.0 dB

3.2.3 Effect of implementing DGS in the ground plane:

The microstripline, used to excite the antenna, is surrounded by two CPW ground planes symmetrically placed on either side of it. Defects, in the form of rectangular slots, are incorporated in the CPW ground of the antenna to form Defected Ground Structures (DGS), as can be seen in Figure 3.5. Slots are created to adjust the value of resonance of the upper frequency band at 5.15 GHz. The resonance is affected by the position and dimensions (length and width) of the slots cut out from CPW ground planes on both sides of the microstripline feed. The optimized position and dimensions of the slots are found to be different in both the ground planes. Formation of defected ground structures has significant effect on the resonant behavior of the antenna at the upper band. The band at 6.4 GHz is moved to lower frequency and combines with 5 GHz band to form a single wider band ranging from 5.25 GHz to 5.65 GHz generating a bandwidth of 400 MHz. It remarkably recovers the return loss value to -21dB as shown in Figure 3.6. The DGS in CPW ground do not seem to disturb the lower frequency band at 2.4 GHz. Table 3.3 summarizes the results obtained for antenna after implementing DGS in the ground plane.



Figure 3.5 Modified antenna after implementing DGS in the CPW ground plane

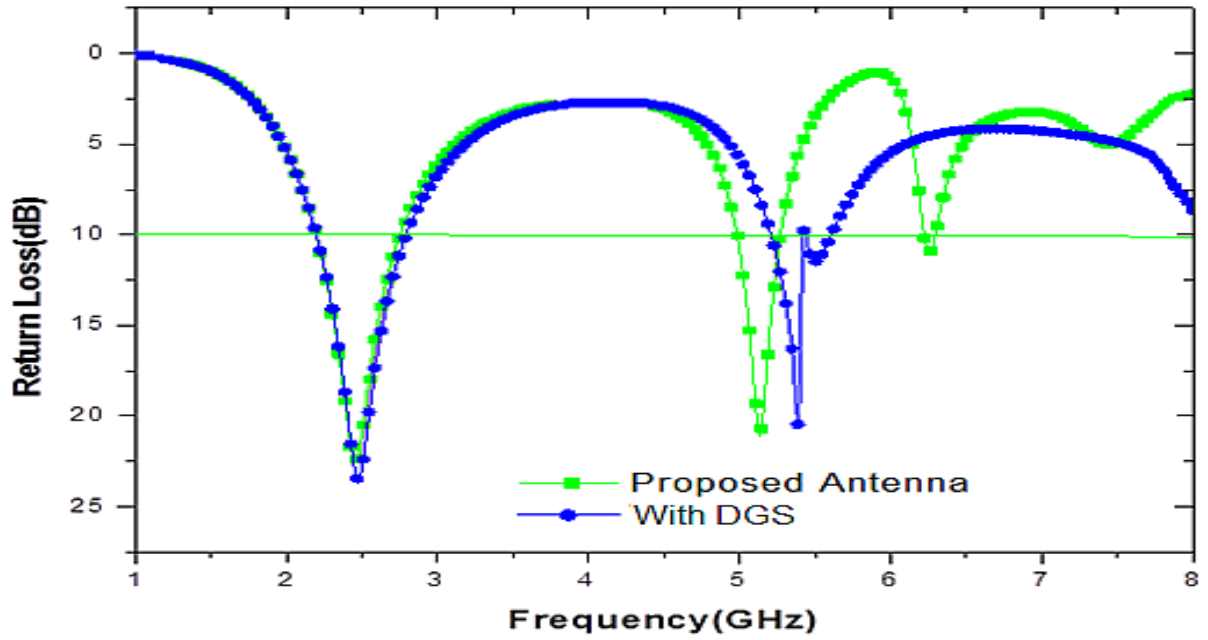


Figure 3.6 Return loss obtained after implementing DGS in the ground plane (compared with the proposed antenna)

Table 3.3 Results obtained for antenna after implementing DGS in the ground plane.

Band	Frequency Range	Bandwidth	Peak Return Loss
2.4 GHz	2.1 to 2.5 GHz	400 MHz	-26.0 dB
5.15 GHz	5.25 to 5.65 GHz	400 MHz	-21dB

3.2.4 Effect of addition of vertical strip in the large upper ring:

The final configuration of the proposed antenna is formed by dividing the larger upper ring into two, by a vertical strip placed along the length, L_{p2} , of the upper ring as seen Figure 3.7.

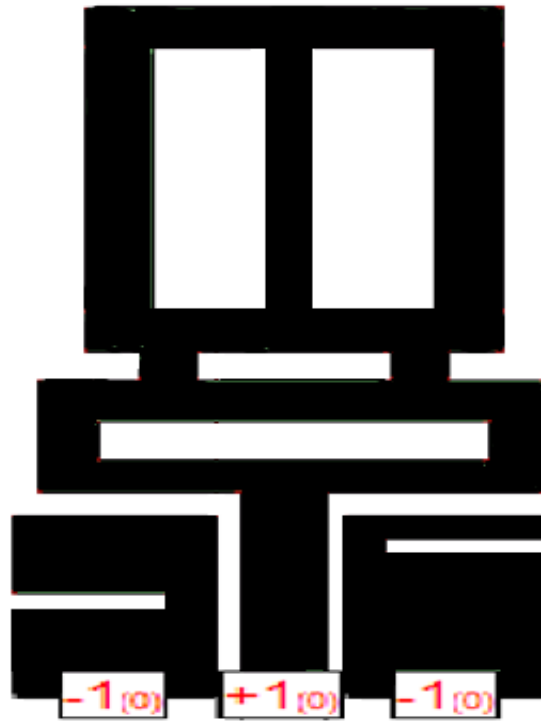


Figure 3.7 Modified antenna after addition of vertical strip in upper ring (the proposed design)

It is evident from the simulation result of the proposed antenna, presented in Figure 3.8, that the vertical strip is responsible for shifting the upper frequency band earlier resonating at 5.45 GHz to now resonate at 5.1 GHz with impedance bandwidth, as desired, ranging from 5.10 - 5.35GHz suitable for UNII 1(lower) and UNII 2(middle) WLAN operation. Further, it produces a band at 6.4 GHz but with nominal return loss value of 11 dB. Effective bands covered by the proposed antenna which are important for WLAN applications range from 2.1 to 2.65 GHz and from 5.1- 5.35 GHz. Table 3.4 summarizes the results obtained for antenna after adding vertical strip to the upper ring (the proposed antenna).

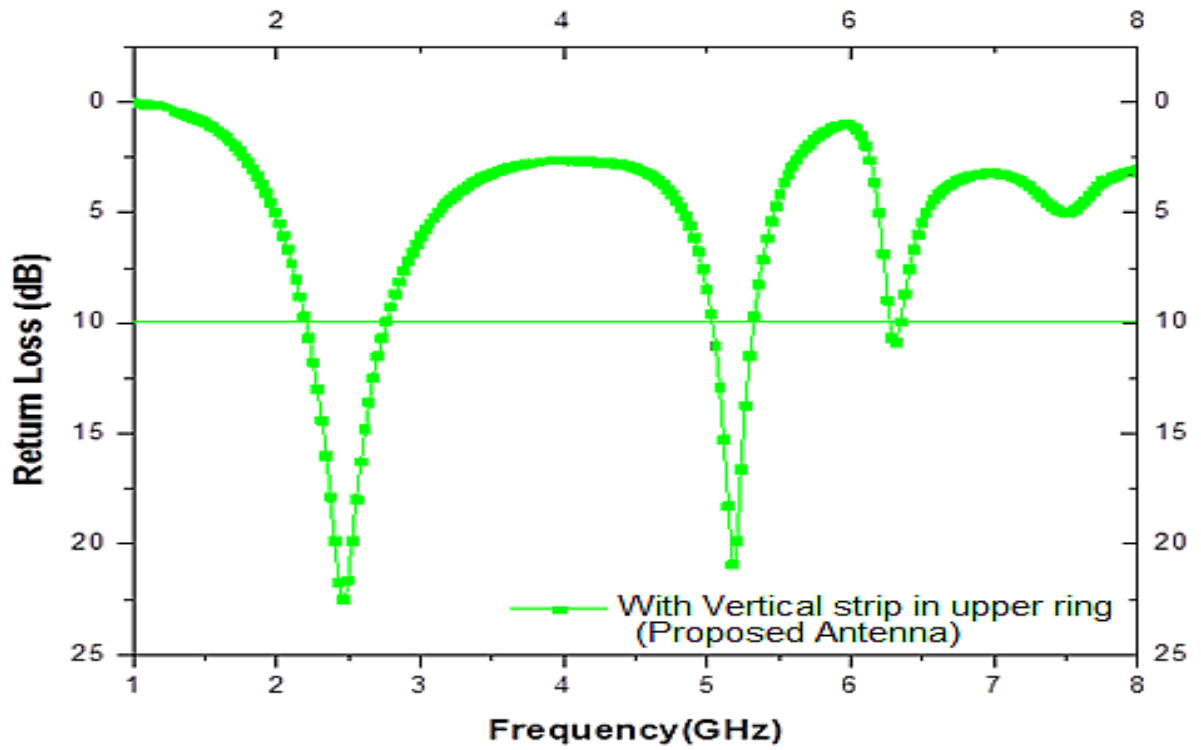


Figure 3.8 Return loss obtained after adding vertical strip to the upper ring (the proposed antenna)

Table 3.4 Results obtained for antenna after adding vertical strip to the upper ring (the proposed antenna)

Band	Frequency Range	Bandwidth	Peak Return Loss
2.4 GHz	2.1 to 2.5 GHz	400 MHz	-26.0 dB
5.1 GHz	5.10 to 5.35GHz	250 MHz	-21.5 dB

3.2.5 Effect of variation of position and width of the vertical strip in the large upper ring

The vertical strip in the larger upper ring is used to segregate it into two rings as shown in Figure 3.7. The position and dimension of the vertical strip are varied from its central position to see its effect on the antenna performance. The simulated results of return loss with respect to frequency, reveal that the variation in the position of the vertical strip from the center does not have a significant impact on either of the two bands. Its center lies at 7.5mm. The 1 mm left from the center strip is considered to be its optimum value i.e. at 6.5 mm from the left hand side edge of upper ring, where the resonance lies at 5.1 GHz as can be seen in the Figure 3.9.

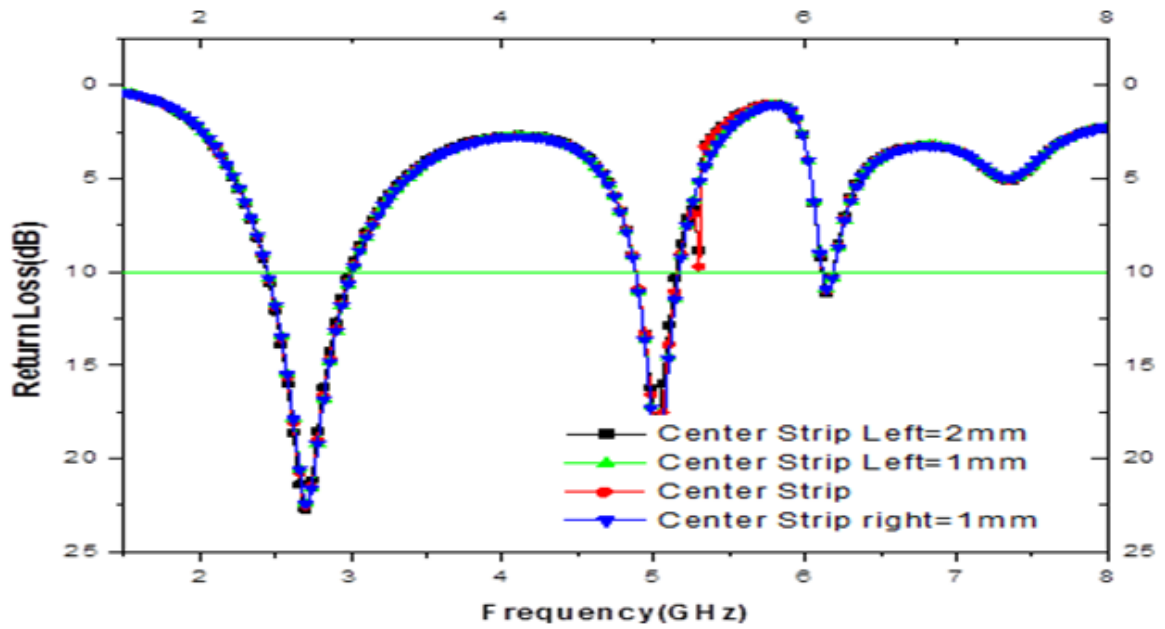


Figure 3.9 Effect of variation of position of vertical strip in the large upper ring

The width of the vertical strip is also varied to see its effect on return loss characteristics or the impedance bandwidth of the proposed antenna. As can be seen in the simulated results in Figure 3.10, when the width of the strip is widened from 1mm to 3mm, the return loss at the upper frequency band shows considerable improvement from a value of -12dB at 1mm width to -32.5dB at 3mm width for the required resonant frequency of 5.15 GHz. The optimum value of the strip width is found to be 3mm.

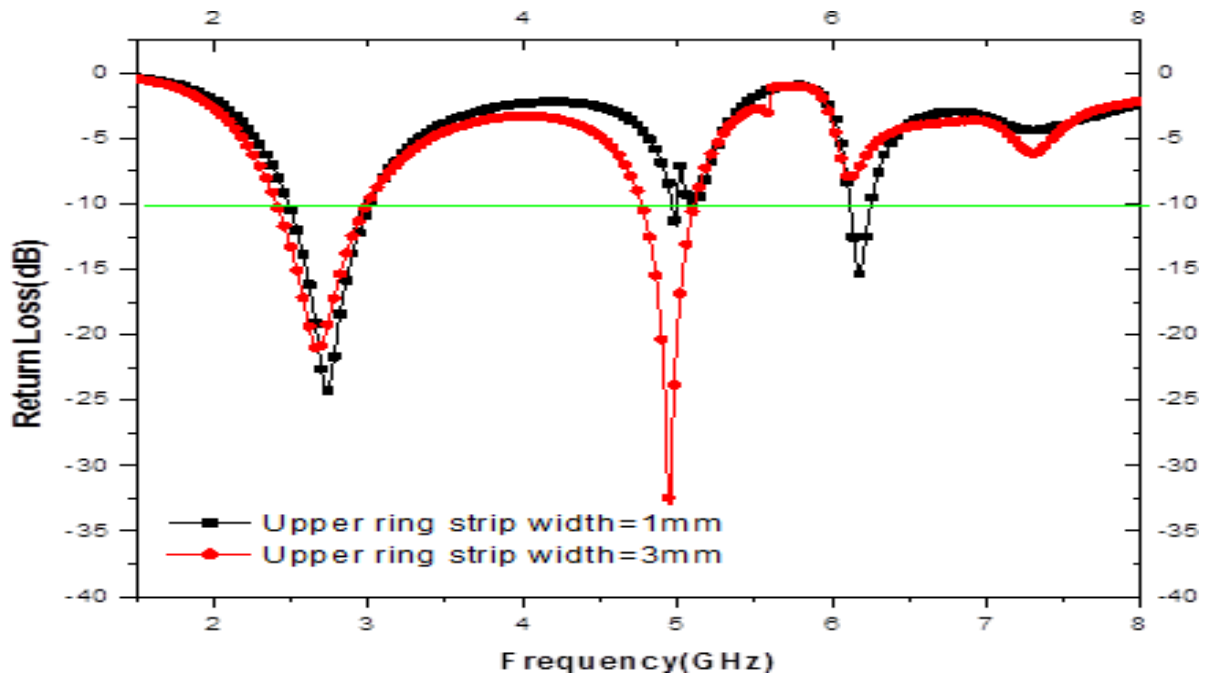


Figure 3.10 Effect of variation of width of vertical strip in the large upper ring

3.2.6 Effect of variation of position and dimension of DGS slots in CPW ground plane

The length of the slot in the left CPW ground is varied to demonstrate its effect of on the performance of the proposed antenna. It is apparent from Figure 3.11, that an increase in the length of the rectangular slot from 2.64mm to 5.64mm in left ground plane, along the positive x-axis, shifts the upper frequency band towards lower side to attain resonance at the anticipated value of 5.15 GHz, with the optimized value at, $L_f = 5.64$ mm. Increasing the length of the slot beyond this optimum value, shifts the resonance further to lower frequency and also, it creates additional band at a higher frequency at 6.1 GHz. It can be well interpreted from the simulation result that alteration in the length of the slot (L_f) in left ground plane, primarily moves the upper frequency band and has little influence on the lower band. Figure 3.11 shows the effect of varying the length of the slot in left CPW ground on S_{11} parameter with reference to frequency.

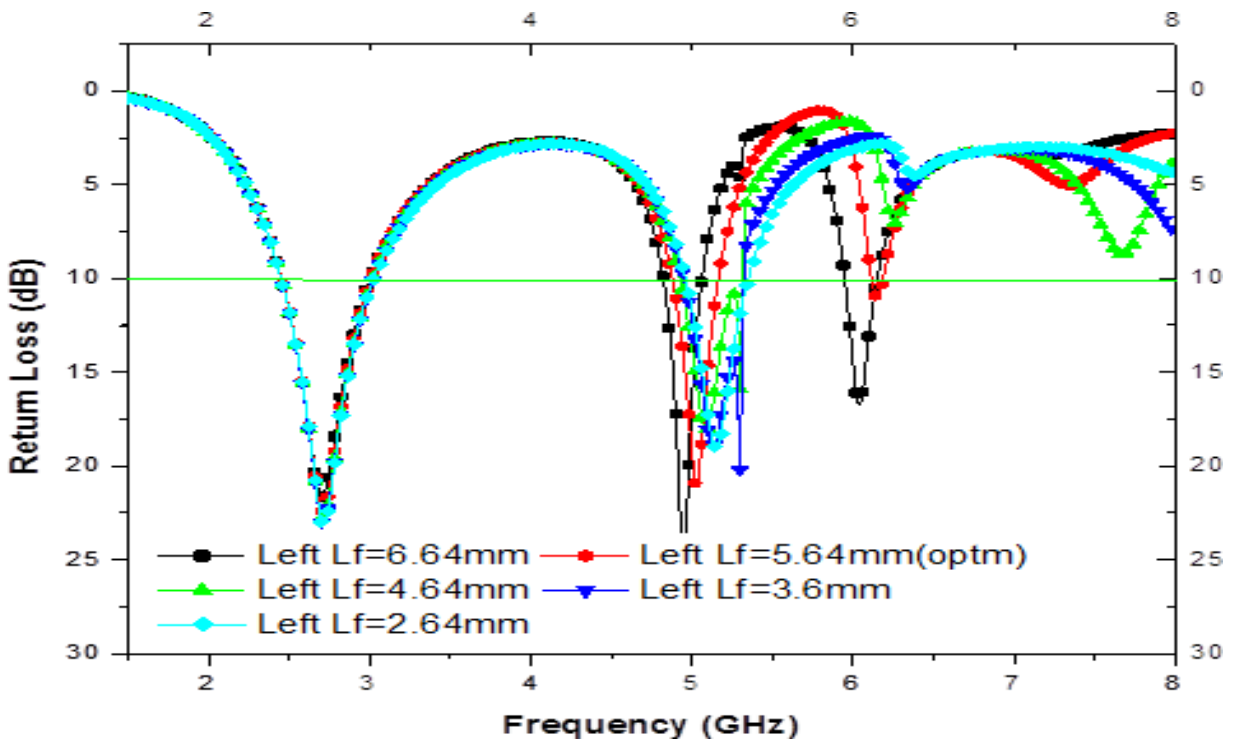


Figure 3.11 Effect of variation of slot length of DGS in the left ground plane

Similar variation is applied to the length of the slot in the right CPW ground plane and the results are plotted in terms of S_{11} parameter with respect to frequency. Figure 3.12 makes it clear that an increase in the length of the slot from a value of 3mm to 7mm causes a continual swing of the upper band of frequency from 5.4 GHz to 4.8 GHz. It has no effect on the lower

frequency band resonating at 2.45 GHz. Increasing the length of the slot beyond this optimum value, shifts the resonance further to lower side at the upper band and it also creates an additional band at a higher frequency at 6.2 GHz. The optimum value of length of the slot in right CPW ground plane is found to be 6mm which causes resonance at 5.15 GHz.

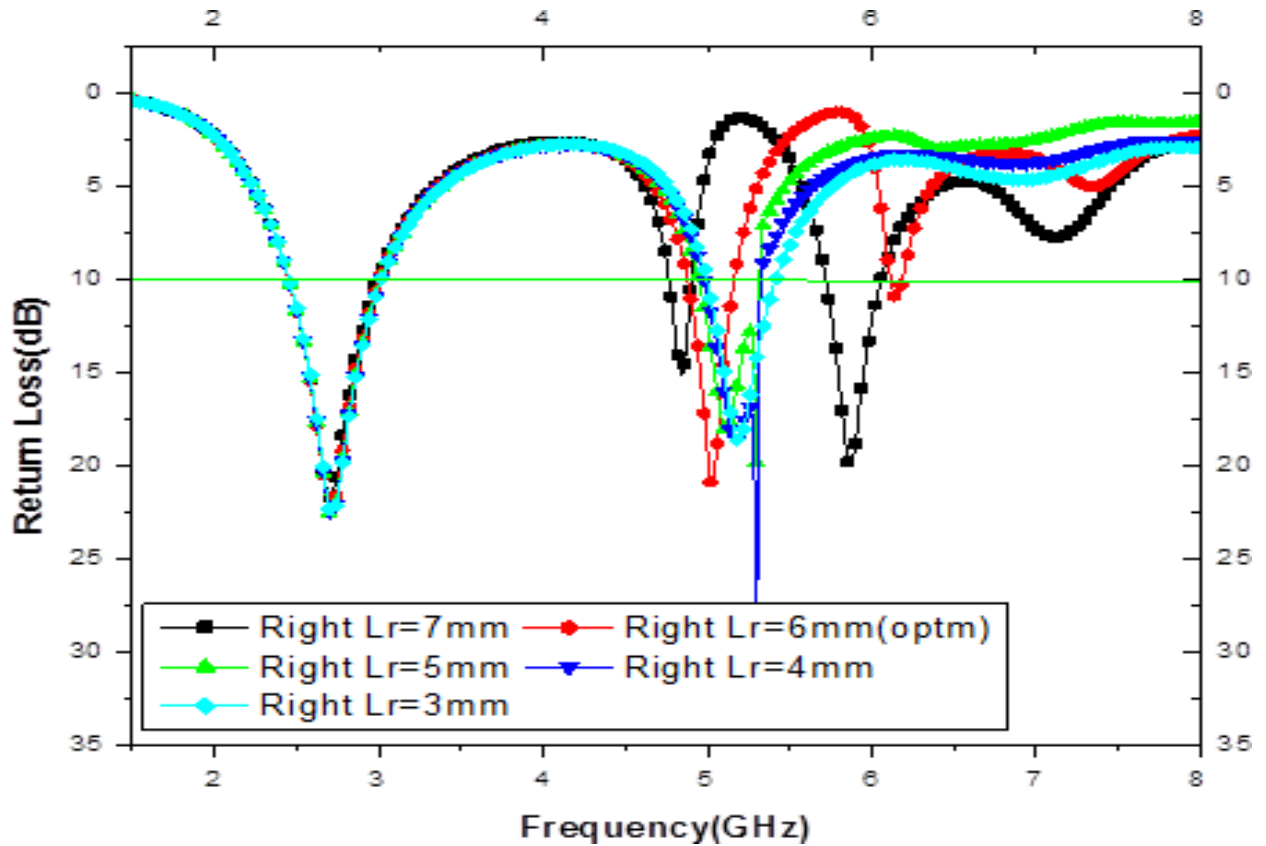


Figure 3.12 Effect of variation of slot length of DGS in the right ground plane

The width of the rectangular slots in the CPW ground is then varied to see their effect on the performance of the antenna. As depicted in the simulation results of Figure 3.13, the effect of variation of width of the slot in the left ground plane can be observed to affect the resonance frequency and the impedance bandwidth. The resonance at the desired value of 5.15 GHz is achieved by optimizing the value of the slot width at 0.5mm and increasing the value any further distracts the resonating value and also decreases the bandwidth.

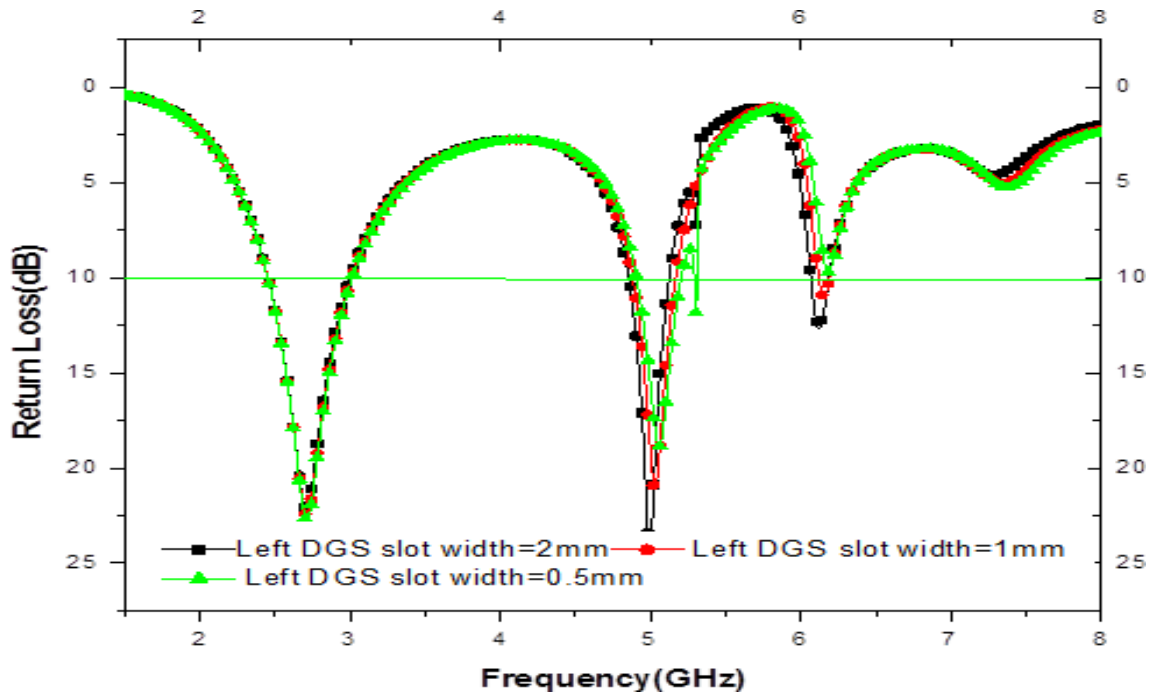


Figure 3.13 Effect of variation of slot width of DGS in the left ground plane

The slot in the right ground plane is then varied from a value of 0.5mm to 2mm, which shows the similar results as obtained for the left CPW slot (Figure 3.14), with the optimized value of slot width of 2mm to obtain the desired band at 5.15 GHz and required bandwidth. As the width of the slot is increased from 0.5mm the bandwidth is reduced in upper band. It does not have any impact on the lower frequency band as shown in Figure 3.14.

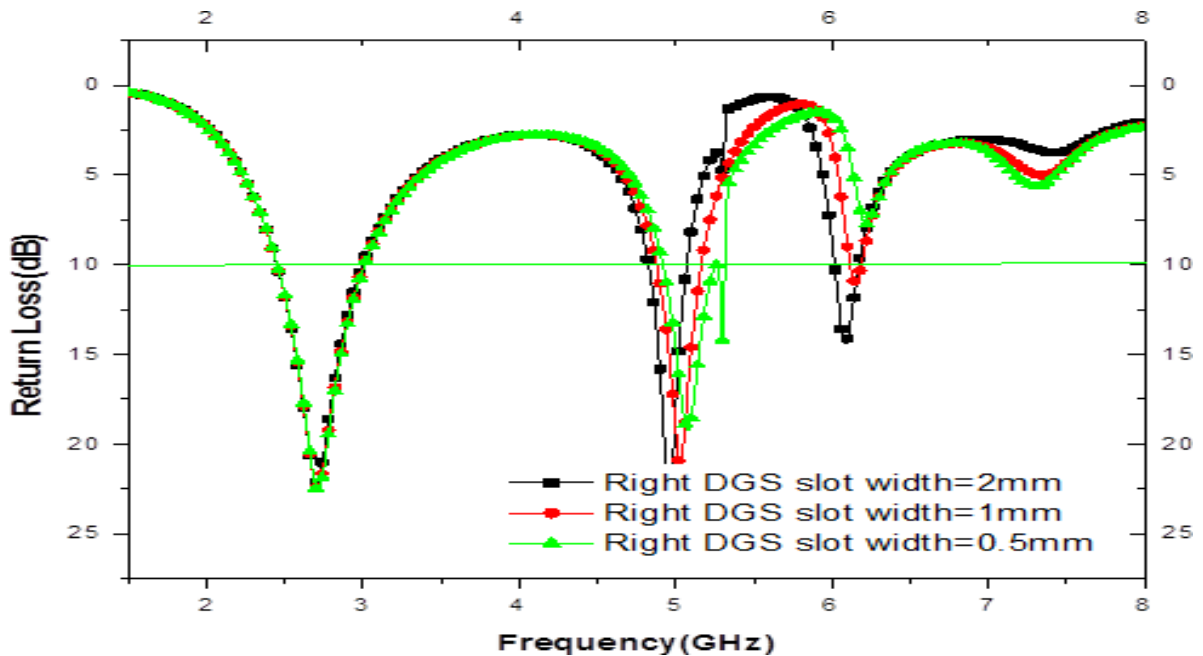


Figure 3.14 Effect of variation of slot width of DGS in the right ground plane

The position of the rectangular shaped slots on either CPW ground planes is varied to see if they have any significant impact on the return loss of the antenna. As seen in Figure 3.15, the slot in the left CPW ground is moved along y- axis from the central position of 6mm. The position is incremented up by 1mm, 2mm and 3 mm and decremented by 1mm, but it does not seem to have any significant effect on the return loss or the impedance bandwidth of the antenna.

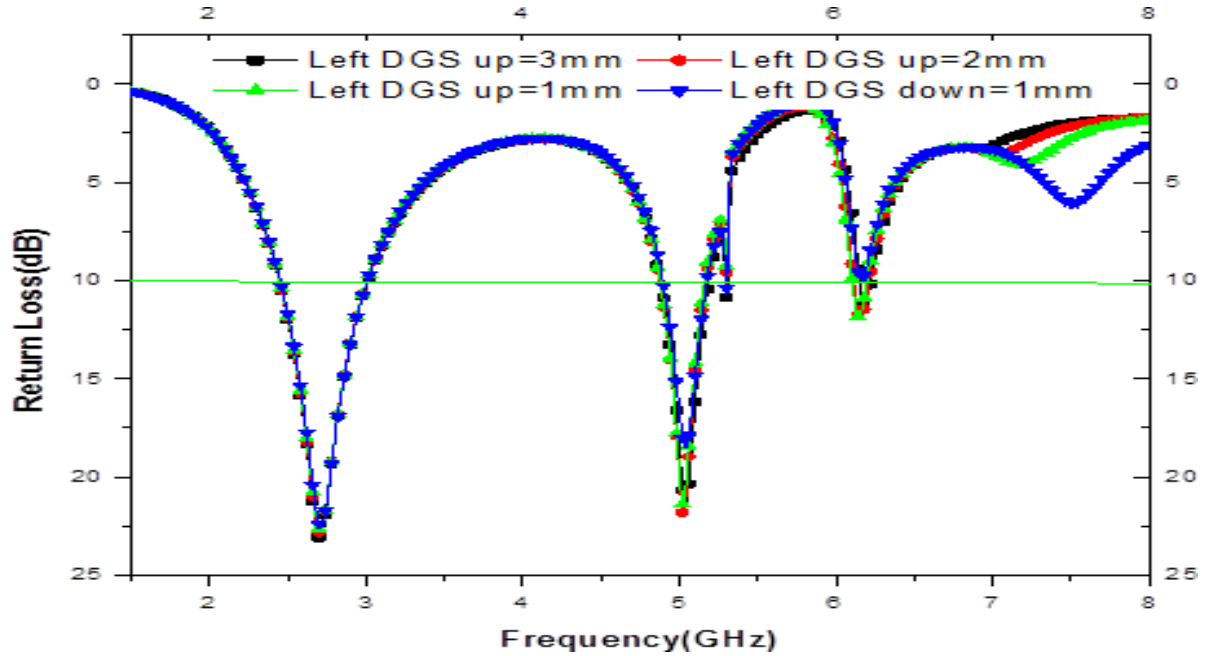


Figure 3.15 Effect of variation of position of slot in the left ground plane

Unlike the left slot, the variation of the location of the slot on right CPW ground has a substantial influence on the antenna performance as shown in Figure 3.16. Initially the slot is positioned at a distance of 1mm from the upper edge and moved down further to lie at a distance of 2mm, 3mm and 4mm which causes deviation in the upper band. For values 1mm, 2mm and 3mm, almost same results are obtained at the desired band of operation. At a value of 4mm, although a remarkable change is produced in the upper band, which gets shifted to 4.75 GHz with creation of an additional band at 5.8 GHz, this is not as desired. Therefore we choose 1mm to be the optimum value for positioning the slot in right ground plane.

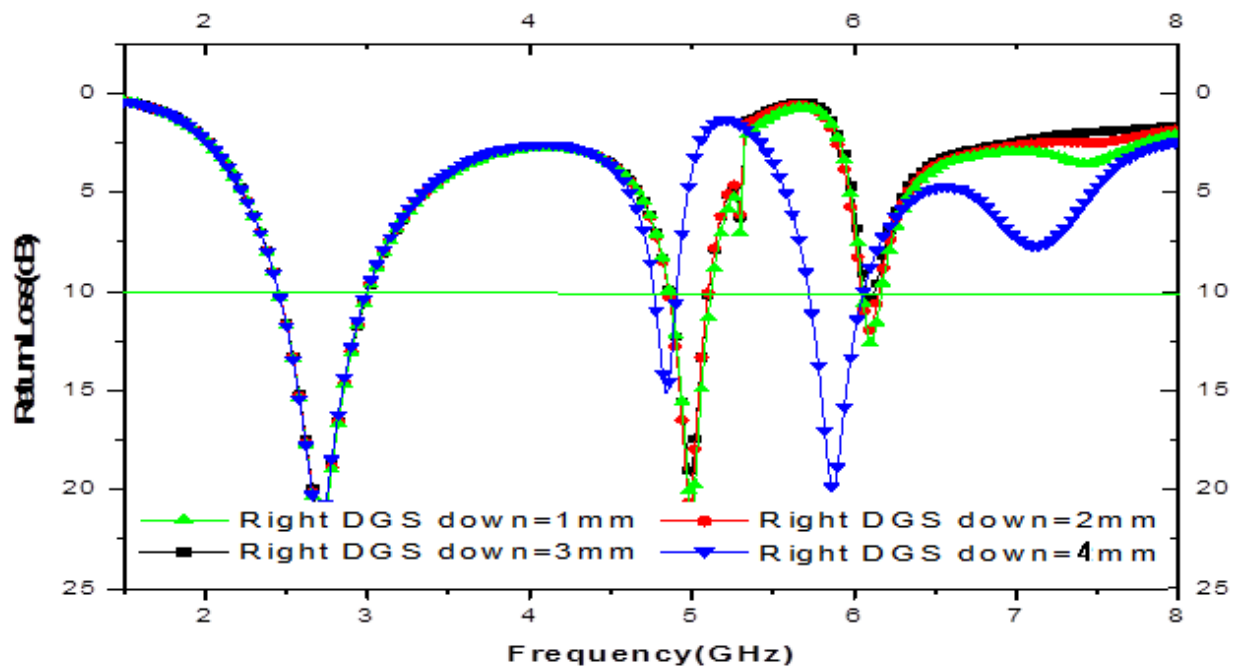


Figure 3.16 Effect of variation of position of slot in the right ground plane

3.3 OPTIMIZED DIMENSIONS OF THE PROPOSED ANTENNA DESIGN

After the parametric study, final configuration of the antenna, as shown in Figure 3.17 (a) and (b), is obtained by applying various modifications in the initial single ring design of antenna, represented in Figure 3.1. The optimized dimensions of the proposed antenna are summarized in Table 3.5.

Table 3.5 Final configuration of the proposed antenna

S.No.	Parameter	Size
1.	L_{p1}	7 mm
2.	W_{p1}	19 mm
3.	W_{p2}	15mm
4.	L_{p2}	22 mm
5.	w_1	2 mm
6.	w_2	2.4 mm
7.	$w_3 = w_4$	2 mm

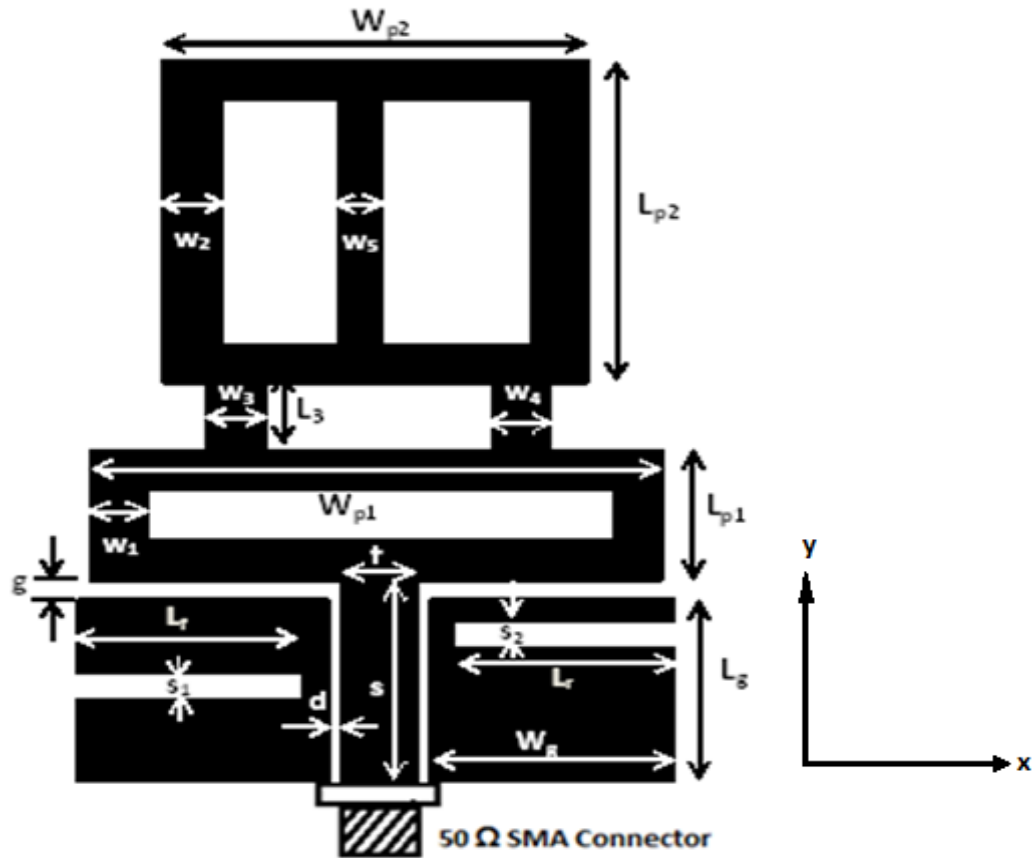
8.	w_5	1.5 mm
9.	L_g	11.25 mm
10.	W_g	7.2 mm
11.	S	12.77 mm
12.	T	3 mm
13.	D	0.6mm
14.	G	1.52 mm
15.	$s_1 = s_2$	1 mm
16.	L_f	5.64mm
17.	L_r	6mm

3.4 FINAL ANTENNA DESIGN AND GEOMETRY

Figure 3.17 illustrates the final designed geometry of the proposed MPA. It comprises of two variable sized rectangular rings printed on a copper layer of thickness 0.02mm. The antenna structure is fabricated on 1.6mm thick sheet of FR4 substrate material whose dielectric constant is 4.4. The antenna is excited by a CPW feed assembly which is designed and fabricated on the same plane as that of the main patch. It makes the design simpler and enhances the impedance bandwidth of the proposed antenna. Mainly, the CPW feed is formed of a single signal strip whose length is designated as ‘s’ and width as ‘t’. On both sides of the signal strip, lie two equi-sized, finite ground planes, each one with a length and width of L_g and W_g , respectively. The signal strip and the CPW ground planes on either side of it are separated by a gap whose distance is measured as ‘d’.

A rectangular patch of length L_{p1} and width W_{p1} is slotted to form a single ringed structure as shown in Figure 3.17 [181]. The width of the slotted patch/ring is specified as ‘ w_1 ’. Another large rectangular ring is incorporated in the single ring design with the help of two small parasitic strips of width w_3 and w_4 and same length L_3 . The outer dimensions of the large upper ring are $L_{p2} \times W_{p2}$. The width of the second slotted patch/ring is designated as ‘ w_2 ’. The slots

are then cut out from the on left hand side as well as right hand side CPW ground plane, which have dimensions of $L_f \times s_1$ and $L_r \times s_2$ respectively. The final structure of the antenna is constructed by adding a vertical strip of width ' w_s ', along the complete length of the large upper ring. The results of applying various modifications in the initial single ring design, in terms of structural variations and the dimensional variations are presented in the subsequent sections. The final antenna configuration, illustrated in Figure 3.17, is the upshot of different parametric variations applied to the preliminary design as demonstrated next.



(a) Top view



(b) Front view

Figure 3.17 Geometry of the proposed antenna

3.5 SIMULATED RETURN LOSS

The simulated return loss for the final configuration, after optimizing all the structural and dimensional parameters of the proposed antenna is presented in Figure 3.18. The figure shows that the proposed antenna has two resonance peaks at a frequency of 2.45 GHz and 5.15 GHz and cover considerable bandwidth. It is evident from the simulation results that the impedance bandwidth of the lower band is 400 MHz which swipes from 2.1 GHz to 2.5 GHz and 300 MHz for the upper frequency band extending from 5.05 to 5.35 GHz. The proposed antenna is capable of operation at 2.4 GHz WLAN band and at 5.1 GHz UNII 1/2 bands. Table 3.6 summarizes the simulated results of the proposed antenna.

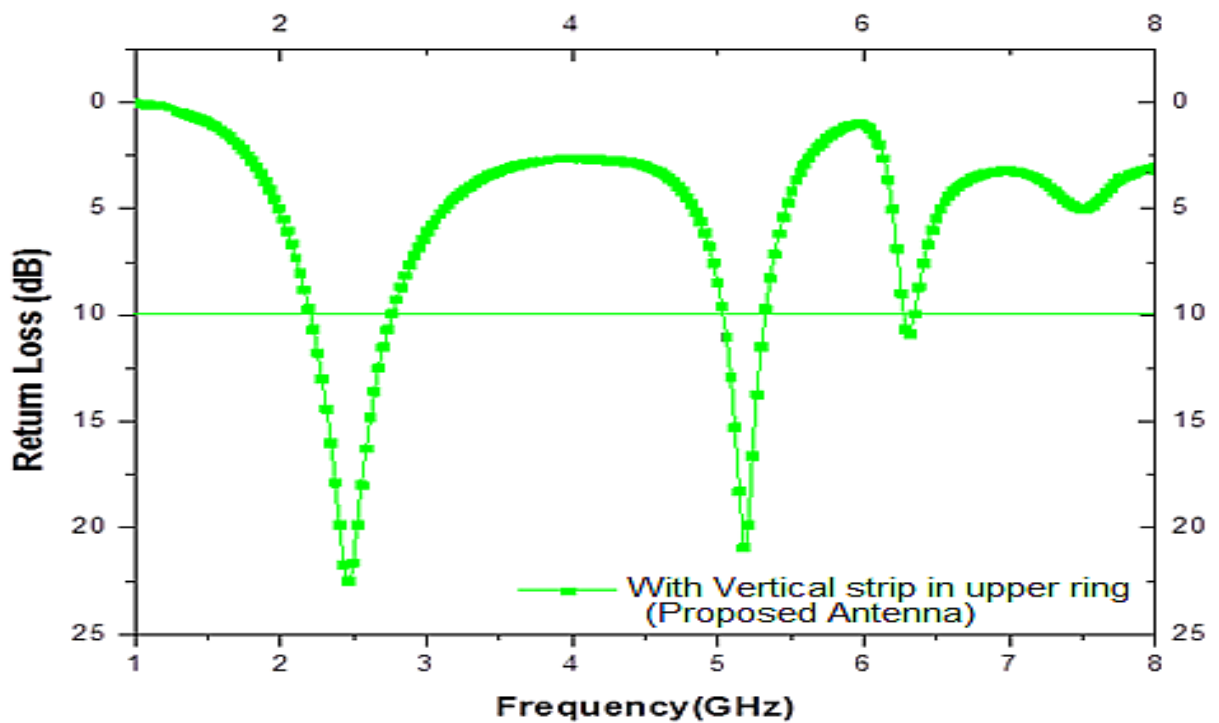


Figure 3.18 Simulated return loss of proposed antenna

Table 3.6 Simulated results of the proposed antenna.

Band	Frequency Range	Bandwidth	Peak Return Loss
2.4 GHz	2.1 - 2.5 GHz	400 MHz	-26.0 dB
5.1 GHz	5.05 - 5.35GHz	300 MHz	-21.5 dB

3.6 MEASURED RESULTS

The proposed antenna is fabricated on one side of the FR4 substrate using the wet etching photolithographic technique. The prototype of the final fabricated antenna structure is shown in Figure 3.19. It is tested for its performance in terms of return loss (S_{11} parameter), impedance bandwidth, radiation pattern and gain over the desired frequency bands. The measurements are as per procedure described in chapter 1.

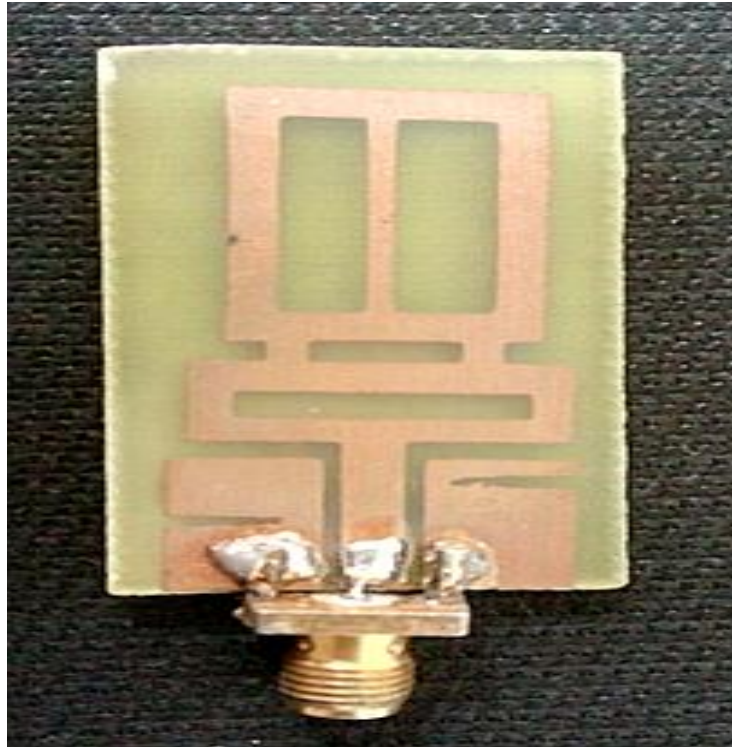


Figure 3.19 Prototype of fabricated antenna

The comparison of the measured results and the simulated ones is carried out and represented in next section plots which confirms and validates the simulated results except for minor differences at some frequencies, which could be due to imprecisions crept in during fabrication procedure, due to the misalignment of the cable feeding the antenna or the loading effect of connector.

3.6.1 Simulated and Measured Return Loss

The comparative measurements of S_{11} parameter at different frequency points are shown in Figure 3.20, which identifies a considerable value of return loss well below -10dB. The measured impedance bandwidth of the antenna over the operational bands is 450 MHz ranging from 2.20 to 2.65GHz in the lower frequency band and 450 MHz from 5.0 GHz to 5.45 GHz at

the higher frequency band. This much bandwidth is good enough to cover the proposed WLAN bands.

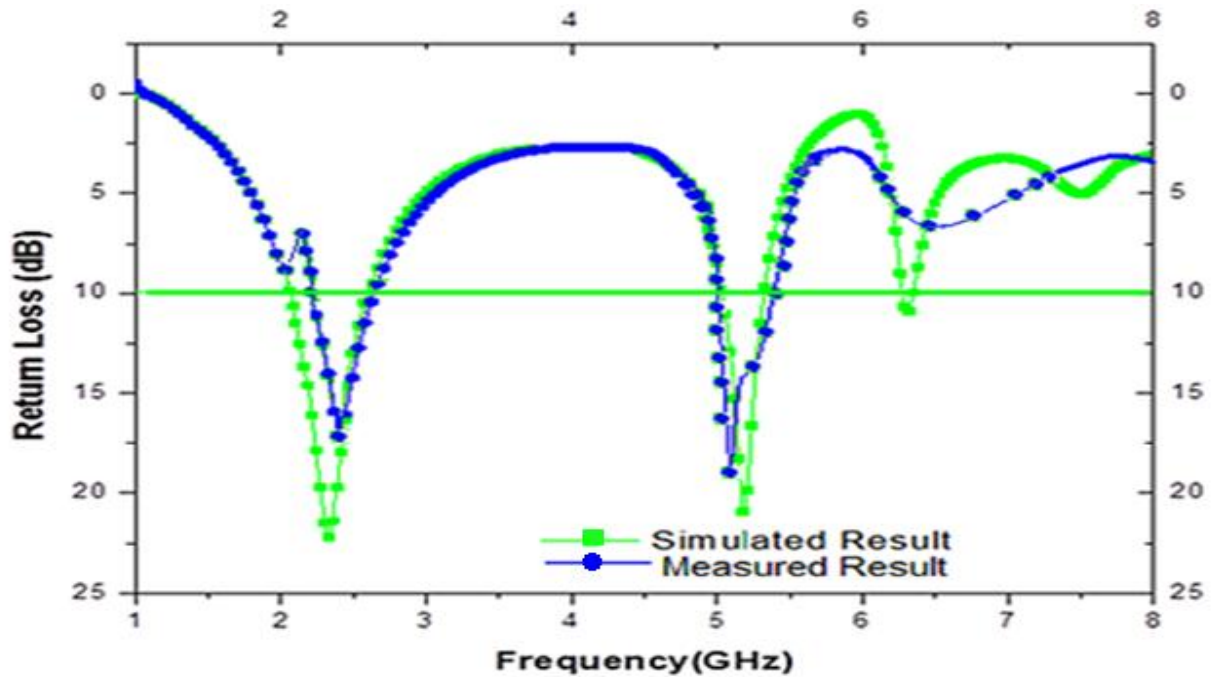


Figure 3.20 Comparative return loss curve of simulated and measured result of the proposed antenna

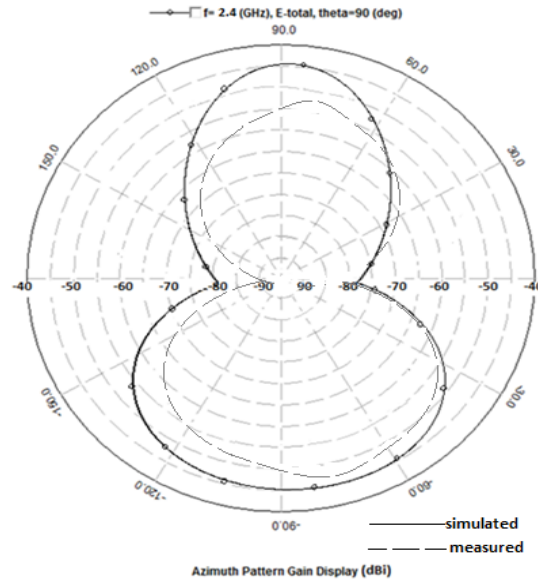
Table 3.7 Summary of the measured and simulated results of the proposed antenna.

Paramter →	Frequency of resonance	Band covered	Impedance	Return loss
Band ↓	Measured (Simulated) (in GHz)	Measured (Simulated) (in GHz)	Bandwidth Measured (simulated) (in MHz)	Measured (simulated) (in dB)
Lower Band	2.45 (2.4)	2.20 - 2.65 (2.1 - 2.5)	450 (400)	-21.9 -26.0
Upper band	5.15 (5.1)	5.0 - 5.45 (5.05 - 5.35)	450 (300)	-29.8 -21.5

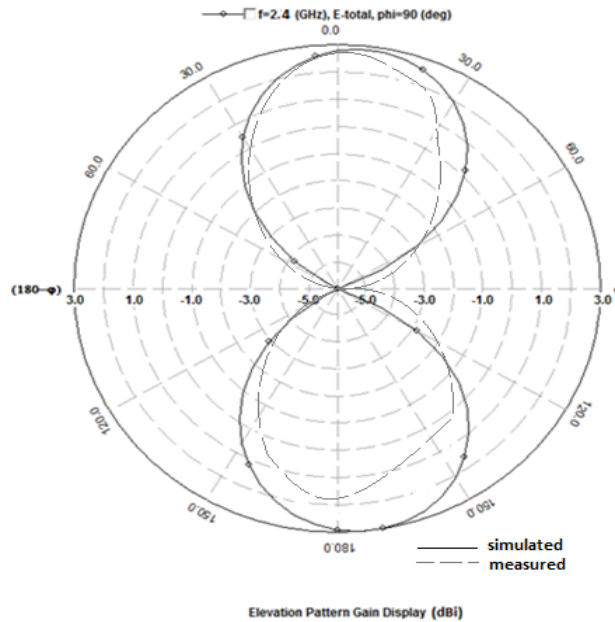
3.6.2 Simulated and measured Radiation pattern

The simulated and measured radiation pattern plots of the designed antenna are evaluated at different frequency values. The comparative simulated and measured radiation pattern plots obtained in the azimuthal plane and the elevation plane for lower frequency band i.e. at 2.45

GHz are displayed in Figure 3.21 (a) and (b) respectively whereas Figure 3.22 (a) and (b) depict the radiation pattern plots at upper frequency band at 5.15 GHz, respectively. The radiation pattern shows directional characteristics with two lobes in the azimuthal plane at frequency 2.45 GHz as well as at 5.15 GHz. Also, it represents a numeral character ‘8’ in the elevation plane, at lower as well as higher frequency band. Overall, it displays stable radiation patterns across the two functional bands of the antenna at 2.45 GHz and at 5.15 GHz, respectively.

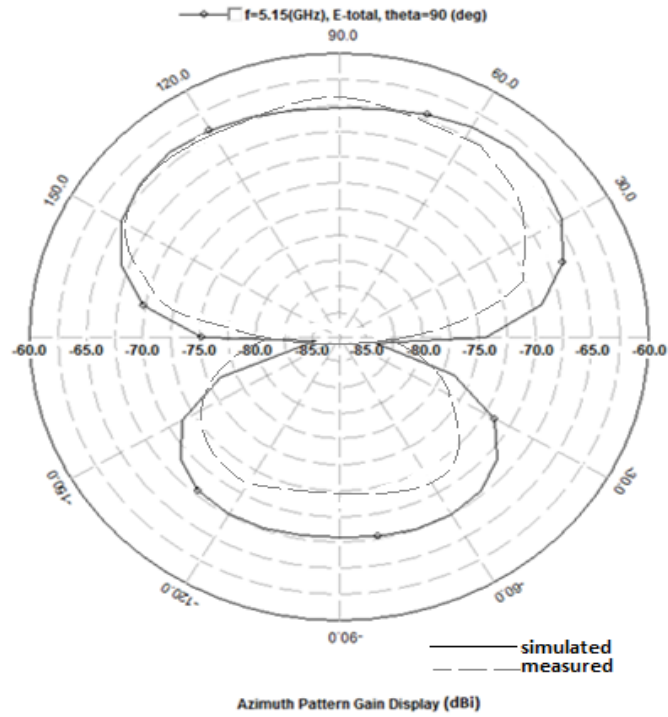


(a) Azimuth plane (at 2.45 GHz, $\theta=90^\circ$)

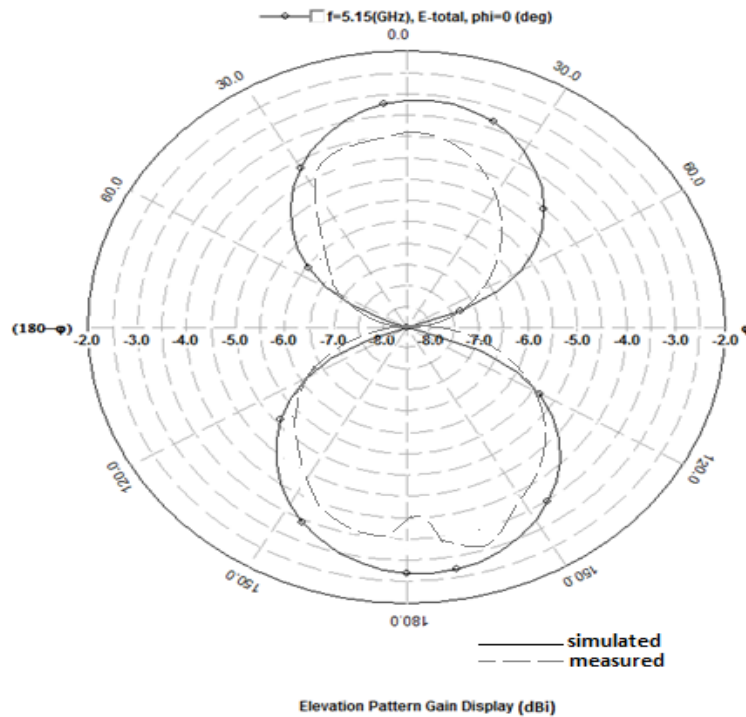


(b) Elevation plane (at 2.45 GHz, $\phi=90^\circ$)

Figure 3.21 Comparative simulated and measured Radiation pattern plot of proposed antenna at 2.4 GHz in (a) Azimuthal plane and (b) Elevation plane



(a) Azimuth plane (at 5.15 GHz, $\theta=90^\circ$)



(b) Elevation plane (at 5.15 GHz, $\phi=90^\circ$)

Figure 3.22 Comparative simulated and measured Radiation pattern plot of proposed antenna at 5.15 GHz in (a) Azimuthal plane and (b) Elevation plane

3.6.3 Simulated and measured Gain

Figure 3.23 demonstrates the simulated versus measured gain at different frequencies across the two bands for the proposed antenna. It exhibits ample gain values at the desired bands of operation. For the lower frequency band, the antenna gain swings from 4.6 dBi to reach a maximum value of 5.5 dBi, while at the higher operating band, the antenna gain offers small variation and most values are contained between 4.8 and 4.9 dBi. The proposed antenna fulfills the gain requirements of WLAN operating bands. The simulated and measured gain values obtained at two bands comply well with each other and represent acceptable values at both the bands.

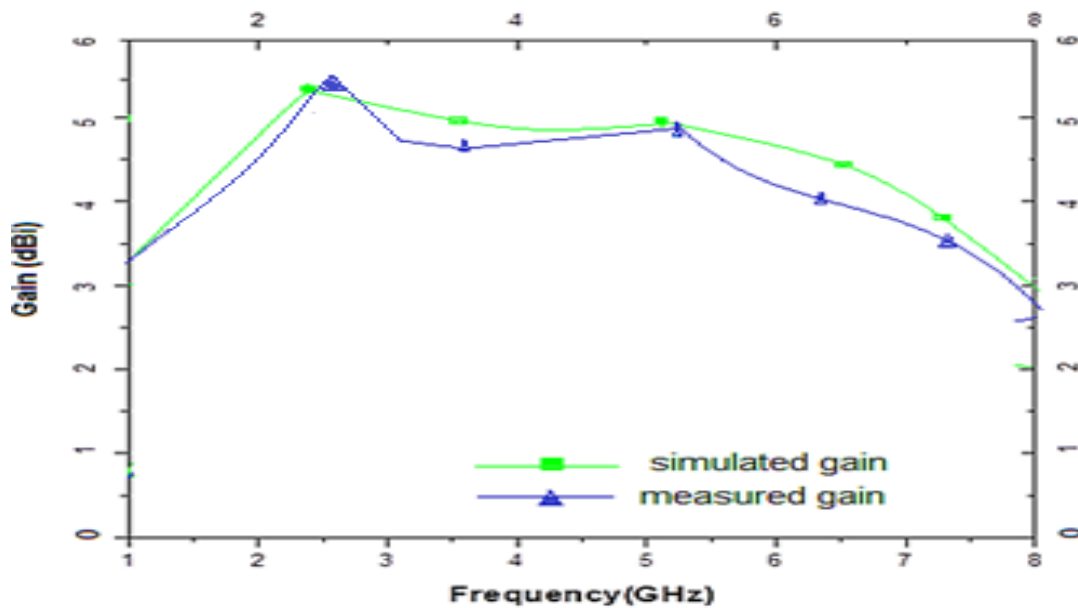


Figure 3.23 Simulated v/s measured gain of the proposed antenna

3.7 SUMMARY OF THE CHAPTER

In this chapter a planar rectangular ringed antenna with DGS in the CPW ground plane is designed and fabricated to work in homogeneous bands of WLAN standard. It provides acceptable return loss values at resonance peaks over the two frequency bands, ranging from 2.20-2.65 GHz (WLAN band) at lower frequency and from 5.0-5.45 GHz (UNII-1/ UNII-2 bands) at higher frequency, which is verified by experimental results. With the insertion of the slots into the CPW ground planes and segregation of larger ring into two by a vertical strip, the proposed antenna can provide sufficient impedance bandwidths and suitable radiation characteristics over the 2.4/ 5.15 GHz bands. Also, measurements of the fabricated prototype

confirm the simulated results of the proposed antenna. The lower band has an impedance bandwidth of 450 MHz with return loss of -16 dB and maximum gain value of 5.5 dBi. At the UNII bands, the impedance bandwidth of 450 MHz is achieved with return loss of -19 dB and gain value of 4.9 dBi at the maxima point.

The next chapter caters to the problem of interference whereby a UWB antenna with band stop characteristics is designed and then modified to work extensively for WLAN applications.

This work has been communicated as “CPW fed Rectangular Rings based patch Antenna with DGS for WLAN applications”, in Microwave and Optical Technology Letters.

CHAPTER 4

A MODIFIED COMPACT ULTRA WIDEBAND ANTENNA WITH BAND REJECTION FOR WLAN APPLICATIONS

4.1. INTRODUCTION

IEEE 802.15.3 standard is a Ultra Wideband (UWB) system, earlier known by the names of ‘carrier less signals’, ‘impulse’, ‘super wideband’ system. It represents a WPAN (Wireless Personal Area Network) technology that uses very low energy pulses for short distance communication over a vast range of radio spectrum with high bandwidth (more than 500 MHz) and high data rate[164]. Although UWB antenna has an advantage of wide bandwidth, a proper UWB antenna should have 500 MHz bandwidth or has at least, 0.2 fractional bandwidth. Therefore it is also called “wider than wide band”. UWB system is capable of determining the "time of flight" of transmissions at different frequencies which checks multipath propagation. Also, the pulses are of very short duration which prevents the signal reflections to overlap with the original ones, thus avoiding multipath fading. It is different from conventional system as the UWB communication does not interfere with conventional narrowband and carrier wave system located in the same frequency band [139-140].

UWB is also different from the spread spectrum system, in a way that its fractional bandwidth is quite low (less than 25%). UWB systems are used in non-cooperative radar imaging and precision locating, target sensor data collection and tracking applications. Due to wider frequency range and lesser power requirements, UWB antennas are being used for indoor wireless applications [164].

For any conventional system or a UWB system, antenna design is critical for its performance. Its performance, in terms of impedance matching, antenna radiation patterns and gains; should be consistent across the entire operational wide band. It should have preferably omni-directional or directional radiation characteristics for mobile/ hand-held systems or radar systems respectively. As UWB systems use short pulses for transmitting data and occupy huge bandwidth, pulse distortion should be minimum. Therefore it should have stable time domain

characteristics. Wireless standards such as WLAN (Wireless Local Area Network) and WiMAX (Worldwide Interoperability for Microwave Access) and UWB (Ultra Wide Band) standards are most sought after in a variety of wireless application areas [1, 2]. In next generation wireless communication systems they are bound to coexist in a device. Therefore, UWB antenna should have interference rejection capability, to allow other wireless applications and services to coexist in the same effective band [128,139,166-167].

It should be small, low profile and compatible to other integrated circuits and printed circuit boards (PCBs). The antenna should comply with the overall system design and the requisite power emission mask specified by FCC [168-171]. For a wireless standard device to operate along with UWB standard, we need separate antenna for each standard and a RF filter at the frontend. However by using electromagnetic bandgap (EBG) or defected ground structures (DGS) the need of RF filter can be avoided [158, 172-173]. Carbon nanotube (CNT), DGS (Defected Ground Structures) and EBG (Electromagnetic Band Gap) are effective candidates which are being used extensively for millimeter wave and microwave frequencies to implement such applications. EBG cells on ground plane underneath microstrip feed lines seem to support the development of stopband or passband characteristics [158, 174-177]. These features are being used in bandstop or bandpass filter applications to remove the unwanted frequencies and to scale down the size of microstrip antenna [166].

In this chapter a new methodology is adopted to improve the antenna performance using EBG filter structure that is incorporated in a UWB antenna in such a way that it is able to operate exclusively at WLAN bands with enhanced bandwidth. Hence, this design investigates the EBG based filter in UWB antenna configuration to achieve improved performance in both stopband and the passband.

Initially, a design of microstripline fed UWB antenna is considered which consists of a planar circular radiating patch and truncated ground plane to generate a bandwidth of 6.8 GHz. To facilitate its exclusive use in WLAN (Wireless Local Area Network) range, the UWB design is modified by modulating the microstrip feedline with filter to create a stopband from 5.9 GHz to 11.3 GHz thereby rejecting the extended C band and X band. The ground plane, beneath the microstripline, is also reformed by etching holes in it to form EBG structure which further helps to improve the stopband performance. It also enhances the performance of the two passband bands generated, which extend from 1.97 GHz to 2.65 GHz and 3.12 GHz to 5.86 GHz. The antenna is capable of operation over the entire ISM range of WLAN bands (from 2.40-2.484

GHz, 5.150-5.350 GHz, and 5.725-5.825 GHz). The various modifications to the initial antenna design and its parametric variations are presented in the subsequent sections.

4.2. PARAMETRIC STUDY

To inspect the performance of the proposed antenna structure, parametric study of the proposed antenna is done in terms of structural and geometrical variations to obtain optimum structure and geometrical parameters to achieve the desired results. In the parametric study, the value of a particular parameter is varied at a time keeping the others constant. The parametric variations are implemented in the structure as well as dimensions of the antenna.

To present the structural variations, step by step modifications in the antenna structure are shown along with its return loss (S_{11} parameter), confirming its effect on the performance of the antenna. The dimensional variations in the various parameters of the antenna are implemented using sweep tool in CST MWS software which shows the results for different values considered for each variation in a combined graphical form. The influence of different parameters on the performance is presented in this section. The circular patch is considered as the radiating patch with microstripline feeding the antenna in the same plane and truncated ground plane, as shown in Figure 4.1 (a) and (b) and an additional sweep is applied to the radius of the patch to obtain the ultrawideband characteristics.

4.2.1 Initial configuration of antenna

Initially, a circular shaped radiating element is constructed on FR4 substrate. Truncated ground plane is used along with the circular radiator to achieve ultrawideband operation. The initial configuration of the antenna is shown in Figure 4.1 (a) and (b). Dimensional variations are applied on the radius of the patch using the sweep tool in CST software as shown in Figure 4.2. Simulation results using optimized value of radius of the circular patch, $R=12$ is presented in Figure 4.3, representing return loss with respect to frequency.

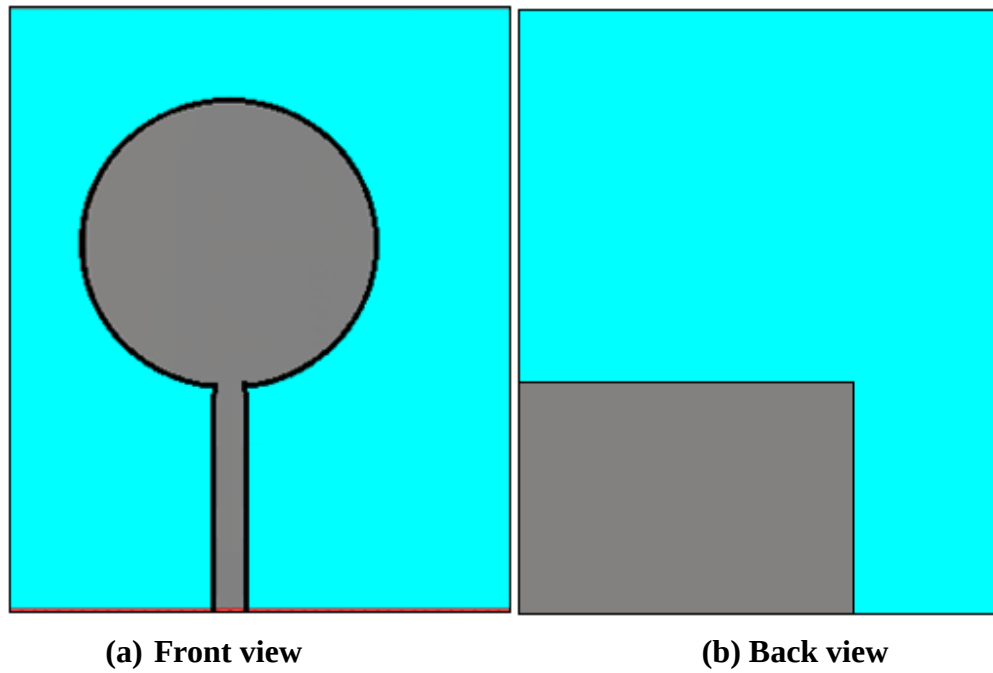


Figure 4.1 Initial UWB Antenna structure

4.2.2 Effect of variation in the radius of radiating circular patch:

The variations are applied on the radius 'R' of the radiating circular patch and the corresponding return loss is examined to see its effect (as shown in Figure 4.2). It is clear from the Figure 4.2, that the value of radius below 12mm does not yield the required bandwidth as the return loss of the curves obtained lie above -10 dB standard value. For values of radius greater 12 mm the antenna starts behaving as ultrawideband. But the best possible curve that has appropriate return loss value is for the radius measurement of 12mm which has highest value of return loss compared to all the values of radius of the main patch. So the optimized value of radius is 12mm with return loss value approximating -63 dB at a frequency of 2.6 GHz.

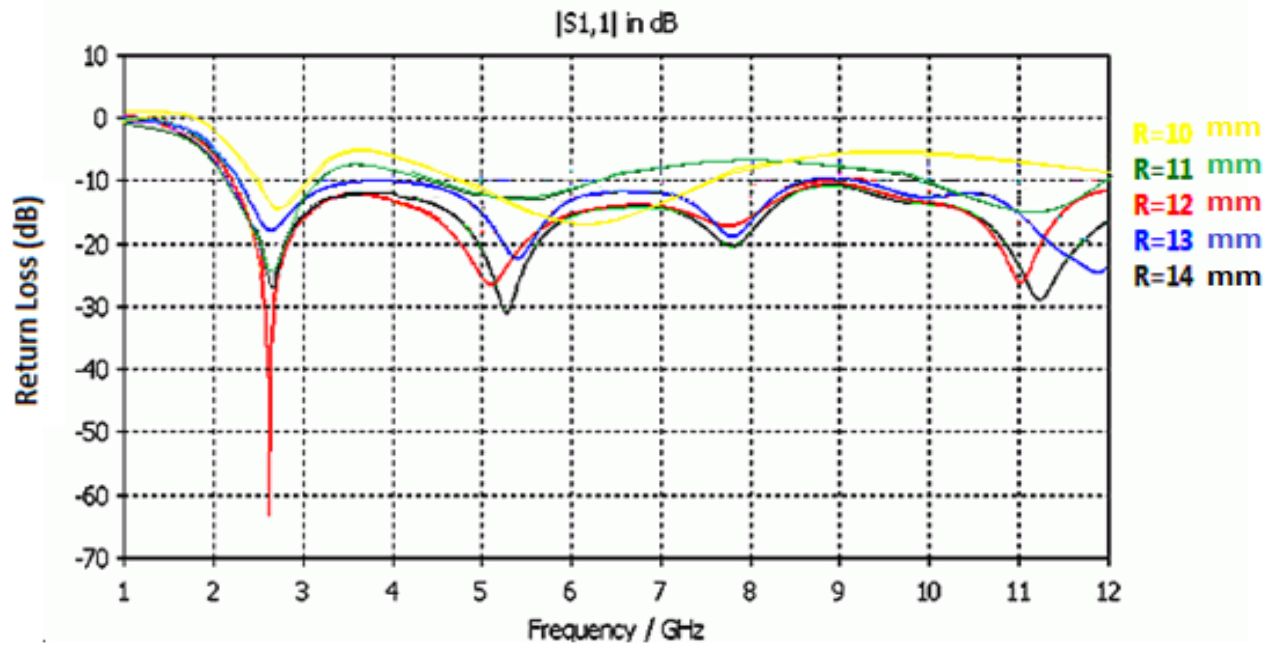


Figure 4.2 Effect of variation of radius of circular patch in terms of S_{11} parameter with respect to frequency.

4.2.3 Simulated Result

The simulated S_{11} parameter graph shows that the antenna radiates over a wide frequency range from 2.2 GHz to 9 GHz achieving wide bandwidth of 6.8 GHz. The return loss value of -52.5dB is obtained at the resonance peak.

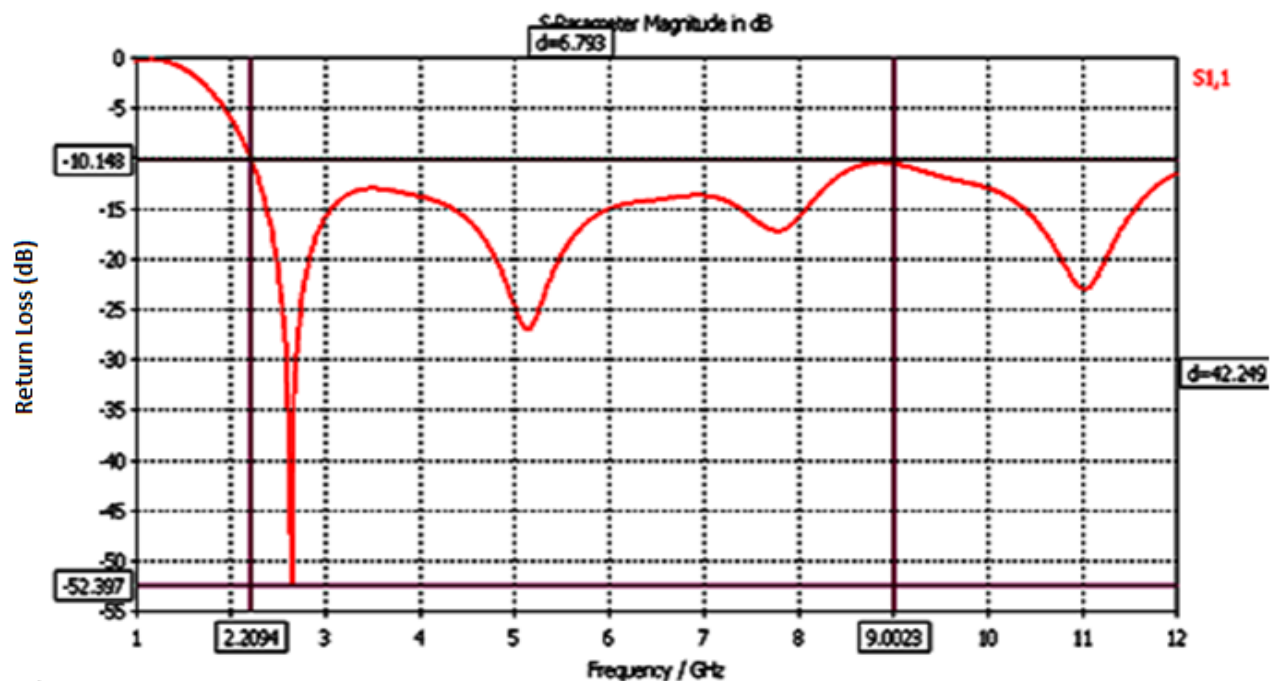


Figure 4.3 Return loss of the initial UWB configuration of antenna.

4.2.4 Microstrip Filter Structure

In order to reject the upper band from the antenna response, a microstrip filter structure is formed by modulating the microstrip line of the initial structure. The microstrip line is modulated with square patches inserted periodically in it as shown in Figure 4.4. The modified antenna design with square patches is based on Bragg Reflection condition [25]. The length and width of the patch is represented by l_a and w_a respectively. The width of the microstrip line is w_f . In this structure, the range of w_a is expressed as:

$$w_a > w_f \quad (4.1)$$

The difference in dimensions of the microstripline and the width of square patches creates an EBG edifice. The structure formed varies the coupling between the microstrip feed and the ground plane. This planar EBG structure reveals a bandgap when the Bragg reflection condition is satisfied [25]. The distance amidst the centers of two neighboring patches is specified by 'd', also known as period of the structure. According to Bragg reflection condition:

$$\beta \cdot d = \pi \quad (4.2)$$

where; β is the guided wavenumber in the substrate material given by:

$$\beta = \frac{2\pi}{\lambda_g} \quad (4.3)$$

Guided wavelength λ_g is given by:

$$\lambda_g = \frac{c}{f_o \sqrt{\epsilon_{\text{eff}}}} \quad (4.4)$$

where; c is the speed of light in free space, f_o is the center frequency of the stopband and ϵ_{eff} is the effective permittivity of the substrate [2] given by:

$$\epsilon_{\text{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2\sqrt{1 + \frac{12h}{w}}} \quad (4.5)$$

Using equation (4.2), the period 'd' equals half the guided wavelength given as[25]:

$$d = \frac{\lambda_g}{2} \quad (4.6)$$

4.2.5 Effect of addition of square patches in the microstripline

For a center frequency of 9 GHz for the stop band and dielectric constant and height of substrate as 4.4 and 1.6mm respectively, using the relation described above, the period 'd' of the patches obtained is 9mm and the length and width of the inserted patches in the microstrip line are both fixed to 5mm. This structure creates a stop band in the frequency response of the antenna as discussed next.

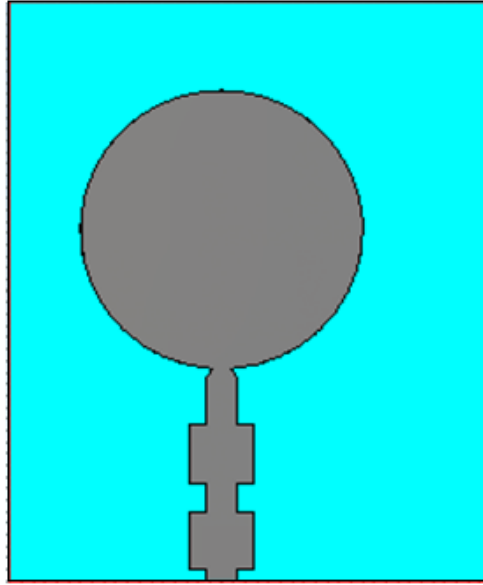


Figure 4.4 UWB antenna with modulated microstripline feed.

4.2.6 Effect of variation of width of square patches in the microstripline:

Parametric sweep is applied to the width of the patches and the results are plotted in terms of return loss with respect to frequency. Initial value of the width of the square patch is taken as 2.5 mm. Sweep is then applied to vary the width of each square patch, w_a , along the y axis taking five samples at intervals of 1mm to find the optimized value. The effect of variation of width of square patches is presented in Figure 4.5. For $w_a = 2.5$ mm, it is observed that the stop band response is very poor and antenna is not able to reject higher frequencies. For $w_a = 3.5$ mm, it creates a stop band at 6.99 GHz with reasonable stopband characteristics. At $w_a = 4.5$ mm, the stopband shifts to a lower frequency of 6.32 GHz with improved attenuation at the stop band which extends to even higher frequencies. By increasing the value of w_a any further does not generate clear stop band in the response. Therefore the best value obtained for the width of square patch is 4.5mm.

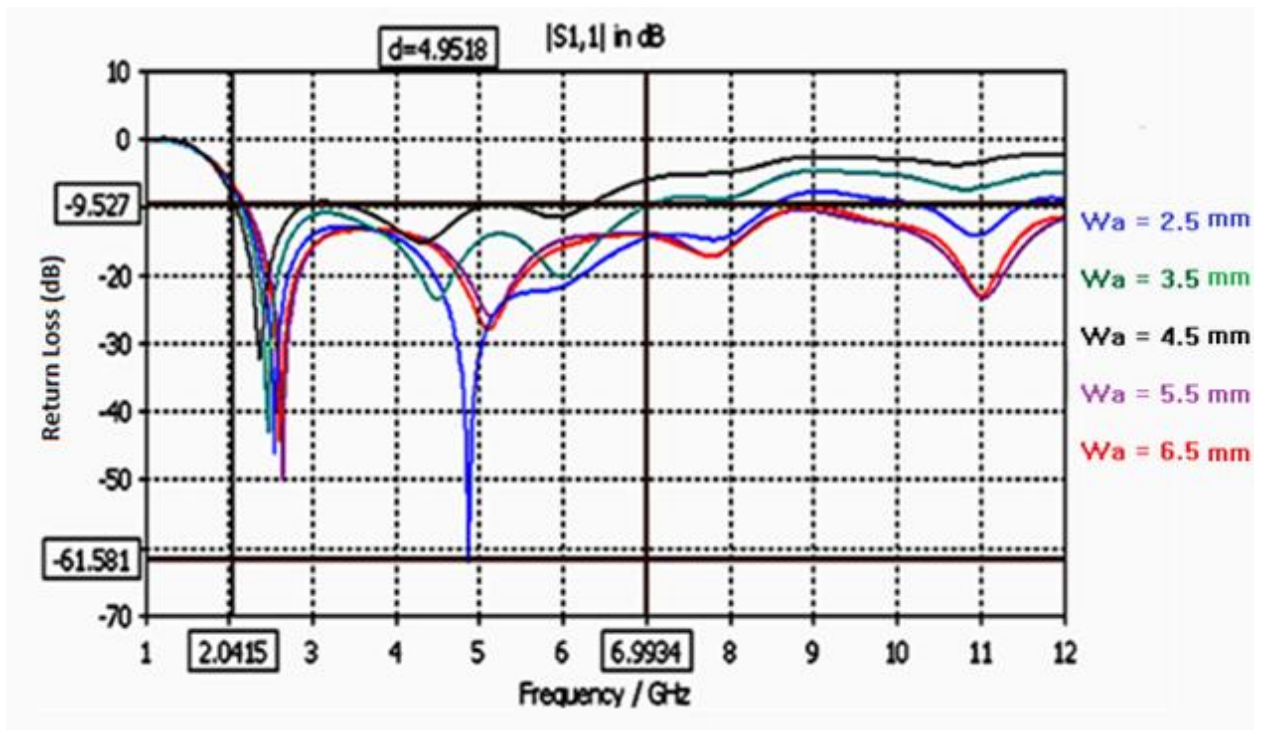


Figure 4.5 Effect of variation of width of square patches inserted in the microstripline in terms of S_{11} parameter with respect to frequency.

4.2.7 Effect of variation of length square patches in the microstripline

Figure 4.6 shows the effect of variation of length of the square patches on the performance of the antenna. Since we want the antenna to resonate in the WLAN frequencies, we need to reject frequencies above 5.85 GHz. Keeping this objective in mind, the microstripline is modulated and the length of the square patches is swept across different values along x axis, using sweep tool in CST design software, to achieve an optimized value. Initial value of the length of the square patch of microstripline filter is taken as 4mm. The variable length ' l_a ' of square patch is increased from 4mm to 5mm in step size of 0.5mm. The three values of the length of the square patch have been shown to be tested in Figure 4.6. For $l_a = 4$ mm, the lower cut off frequency of the filter lies at 7.15 GHz which is undesirable for our design. For $l_a = 4.5$ mm, the stop band occurs at the desired frequency of 6 GHz with clear and distinct stop band from 6 – 11.19 GHz. On increasing the value of l_a any further, the stop band tends to shift to higher values and overall bandwidth of stopband reduces. Therefore, $l_a = 4.5$ mm is considered the best value since the antenna reject all frequency values above 6 GHz and generates continuous pass band from 2.0 GHz to 6.0 GHz, which is required for the operation of the proposed antenna over the WLAN bands.

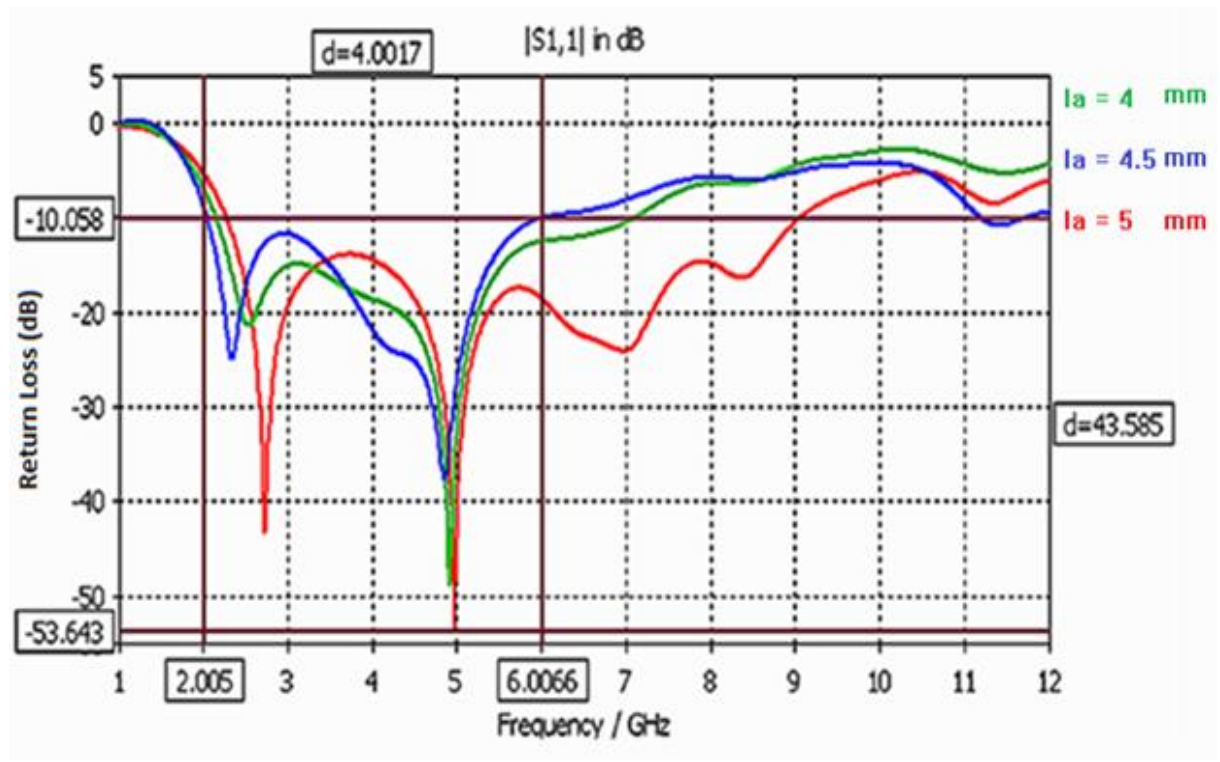


Figure 4.6 Effect of variation of length of square patches inserted in the microstripline in terms of S_{11} parameter with respect to frequency.

Therefore the final values of the width ' w_a ' and length ' l_a ' of the patches inserted in the microstripline obtained after applying variations along y and x axis, respectively, are $w_a = 4.5$ mm and $l_a = 4.5$ mm respectively. The bandwidth of stopband can be controlled by altering the width of the patches on the modulated microstripline.

4.2.8 Simulated Result

Figure 4.7 shows the return loss characteristics of the circular antenna with modulated strip line structure. It is apparent from the simulation results that the addition of the square patches in the microstripline feed of the antenna has a remarkable effect on its impedance bandwidth. The antenna rejects all frequencies above 5.9 GHz, thereby discarding the extended C band and X band. It also creates a single wideband extending from 1.93 GHz to 5.94 GHz with significant return loss value of -55dB. The stop band ripples exist at higher frequency of 11.5 GHz with return loss of -13 dB. The maximum stop band attenuation is -3 dB.

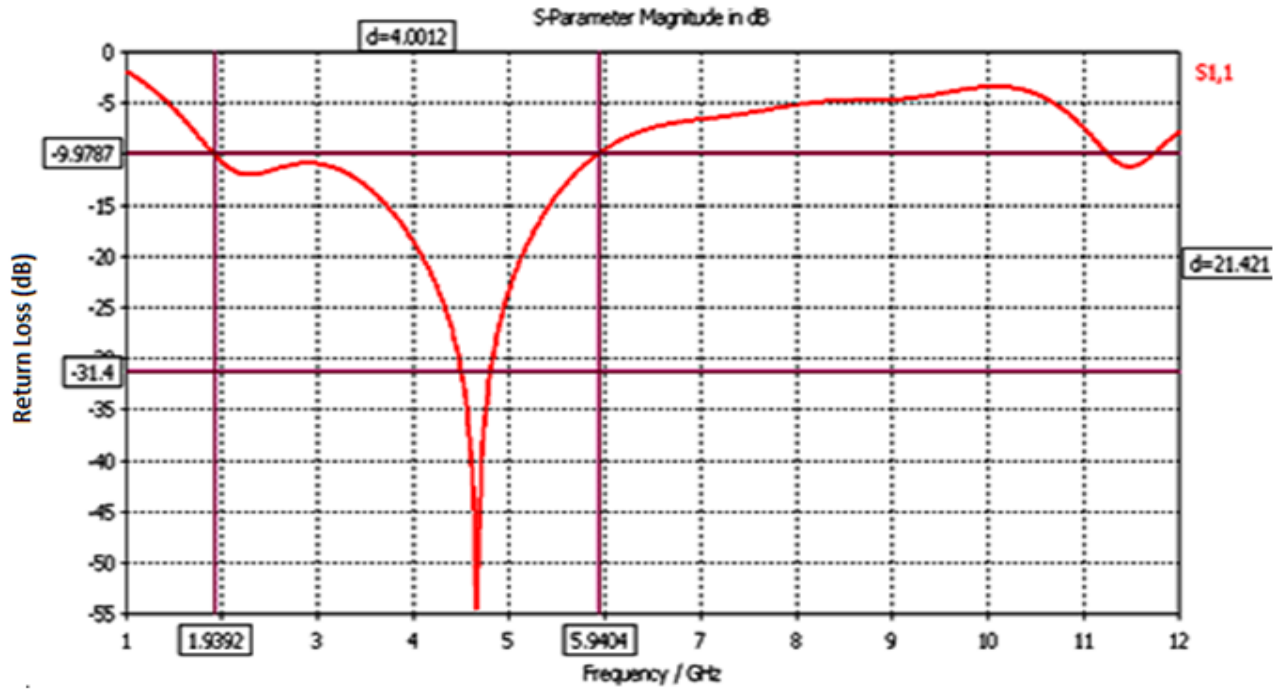


Figure 4.7 Return loss of UWB antenna with modulated microstripline feed.

4.2.9 EBG based Microstrip Structures

To improve the response of filter and its characteristics, an EBG based microstrip structure consisting of a single column of circles with uniform dimension is etched in the ground plane below the modulated microstrip line to form a typical 1-D planar EBG structure. By etching circles in the ground plane, the coupling between the microstrip line and the ground plane is reduced. This 1-D planar EBG structure also satisfies the Bragg reflection condition and the period of the structure ' d_1 ' can be obtained, where d_1 is the distance between the centers of the two adjacent circles.

A single column of ' n ' circles are etched in the ground plane. In this thesis we have designed the structure with $n = 4$, as shown in Figure 4.8. The ratio of r_0 (radius of uniform circles) and d_1 is called the filling factor which indicates the relative size of the EBG cell to the period of the structure. For no overlap between any two adjacent circles it ranges from 0 to 0.5 for radius of the uniform circles as r_0 . However, for an EBG structure with uniform distribution, the large filling factor indicates a wide and deep stopband while increasing ripple level in the passband. The optimum value of r_0/d_1 is found to be 0.25, where a good compromise between the stopband and passband performance can be obtained [33].

4.2.10 Effect of addition of circular defects in ground plane beneath microstripline

The circular periodic EBG structures are formed in the reduced ground plane of the antenna which creates passband with modified characteristics for WLAN bands. Four uniform circles are etched on the ground plane underneath the length of modulated microstripline feed. It thus helps to create multibanding in the antenna by segregating a single wider band into two bands with three resonant peaks. The initial radius of the circles, r_0 , is taken to be 2.5 mm which causes the antenna to resonate at two operational WLAN bands. Since it creates overlapping of the circles, therefore sweep is applied to find another suitable value for the radius of the circles etched in the ground plane beneath the microstripline.

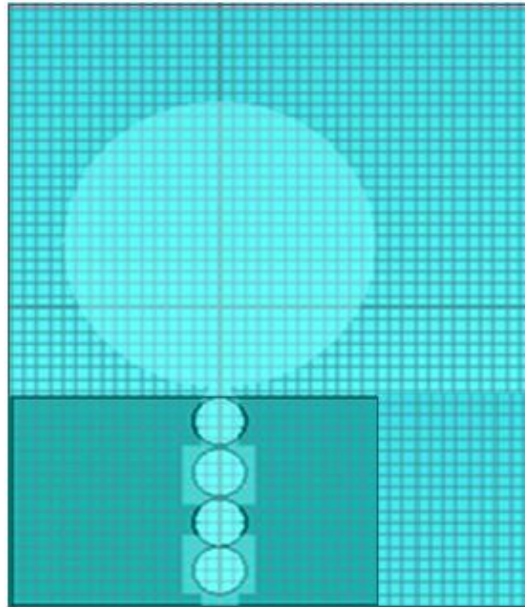


Figure 4.8 UWB antenna with a column of four circles etched in reduced ground plane

4.2.11 Effect of variation of radius of circular defects beneath the microstripline:

The effect of variation of radius of the circles etched in the ground plane is shown in the Figure 4.9. For the value of radius, $r_0 = 2.5\text{mm}$, the return loss at the lower band, resonating at 2.45 GHz presents a value of approximately -20 dB and significant value of -45 dB and -39 dB at the higher frequency band which has dual peaks at 4GHz and 5 GHz respectively. But, this increases the size of the circles and it becomes difficult to accommodate it below the microstripline as it results in overlapping of circles. For $r_0=2\text{mm}$, there is a considerable fall in the return loss values at the upper band as is evident from the Figure 4.9. For $r_0 = 1\text{mm}$, the two distinct dual bands with three sharp resonant peaks is obtained with permissible return loss of -20

dB at the lower band and -37 dB at the higher band. Also the attenuation band is widened towards higher frequency.

Thus, to avoid overlapping of the circles and to maintain a noble value of return loss at both bands, the radius of circles is optimized at 1mm, for which the two bands are obtained. The lower band resonates at 2.45 GHz and has a impedance bandwidth of 600 MHz from 2.15 GHz to 2.75 GHz and the second wideband is obtained ranging from 3.2 GHz to 5.6 GHz forming two return loss peaks of values -36 dB and -37 dB.

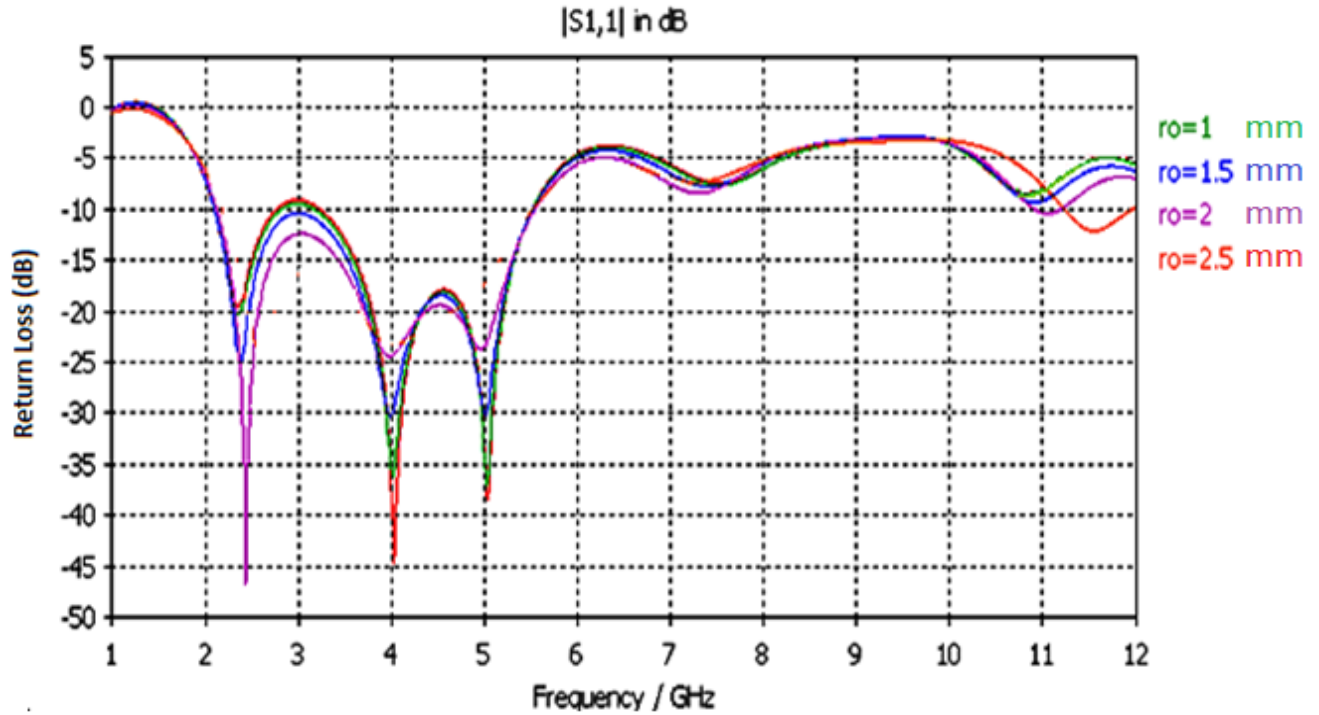


Figure 4.9 Effect of variation of circles etched in the reduced ground plane in terms of S_{11} parameter with respect to frequency.

4.2.12 Simulated Result

The return loss of the proposed antenna with optimized EBG filter structure is obtained using S_{11} parameter, as demonstrated in Figure 4.10 (a). It has been observed from the simulation results that the proposed antenna has a capability to reject the frequencies higher than 5.9 GHz. Figure 4.10 (a) show that the antenna attains remarkable return loss and the impedance bandwidth at the two bands. The lower frequency band, ranging from 1.97 GHz to 2.65, attains a bandwidth of 681 MHz and return loss value of -31.93 dB. The upper band forms quite a wideband which extends from 3.12 GHz to 5.86 GHz, having an impedance bandwidth of 2.74 GHz and return loss of -47.95 dB. The values are quite appropriate for operation in all the ISM bands of WLAN standard at 2.4 GHz, 5.2 GHz and 5.8 GHz with the good bandwidth.

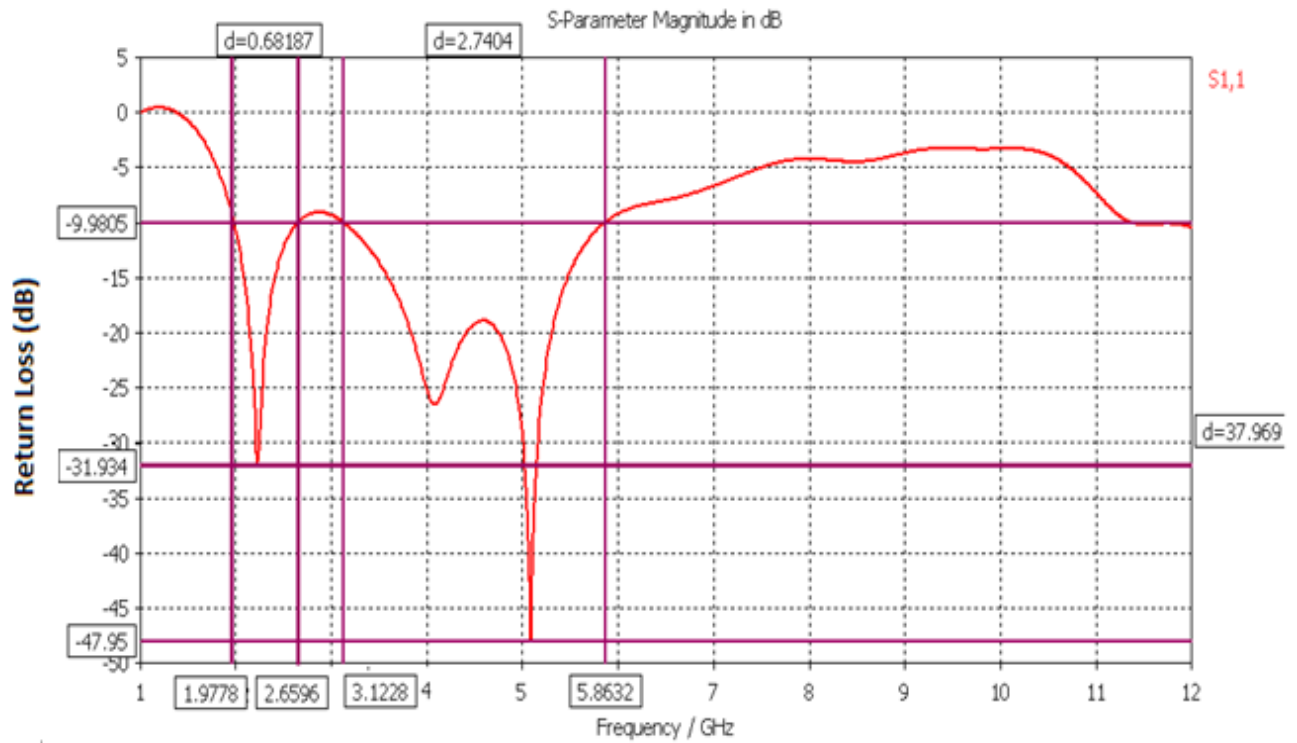


Figure 4.10(a) Return Loss of UWB antenna with modulated microstripline feed and circles etched in reduced ground plane

It is also observed that by using EBG filter structure along with microstrip line structure, the attenuation in stop band increases by 2 dB at a frequency range of 7.5 to 9.5 GHz. Also the attenuation band gets extended towards higher frequency. Moreover, the ripples in the band decrease by a value of 5 dB.

As shown in Figure 4.10 (b), the value of VSWR lies between 1 and 2 over the range of two pass bands from 1.97 GHz to 2.65 GHz and 3.12 GHz to 5.86 GHz and it attains values higher than 3 for the rejected band which verifies the creation of stop band from 5.9 GHz to 11.3 GHz.

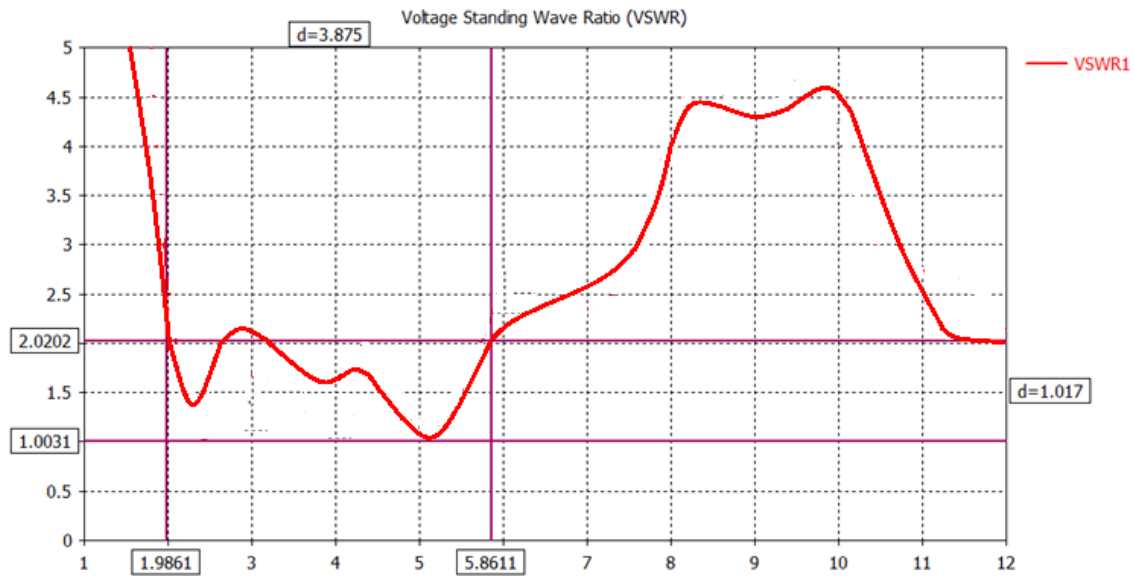


Figure 4.10(b) VSWR for the proposed antenna

4.3 OPTIMIZED DIMENSIONS OF THE PROPOSED ANTENNA

After the parametric study is completed by carrying out the variations in the geometrical as well as dimensional parameters, the optimized dimensions of the antenna are found, which optimize the performance of the antenna. The final values of all the parameters which have been optimized using sweep variations are shown in Table 4.1.

Table 4.1. Optimized dimensions of the proposed antenna.

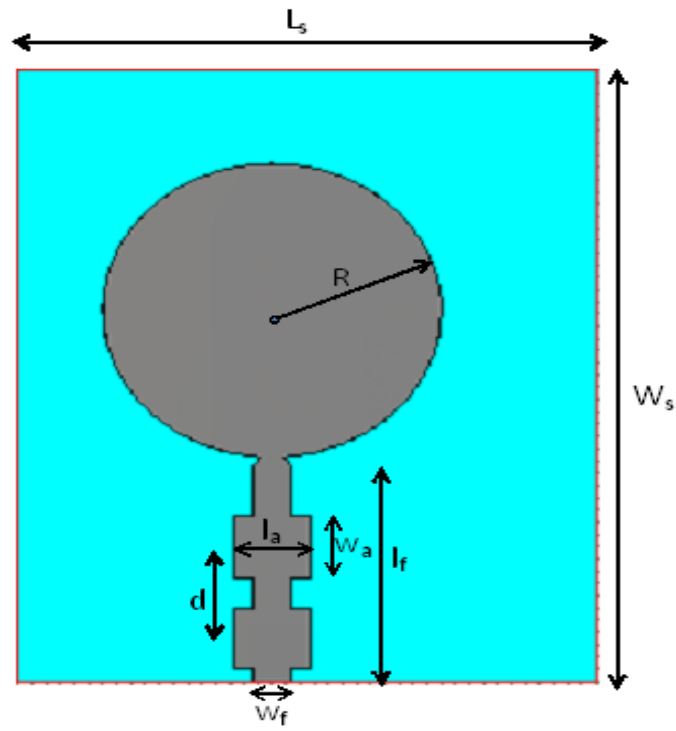
Parameter	Dimension (in mm)
L_s	40mm
W_s	50mm
L_g	30mm
W_g	17.5mm
R	12mm
l_f	18.5mm
w_f	2.6mm
l_a	4.5mm

w_a	4.5mm
d	9mm
r_o	1mm
d_1	4mm

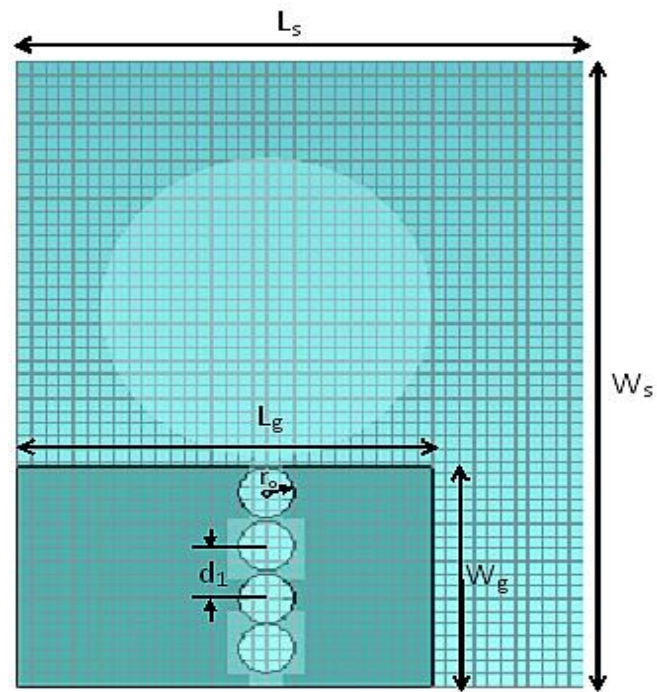
4.4 ANTENNA DESIGN

The final configuration of the antenna designed for WLAN applications is illustrated in Figure 4.11 (a) and (b). It involves the use of a planar disc or circular shaped radiating element of radius ‘R’ and a reduced ground plane of 30mm x 17.5mm to construct a UWB antenna, constructed on FR4 substrate material. The substrate dimensions are 40 x 50 mm² ($L_s \times W_s$) and the thickness of the sheet measures 1.6 mm. A reduced ground plane of PEC (Perfect Electric Conductor) material is imprinted on one side of the FR4 substrate sheet and a circular radiating patch element of radius $R = 12$ mm is placed on the other side of the substrate sheet. It is located in the x–y plane, centered at (0, 5.3, 0) in the Cartesian coordinate system. The circular patch is connected to a 50 Ω microstrip feed of length, $l_f = 18.5$ mm and width, $w_f = 2.6$ mm. The microstripline feed ends in a waveguide port which provides the path to power up or excite the antenna to cause radiation. The dimensions of the antenna are optimized to deliver a bandwidth of 6.8 GHz.

The microstripline of the antenna is then modulated by inserting square patches of length l_a and width w_a which attain an optimum value of 4.5mm. The distance between the center of two square patches, represented by ‘d’ is 9mm. A column of four uniform circles of radius ‘ r_o ’= 1mm is scratched in the reduced ground plane of the antenna beneath the modulated microstrip line. The distance between the centers of two circles, represented by ‘ d_1 ’ is 4mm.



(a) top view



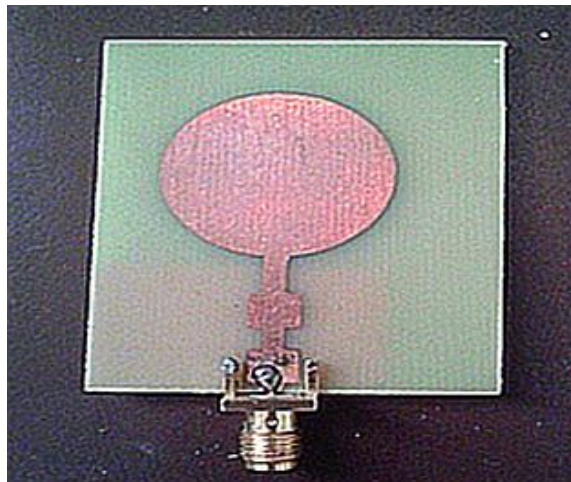
(b) bottom view

Figure 4.11 Final geometry of the proposed antenna

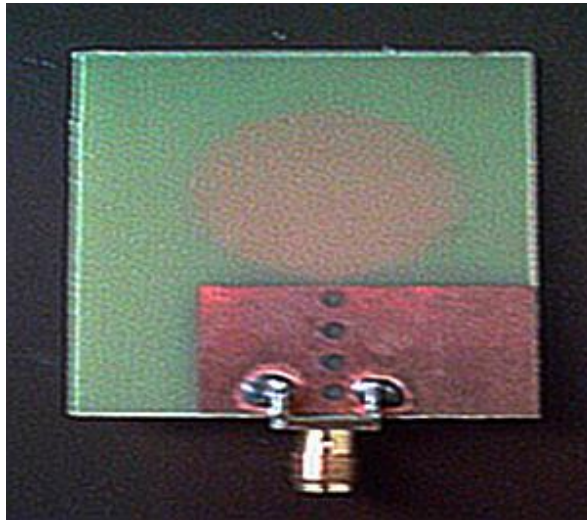
4.5 MEASURED RESULTS

The optimized antenna structure is then photo lithographically fabricated on a FR4 substrate and tested for its performance using VNA (Vector Network Analyzer). The prototype of the fabricated antenna is shown in Figure 4.12 (a) and (b). The S_{11} parameter of the proposed antenna is evaluated in terms of return loss and impedance bandwidth which is measured on VNA. Figure 4.13 shows the simulated and the measured return loss. Figure 4.14 (a), (b) and (c) display the absolute power flowing on the surface of the radiating patch and the filter structure formed at the input of the antenna, that is, the microstripline which verifies the operation of the antenna in the designated bands. The 2D radiation pattern plots are also obtained in Figure 4.15 (a) and (b), 4.16 (a) and (b), 4.17 (a) and (b) which show the far field results whereas Figure 4.18 (a), (b) and (c) show 3D directional properties and efficiency of the antenna at the proposed bands.

The simulated results and measured data have good agreement except for minor deviation which may arise due to imprecisions crept during fabrication process. Both of the curves display similar drifts over the complete operating range. The lower band is shifted slightly towards lower frequency and the upper band undergoes slight reduction in its effective bandwidth. This difference might be due to the minor dimensional inaccuracies while fabricating the antenna. The cable or SMA connector might introduce some variable reactance which affects the return loss of the proposed antenna.



(a) front view



(b) back view

Figure 4.12 Fabricated antenna

4.5.1 Measured Return Loss

The comparison of both the simulated and the measured results is illustrated in Fig. 4.13 which shows a good matching between the two, as presented in Fig. 4.13. For the proposed antenna with the EBG filter structure, the final outcomes of the measured results indicate impedance bandwidths of 550 MHz and 2.55 GHz at the two pass bands from 1.90 to 2.45 GHz and 3.3 to 5.85 GHz, respectively. The return loss at the two bands is -25 dB (at lower frequency band) and -25.5 dB (at the upper frequency band). The antenna shows a good band rejection performance from 5.85 to 11.0 GHz. The measured band reject filter attenuation also decreases as compared to simulated one but the fabricated antenna has wideband rejection response. The ripple level in stop band also increases at higher frequency.

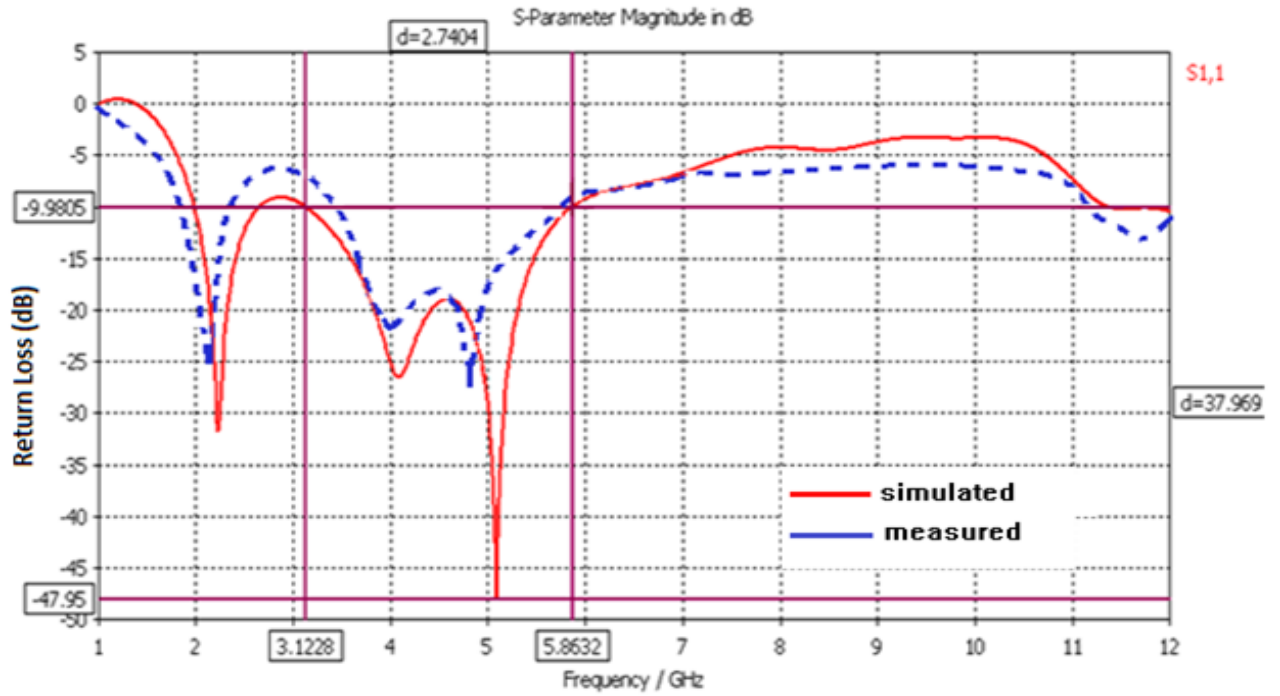


Figure 4.13 Comparison of simulated and measured return loss of the proposed antenna.

Table 4.2 Summary of the measured and simulated results of the proposed antenna.

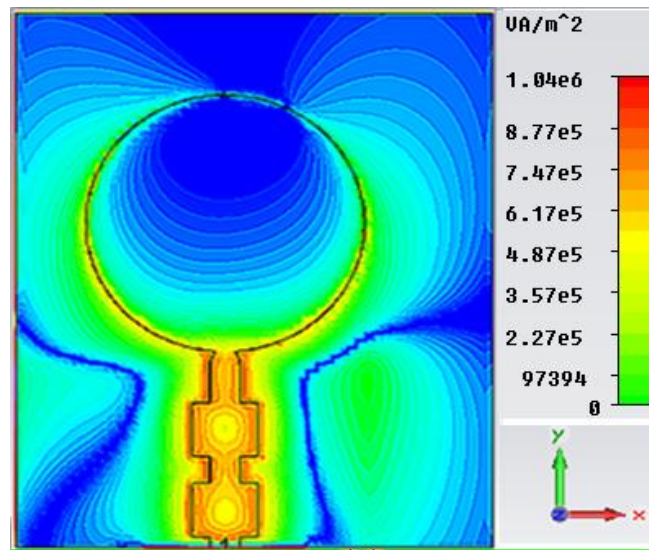
Paramter→ Band ↓	Frequency of resonance Measured (Simulated) (in GHz)	Band covered Measured (Simulated) (in GHz)	Impedance Bandwidth Measured (simulated) (in MHz)	Return loss Measured (simulated) (in dB)
Lower Band	2.2 (2.3)	1.90 - 2.45 (1.97 - 2.65)	550 (681)	-31.9 (-25.0)
Upper band	5.15 (4.90)	3.3 - 5.85 (3.12 - 5.86)	2550 (2740)	-47.95 (-27.80)

4.5.2 Power flow

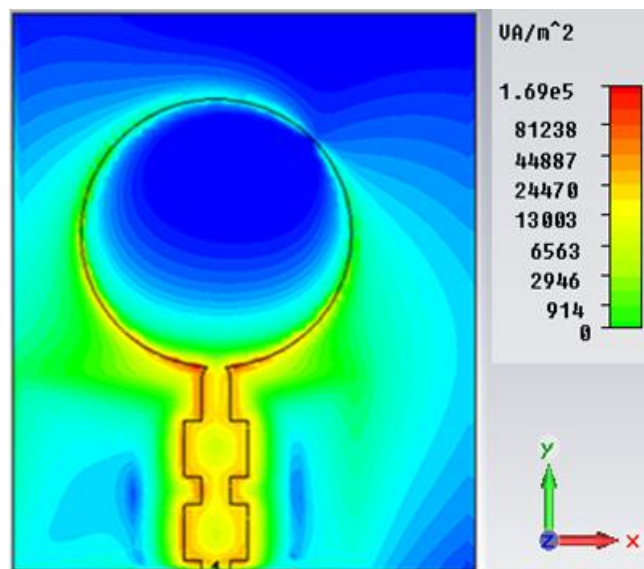
Figure 4.14 (a), (b) and (c) shows the absolute value of power flow at the resonant frequency of 2.43 GHz, 3.89 GHz and at frequency of 5.14 GHz respectively. Since the circular EBG structures are etched out of ground plane beneath the square patches of the microstripline, therefore it varies the coupling between the patch and the circles. This magnetic

coupling increases the current flow at certain frequencies and inhibits signal propagation at a certain frequencies which improves the band-pass and band-stop characteristics.

As can be seen in Figure 4.14 (a), the power flow dominates on the circular EBG rings with their track opposite to the patch current flow at 2.43 GHz. Due to this current distribution, the antenna does not respond at this frequency, whereas, in Figure 4.14 (b) feeble surface current distributions on the EBG circles is observed at the pass band at 3.89 GHz. In Figure 14 (c), the lower portion of the circular patch and modulated stripline seem equally responsible for the radiation at 5.14 GHz.



(a) 2.43 GHz



(b) 3.89 GHz

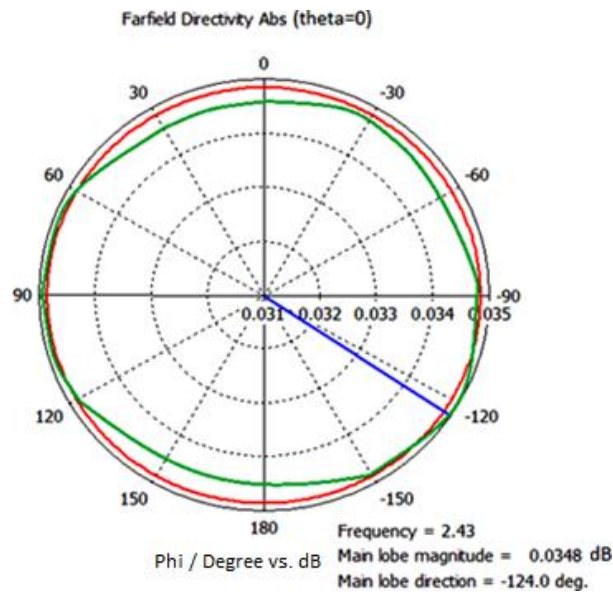


(c) 5.41 GHz

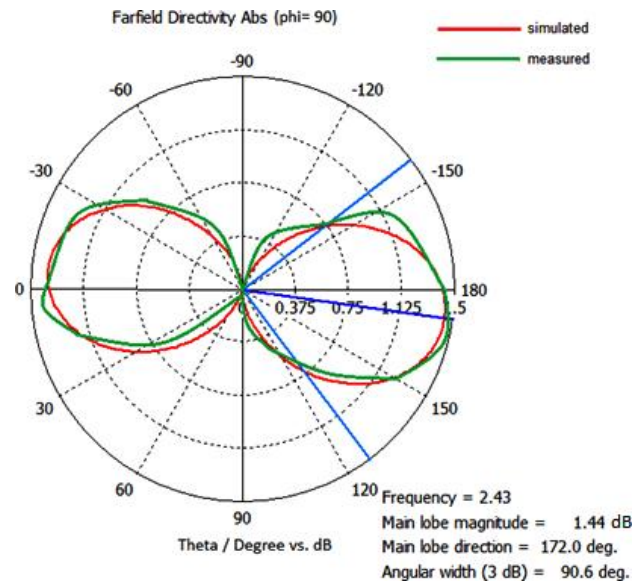
**Figure 4.14 Total absolute power flow (peak) at the antenna at (a) 2.43GHz (b) 3.89GHz
(c) 5.14GHz**

4.5.3 Radiation Pattern

The simulated and measured radiation patterns of the projected antenna in azimuth (H-plane) and the elevation (E-plane) at frequencies 2.43 GHz, 3.89 GHz and at frequency of 5.14 GHz are illustrated in Figure 4.15(a) and (b), 4.16(a) and (b), and 4.17(a) and (b), respectively. The radiation patterns exhibit that the antenna essentially radiates over a wide frequency band with omnidirectional pattern over the operating bands.

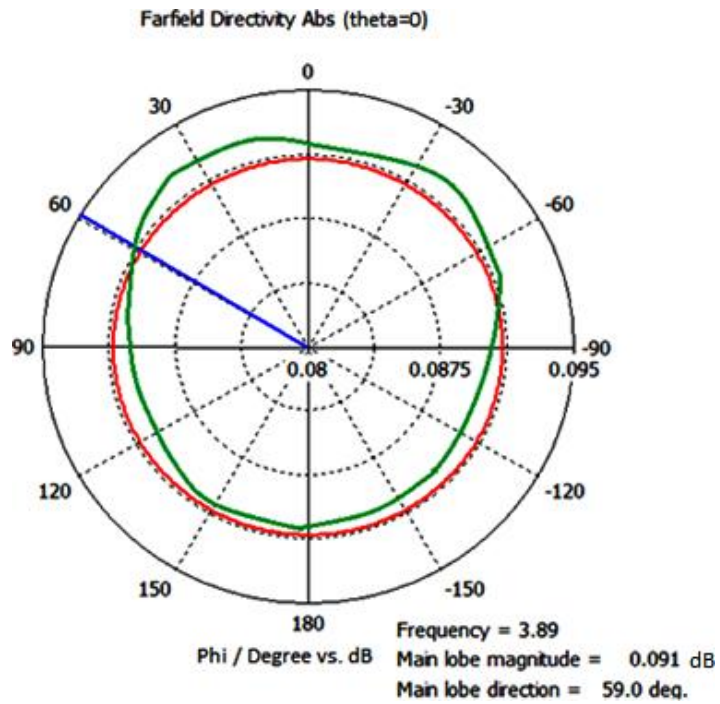


(a) 2.43 GHz Azimuth plane

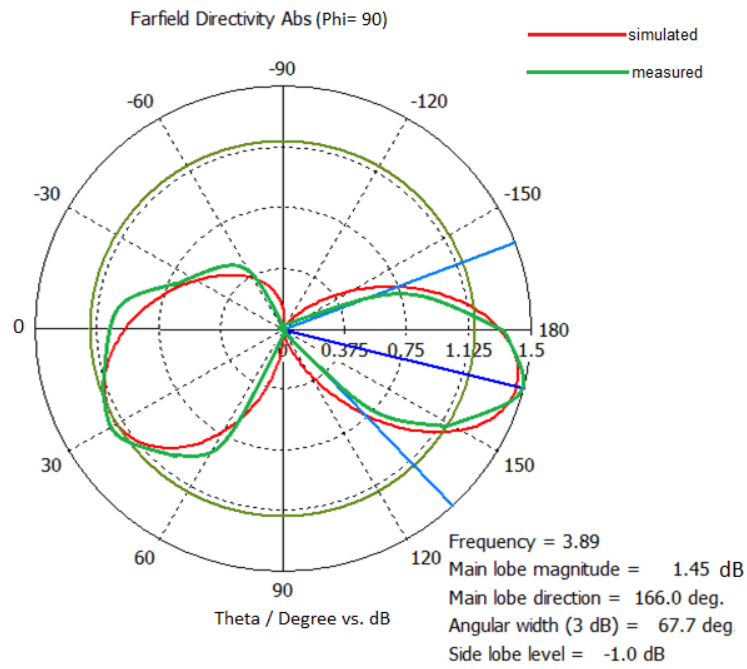


(b) 2.43 GHz Elevation plane

Figure 4.15 Radiation pattern plots of the antenna at 2.43GHz

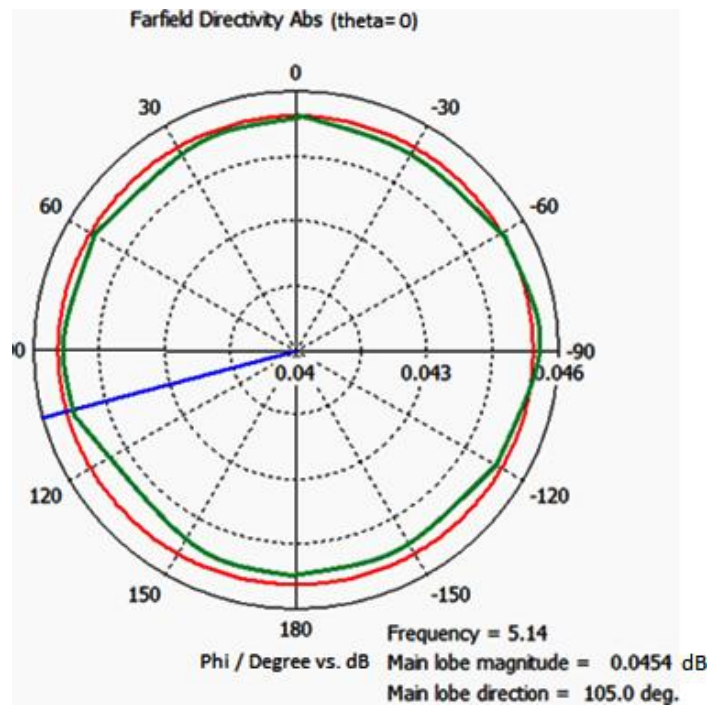


(a) 3.89 GHz Azimuth plane

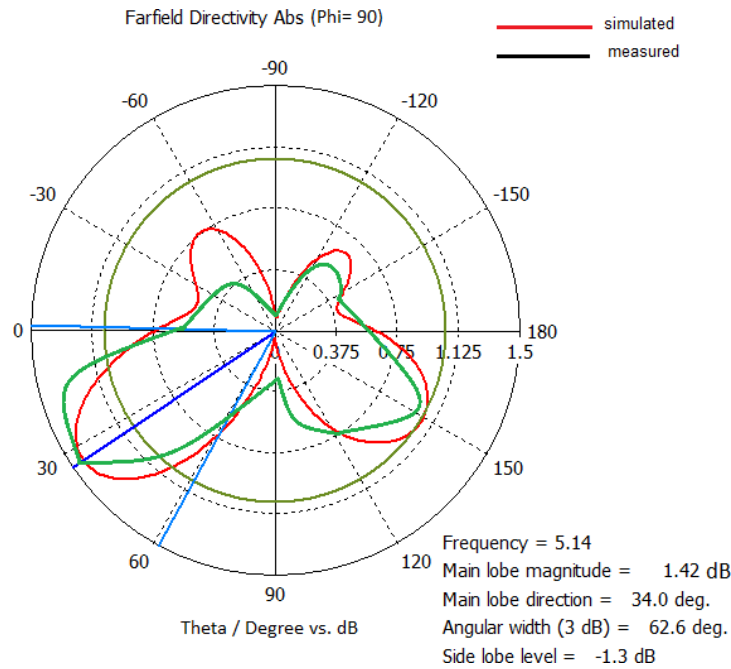


(b) 3.89 GHz Elevation plane

Figure 4.16 Radiation pattern plots of the antenna at 3.89GHz



(a) 5.14 GHz Azimuth plane

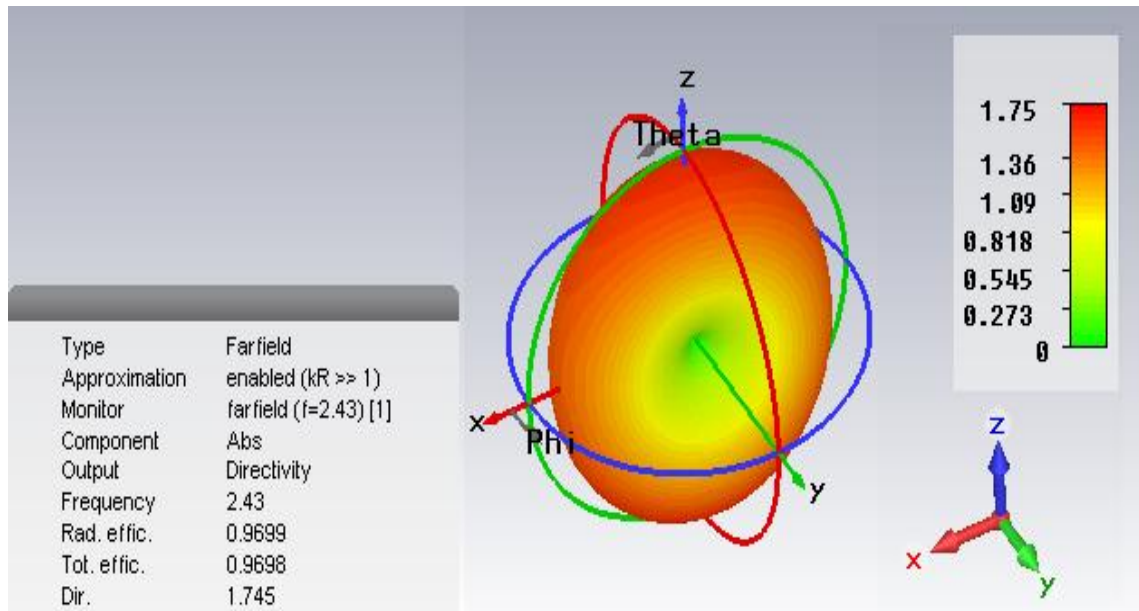


(b) 5.14 GHz Elevation plane

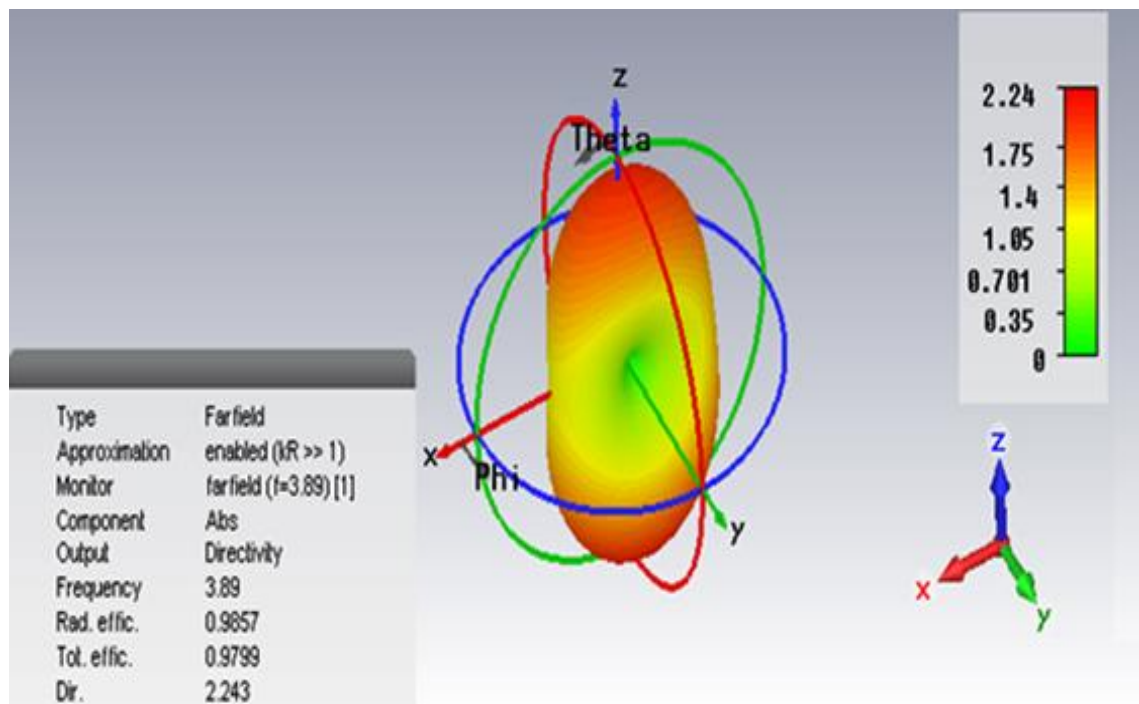
Figure 4.17 Radiation pattern plots of the antenna at 5.14 GHz

4.5.4 3D Radiation Pattern

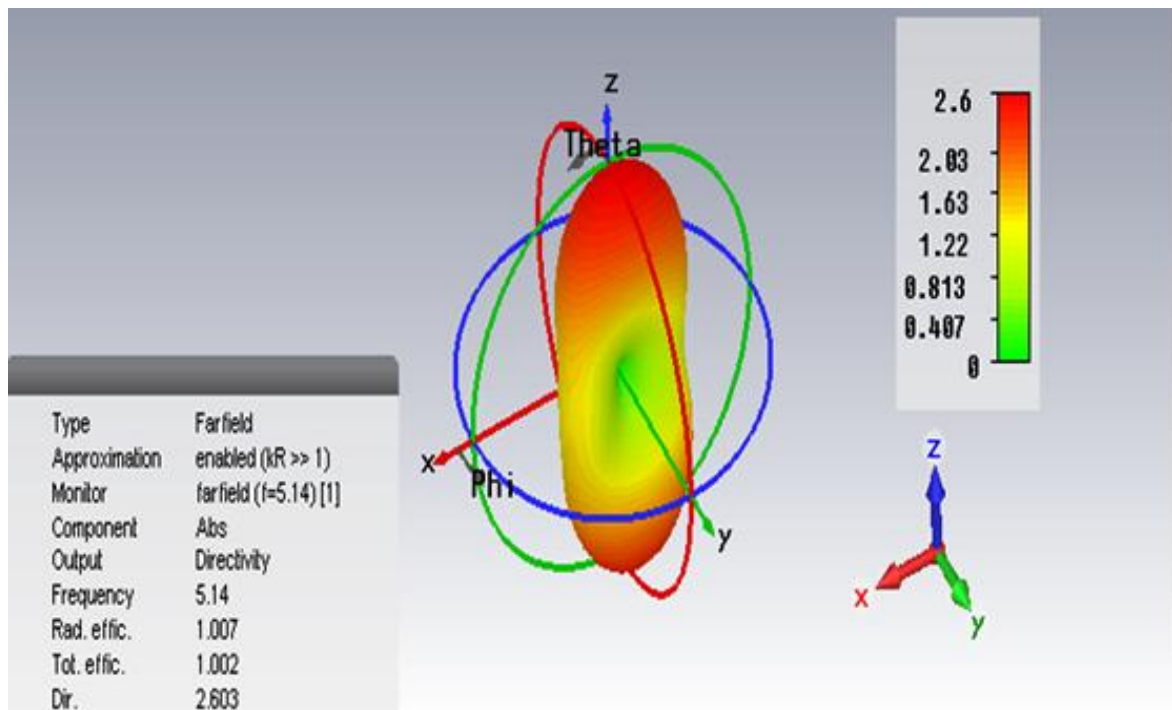
The 3D radiation patterns obtained in CST are indicative of the omnidirectional pattern formed by the antenna at different frequencies shown in Figure 4.18 (a), (b) and (c). Moreover, it reveals that the radiation efficiency of the proposed antenna is 96.83%, at the resonating frequency of 2.43 GHz, 97.56 % at 3.89 GHz and 98.52% at 5.14 GHz.



(a) 2.43 GHz



(b) 3.89 GHz



(c) 5.14 GHz

Figure 4.18 3D radiation pattern plotted at frequency at (a) 2.43 GHz (b) 3.89 GHz and (c) 5.14 GHz

4.6 SUMMARY OF THE CHAPTER

In this chapter, a circular UWB antenna using EBG filter structure and modulated microstripline is designed and fabricated to be used for WLAN applications. The measurements show that the proposed antenna creates a stopband from 5.9 to 11.3 GHz. The rejected band is obtained by integrating a modulated microstripline that resonates at the required rejection frequency band with the circular EBG structures etched in the ground plane of antenna. It generates two distinct pass bands extending from 1.95 GHz to 2.45 GHz and 3.3 GHz to 5.85 GHz. It provides permissible return loss values of -25 dB at lower frequency band and -25.5 dB at the upper frequency band, respectively. The impedance bandwidth at the two bands is 550 MHz and 2.55 GHz. It is therefore able to serve all the ISM bands of WLAN at 2.45/ 5.15/ 5.8 GHz. The antenna provides almost omnidirectional patterns over an entire UWB frequency band apart from the rejected band. It has high radiation efficiency of 96.83%, 97.56 % and 98.52% at the resonating frequency of 2.43 GHz, 3.89 GHz and 5.14 GHz respectively. The measured data of the antenna matches well with the corresponding simulated results.

This work has been published as: “A modified Compact Ultra Wideband Antenna with band rejection for WLAN applications” in Wireless Personal Communications. DOI:10.1007/s11277-017-4531-6.

CHAPTER 5

MODIFIED CPW-FED ROTATED E-SLOT ANTENNA FOR HETEROGENEOUS NETWORKS

5.1 INTRODUCTION

In most of the current mobile devices, access to different bands working on the same protocol can be provided by a homogeneous network. But these devices are unable to completely satisfy the user requirements for accessing different technological standards due to presence of single standard antenna. There has been a significant increase in wireless data traffic flow in recent times which demands increased capacity and bandwidth for running applications like video, multimedia messages etc. [178-179]. Also, with the migration from voice to data centric services, enhanced radio link budget and extended coverage is required to provide uninterrupted user access to network operating from indoors. All these services have to be provided, uninterrupted, to an indoor as well outdoor user. To provide data centric services to outdoor user, it needs device to support standards like WiMAX or LTE also. A network in which different wireless standards coexist is called a heterogeneous network and forthcoming heterogeneous networks will take user experience to an altogether different level [178-179]. Few examples of heterogeneous networks are given next.

Consider an example [179] of a man getting into his car using NFC (Near Field Communication) ID feature in his smartphone and looking for the right route using GPS navigation to reach his destination. He has the facility to use Bluetooth headset while making a call from his mobile through GSM network. He is using data services using a WiFi hot spot, while he is listening to his MP3 song list through FM radio in the car. Co-existence of different technologies, based on FDM (Frequency Division Multiplexing), TDM (Time Division Multiplexing), SDM (Space Division Multiplexing) realms, comes to be progressively critical [179].

Heterogeneous networks deal with the interworking of wireless local area networks and cellular networks which serve as an efficient way to improve system capacity as well as

effectively enhance network coverage. It may be envisioned as an overlaid network of non-cellular networks of different sized base station cells like of macro, micro, pico or femto cells as in WWAN/ WMAN/ WLAN/ WPAN networks. It may consist of different network topologies like a cellular network like GSM and a non-cellular network like WiFi or WiMAX. It may include different connections like device to device, peer to peer, private hotspot, NFC as a part of heterogeneous access networks. It may also consider the use of cognitive radios as a part of heterogeneous network for dynamic sharing and accessing wireless spectrum. In a nutshell, a heterogeneous network is a system comprising network cells with diverse characteristics like RF coverage area and transmission power. The high power macro cells providing coverage to large area are installed to provide extensive coverage to urban, suburban, or rural areas, whereas, low power local micro cells with lesser RF coverage area provide capacity improvement in conjunction with macro cells [179].

In a homogeneous network a mobile device generally uses a single radio link to access the network, whereas, in a heterogeneous network several air interface technologies are allowed to function simultaneously, forming many radio links amongst the device and the network. For example, a 3G smartphone with activated WiFi/ WiMAX link where the mobile can utilize the cellular link for voice service and the WiFi/ WiMAX for high speed internet access. A heterogeneous network may provide diverse routing possibilities to different layers inside the infrastructure network. LTE and LTE-Advanced offer this flexibility which improves spectral efficiency. By integrating heterogeneous cellular and non-cellular architectures, heterogeneous networks provide enormous system capacity and network efficiency and offer new services with always-on connectivity [178-179].

An LTE pico base station overlaid by an LTE macro cellular network is an example of a multi-tier single-air interface heterogeneous network , whereas, a WiFi network overlaid by LTE macro cellular base station forms a multi-tier heterogeneous network with multiple air-interface. To enable the heterogeneous networks to function well, alliance amongst bodies developing different air interface standards is essential such as 3GPP in case of LTE and Wi-Fi Partnership [178-179].

The study of antennas for heterogeneous cellular networks is on the rise in academic world and commercial industry to improve the understanding about the technological details and performance parameters of antennas in different heterogeneous networks and make their deployment feasible. The upcoming heterogeneous networks require unconventional multi-mode

and multi-band consumer devices. Hence the future smart handheld and portable wireless devices, with cutting-edge technologies should be capable of supporting heterogeneous standards. This chapter addresses the need to integrate heterogeneous cellular and non-cellular networks consisting of mobile satellite, LTE and WiMAX and other networks, and design a multiband antenna which can operate in these bands simultaneously with the required bandwidth necessary for the operation at different bands.

This chapter presents the design of a rectangular microstrip patch element with a modified CPW feed and rotated E-slot in the radiating patch to obtain multiband operation with wideband characteristics for heterogeneous networks. The proposed antenna comprises of a planar rectangular patch element embedded with E-slot rotated 90° anticlockwise on the radiating side. The CPW feed is modified by extending the ground plane throughout the substrate to surround the rectangular patch. This structure is capable of generating three separate resonant modes with good impedance matching. The antenna is designed on an FR4 substrate of 1.6 mm thickness. The proposed antenna can cover various communication standards for heterogeneous wireless applications such as Mobile satellite (1.5 – 1.7 GHz), aeronautical radionavigation radiolocation (2.7–2.9 GHz), radiolocation radionavigation (2.9–3.1 GHz), radiolocation earth exploration-satellite (active) mobile (3.1–3.3 GHz), radiolocation amateur mobile (3.3–3.41 GHz), mobile (3.41–3.6 GHz), LTE (3.4-3.6 GHz) and WiMAX (3.4-3.69 GHz).

The simulated results are confirmed by matching the simulated results with the measured ones. The proposed antenna provides good return loss S_{11} and impedance behavior.

5.2 PARAMETRIC STUDY

To understand the performance of the designed antenna structure, parametric study of the proposed antenna is done to obtain optimum geometrical parameters for achieving the desired results. The structure of initial design is modified in steps and effect of variation of dimensions on the antenna performance is studied. A rectangular patch is considered as the main radiating patch which is connected to microstripline feed located in the same plane as the patch. Antenna uses the CPW ground plane, which forms CPW feed assembly along with microstrip feed. The influence of different parameters on the performance of the proposed antenna in terms of return loss, impedance bandwidth and gain is presented in this section.

5.2.1 Initial Antenna Design

Initially, the antenna design consists of a rectangular patch, fed by a microstripline is shown in Figure 5.1. A rectangular patch is considered as the main radiating patch which is connected to microstripline feed located in the same plane as the patch. Antenna uses the CPW ground plane, which forms CPW feed assembly along with microstrip feed. CPW ground plane is designed on the same plane as the patch which surrounds the rectangular patch on all sides with a variable gap between it and the rectangular patch on X-axis and Y-axis as shown in Figure 5.1. The gap between the rectangular patch and the CPW ground is represented by variable 'x' along the X- axis and by variable 'v' on the Y- axis as shown in Figure 5.14. This initial distance is kept at a value of 12mm along X- axis and 1mm along Y- axis. The simulation results are plotted for the design in terms of reflection coefficient at different values of frequency.

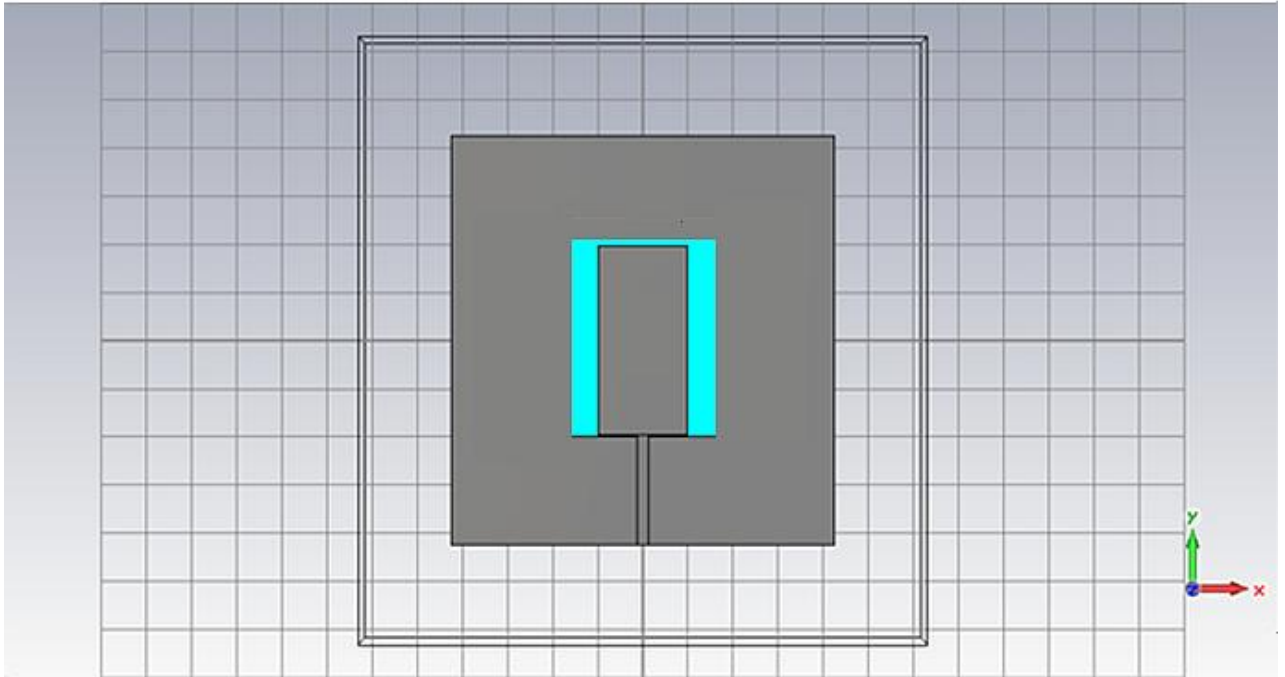


Figure 5.1 Initial Antenna Design.

5.2.2 Simulated Result

The reflection coefficient results for the planned antenna structure is presented as Return loss curve for different values of frequency are illustrated in Figure 5.2. It is evident from the figure, that the initial design structure is capable of generating two bands resonating at frequencies 2.45 GHz and 3.25 GHz. The impedance bandwidth at the lower frequency band, ranging from 2.168 GHz to 2.554 GHz, is 385 MHz and for the upper band, extending from 3.05

GHz to 3.54GHz, is 484 MHz which is suitable for WLAN band at 2.4GHz. But it is unable to cover WiMAX bands fully. The resonant bands of initial structure are summarized in table 5.1.

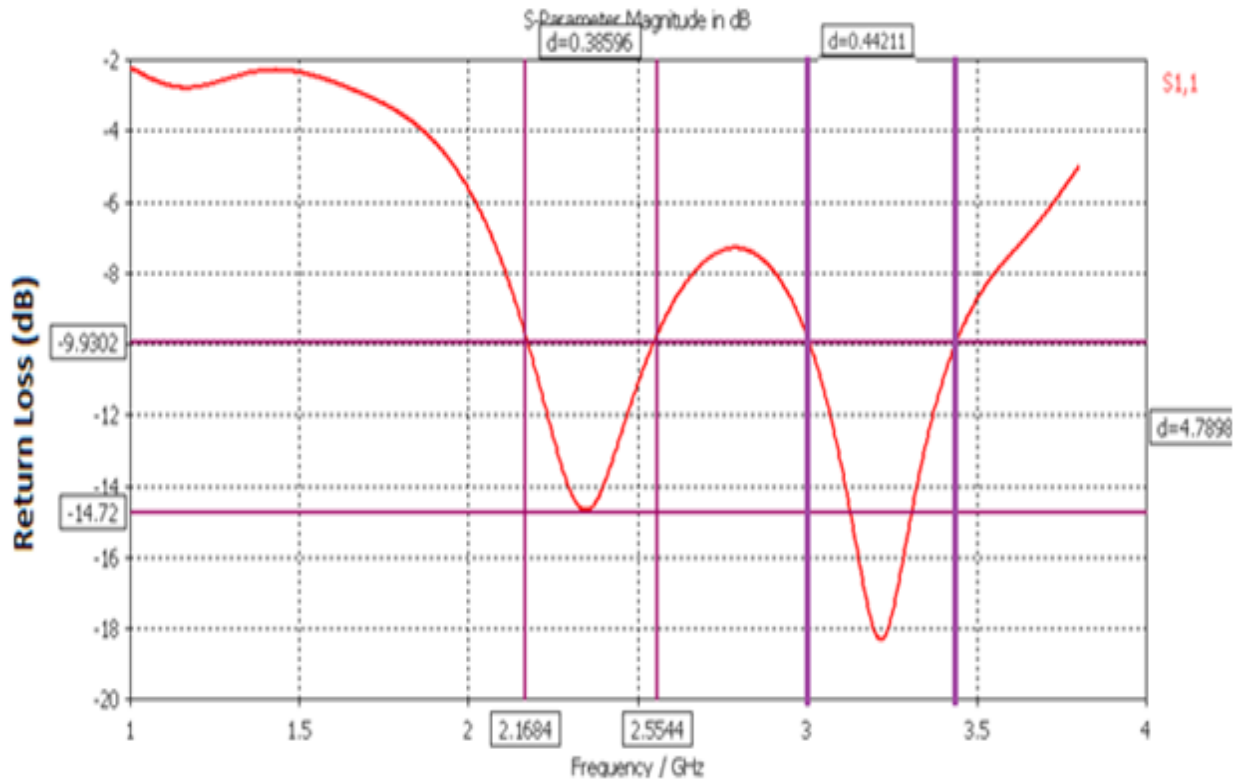


Figure 5.2 Return loss curve v/s frequency for initial antenna design.

Table 5.1: Resonant Bands of initial antenna structure

Band	Frequency Range	Bandwidth	Peak Return Loss
Lower Band	2.168 to 2.554 GHz	385 MHz	-14.7 dB
Upper Band	3.05 to 3.54GHz	484 MHz	-18.20 dB

5.2.3 Effect of addition of E-Slot on the Radiating Patch:

The multiband traits of the projected antenna are achieved by integrating an E-shape slot, rotated 90° anticlockwise, into the patch. Slot loading in the patch antennas is useful to achieve broadband and multiband operation in microstrip antennas. Four slots are etched in the main rectangular patch to form a shape of letter ‘E’. The slots are designated as S₁, S₂, S₃ and S₄, as shown in Figure 5.3. The antenna structure, with E-slot lying approximately in its center, is depicted in Figure 5.4. The slots of letter ‘E’ are varied in length and width to study its effect on antenna performance. The electrical length of the slots integrated in the radiating patch decides

the frequency of resonance for the proposed antenna structure.

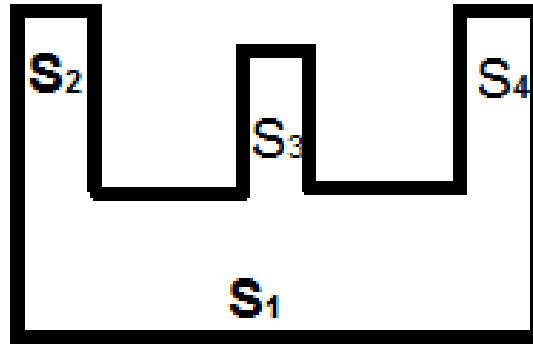


Figure 5.3 Four slots S1, S2, S3 and S4 forming an E-shaped slot.

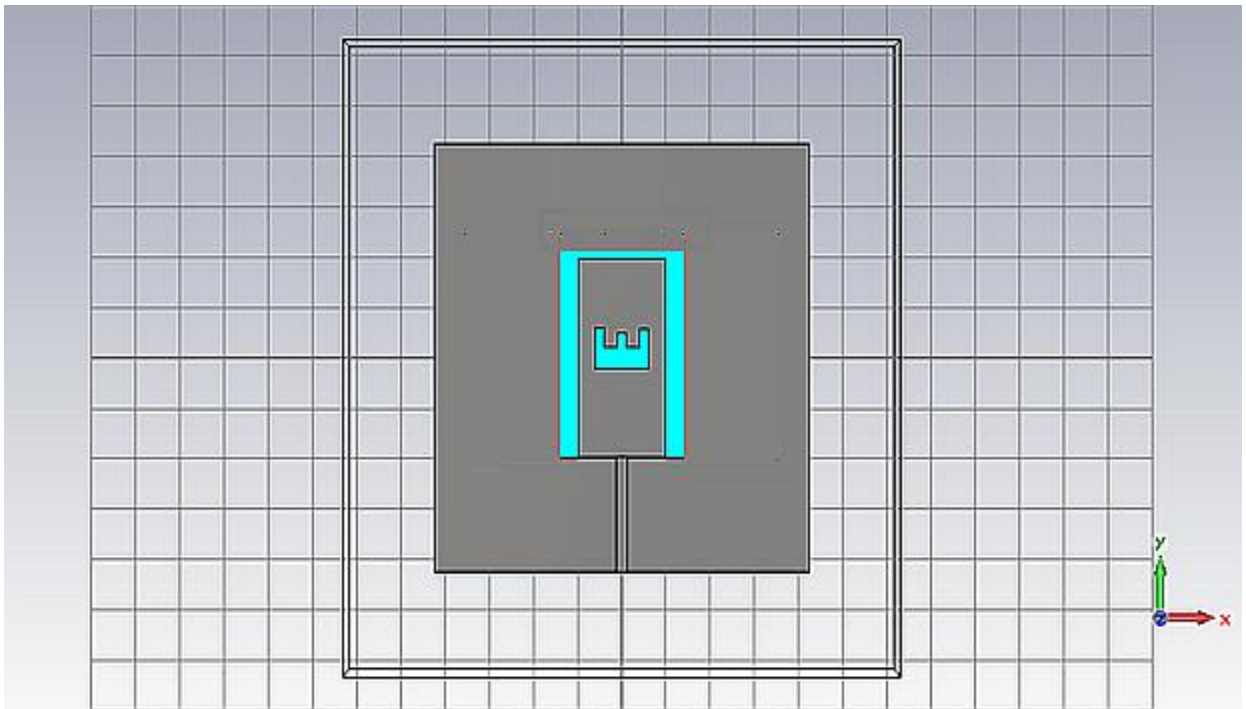


Figure 5.4 Antenna with rotated E- slot in the rectangular patch of antenna.

5.2.4 Simulated Result

The simulation results in Figure 5.5 display a triple band operation for the designed antenna after addition of E slot as shown in Figure 5.4. The value of impedance bandwidth obtained for lower frequency band is 136 MHz from 1.58 GHz to 1.72 GHz and return loss value of -17 dB. The impedance bandwidth attained for middle frequency band is 252 MHz ranging from 2.70 GHz to 2.95 GHz and the return loss achieved at the resonant frequency is -22.7 dB. The higher frequency band extends from 3.49 GHz to 3.78 GHz with the impedance bandwidth

of 291 MHz with return loss value of -26.3 dB. The value of return loss suggests that there is an adequate impedance matching beneath the -10 dB frequency point. Thus the antenna produces three resonant bands. The antenna has sufficient value of reflection coefficient magnitude and wide enough bandwidth at the three bands and has matched antenna impedance to approximately 50-ohm. The results are summarized in table 5.2.

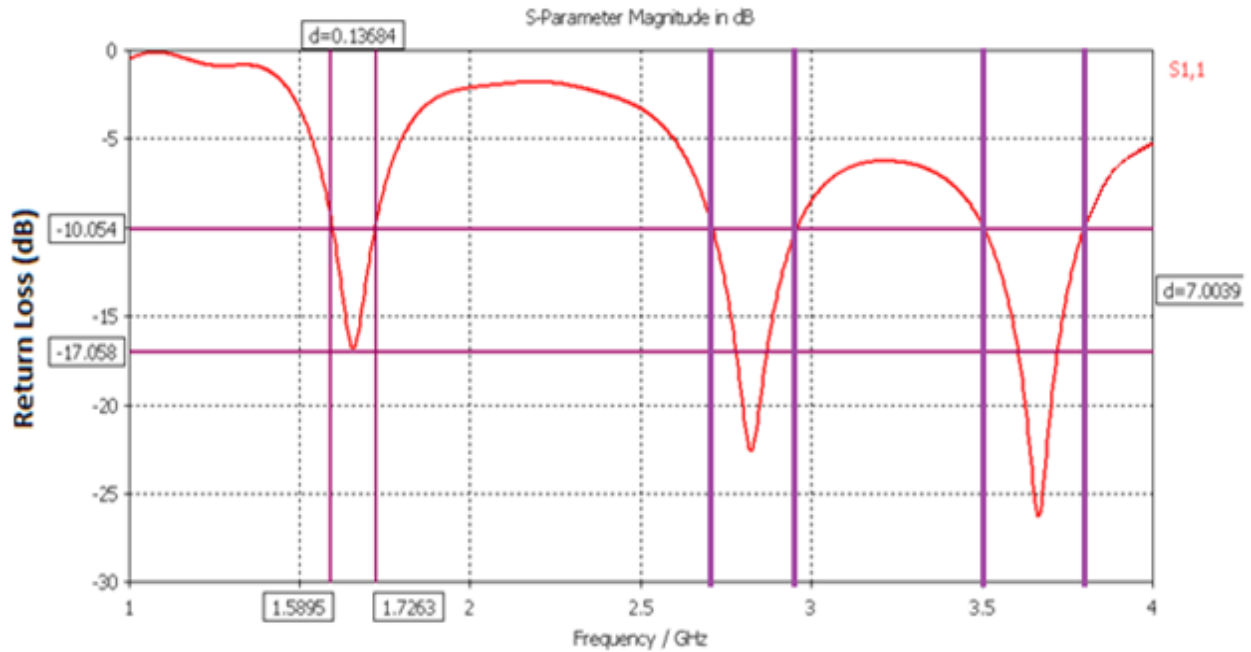


Figure 5.5 Return loss of antenna after addition of E-slot in the rectangular patch.

Table 5.2: Resonant Bands of antenna after the addition of ‘E’-Slot on the Radiating Patch

Band	Frequency Range	Bandwidth	Peak Return Loss
Lower Band	1.58 GHz to 1.72 GHz	136 MHz	-17 dB
Middle Band	2.70 GHz to 2.95 GHz	252 MHz	-22.7 dB
Upper Band	3.49 GHz to 3.78 GHz	291 MHz	-26.3 dB

5.2.5 Final Antenna design with modified CPW structure:

The final design of the antenna formed by modifying the CPW ground plane structure along X axis and Y axis is illustrated in Figure 5.6. The parametric variations applied on the dimensions of the gap space between the patch edge and the CPW ground planes along X and Y axes are discussed in section 5.3.11 and 5.3.12.

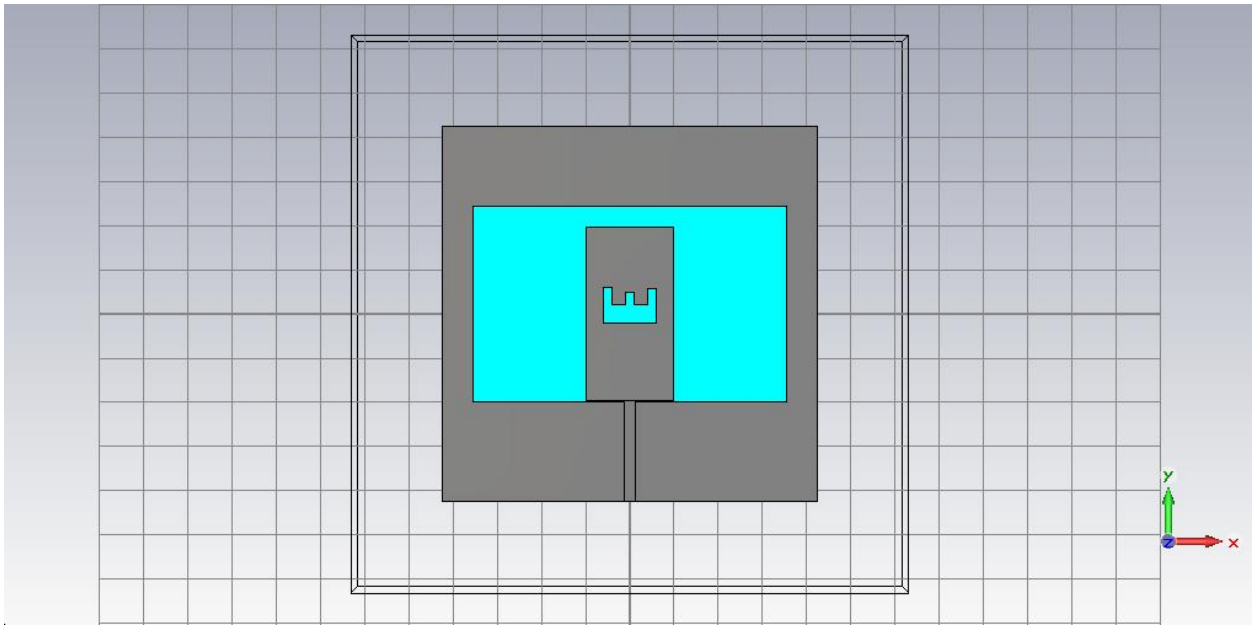


Figure 5.6 Final Antenna design with modified CPW structure

5.2.6 Simulated Result

Transient solver is run to simulate the proposed antenna in CST software with port impedance matched to 50-ohm. The simulated reflection coefficient result for the antenna with variation in the CPW ground plane structure is plotted in Figure 5.7. The patch antenna resonates at 1.66 GHz with impedance bandwidth of 128 MHz (1.56-1.69) GHz and generates another broadband from 2.6 to 3.75 GHz with impedance bandwidth of 1.14 GHz. The peak return loss value at the two bands is found to be -14.6 dB and -19.76 dB, which is well beyond the standard value of -10 dB required for satisfactory operation.

Examining the bandwidth covered by the advocated patch antenna, it has been found that the proposed antenna is a viable candidate for a number of wireless applications including mobile satellite (1.5-1.7 GHz), aeronautical radionavigation radiolocation (2.7–2.9 GHz), radiolocation radionavigation (2.9–3.1 GHz), radiolocation earth exploration-satellite (active) mobile (3.1–3.3 GHz), radiolocation amateur mobile (3.3–3.41 GHz), LTE (3.4-3.6 GHz) and WiMAX (3.4-3.69 GHz). Such a huge impedance bandwidth validates the multi-frequency and wideband operation at desired bands which has been obtained by making modifications in the rectangular radiating patch, which causes redistribution of surface across the patch and yields desired results to cover the heterogeneous wireless applications.

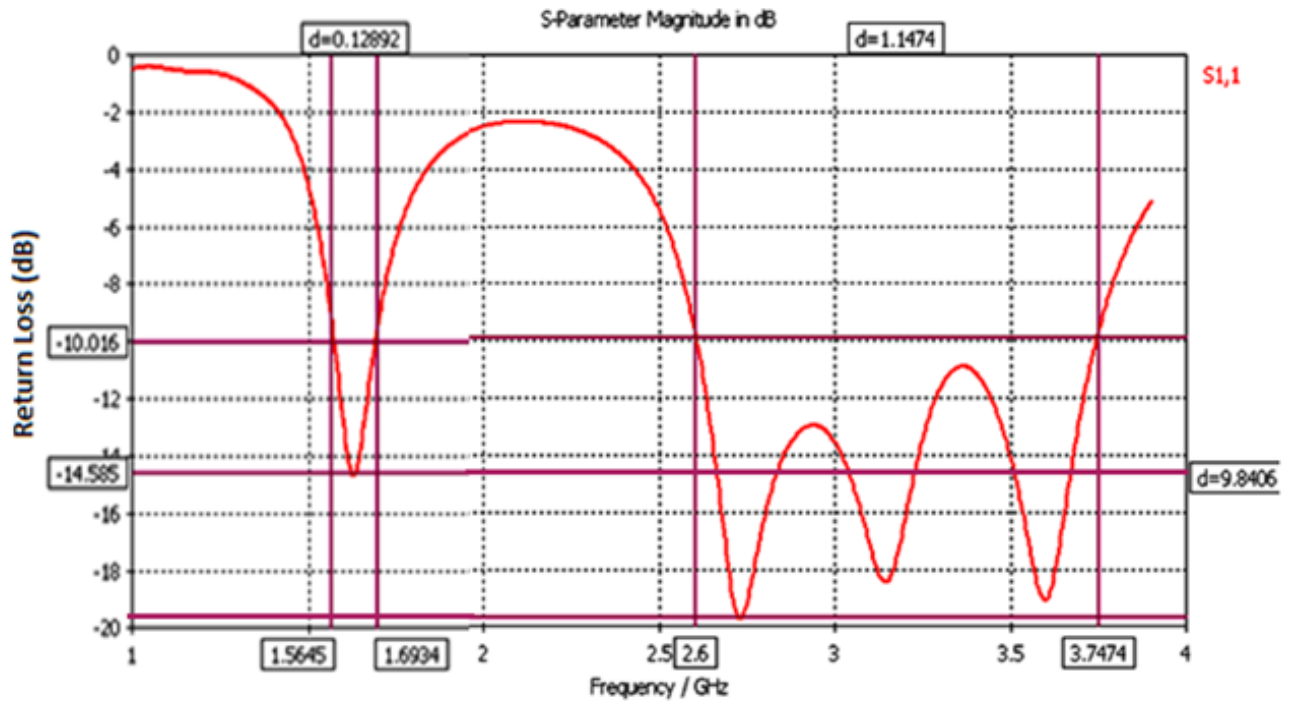


Figure 5.7 Return loss of Final Antenna design with modified CPW structure.

5.2.7 Effect of variation of slot length L_{S1}

In the beginning, the slots are cut and assigned arbitrary values to form an ‘E’ slot. Then the length of slot S_1 is varied using sweep tool in CST MWS starting with an initial value of 10 mm. The Figure 5.8 shows the effect of variation of slot length L_{S1} upon the return loss and impedance bandwidth of the antenna. The figure reveals that for values of $L_{S1}=10\text{mm}$, three bands are generated at a frequency of 1.6GHz, 2.85 GHz and 3.63 GHz. As the value of L_{S1} is increased, the lower band resonates at same frequency of 1.6 GHz except for $L_{S1}=22\text{mm}$ at which the band seems to shift towards higher frequency, finding a new resonance at 1.7GHz. Also, it experiences little fall in the value of return loss as the value of L_{S1} is increased.

The upper band is mainly affected by the change in slot length L_{S1} . It is evident from the Figure 5.8 that an increase in the value of L_{S1} from 10 mm to 22mm creates two bands which gradually converge to form a single wideband at $L_{S1}=24$, at which we obtain the maximum bandwidth of 3.1 GHz, from 2.6 to 3.7 GHz and return loss of -18.5 dB. As the value of L_{S1} is increased any further, the bandwidth of the higher band decreases. Therefore, 24mm is the optimized value of the slot length L_{S1} .

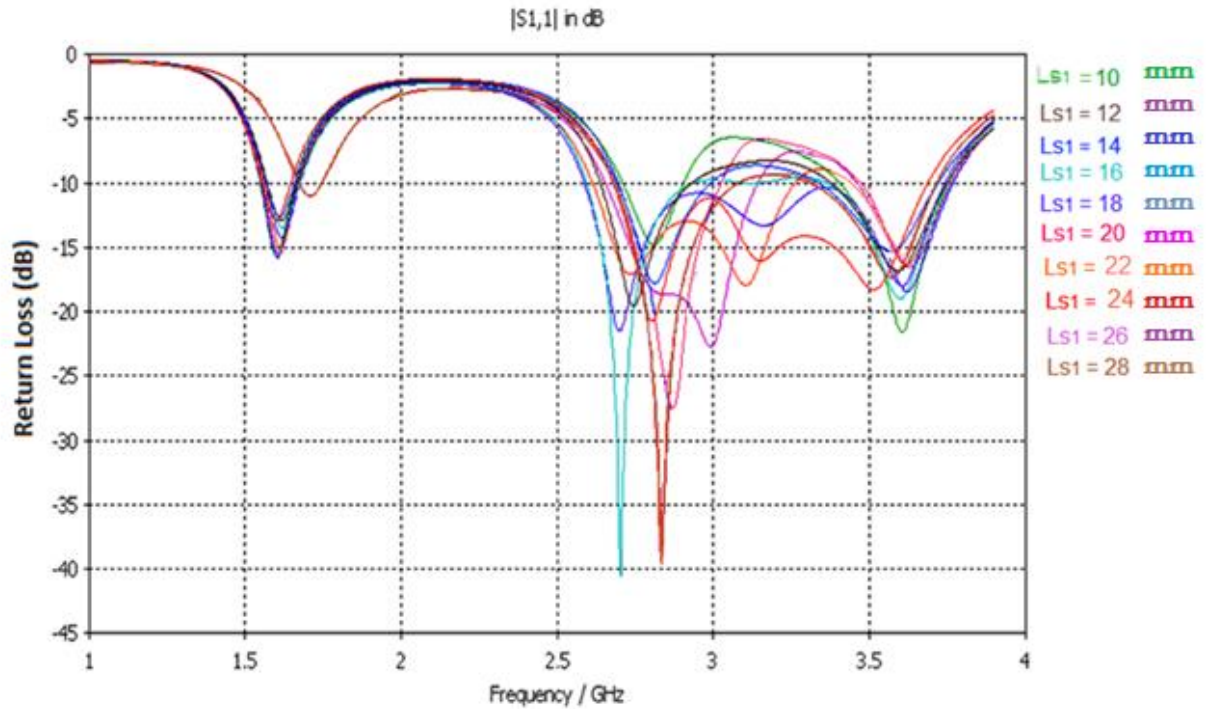


Figure 5.8 Effect of variation of slot length L_{s1} .

5.2.8 Effect of variation of slot length L_{s2} , L_{s3} and L_{s4}

The lengths of slots, represented by $L_{s2} = L_{s3} = L_{s4} = L_s$ are collectively varied from its initial fixed value to see its effect on the performance of the antenna. The length of different slots is varied jointly along X axis by applying parametric sweep in CST software whose results are represented in Figure 5.9.

The Figure 5.9 shows that when the length of the three slots is kept 1 mm, it produces two bands, the lower band extending from 1.55 to 1.68 GHz and the upper one from 2.6 to 2.9 GHz generating a bandwidth of 130 MHz and 300 MHz in the lower and upper band respectively. But the return loss value of the two bands obtained is insignificant at both the bands. On increasing the value of L_s further, the return loss seems to improve at both the bands. As the value of L_s varies from 1mm to 4mm, it causes a remarkable increase in the bandwidth of upper band. At $L_s=4$ mm, the upper band attains maximum bandwidth of 1 GHz (2.7 GHz to 3.7 GHz), which decreases at any further increase in the value of L_s . Also the value of return loss is improved and reaches -21 dB at $L_s=4$ mm. The opposite effect is observed at the lower band, whose bandwidth decreases by small values as L_s is increased from 1mm to 5mm. Therefore $L_s=4$ mm is the optimized value for slots S_2 , S_3 and S_4 .

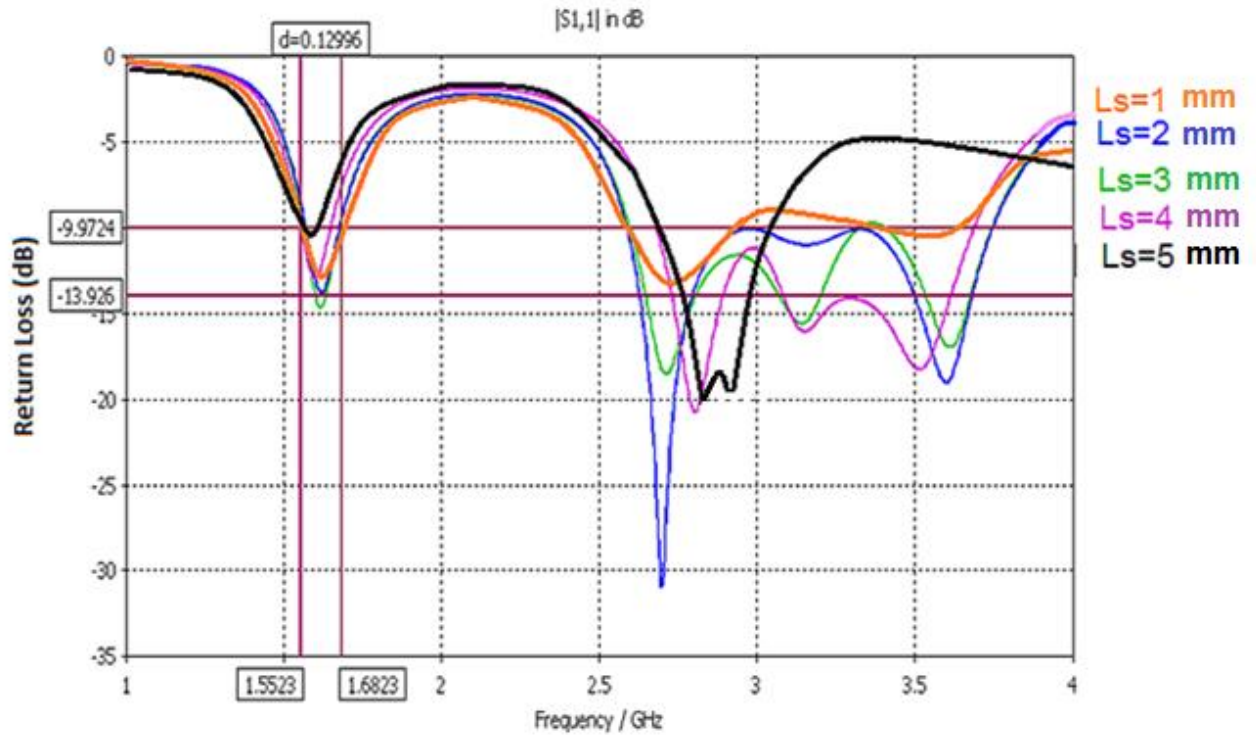


Figure 5.9 Effect of variation of slot length $L_{s2} = L_s = L_{s4} = L_s$.

5.2.9 Effect of variation of width W_{s1} and W_{s3}

A similar variation is applied on the width of the outer two slots, W_{s1} and W_{s3} , along Y axis, keeping a same fixed initial value for width of the slots W_{s1} and W_{s3} . As shown in Figure 5.10, six samples with an interval of 1mm have been considered while applying parametric sweep on the width of the slots i.e. W_{s1} and W_{s3} . The variations are first applied to left hand side slot and then to right hand slot. It is clearly seen in the sweep results, that for $W_{s1}=10\text{mm}$, three resonant bands are formed at frequencies 1.65 GHz, 2.8 GHz and 3.55 GHz. As the value of W_{s1} is increased, the upper frequency band merges to form a single wideband at $W_{s1}=12\text{mm}$. At this value, the antenna achieves a maximum impedance bandwidth of 1.13 GHz ranging from 2.62 GHz to 3.55 GHz. It has considerable return loss value of -15 dB and -24 dB at the lower and the higher frequency band respectively. It is observed that if the value of W_{s1} is increased to 13mm, the value of bandwidth at the upper band reduces to 700 MHz (from 2.6 to 3.3 GHz). On increasing the value of W_{s1} any further, it results in disintegration of the higher band with reduced bandwidth. Therefore, for the generation of wideband, the optimized values of slot width as $W_{s1}=12\text{mm}$. Since the same variations are applied on the right hand side slot width W_{s3} also,

which lies symmetrically on the other side of the X axis, the same results are generated for W_{s3} . Therefore the optimized value of slot width $W_{s3}=12\text{mm}$. The lower band remains unaffected by the change in the width W_{s1} and W_{s3} .

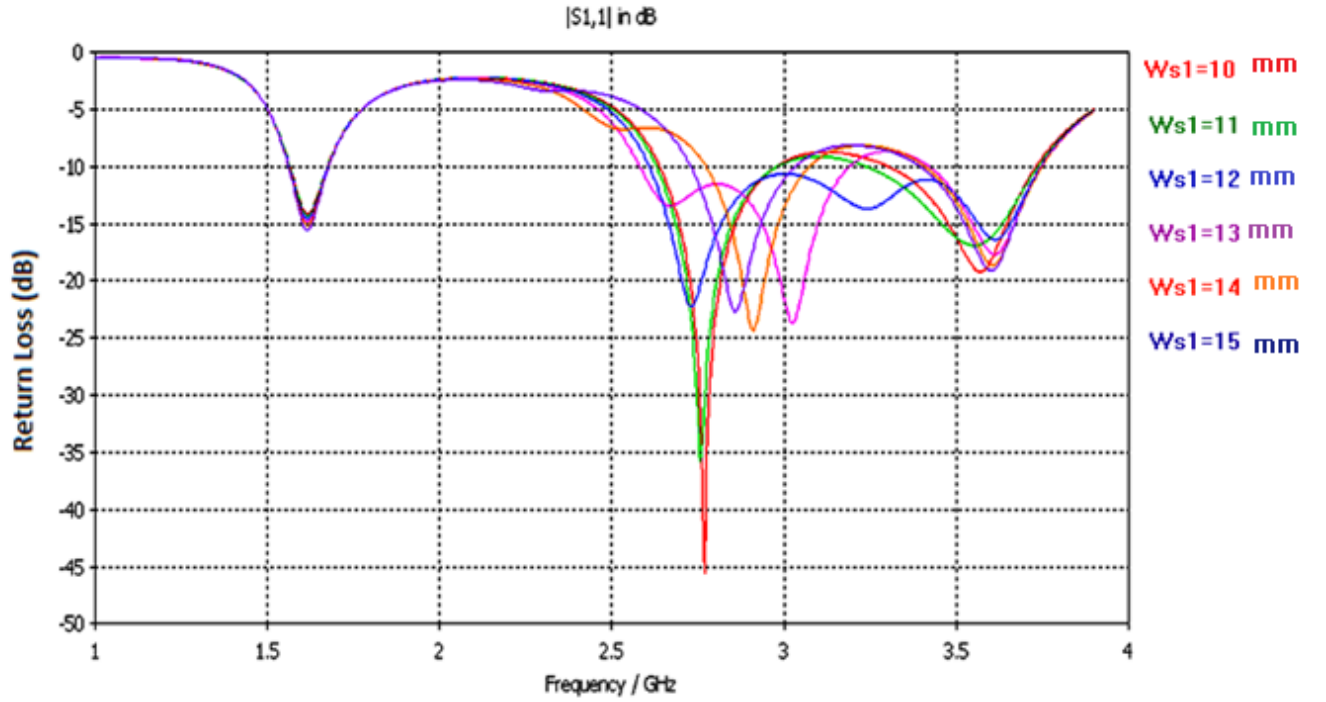


Figure 5.10 Effect of variation of slot width $W_{s1} = W_{s3}$.

5.2.10 Effect of variation of slot width W_{s2}

The width of the middle slot of the ‘E’ slot is varied along Y axis to study its effect on the S_{11} parameter in terms of return loss and impedance bandwidth of the antenna. Figure 5.11 shows the result of variation of W_{s2} . The results are identical to the ones obtained for the variation of slot widths W_{s1} and W_{s3} . Parametric sweep is applied on the width of the middle slot i.e. W_{s2} by taking six samples differing by an interval of 1mm. It is clearly seen in the sweep results, that for $W_{s2}=9\text{mm}$, three resonant bands are formed at frequencies 1.65 GHz, 2.77 GHz and 3.6 GHz. When the value of W_{s2} is increased, the upper band shifts down and merges to form a single wideband at $W_{s2}=10\text{mm}$. At this value, the antenna achieves a maximum impedance bandwidth of 1.15 GHz ranging from 2.60 GHz to 3.75 GHz. It has considerable return loss value of -15 dB and -27 dB at the lower and the higher frequency band respectively. Increasing the value of W_{s2} further, causes the value of bandwidth to decrease at the upper band

and finally segregates into two separate bands at $W_{s2}=12\text{mm}$ and 13mm . Hence the optimized value of slot width W_{s2} is found to be 10mm . The lower band remains unaffected by the change in the width W_{s2} .

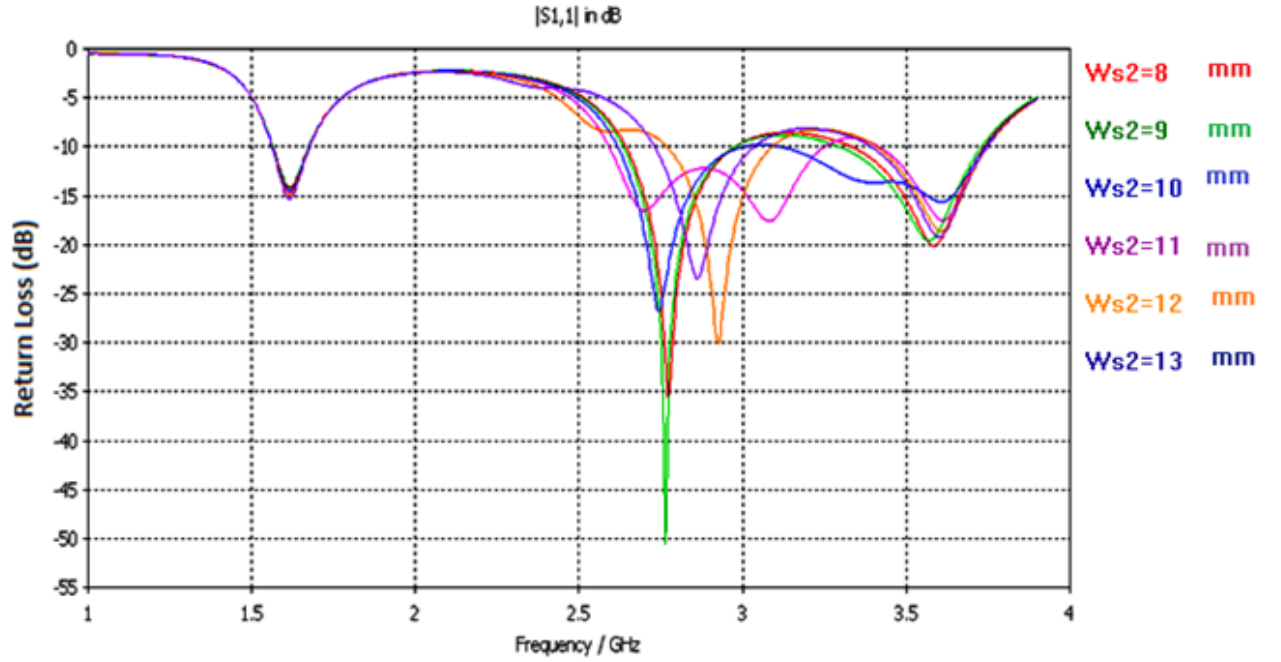


Figure 5.11 Effect of variation of slot width W_{s2} .

Parametric sweep applied on the length and width of slots shows that the optimum values for slot lengths L_{s1} , L_{s2} , L_{s3} and L_{s4} are found to be 24mm , 4mm , 4mm and 4mm respectively and slot widths W_{s1} , W_{s2} and W_{s3} to be 12mm , 10mm and 12mm respectively.

5.2.11 Effect of variation of gap space between CPW ground and the rectangular patch

The CPW ground plane surrounds the patch on all sides with little spacing between the edges of the patch and the ground plane. The horizontal spacing between the patch edge and the CPW ground along the X axis is represented by 'x' and vertical gap space between the patch edge and the CPW ground along the Y axis is denoted by 'v' (Figure 5.14). Both these distances are varied along both the axis to see their effect on the performance of the antenna. In Figure 5.12, the result of variation of spacing along X axis is presented in terms of return loss with respect to frequency. The value of the gap on both sides is varied by equal value 'x' using sweep function. The parameter 'x' is varied from 16mm to 21mm in steps of 1mm . It is observed that at $x=16\text{mm}$, we get a triple band, one lower band at 1.6GHz and two upper bands at 2.6GHz and

3.7 GHz. When the value of x is increased beyond 16mm, it leads to merging of two upper bands generating a broadband antenna, the best value being $x=18\text{mm}$ or the total gap value of 18mm for which the bandwidth is 1.15GHz. There is a very little effect of varying ' x ' on the lower band. The antenna responds symmetrically along the positive and negative X-axis yielding same results as shown in Figure 5.12.

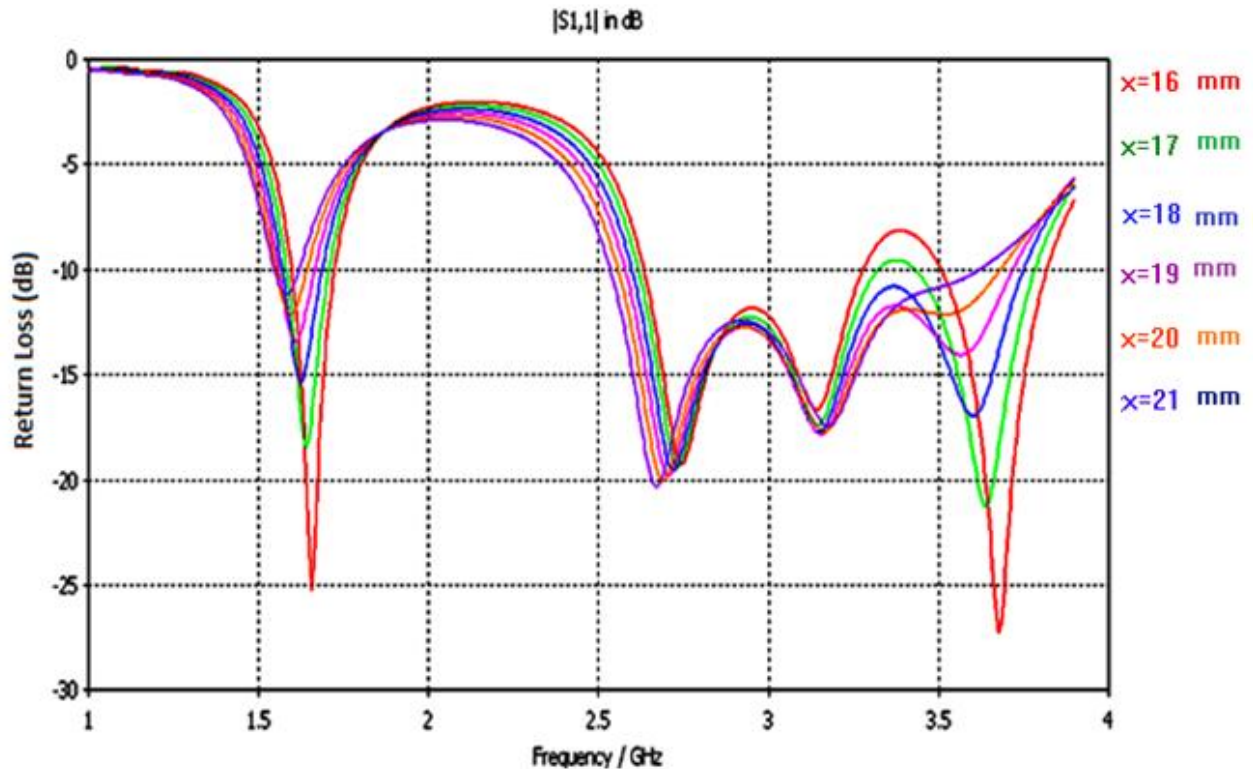


Figure 5.12 Effect of variation of horizontal gap space between the patch edge and the CPW ground plane along X axis.

5.2.12 Effect of variation of vertical gap space between the patch edge and the CPW ground plane along Y axis

The vertical spacing ' v ' is also analyzed along Y-axis to achieve broadbanding and multiband characteristics. ' v ' is varied from 1mm to 6 mm with step size of 1mm. It is observed from Figure 5.13, that the initial value of 1mm gives the best results producing dual band performance of the antenna. The first band extends from 1.49 GHz to 1.8 GHz generating a bandwidth of 310 MHz at the lower frequency band and 1.15 GHz (2.6 to 3.75 GHz) at the upper band. The return loss obtained at the two bands is -14.1 dB and -18.1 dB at lower and higher frequency band respectively. At $v=2\text{mm}$, the upper frequency band vanishes and the antenna behaves as a single band antenna with the band shifted to lower frequency of resonance i.e. 1.49

GHz. The return loss also decreases to -12.05 dB. Any further increase in the value of v does not generate band with the requisite return loss value of -10 dB and is unsuitable for antenna performance. Hence $v=1\text{mm}$, i.e. the vertical gap value of 1mm delivers dual band antenna with wide bandwidth at the upper band.

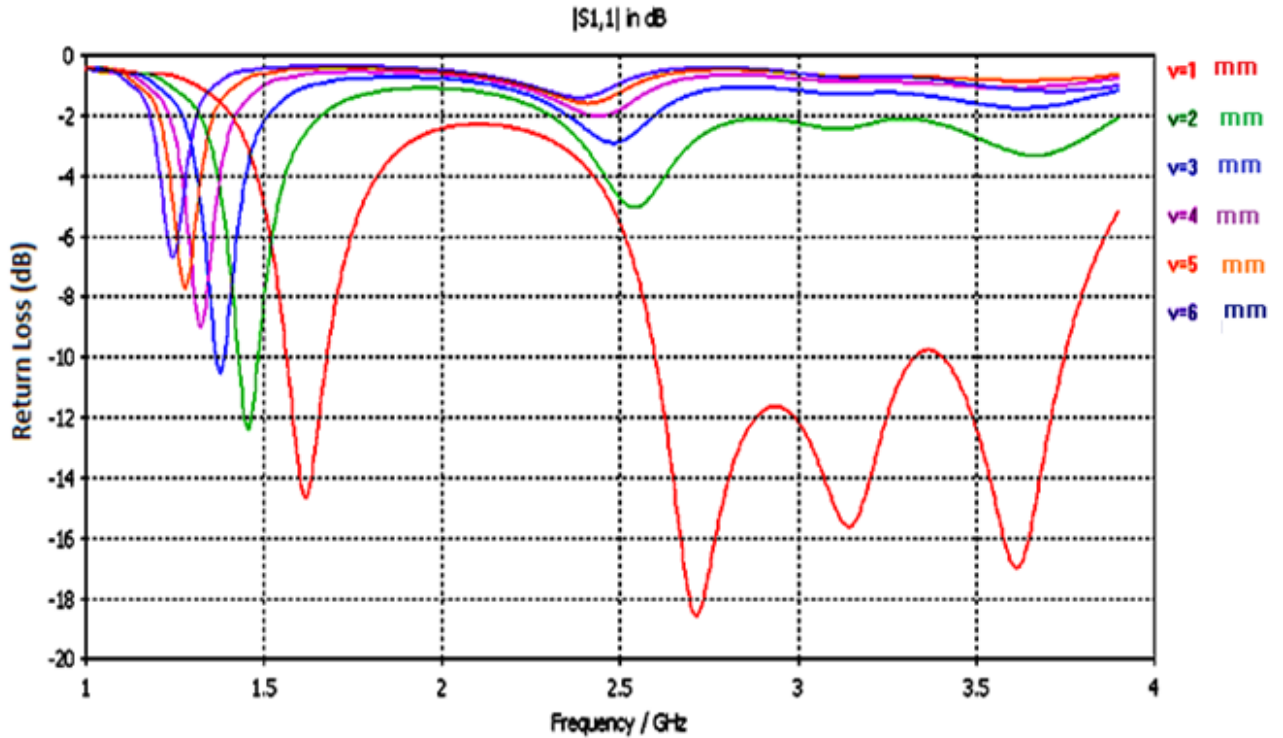


Figure 5.13 Effect of variation of vertical gap space between the patch edge and the CPW ground plane along Y axis.

5.3 OPTIMIZED DIMENSIONS OF THE PROPOSED ANTENNA

The final optimized geometric parameters of the proposed antenna obtained after applying the parametric variations on the structure and the dimensions of the antenna elements are specified in the table 5.1.

Table 5.3 Optimized dimensions of the proposed antenna

Parameter	Dimension (in mm)
L_p	43.75mm
W_p	51.95mm

L_s	70mm
W_s	70mm
W_f	4.94mm
d	0.175mm
L_{s1}	24mm
L_{s2}	4mm
L_{s3}	4mm
L_{s4}	4mm
W_{s1}	12mm
W_{s2}	10mm
W_{s3}	12mm
x	18mm
v	1mm

5.4 ANTENNA DESIGN

The final structure of the proposed antenna is shown in Figure 5.14. In the proposed design, a rectangular patch of perfect electric conducting material copper is mounted on FR4 substrate sheet with relative permittivity ' ϵ_r ' = 4.4 and height ' h ' = 1.6 mm. The initial length and width of the patch and substrate are calculated using the online patch calculator by specifying the frequency of operation, the dielectric constant and height of the substrate used.. The rectangular patch is fed by a microstripline feed of width ' w_f '. It uses CPW ground plane on the same plane as the patch. It surrounds the patch on all sides with a little gap between it and the rectangular patch. The distance or space between the patch and the CPW is represented by ' x ' along the x axis and by ' v ' on the y axis. This distance is varied to see its effect on the performance of antenna. A number of slots are etched in the main rectangular patch of antenna which forms the shape of letter 'E' rotated 90° anticlockwise. The E-slot lies approximately in its center. The slots of letter 'E' are varied in length and width to study its effect on antenna

performance. The final geometry of the proposed antenna is depicted in Figure 5.14.

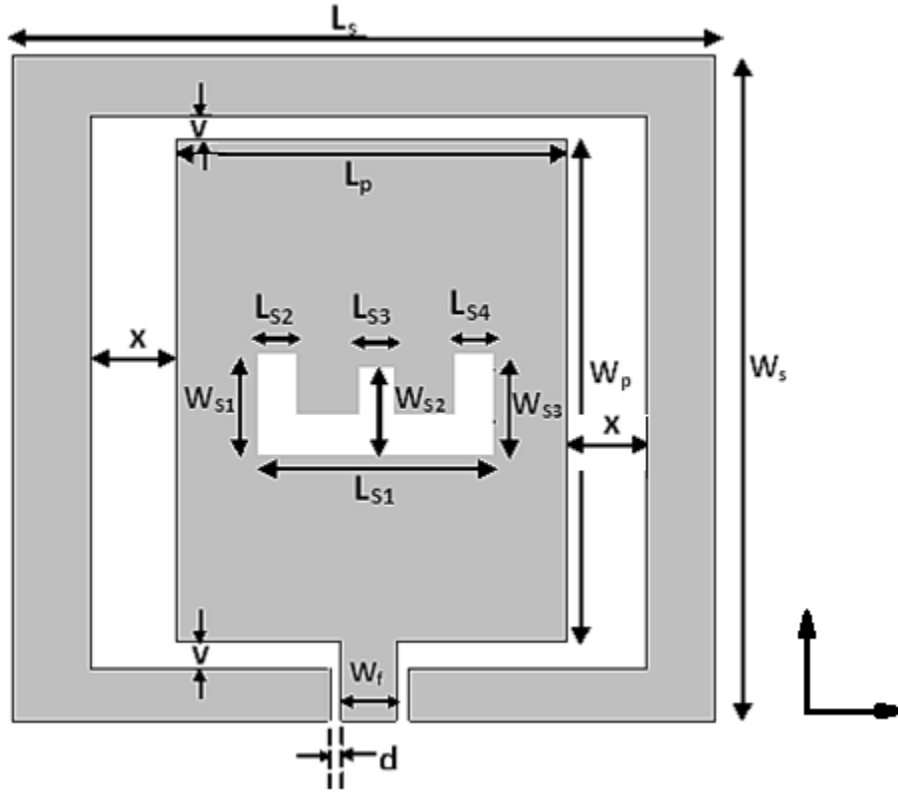


Figure 5.14 Final geometry of the proposed antenna.

It has been noticed in the simulation that the operating bandwidth of the rotated E-shape microstrip patch antenna is critically dependent on the length (L_p) and width (W_p) of the rectangular patch of the antenna. Slots are created in the radiating patch to control the current flow on the antenna surface across the targeted frequency bands. A CPW transmission line, consisting of a signal strip of width $w_f=4.94\text{mm}$ with a gap distance, $d=0.175$ between the signal strip and the coplanar ground plane, is used for feeding the antenna. Two equal finite ground planes are placed symmetrically on each side of the CPW feed-line to surround the rectangular patch. The width and position of the stripline feed determine the impedance matching of the antenna at a particular resonant frequency as shown by the smith chart in Figure 5.15. The antenna has an impedance of 51.06 ohm which is very close to the value used by the feeding cable of 50 ohm.

The final optimized geometric parameters of the proposed antenna are: $L_p=43.75\text{mm}$, $W_p=51.95\text{mm}$, substrate length $L_s=70\text{mm}$, substrate width $W_s=70\text{mm}$.

The optimized slot dimensions obtained are: slot length $L_{s1}=24\text{mm}$, $L_{s2}=4\text{mm}$, $L_{s3}=4\text{mm}$, $L_{s4}=4\text{mm}$; slot width $W_{s1}=12\text{mm}$, $W_{s2}=10\text{mm}$, $W_{s3}=12\text{mm}$.

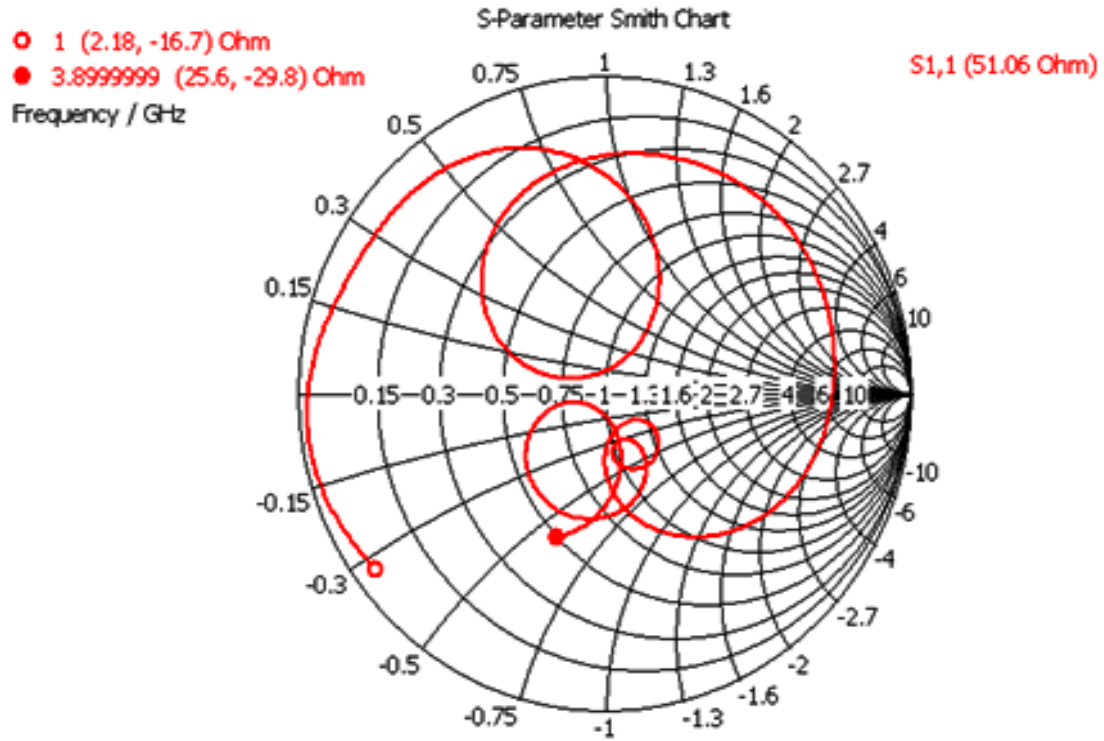


Figure 5.15 Smith chart showing impedance matching of the proposed antenna.

5.5 MEASURED RESULTS

The design of the proposed antenna is fabricated on FR4 substrate by employing photolithographic technique. The photograph of the fabricated antenna is illustrated in Figure 5.16. The VNA (Vector Network Analyzer), shown in Figure 5.17, is used to measure the return loss of the fabricated antenna. Before starting with the measurement of the results on VNA, the equipment is calibrated to remove any errors generated by the Agilent VNA's system setup.

For measuring the return loss, a low loss coaxial cable of 50 ohm impedance value is used to connect the AUT with port1 of VNA. The antenna is then tested to verify the simulated return loss, which validates the antenna design. The measured reflection coefficient is presented in Figure 5.18 in comparison to the simulated value. Both the results match well with each other in terms of return loss and impedance bandwidth with minor shifting of the bands due to inaccuracies while fabricating the structure or the use connector or feeder cable while testing.



Figure 5.16 Fabricated antenna



Figure 5.17 VNA (Vector Network Analyzer), ENA series.

5.5.1 Measured Return Loss

The comparative result between the simulated and measured return loss for the projected antenna is illustrated in Figure 5.18. It is perceived from the simulated plot that two resonating bands are attained for the fabricated antenna structure ranging from 1.56-1.69 GHz and 2.6-3.74 GHz with ample bandwidth of 128 MHz, 1.14 GHz respectively whereas there is a slight decrease in the bandwidth of the antenna from a simulated value of 130 MHz to 120 MHz (from 1.49-1.61 GHz) as the measured value at the lower band. At higher frequency band also, the measured value is 1.13 GHz (from 2.51-3.64 GHz) which is somewhat lower than the simulated bandwidth of 1.14 GHz. The measured return loss at the two bands is -13.8 dB and -16 dB as

opposed to the simulated values of -14.55 dB and -19.7 dB at the resonance peaks of 1.62 GHz and 2.75 GHz respectively.

The maximum peak gain of 3.94 is achieved by the antenna which shows an acceptable value although not too good. At lower frequency band, the antenna can be operated for mobile satellite applications. With such a wideband at the higher frequency, the proposed antenna is capable of operating over several communication standards for heterogeneous wireless applications such as aeronautical radionavigation radiolocation (2.7–2.9 GHz), radiolocation radionavigation (2.9–3.1 GHz), radiolocation earth exploration-satellite (active) mobile (3.1–3.3 GHz), radiolocation amateur mobile (3.3–3.41 GHz), mobile (3.41–3.6 GHz), LTE (3.4-3.6 GHz) and WiMAX (3.4-3.69 GHz).

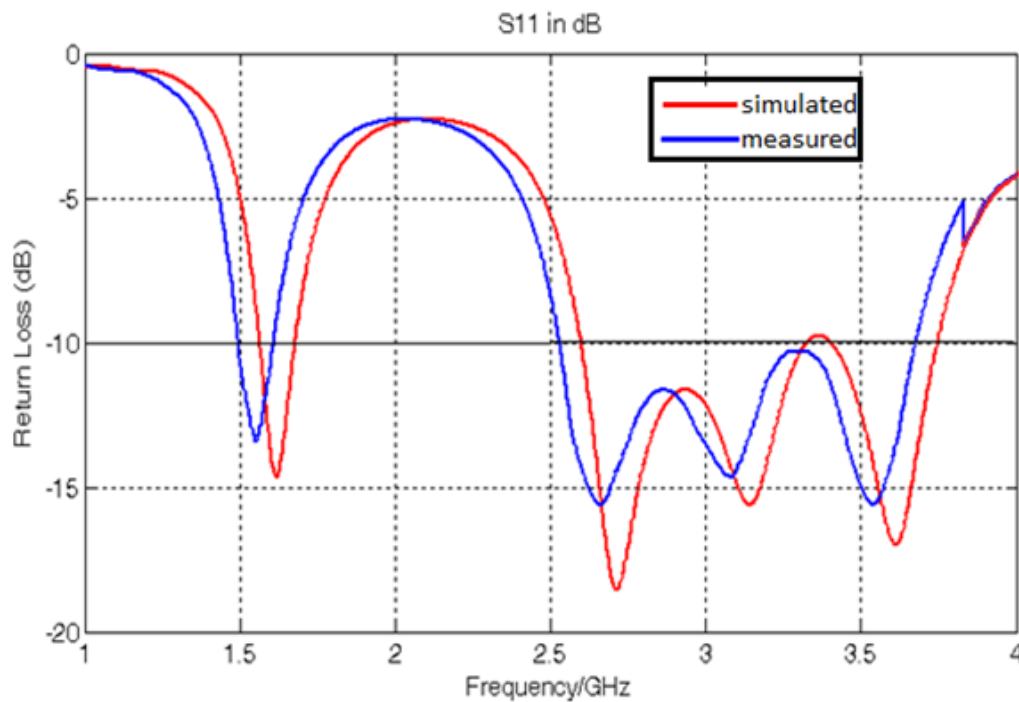


Figure 5.18 Comparison of simulated and measured return loss of the proposed antenna.

The measured results match well with the simulated results across the entire operating region except for a slight shift in the value of peak resonant frequency to higher frequency in the upper band. The reason for shift in peak resonant frequency might be due to the minor dimensional impreciseness during the fabrication process. Connector loading during measurements might introduce some variable reactance, which is not considered during simulation of the design. Feeding cable might introduce some interference and noise which

might bring minor variances between the values of simulated and measured results.

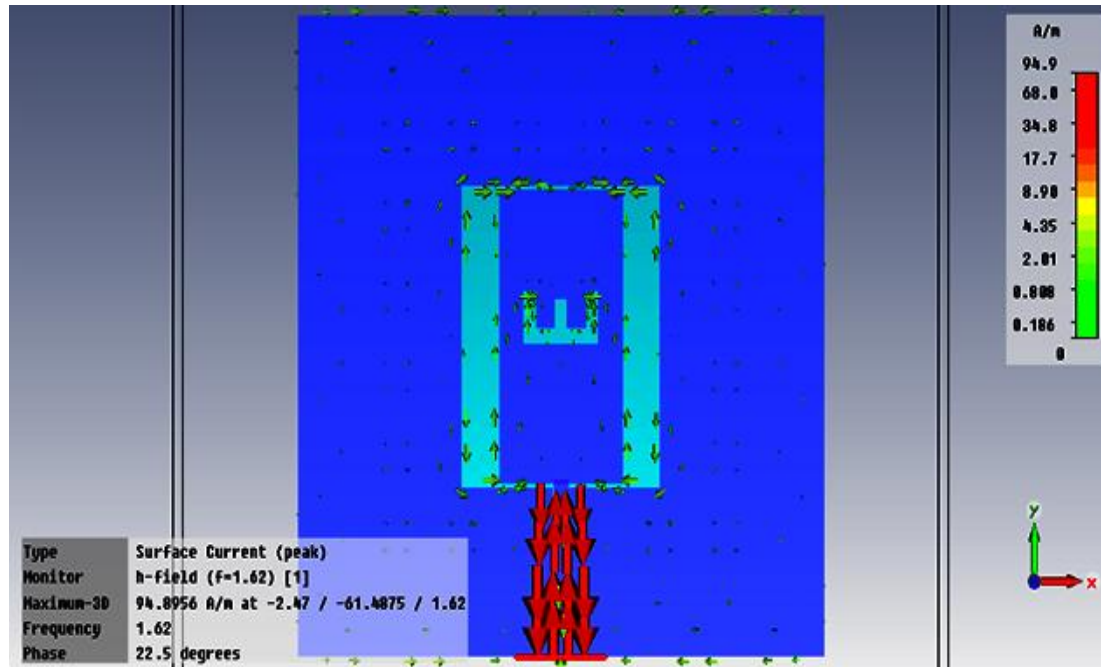
Table 5.4 Summary of the simulated and measured results of the proposed antenna.

Paramter → Band ↓	Frequency of resonance (in GHz)	Band covered (in GHz)	Impedance Bandwidth (in MHz)	Return loss (in dB)	Gain (in dBi)
Lower Band	(1.52) (1.62)	(1.49 to 1.61) 1.56 to 1.69	120 (130)	-13.8 (-14.55)	4.0 3.93
Upper band	2.65 (2.75)	2.51 to 3.64 (2.6 to 3.74)	1.13 (1.14)	-15.8 (-19.7)	3.90 3.90

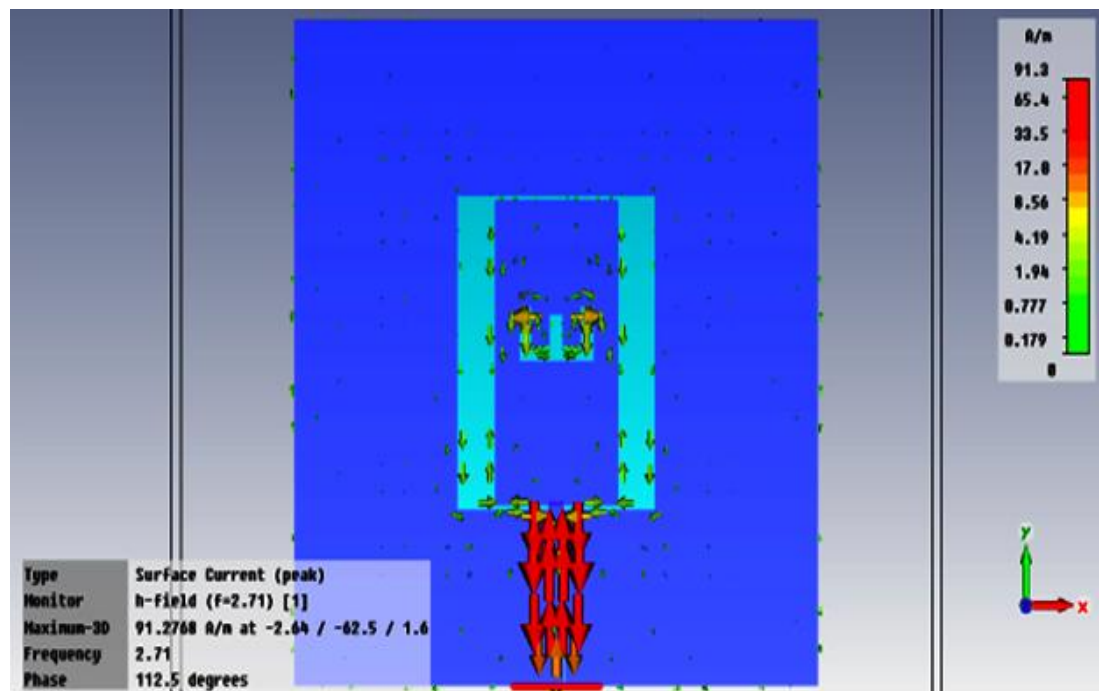
5.5.2 Current distribution

The simulated return loss results display dual banding with four resonant peaks at 1.66 GHz, 2.7 GHz, 3.14 GHz and 3.67 GHz. The current density and radiation patterns are analyzed using CST MWS to better understand the electromagnetic radiation and excitation mechanism of the proposed antenna. A series of simulations are carried out to determine the surface current density across the slotted patch of the antenna. It is evident from the Figure 5.19 (a), that a momentous surface current density is found out to be concentrated on the upper edge of the patch and the two side slots, S_2 and S_4 of E-shaped slot engraved at the center of the rectangular patch. Therefore the configuration provides electrical current path to produce 1.66 GHz resonant mode with vivid and brilliant radiation characteristics. The upper frequency band obtained in the simulation results show three resonant peaks at 2.7 GHz, 3.14 GHz and 3.67 GHz.

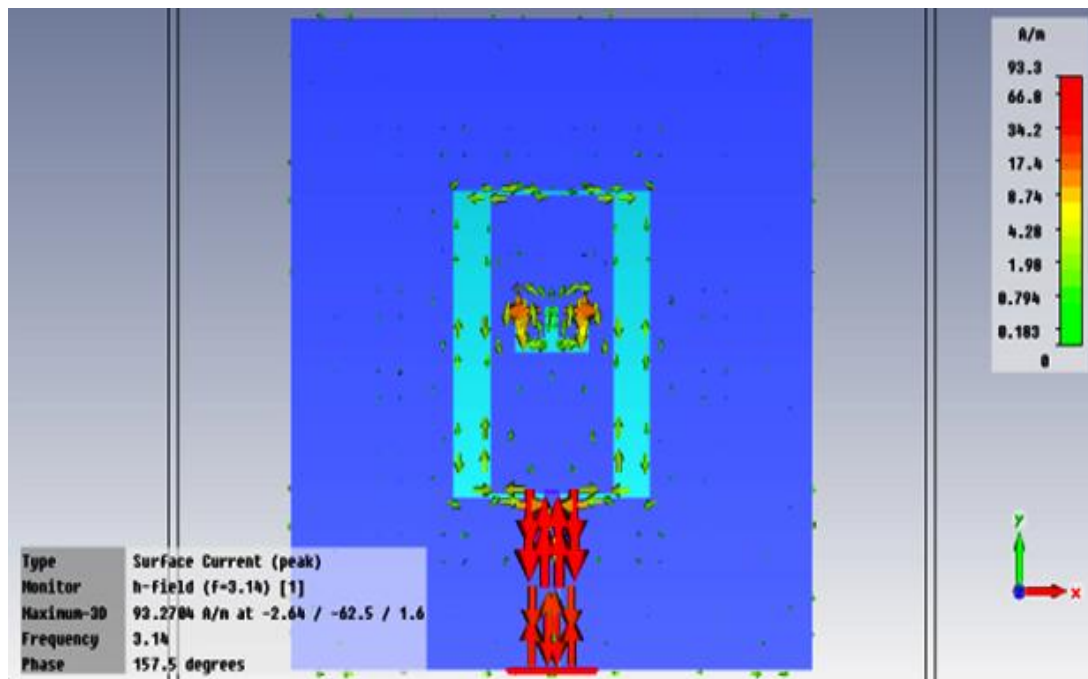
The surface density plots for the proposed antenna shown in Figure 5.19 (b) make it clear that the CPW slots around the lower edge of the patch, the side slots S_2 and S_4 and the base slot S_1 of the E slot are accountable for yielding a resonance peak at 2.7 GHz. Figure 5.19 (c) show that the surface currents chiefly flow through all the lengths of E-shaped slot at the frequency of 3.14 GHz whereas, the CPW vertical slots around the rectangular patch and the side slots, S_2 and S_3 are responsible for resonance at 3.67 GHz of the upper band, as seen in Figure 5.19 (d). Therefore, the suggested MPA generates multi frequency antenna with wide bandwidth to cover mixed standards of wireless communication systems at the same time.



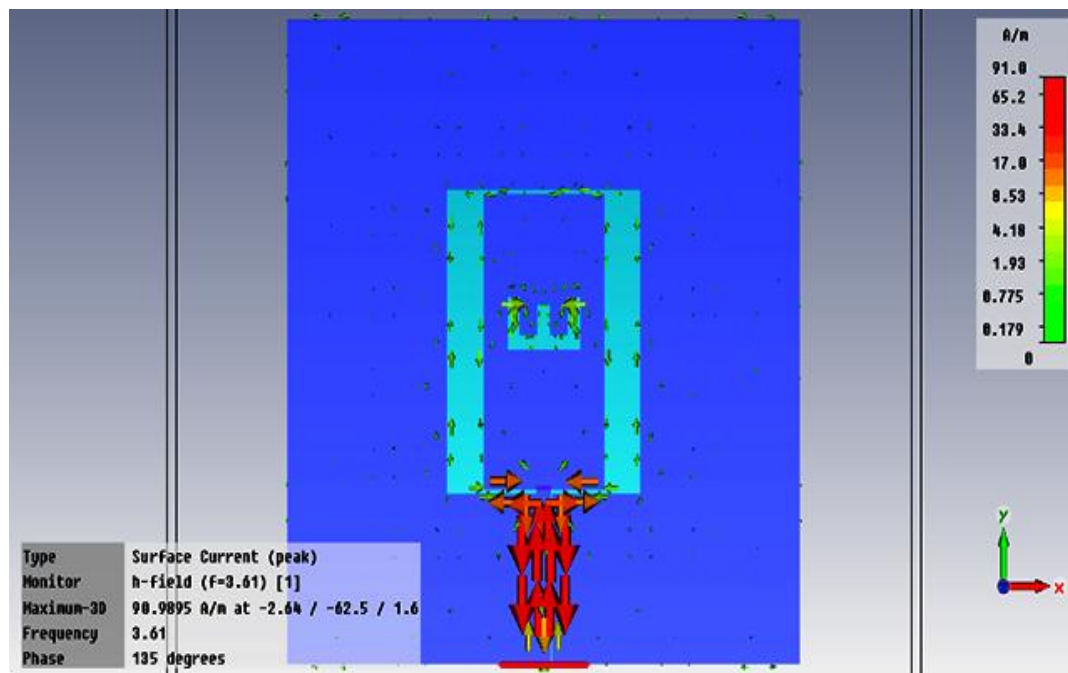
(a) 1.66 GHz



(b) 2.7 GHz



(c) 3.14 GHz

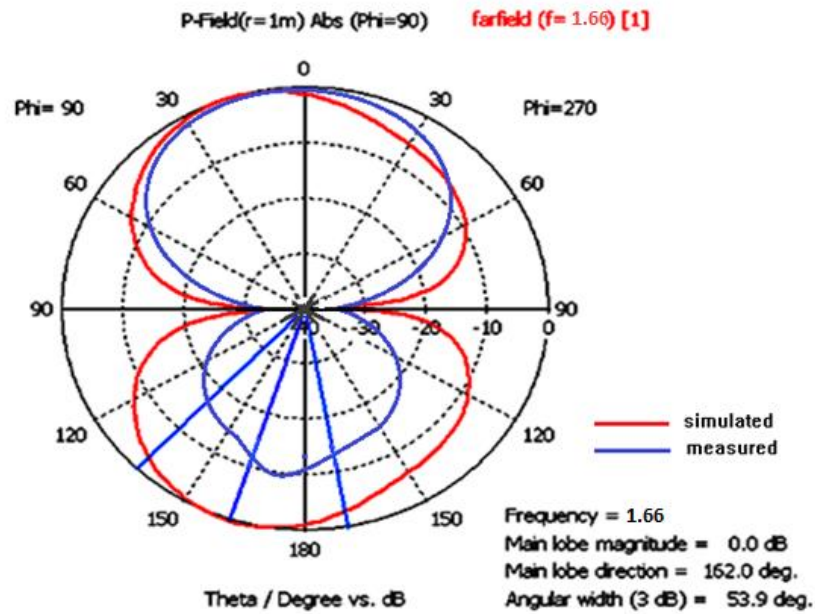


(d) 3.67 GHz

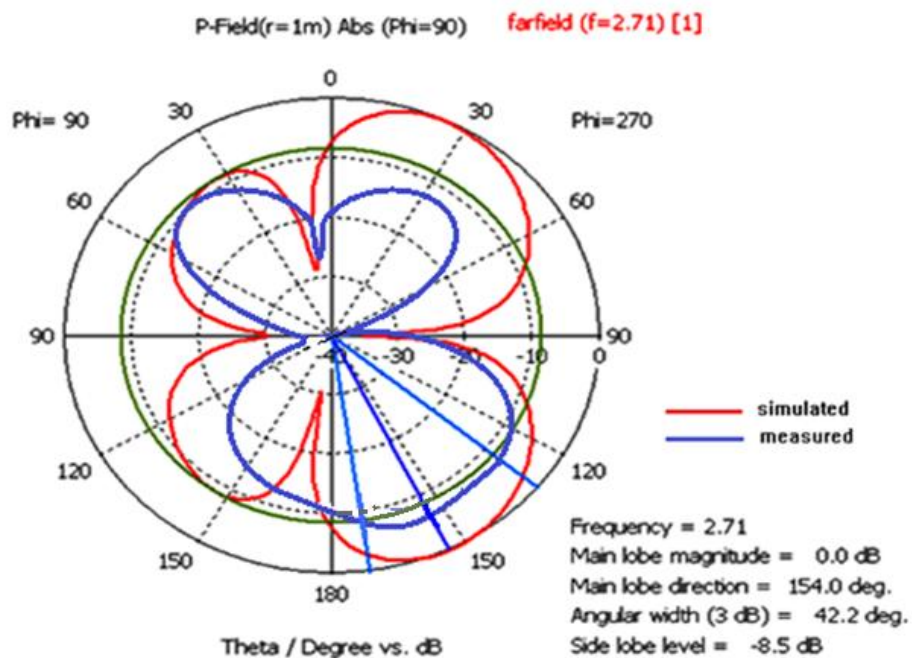
Figure 5.19 Simulated current density on the surface of the antenna at (a) 1.66GHz, (b) 2.7GHz, (c) 3.14GHz and (d) 3.67GHz.

5.5.3 Radiation pattern

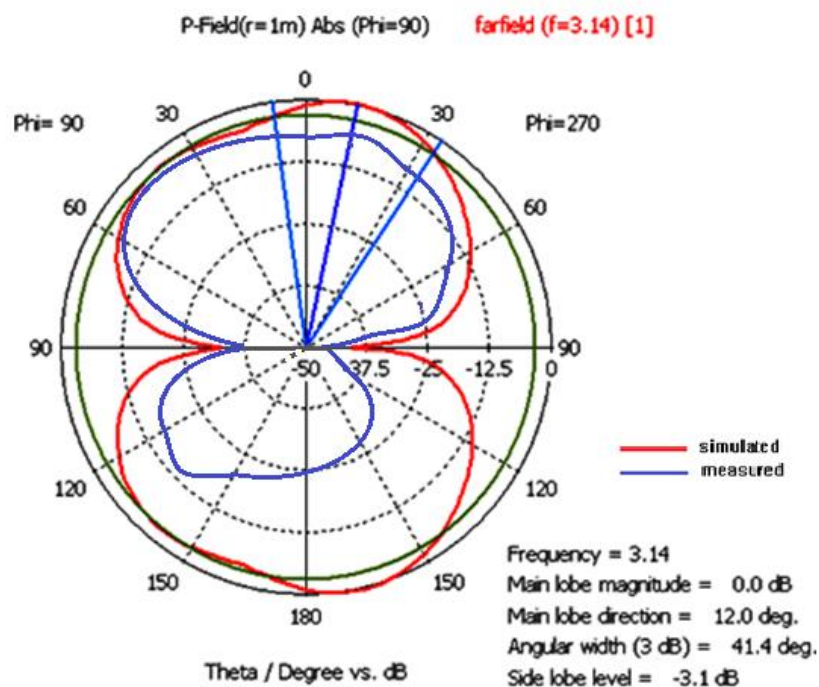
The power pattern of the radiation through the proposed antenna is plotted at the different resonances which show somewhat directional pattern with two or more lobes. Figure 5.20 (a), (b), (c) and (d) display the simulated and measured radiation patterns of proposed antenna at different resonant peaks of two bands. These measurements are obtained at peak resonance frequency of 1.66 GHz, 2.7 GHz, 3.14 GHz and 3.67 GHz.



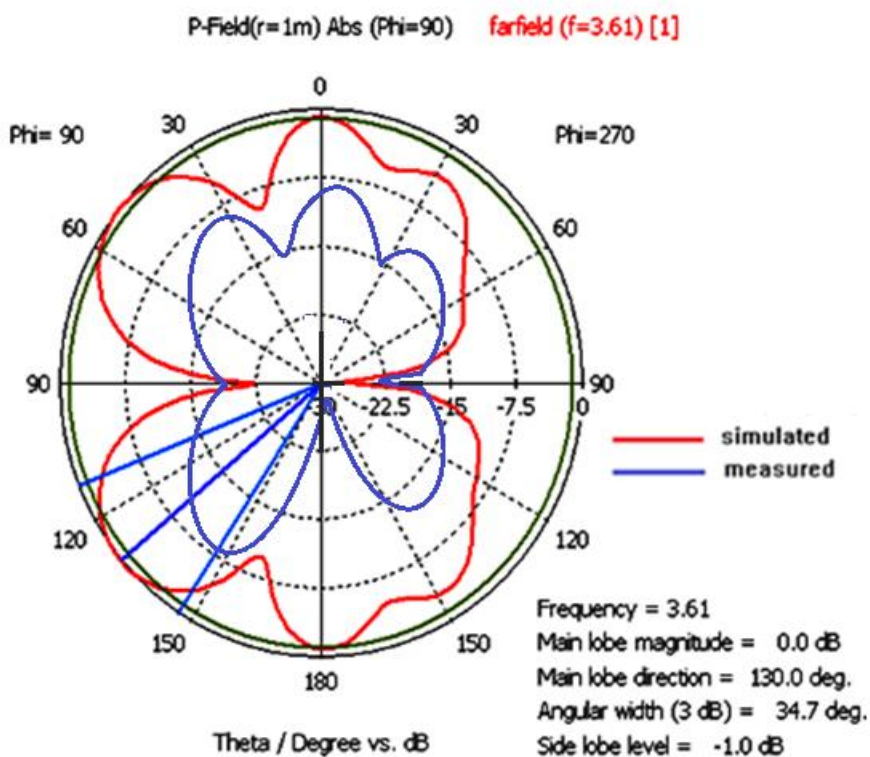
(a) 1.66 GHz, $\phi=90^\circ$



(b) 2.71 GHz, $\phi=90^\circ$



(c) 3.14 GHz, $\phi=90^\circ$



(d) 3.67 GHz, $\phi=90^\circ$

Figure 5.20 Simulated and measured Radiation pattern plots of the antenna at (a) 1.66GHz, (b) 2.7GHz, (c) 3.14GHz and (d) 3.67GHz.

5.5.4 Gain

The gain for the proposed antenna is also simulated as shown in Figure 5.21. The maximum value of gain attained by the proposed antenna at the first resonance peak at 1.66 GHz is 3.93 dB. The gain remains almost constant till the second peak frequency of 2.1 GHz. Further, there is a gradual fall in the gain value which reaches 3.65 at 3.14 GHz and further has a small decline and finally attains a value of 3.19 GHz at 3.67 GHz. Thus the gain of the antenna is more or less found to be constant throughout the operating bands, which makes the antenna stable.

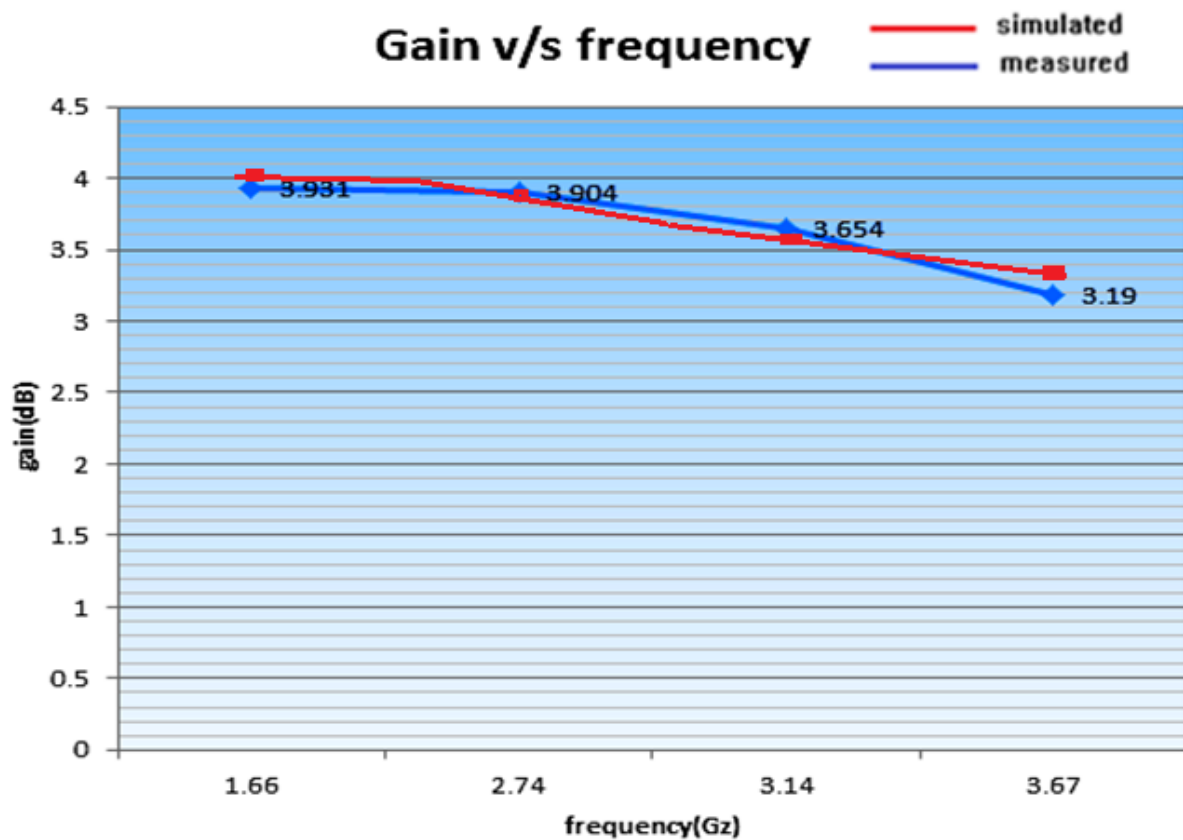


Figure 5.21 simulated and measured gain of the proposed antenna.

5.6 SUMMARY OF THE CHAPTER

In this paper we present a design of a CPW fed Microstrip Patch Antenna with E-shaped slot, rotated 90° anticlockwise, embedded in its center to create multifrequency antenna with enhanced bandwidth at the operating bands. Simulated results indicate that the antenna exhibits a good impedance bandwidth of 130 MHz and 1.14GHz at the two bands extending from 1.56 GHz to 1.69 GHz and 2.6 GHz to 3.74 GHz respectively. The values of return loss defined in terms of S_{11} parameter is found to be well below -10dB for the entire operational bandwidth

with peak value of -14.55 dB at a resonating frequency of 1.62 GHz and -19.7 dB at 2.75 GHz. A considerable value of 3.93 dBi is observed for the antenna gain, which remains almost constant across the desired bands. The proposed antenna can operate at various communication standards for heterogeneous wireless applications such as aeronautical radionavigation radiolocation (2.7–2.9 GHz), radiolocation radionavigation (2.9–3.1 GHz), radiolocation earth exploration-satellite (active) mobile (3.1–3.3 GHz), radiolocation amateur mobile (3.3–3.41 GHz), mobile (3.41–3.6 GHz), LTE (3.4–3.6 GHz) and WiMAX (3.4–3.69 GHz).

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CHAPTER 6

DOUBLE RING MULTIBAND MICROSTRIP PATCH ANTENNA WITH PARASITIC STRIP STRUCTURE FOR HETEROGENEOUS WIRELESS COMMUNICATION SYSTEMS

6.1 INTRODUCTION

It has been emphasized in chapter 5 that new designs for multimode and multiband antennas are required for future wireless devices. The advancement of new technologies in WLAN IEEE 802.11, WiMAX IEEE 802.16 and LTE standards has put new challenges in front of antenna designers also. New bands of operation have been introduced in these standards. The IEEE 802.11 wireless standard provides cost effective implementation of wireless LAN service to homes, offices, and other small public locations in the 900 MHz, 2.4 GHz, 3.6 GHz, 5 GHz, and 60 GHz frequency bands. 2.4 GHz and 5 GHz bands are license-free bands, predominantly used for ISM (Industrial, Scientific and Medical) applications. According to IEEE 802b/g and IEEE 802.11a, Wireless Local Area Networks are planned to work in the 2.4 GHz frequency bands ranging from 2.4 GHz to 2.5 GHz and 5 GHz (5.15 – 5.25 GHz, 5.25 – 5.35 GHz, 5.725 – 5.825 GHz). 802.11b/g and 802.11a provide high data rate of 11Mbps in 802.11b with coverage of 100m and 54 Mbps in 802.11a/g. 802.11n operating at 2.4 GHz and the 5 GHz bands is an improved version of 802.11 standards by implementing multiple-input multiple-output antennas. IEEE 802.11ad operates in 60 GHz millimeter wave spectrum. IEEE 802.11ah is operating at sub-1 GHz license-exempt bands, thus there are multimode operations of WLAN standard [9-11] [180].

IEEE 802.16e standard developed another low cost, easily deployable, broadband wireless access technology, which is complementary to WiFi technology, known as WiMAX used at 2.5/3.4/5.25 GHz frequency bands. It can provide higher data rate values around 70Mbps with larger coverage area of about 8 km. It provides competitive and cost effective broadband service alternative for wired DSL or cable. WiMAX can deliver internet access in rural, suburban

or metropolitan areas which lie far from the closest WiFi hotspot and provide extensive coverage to large areas called Wide Area Networks (WANs) with high speed internet access [11].

Integration of different advanced networks is critical requirement of next generation networks for increasing the usability and productivity of the network. The word ‘interworking’ refers to the links formed for communication or transmission of information between various standards of heterogeneous networks. With the advent of modern communication systems, with highly advanced features, there is a growing demand for compact, cost effective, wide and multiple band antennas for usage in viable wireless communication structures [51, 60]. Rapidly developing wireless technologies mandate the incorporation of different Worldwide Interoperability for Microwave Access (WiMAX) standards and Wireless Local Area Network (WLAN) standards into a single unit. Thus there is a requirement to design a single antenna which can cover these bands completely and can attain higher antenna impedance bandwidth [4-6]. Since the device size of the wireless systems is decreasing manifold, smaller antenna size is required for practical applications [75, 180]. The growing demand in the field of wireless communication and its expanding applications has put a challenge for the antenna designers to accomplish the objectives set forth. To avoid these problems, multi-band antenna designs are recommended, in which the designed antenna covers not only the distinct bands but are have wide bandwidth also.

In this chapter, a CPW-fed planar monopole antenna consisting of two rectangular rings on a rectangular patch is designed to obtain multimode and multiband operation for WLAN (2.4/5.2/5.8 GHz) and WiMAX (2.3/2.5/5.5 GHz) standards. A combination of various techniques such as use of double ringed structure, meandering, use of parasitic strip and CPW feed assembly, have been used to obtain a simple, small sized, multiband, multimode antenna with enhanced bandwidth for WLAN/WiMAX bands. A parasitic strip and meandering along with double ringed structure have been used to achieve enhanced impedance bandwidth in WLAN (from 2.26 GHz to 3.03 GHz) and WiMAX (from 4.48–6.85 GHz) bands. The parametric analysis is carried out to study effect of varying dimensions on antenna performance. The proposed antenna is optimized and prototype is designed and fabricated. Simulated and measured radiation patterns in elevation and azimuthal planes are also observed. The designed antenna has a planar structure with one layer of copper arranged on one side of substrate while the opposite flank is devoid of any metallization. The antenna is printed on 1.6 mm thick FR4 substrate sheet with dielectric constant of 4.4, which makes it easy and economical to

manufacture. The design of the antenna is discussed next. The performance of the designed antenna is analyzed using Zeland IE3D electromagnetic simulator based on MoM (Method of Moments) principle.

6.2 PARAMETRIC STUDY

This section presents the parametric analysis of the antenna to study the influence of the variations of different parameters on the performance of the proposed antenna in terms of resonance, return loss, impedance bandwidth, radiation pattern and gain. To examine the performance of the proposed antenna structure, the basic design structure and geometric dimensions of the antenna are varied at a time keeping the others constant. The dimensional variations in the various parameters of the antenna are implemented in IE3D software which shows the results for different values considered for the variation in a combined graphical form. The optimum dimensions obtained after parametric study are used to finalize the antenna design to achieve the desired results

The parametric variations are implemented in the structure as well as dimensions of the antenna by making step by step modifications in the antenna. Its effect is presented as return loss (S_{11} parameter) characteristics, confirming its effect on the performance of the antenna. The rectangular ringed patch is used initially as the main radiating patch with microstripline feed exciting the antenna. It has a Co Planar Waveguide (CPW) ground plane, located evenly on both sides of the microstripline to form a CPW assembly. The effect of addition of small inner rectangular ring, vertical branch strip or parasitic strip and meandering of outer ring on S_{11} parameter is examined and the effect of dimensional Parasitic Strip Length (L_3) and variation of gap space (G) between the radiating patch and ground plane is also evaluated and presented in the simulation results. The proposed antenna is designed in four steps and the parametric study of structural variations is presented first.

6.2.1 Initial Antenna Design

Initially, a single rectangular ring structure is formed by cutting a large rectangular slot from the metallic patch. The antenna is fed by CPW feed assembly which consists of central microstripline feed surrounded by uniformly placed CPW ground planes on either side of it as illustrated in Figure 6.1. The antenna is simulated and return loss is plotted to see the

performance of the antenna in terms of its frequency of resonance, reflection coefficient and impedance bandwidth.

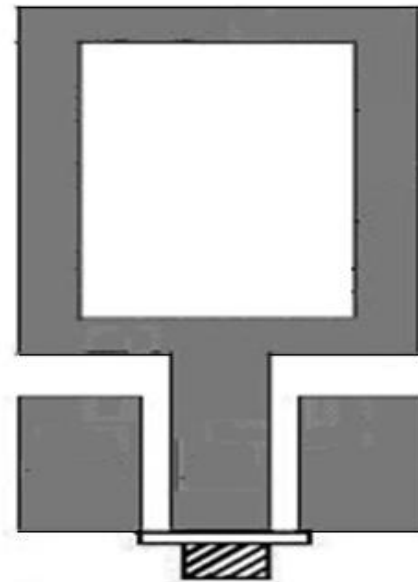


Figure 6.1 Antenna with a single ring.

The graph plotted for S_{11} parameter in Figure 6.2 shows that the antenna is capable of dual band operation at frequencies 2.5 GHz and 6.6 GHz. The antenna is matched to -10 dB value of return loss over the frequency range of 2.26 to 3.07 GHz in the lower band, with impedance bandwidth of 810 MHz and return loss of -23.5 dB. At the higher frequency band, extending from 6.17 GHz to 6.95 GHz, the value of impedance bandwidth obtained is 780 MHz with return loss of -17.20 dB. The antenna is thus able to cover 2.3/ 2.4 GHz WiMAX/ WLAN bands but is unable to cover higher bands of WLAN and WiMAX at 5.2/ 5.5 and 5.8 GHz. The results of structure shown in Figure 6.2 are summarized in table 6.1.

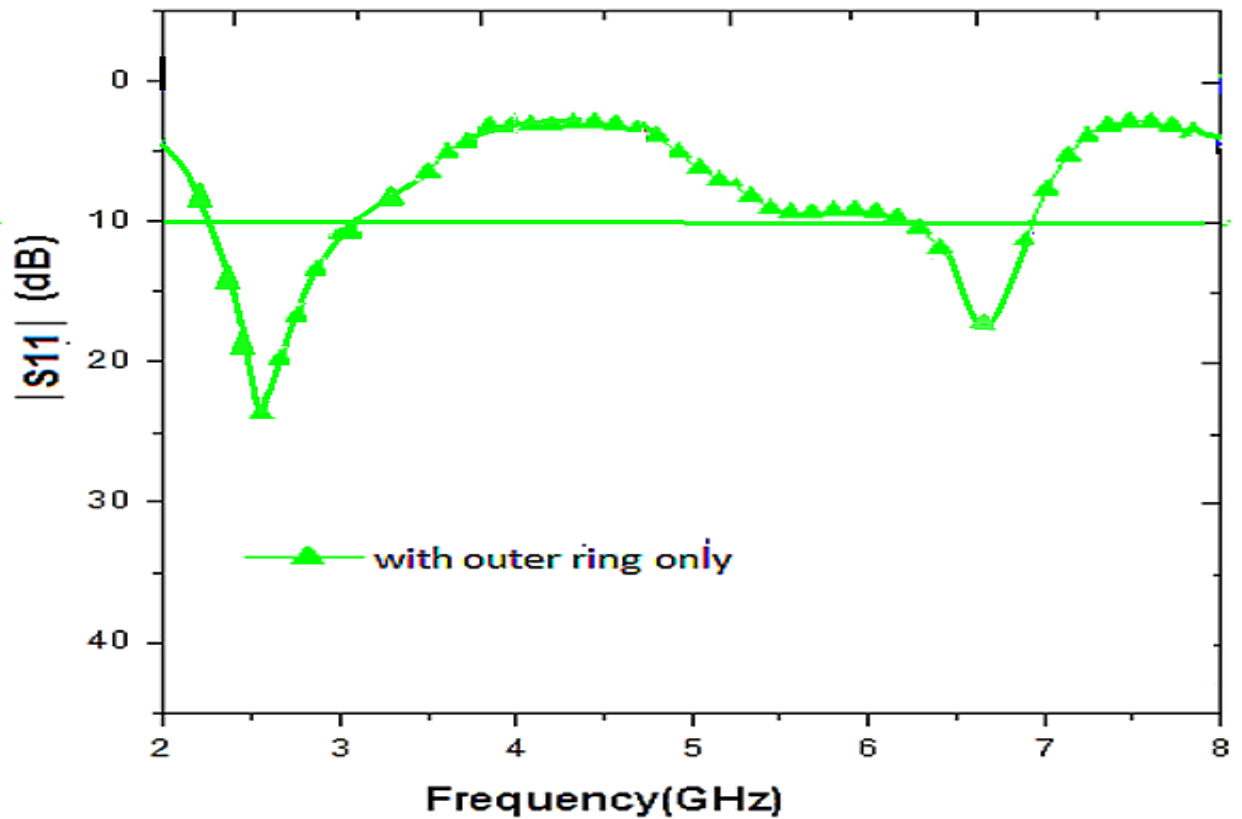


Figure 6.2 Return loss (S_{11} parameter) of antenna with a single ring.

Table 6.1 Results obtained for initial antenna with single ring.

Band	Frequency Range	Bandwidth	Peak Return Loss
Lower Band	2.26 to 3.07 GHz	810 MHz	-23.5 dB
Upper Band	6.17 to 6.95 GHz	780 MHz	-17.20 dB

6.2.2 Effect of addition small inner rectangular ring

Due to the inability of the antenna to resonate at higher bands of WLAN and WiMAX, the antenna structure is modified using another small ring which is incorporated in the right hand inside edge of the ringed patch as illustrated in Figure 6.3. The simulation results are derived to see its effect on return loss and bandwidth of antenna. It is evident from the S_{11} parameter results plotted in Figure 6.4, that the introduction of small inner ring to the rectangular ringed patch has minimal effect on the lower frequency band and its return loss value, but has a significant

influence on the upper frequency band. There is a remarkable increase in the bandwidth of the higher frequency band from 780 MHz to 1.94 GHz which extends from 5.15 GHz to 7.09 GHz. The return loss of the antenna is also improved, reaching a value of -22.6 dB as compared to the earlier value of -17.20 dB. The antenna is capable of covering the WLAN and WiMAX standards at 2.4/2.5/5.2/5.5 GHz bands. The results of this structural modification are summarized in table 6.2.

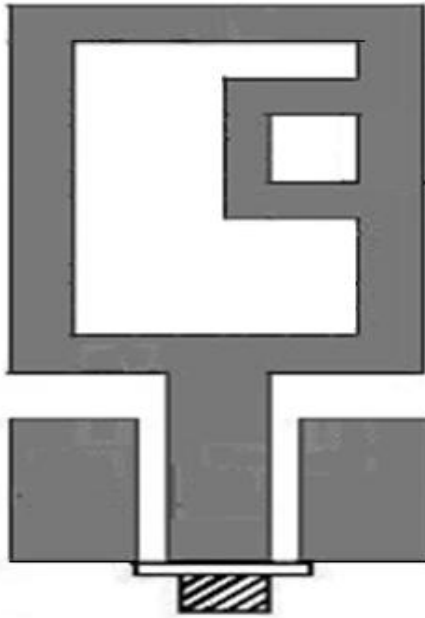


Figure 6.3 Modified antenna after addition of small inner ring.

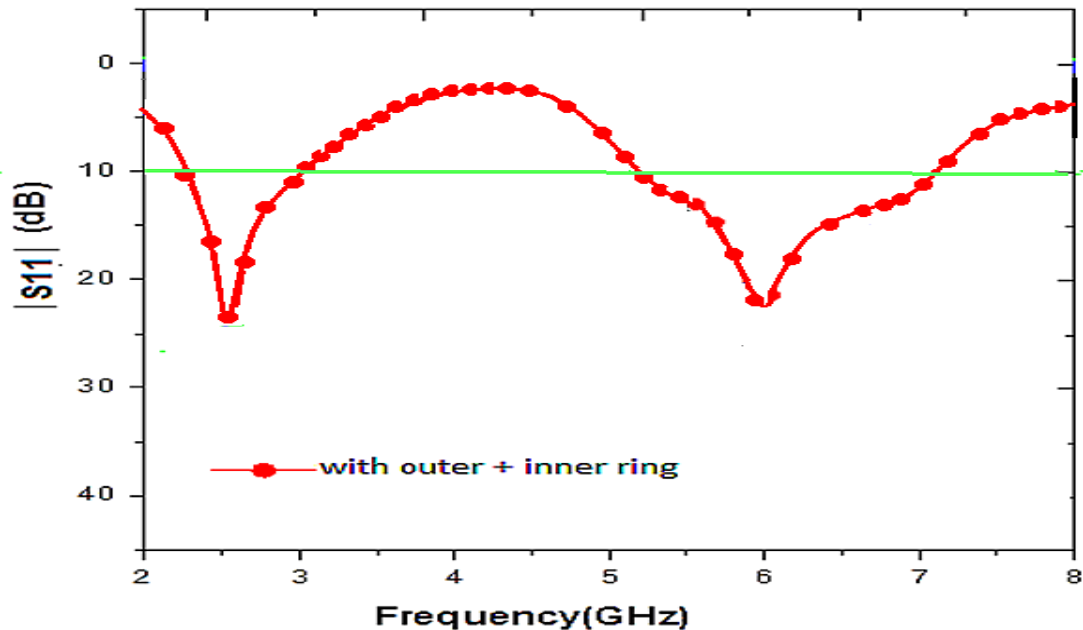


Figure 6.4 Return loss (S_{11} parameter) of antenna after addition of small inner ring.

The table 6.2 summarizes the results obtained using outer and small inner rectangular rings in the antenna structure.

Table 6.2 Results obtained after addition of small inner rectangular ring in the antenna structure.

Band	Frequency Range	Bandwidth	Peak Return Loss
Lower Band	2.26 to 3.07 GHz	810 MHz	-23.5 dB
Upper Band	5.15 to 7.09 GHz	1940 MHz	-22.60 dB

6.2.3 Effect of addition of vertical parasitic strip

Antenna is further modified by adding a vertical parasitic strip in the outer rectangular ringed patch. The parasitic strip is suspending from inner wall of the upper edge of the patch as demonstrated in Figure 6.5. The length of the parasitic strip is varied to see its effect on the performance of the antenna. The altered antenna structure is examined to find the changes produced in the simulation results which are plotted as S_{11} parameter with respect to frequency. It is seen in the Figure 6.6, that the addition of parasitic strip to the antenna structure causes no change in the bandwidth of lower frequency band, whereas the upper band shifts towards higher values of frequency extending from 5.4 GHz to 7.25 GHz. Also, there is an improvement in the return loss value, reaching a maximum value of -26 dB at peak resonant frequency of 5.45 GHz. The results of the antenna structure after second modification are summarized in table 6.3.

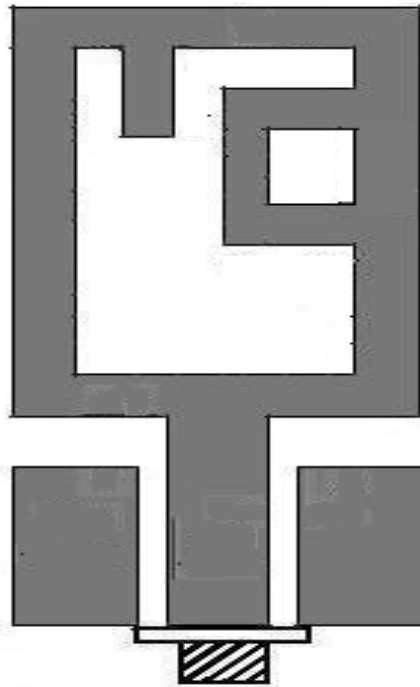


Figure 6.5 Modified antenna after addition of vertical parasitic strip.

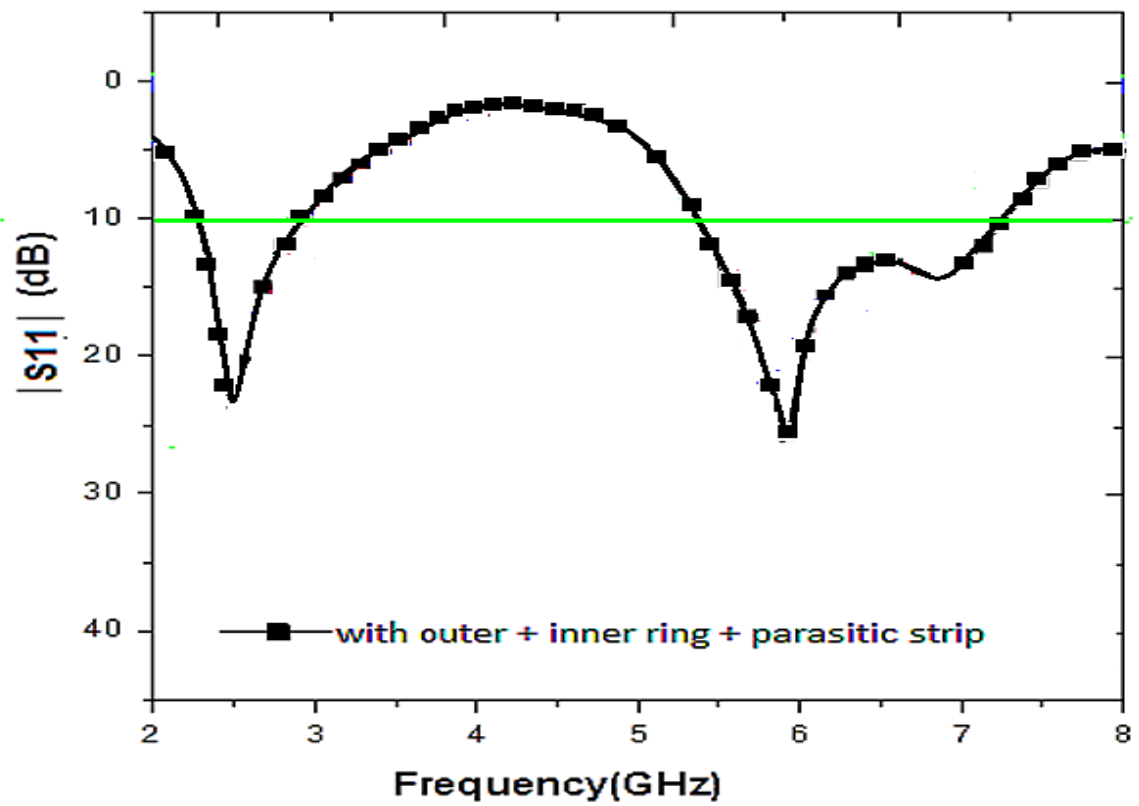


Figure 6.6 Return loss (S_{11} parameter) of modified antenna after addition of vertical parasitic strip.

Table 6.3 Results obtained after addition of vertical parasitic strip in the antenna structure

Band	Frequency Range	Bandwidth	Peak Return Loss
Lower Band	2.26 to 3.03 GHz	770 MHz	-23.5 dB
Upper Band	5.4 to 7.25 GHz	1850 MHz	-26.0 dB

6.2.4 Effect of incorporation of meandering

The final configuration of the antenna is achieved by meandering the boundary of the rectangular ringed patch which is common to outer and inner ring (Figure 6.7). Incorporating meandering in the patch causes the upper band to spread out in both the directions extending from 4.75 GHz to 7.15 GHz as shown in Figure 6.8. It, therefore, produces significant increase in the impedance bandwidth at upper frequency band value which is around 2.40 GHz. Also, it yields considerable return loss value of -32.5 dB at peak resonant frequency of 4.9 GHz. Meandering negligibly affects the lower frequency band. The antenna is thus capable of operating in the entire ISM range of frequencies for WLAN and WiMAX bands.

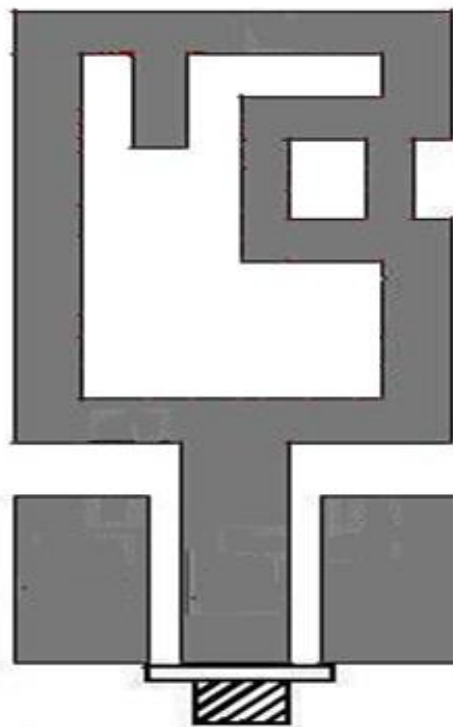


Figure 6.7 Final Antenna structure obtained after incorporating meandering.

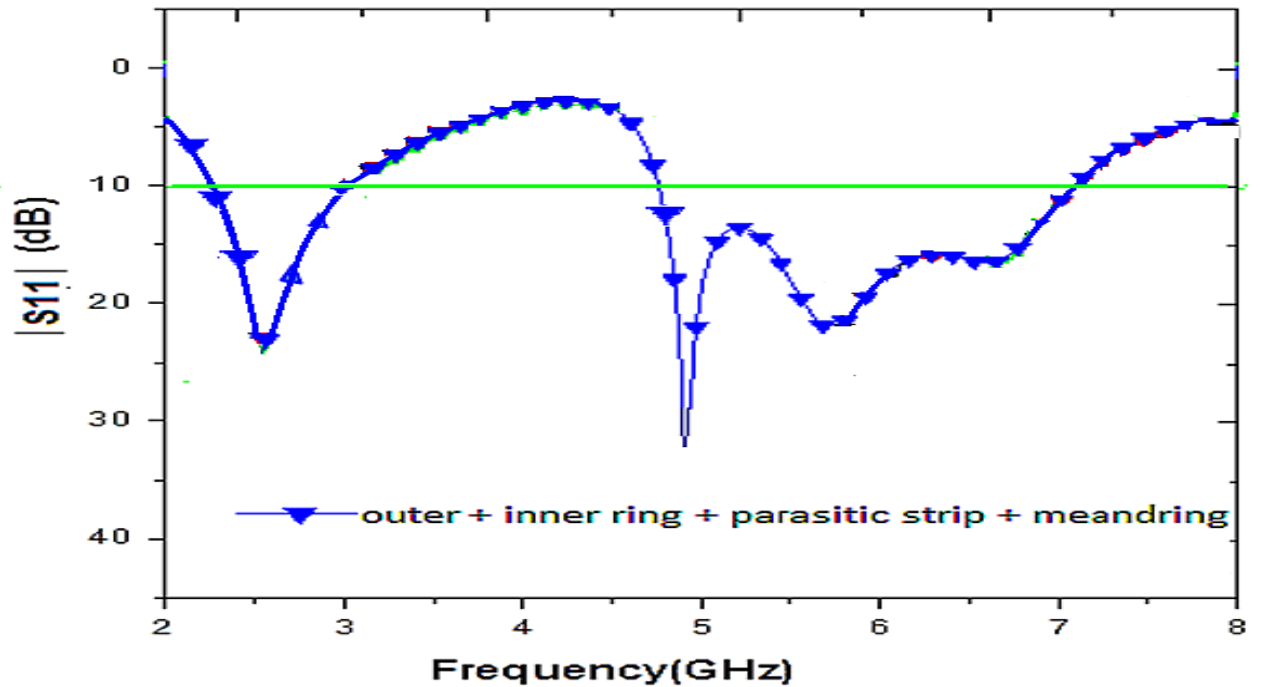


Figure 6.8 Return loss (S_{11} parameter) of final antenna structure after incorporating meandering.

The results of the final antenna structure summarized in table 6.4.

Table 6.4 Final results obtained after incorporating meandering in the antenna structure.

Band	Frequency Range	Bandwidth	Peak Return Loss
Lower Band	2.26 to 3.03 GHz	810 MHz	-23.5 dB
Upper Band	4.75 to 7.15 GHz	2400 MHz	-32.5 dB

6.2.5 Effect of Variation in Parasitic Strip Length (L_3)

The length of parasitic strip (L_3) is varied to demonstrate its effect on the performance of the proposed antenna. Figure 6.9 shows the effect of varying parasitic strip length L_3 on S_{11} parameter with reference to frequency.

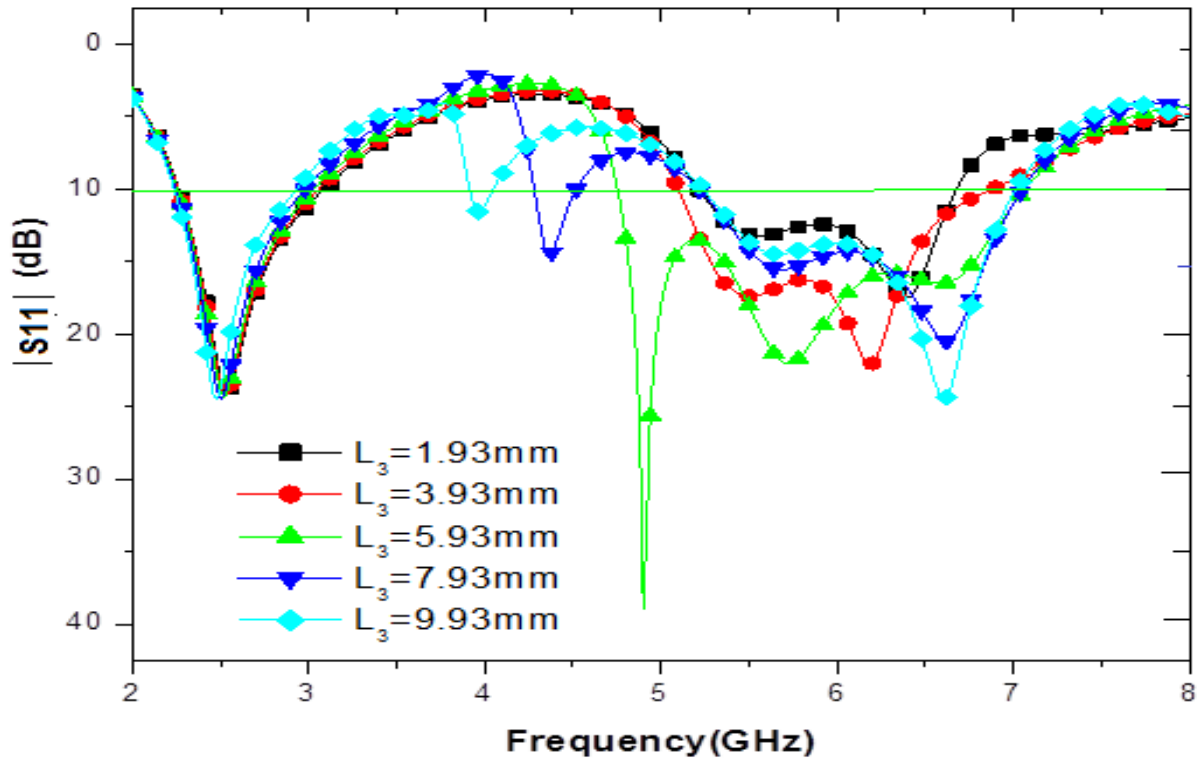


Figure 6.9 Effect of variation in length of parasitic strip (L_3).

It is clear from Figure 6.9 that at $L_3=1.93\text{mm}$, the antenna achieves an impedance bandwidth of 770 MHz at lower frequency band and 970 MHz at the upper band, which extends from 5.2 GHz to 6.17 GHz and return loss value of -17.4 dB. At $L_3= 3.93\text{mm}$, the bandwidth gets improved attaining a value of 1800 MHz (from 5.1 GHz to 6.9 GHz) with return loss of -21.9 dB. There is no effect of increase of $L_3= 3.93\text{mm}$ on lower frequency band. Increase in the vertical strip length (L_3) to 5.93 causes further increase in bandwidth of the upper band to 2300 MHz with return loss peak reaching -39 dB. Thereafter, bandwidth as well as the return loss decrease on further increase in the length of L_3 . It is seen in simulation results that change in the branch strip length (L_3), mainly affects the upper frequency band and has negligible effect on the lower frequency band whose bandwidth remains almost same at all values of L_3 .

6.2.6 Effect of variation of gap space (G) between the radiating patch and the ground plane

Figure 6.10 represents the effect of varying gap space (G) between the radiating patch and ground plane on S_{11} parameter. It is seen that, at $G=1.6\text{mm}$, the lower band attains a

bandwidth of 80 MHz and the upper 1970 MHz with a return loss of -20.5 dB and -13 dB respectively. At $G=2.6\text{mm}$, the value of bandwidth at both the bands increases and attains a value of 230 MHz at the lower band and 2000 MHz at the upper band with -41.8 dB and -30 dB respective return loss values. On increasing the value of gap distance, G to 3.6mm , the bandwidth at the lower band becomes 780 MHz with return loss of -24.5 dB and 2320 MHz at the upper band with significant return loss value of -39 dB. So, it is evident from the Figure 6.10 that with the increase in the gap distance (G), the bandwidth first increases in both the lower and upper frequency bands up to the optimum value of $G=3.6\text{mm}$ and further increase in G after that decreases the bandwidth in both the bands. Also, it can be well interpreted from the return loss curve, that an increase in the gap distance ' G ' moves the peak resonant frequency towards lower side in both resonant bands.

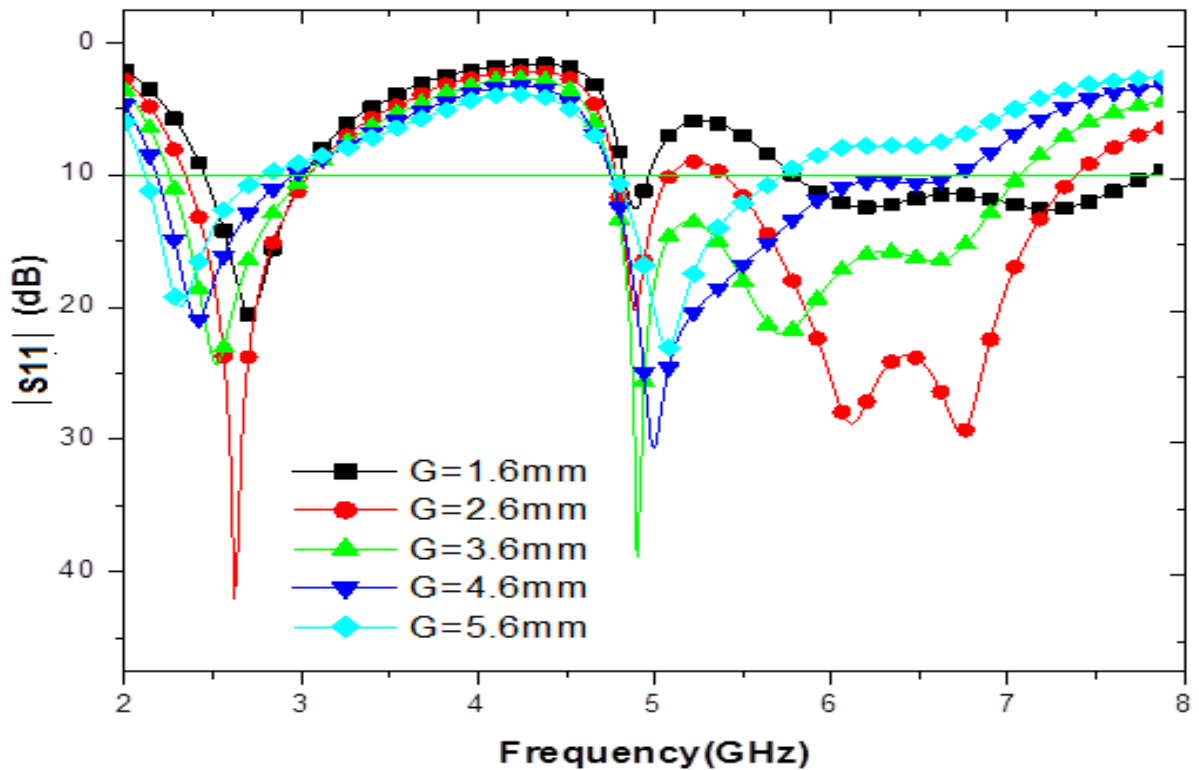


Figure 6.10 Effect of variation of gap space (G) between the radiating patch and ground plane.

6.3 OPTIMIZED DIMENSIONS OF THE PROPOSED ANTENNA

The various optimized dimensions of the proposed antenna, after structural and dimensional parametric analysis, are presented in tabular form below in table 6.5:

Table 6.5 Optimized dimensions of the proposed antenna

L	29.10 mm
W	19 mm
L_g	11.25 mm
W_g	6 mm
W_F	4.75 mm
L_1	8.8 mm
L_2	5.3 mm
L_3	5.93 mm
S_{w1}	3 mm
S_{w2}	2 mm
W_1	6 mm
d	1.35 mm
G	3.6 mm

6.4 ANTENNA DESIGN

Figure 6.11 exhibits the geometry of the proposed CPW fed planar monopole antenna for heterogeneous wireless applications with optimized dimensions. The elementary design of the antenna structure consists of an arrangement of two rectangular rings and a vertical branch strip. The main purpose of two rectangular ring antennas with a parasitic strip is to accomplish the multiband operation for mixed wireless applications. The outer rectangular ring of the proposed antenna has a fixed strip width of ' S_w '. An additional rectangular shaped ring of same width but smaller in size is formed inside the larger ring by cutting the right hand side of the larger ring. A fixed metal strip CPW transmission line is used to excite the antenna. The width of the CPW transmission line is designated as ' W_F '. Two same sized finite ground planes of width ' W_g ' and length ' L_g ' are positioned evenly on either side of the feed line. The gap between the CPW transmission line and ground planes is ' d '.

The various optimized dimensions of the proposed antenna, after parametric analysis, attain the following geometric values: length and width of rectangular patch as $L = 29.10$ mm and $W = 19$ mm respectively, length and width of ground plane as $L_g = 11.25$ mm, and $W_g = 6$ mm respectively, feed-line width $W_F = 4.75$ mm, strip length $L_1 = 8.8$ mm, $L_2 = 5.3$ mm, strip length $L_3 = 5.93$ mm, strip width $S_{w1} = 3$ mm, $S_{w2} = 2$ mm, width $W_1 = 6$ mm, spacing between feed length and ground plane $d = 1.35$ mm and gap between the lower edge of main radiating patch and ground plane, $G = 3.6$ mm. The proposed antenna acquires a total volume of 1.35 cm^3 . The various optimized dimensions are listed in table 6.5.

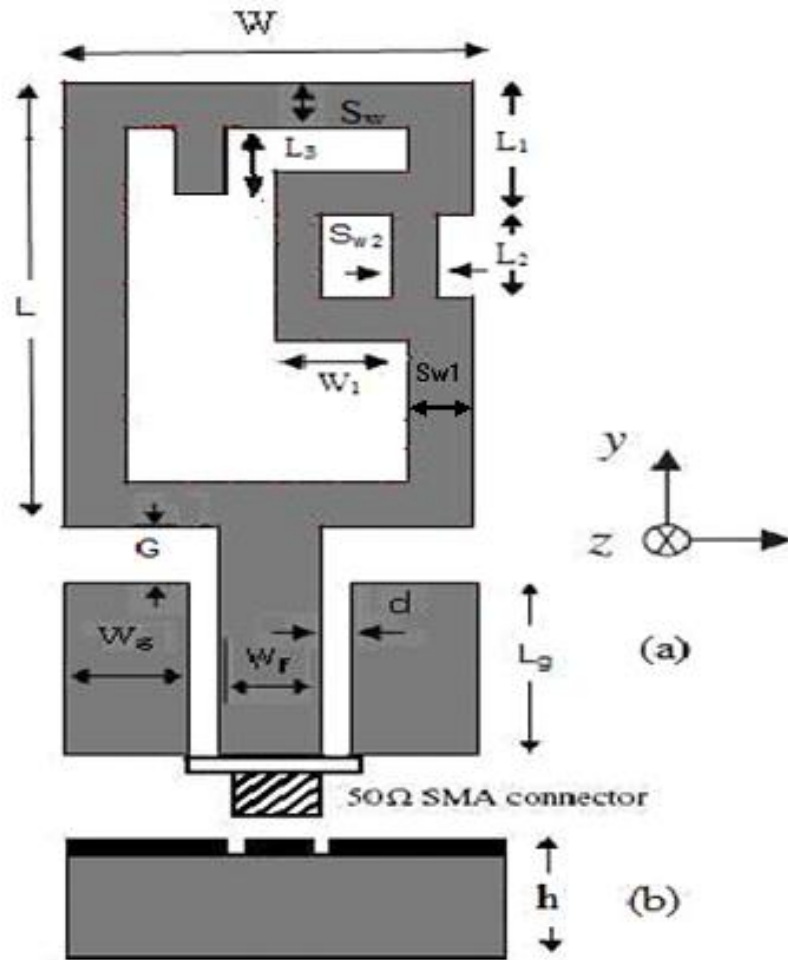


Figure 6.11 Geometry of the proposed antenna (a) top view (b) front view.

6.5 CUMULATIVE SIMULATED RESULT

The antenna design is simulated in IE3D. The cumulative result of the optimized antenna is presented in Figure 6.12. It is observed from Figure 6.12 that when only outer ring (Figure 6.1) is used, two resonant bands appear in the return loss curve one from 6.2 to 6.9 GHz in upper

frequency band another from 2.26 to 3.03GHz in lower frequency band. When an inner ring (Figure 6.3) is added to outer ring the bandwidth in upper band increases with a shift in resonant frequency to lower side in upper band. The lower band is not affected by addition of inner ring. With addition of parasitic strip (Figure 6.5) to above structure, there is no change in the bandwidth of lower band whereas there is a slight improvement in the bandwidth at upper band along with increase in return loss at peak resonant frequency. Introducing meandering (Figure 6.7) in the patch causes significant increase in the bandwidth at upper frequency band and improves the return loss at peak resonant frequency. Meandering negligibly affects the lower frequency band.

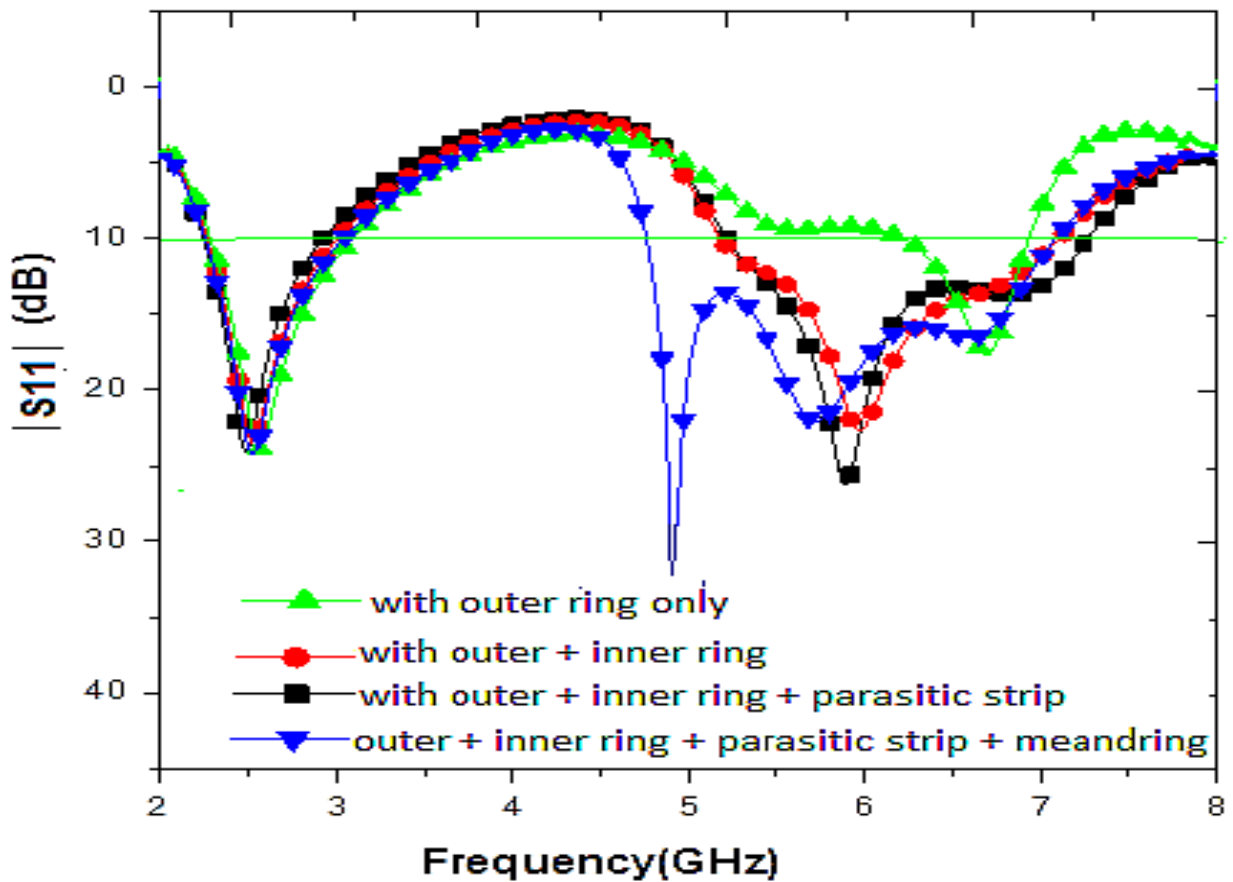


Figure 6.12 Cumulative effect of rectangular rings, parasitic strip and meandering on the antenna performance.

6.6 FABRICATED AND MEASURED RESULTS

The fabricated prototype was tested for return loss measurements for validation of impedance bandwidth results on VNA. The simulated and measured results for the proposed antenna have been observed and compared in Figure 6.13. It reveals a close proximity between

the simulated and measured results of the proposed antenna. Return loss (S_{11} parameter) curve shows that, two resonant bands with wide operating bandwidths are obtained. A small variation in 10 dB down bandwidth between measured and simulated results is seen at the upper frequency band. The main reason for variation in the results can be attributed to the inaccuracies imported while constructing the antenna using wet etching technique and also because of the alignment issues associated while connecting the antenna to the Vector Network Analyzer (VNA) using a SMA connector and the feeder cable.



Figure 6.13 Photograph of the fabricated antenna.

6.6.1 Measured Return Loss

It is observed from measured results shown in Figure 6.14, that (10 dB) impedance bandwidth of 28.52% at lower frequency band, extending from 2.26 GHz to 3.03 GHz, with respect to the resonant frequency of 2.652 GHz, and the bandwidth of about 41.87%, for the upper band extending from 4.48–6.85 GHz with reference to the central frequency at 5.66 GHz is

achieved. The projected antenna is capable of operating at IEEE 802.11 WLAN bands at 2.4/5.2/5.8 GHz and IEEE 802.16 WiMAX bands at 2.3/2.5/5.5 GHz.

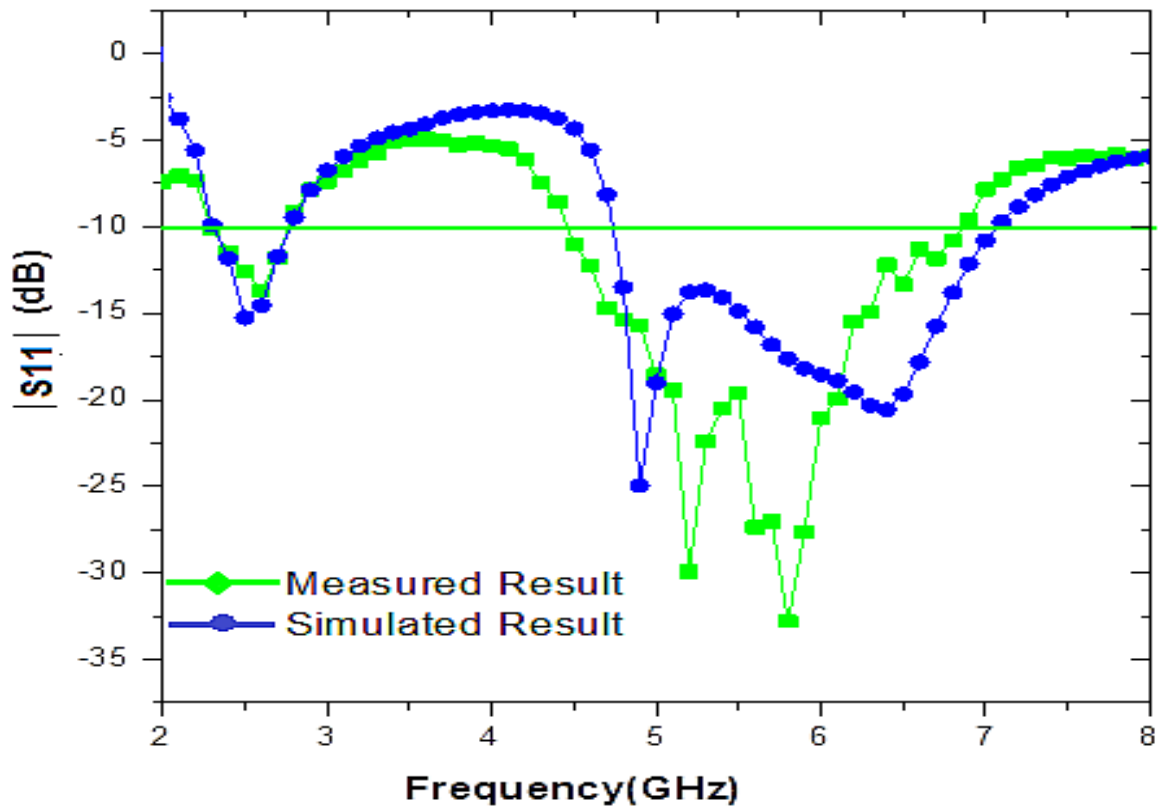


Figure 6.14 Simulated and Measured return loss curve of the proposed antenna.

6.6.2 Measured Gain

The gain of the proposed antenna, at upper and lower bands of operation, has a significant value as shown in Figure 6.15. In lower frequency band (2.26 GHz to 3.03 GHz), the measured gain of antenna lies in the range 1 dBi to 2.89 dBi, while in the upper band (4.766–7.062 GHz), the gain lies between 3.14–7.33 dBi. The comparative gain curve of simulated and measured values is plotted in Figure 6.15 in which the measured gain shows slight variations from the simulated values which may be due to alignment error in VNA. The summary of results of the proposed antenna is given in table 6.6.

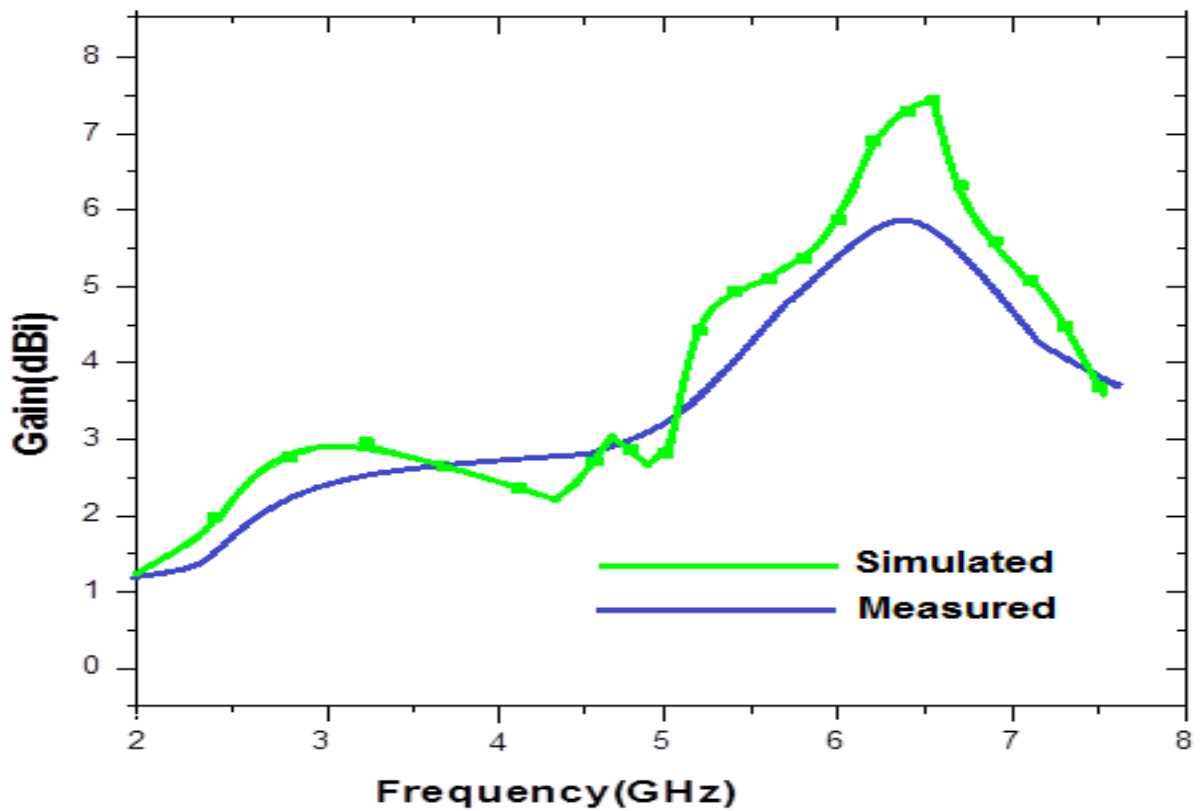


Figure 6.15 Simulated and measured gain curve of the proposed antenna.

Table 6.6, drawn below, presents the comparison between simulated and measured values of the bands covered, the bandwidth obtained at both the bands. It also compares the simulated and measured values of gain of the antenna across the operative bands.

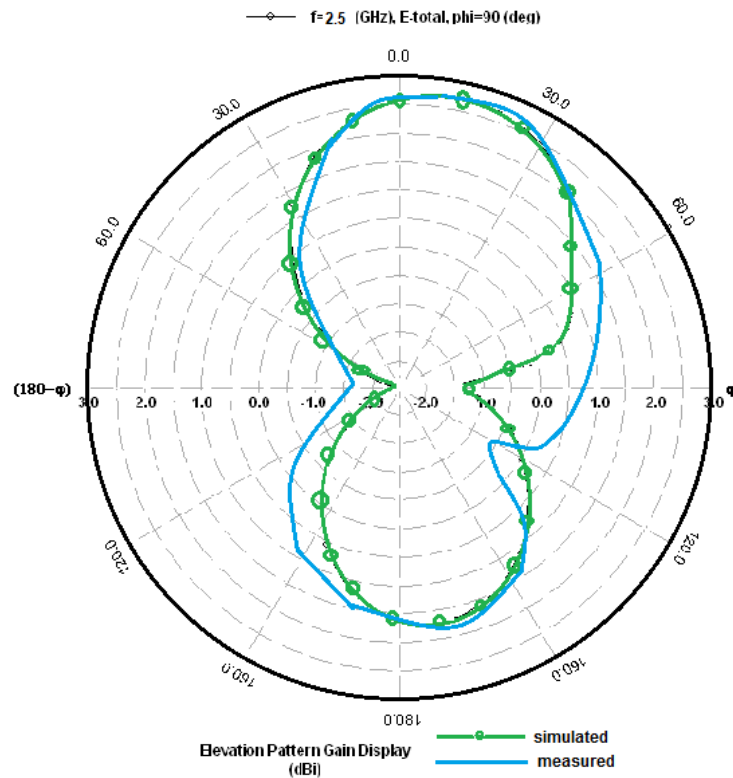
Table 6.6 Summary of the measured and simulated results of the proposed antenna.

Paramter → Band ↓	Frequency of resonance Measured (Simulated) (in GHz)	Band covered Measured (Simulated) (in GHz)	Impedance Bandwidth Measured (simulated) (in MHz)	Return loss Measured (simulated) (in dB)
Lower Band	2.652 (2.80)	2.26 – 3.03 (2.25 - 3.03)	770 (780)	-21.9 -24.5
Upper band	5.66 (4.90)	4.48–6.85 (4.75–7.15)	2370 (2400)	-29.8 -32.8

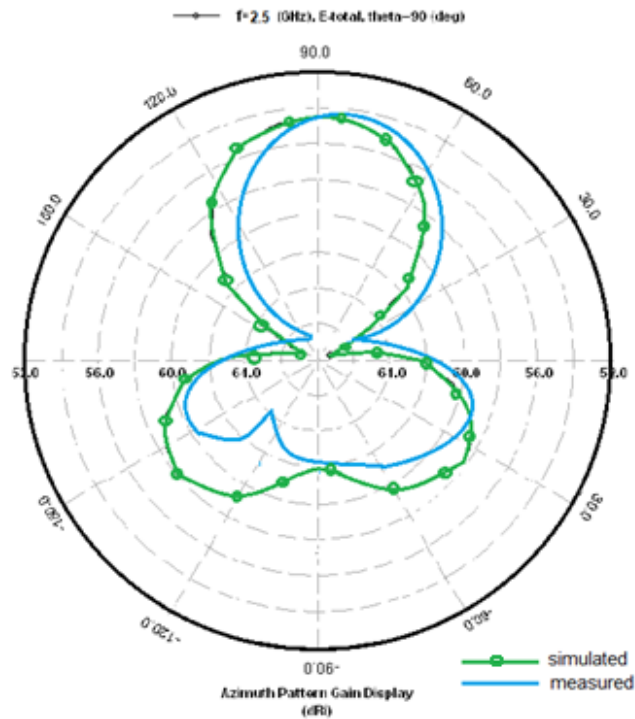
6.6.3 Radiation Pattern

The radiation pattern of the antenna in elevation and azimuth planes are measured at three different frequencies namely 2.5 GHz, 5.0 GHz and 6.54 GHz as shown in Figure 6.16 (a) and (b), 6.17(a) and (b) and 6.18 (a) and (b) respectively. The radiation pattern of the fabricated antenna is measured in an anechoic chamber discussed in chapter 1. The validation of its results is done on VNA.

An approximate figure of eight is formed in the elevation plane and somewhat directional characteristics are observed in the azimuthal plane. Realistic agreement is found between the simulated and measured results of radiation patterns at the distinct operating bands of frequency which authenticate the proposed design of antenna. Some minor differences between the simulated and measured results of field patterns are observed which might be attributed to placement error and probable presence of noise and interference. The proposed antenna exhibits a good radiation performance over all the desired frequencies.

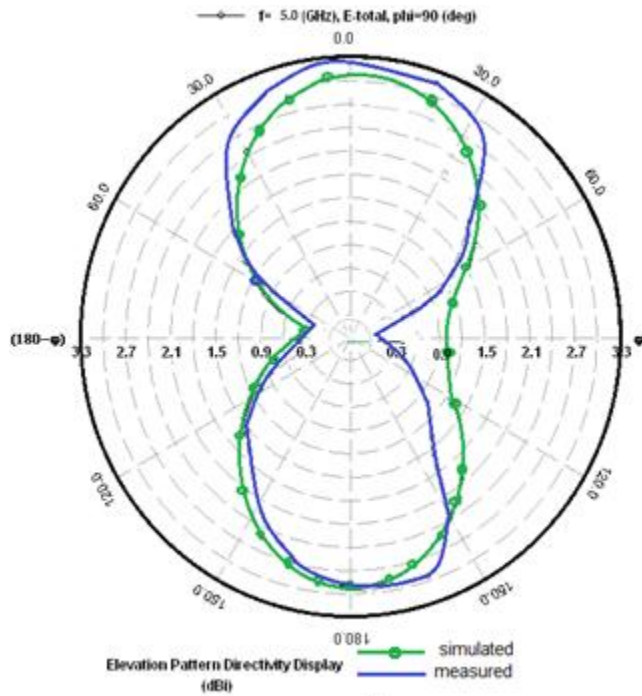


(a) 2.5 GHz Elevation, $\phi=90^\circ$

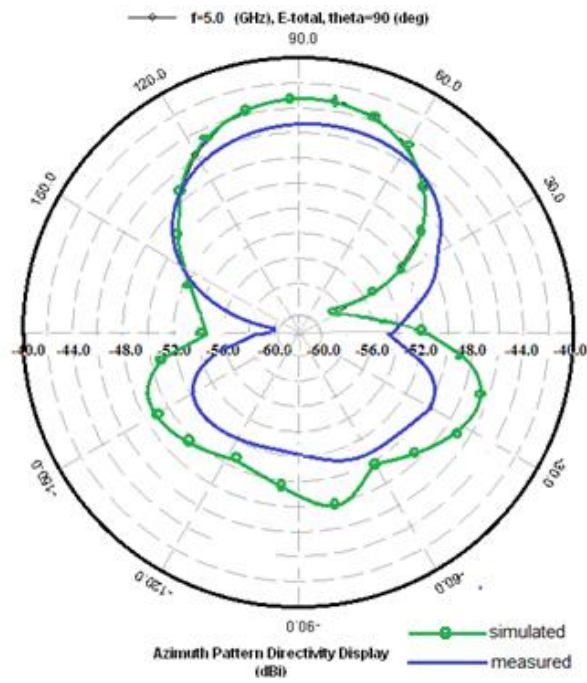


(b) 2.5 GHz Azimuth, $\theta=90^\circ$

Figure 6.16 Simulated and measured radiation pattern plot of the designed CPW-fed planar antenna at 2.5 GHz in (a) Elevation plane and (b) in Azimuth plane

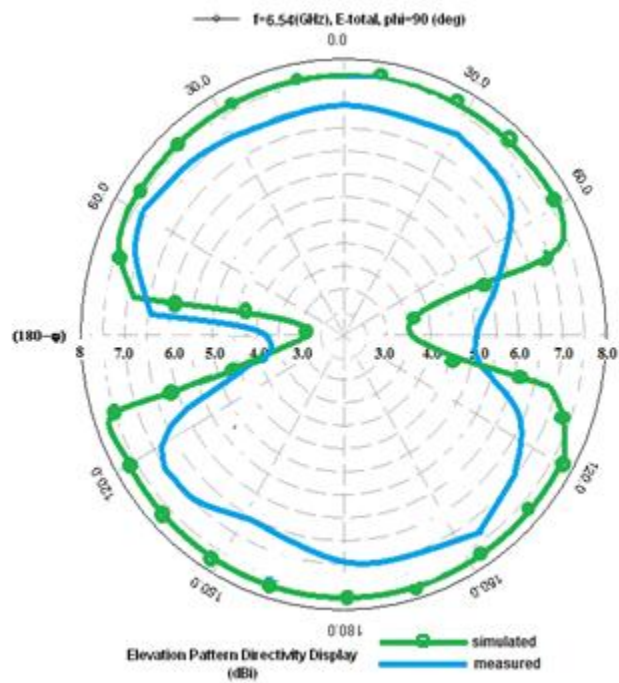


(a) 5 GHz Elevation, $\phi=90^\circ$

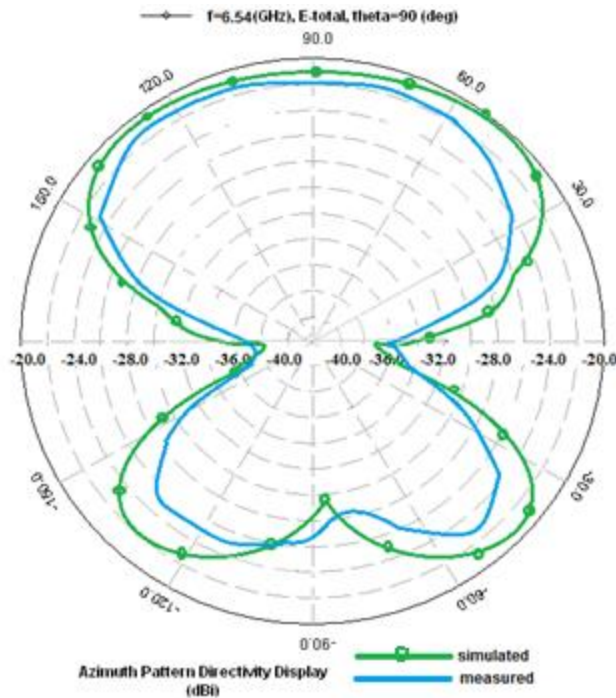


(b) 5 GHz Azimuth, $\theta=90^\circ$

Figure 6.17 Simulated and measured radiation pattern plot of the designed CPW-fed planar antenna at 5 GHz in (a) Elevation plane and (b) in Azimuth plane



(a) 6.54 GHz Elevation, $\phi=90^\circ$



(b) 6.54 GHz Azimuth, $\theta=90^\circ$

Figure 6.18 Simulated and measured radiation pattern plot of the designed CPW-fed planar antenna at 6.54 GHz in (a) Elevation plane and (b) in Azimuth plane.

6.7 SUMMARY OF THE CHAPTER

In this chapter, a CPW fed compact planar Microstrip Patch Antenna consisting of two rectangular rings, a parasitic strip and meandering has been proposed, designed, fabricated and tested for multiband operation. The various parameters of the proposed antenna are tested for S_{11} parameter, gain, and radiation pattern. Simulation results demonstrate that the proposed antenna has good return loss (S_{11} parameter), radiation characteristics and impedance bandwidth across the desired bands. The other parameters of the antenna also comply with the standard results desirable for the performance of the antenna. The antenna shows significant gain of 7.33 dBi at 6.54 GHz frequency.

The measured results for the antenna show an impedance bandwidth of 27.48% for the lower band, ranging from 2.26 – 3.03 GHz, at the central frequency of 2.652 GHz. In the upper band, it attains a significant impedance bandwidth of about 41.87% (4.48–6.85) GHz at a central frequency of 5.66 GHz. Considerable return loss values of -21.9 dB and -29.8 dB at the peak resonance of 2.80 GHz and 4.90 GHz are measured at lower and higher frequency bands

respectively. The peak measured gain of 5.86 dB achieved by the antenna and stable radiation patterns over the required functional bands make the designed antenna appropriate for heterogeneous wireless networks.

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CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 CONCLUSIONS

This chapter presents a concluding remark by summarizing the outcomes of the research work obtained after simulating, fabricating and testing the designed antennas and by carrying out the experimental investigations on the parameters of the proposed antenna. The research work outlined in this thesis is motivated by the continuing demand for advanced wireless devices which are capable of supporting multiple systems, standards and services. At microwave frequencies, microstrip antennas act as efficient radiators that can be fabricated in small size with advantageous features of being light weight, low profile, less complex and easy to implement in the RF front end devices. To enable their effective usage in communication systems, certain drawbacks need to be overcome which might hamper the performance of the microstrip antennas in terms of low impedance bandwidth, low gain, spurious radiation occurring from its feeds and junctions and excitation of surface waves. In some applications, the size of the microstrip antenna is too large to be used which needs to be reduced.

Therefore research in recent years has been dedicated to improve the electrical and mechanical characteristics of microstrip antennas and, mainly developing antennas with increased bandwidth and gain. Furthermore, due to advances in signal processing and improvements stirring in the wireless communication industry, devices integrating multiple communication standards in a single condensed lightweight system are on high demand. Hence, modern communication systems with small sized, wideband, multifrequency antennas which are capable of operation in more than one homogeneous or heterogeneous frequency bands have acquired pronounced attention for applications concerning multimode wireless communication. Keeping in mind the absolute necessity of such antennas, this research work is carried out to find innovative designs to achieve microstrip patch antennas with multiband and wideband performance.

An introduction to the multifrequency antenna and its parameters, motivation and objectives of the research work has been deliberated. Then, the study of literature review on homogeneous multiband antennas and heterogeneous multiband antennas with wide bandwidth over the operational bands is carried out which portrays the present scenario in the development of multifrequency microstrip antenna design. A large number of papers were referred to, many thesis works were consulted and numerous sites were explored to study the improved techniques to design antennas working in multiple bands with wide bandwidth, small size and good radiation characteristics. Extensive research is going on in the field of multiband and wideband designs for antenna in different standards such as Wi-Fi, WLAN, WiMAX and UWB. The techniques of designing a modified antenna with band rejection capability from the original wideband antenna using different techniques are also presented. It discusses the results obtained for various structures implemented by different authors to get multi-frequency microstrip antenna.

The literature review evidently proves the significance of this research and originality of the work presented. Furthermore, literature review demonstrates the research gaps in the existing multiband antennas for WLAN, WiMAX and UWB applications which provides main motivation for this thesis work. The problem statement, research objectives and entire methodology for conducting the necessary has been discussed. Some novel design techniques for producing multi-frequency antennas with wideband operation of Microstrip Patch Antennas are identified as the main objective of the thesis. The choice of materials for antenna design and research methodology used for calculation of different parameters of antenna, its simulation, fabrication and experimental verification has been described in detail.

In this thesis work, four novel configurations of microstrip antennas that accomplish the design aims of antennas for homogeneous and heterogeneous wireless communication networks are designed, fabricated and tested to achieve multi-frequency operation with perfect impedance matching, wide bandwidth, better return loss, increased gain with reasonable antenna size. The summary of the designs is presented below:

In the first design, a dual band antenna is presented which operates in WLAN at 2.4 GHz band and UNII 1/ UNII 2 bands at 5.15 GHz. Bandwidth enhancement is kept as the goal while designing the proposed antenna for WLAN bands since it is essential to provide a high data rate in these bands. The design illustrates a novel, compact, rectangular microstrip antenna with CPW feeding mechanism. It makes use of multiple rings in the main patch and DGS in

CPW ground plane to improve the performance of the antenna in terms of frequency of resonance and the impedance bandwidth obtained at each band to accommodate homogeneous WLAN bands. The rectangular ringed patch and CPW feed assembly is placed on FR4 substrate of 1.6 mm thickness and loss tangent value of 0.018. The antenna is modified by connecting the ringed patch to another rectangular ring with the help of two small parasitic strips, etching defects in both the CPW ground planes and segregating the upper ring with the help of a vertical parasitic strip. The parametric analysis is carried out to study effect of modifications made in the structure on the performance of the antenna. The optimized antenna is then fabricated and tested for verification of results. The measured and simulated results are compared in table 7.1.

Table 7.1 Comparison of simulated and measured results of antenna 1.

Parameter → Band ↓	Band covered Measured (Simulated) (in GHz)	Impedance Bandwidth Measured (Simulated) (in MHz)	Return Loss Measured (simulated) (in dB)	Maximum Gain Measured (simulated) (in dBi)
(UNII 1)	2.20 - 2.65 (2.05 – 2.60)	450 (550)	-16.0 (-25)	5.5 (5.40) at 2.4 GHz
(UNII 2)	5.0 - 5.45 (5.0 – 5.35)	450 (350)	-19 (-22.5)	4.90 (4.98) at 5.15 GHz

The experimental results show good impedance bandwidth, return loss characteristics, gain and stable field pattern over the desired frequency bands. The measurements of the fabricated prototype confirm the simulated results of the proposed antenna.

The second design also targets to cover the homogeneous WLAN bands at 2.4/ 5.2/ 5.8 GHz bands. It's design is somewhat different in a sense that it uses a circular ultra-wideband antenna as an initial design and modifies it by inculcating filter structure in it, such that it rejects all frequencies above the ISM range defined for WLAN systems, thus enabling its extensive use in WLAN bands. Therefore, it addresses the problem of interference rejection. The design comprises of a planar circular patch element with microstripline mounted on grounded FR4

substrate which generates a bandwidth of 6.8 GHz. It is then modified by altering the simple microstrip line by inserting square patches in it which generates a stopband from 5.9 GHz to 11.3 GHz, rejecting the higher bands. Then the ground plane is etched out to form a column of circular defects forming Electromagnetic Band Gap structure. It helps to achieve preferred passband extending from 1.97 to 2.65 GHz in the lower frequency band and from 3.12 to 5.86GHz in the higher frequency band, suitable for WLAN operation over the bands 2.40-2.484 GHz/ 5.150-5.350 GHz/ 5.725-5.825 GHz. The passband and stopband characteristics are plotted to verify the results. Return loss is plotted which is well beyond -10 dB for operating bands and nearly omni-directional field pattern is obtained over the passband. The comparative analysis of the results is presented in table 7.2

Table 7.2 Comparison of simulated and measured results of antenna 2.

Parameter→ Band ↓	Frequency of resonance Measured (Simulated) (in GHz)	Band covered Measured (Simulated) (in GHz)	Impedance Bandwidth Measured (simulated) (in MHz)	Return loss Measured (simulated) (in dB)
Lower Band	2.2 (2.3)	1.90 - 2.45 (1.97 - 2.65)	550 (681)	-31.9 (-25.0)
Upper band	5.15 (4.90)	3.3 - 5.85 (3.12 - 5.86)	2550 (2740)	-47.95 (-27.80)

The third design presents a rectangular microstrip patch element with modified Co-Planar waveguide (CPW) feed and rotated E-slot in the radiating patch to obtain multiband operation with wideband characteristics for heterogeneous networks. Good impedance matching is obtained over the three resonant modes providing coverage to several wireless applications such as LTE (3.4 to 3.6 GHz) and WiMAX (3.4– 3.694 GHz), aeronautical radionavigation radiolocation (2.7–2.9 GHz), radiolocation radionavigation (2.9–3.1 GHz), radiolocation earth exploration-satellite (active) mobile (3.1–3.3 GHz), radiolocation amateur mobile (3.3–3.41 GHz), mobile (3.41–3.6 GHz) standards. Effect of modifications in CPW ground slot length and width of E slot is studied. The results obtained for the proposed antenna are summarized in the table 7.3 below:

Table 7.3 Comparison of simulated and measured results of antenna 3.

Paramter → Band ↓	Frequency of resonance (in GHz)	Band covered (in GHz)	Impedance Bandwidth (in MHz)	Return loss (in dB)	Gain (in dBi)
Lower Band	(1.52) (1.62)	(1.49 to 1.61) 1.56 to 1.69	120 (130)	-13.8 (-14.55)	4.0 3.93
Upper band	2.65 (2.75)	2.51 to 3.64 (2.6 to 3.74)	1.13 (1.14)	-15.8 (-19.7)	3.90 3.90

In the fourth design, a novel, compact, CPW fed, planar monopole antenna with enhanced bandwidth and multiband characteristics has been presented for WLAN/ WiMAX standards. Two rectangular rings are incorporated in a rectangular patch to obtain multiband operation for WLAN (2.4/5.2/5.8 GHz) and WiMAX (2.3/2.5/5.5 GHz) bands. A parasitic strip and meandering along with double ringed structure are used to achieve enhanced impedance bandwidth in WLAN (from 2.26 GHz to 3.03 GHz) and WiMAX (from 4.48–6.85 GHz) bands. The parametric analysis is carried out to study the effect of varying dimensions on antenna performance. The proposed antenna is optimized and prototype is designed and fabricated. The proposed antenna has a small size of 1.35 cm³. Simulated and measured radiation patterns in elevation and azimuthal planes are also observed. The comparison of simulated and measured results of the proposed antenna is presented in the table 7.4 below:

Table 7.4 Comparison of simulated and measured results of antenna 4.

Parameter→ Band ↓	Frequency of resonance Measured (Simulated) (in GHz)	Band covered Measured (Simulated) (in GHz)	Impedance Bandwidth Measured (simulated) (in MHz)	Return loss Measured (simulated) (in dB)	Maximum Gain Measured (simulated) (in dBi)
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Lower Band	2.652 (2.80)	2.26 – 3.03 (2.25 - 3.03)	770 (780)	-21.9 -24.5	2.61 (2.61)
Upper band	5.66 (4.90)	4.48–6.85 (4.75–7.15)	2370 (2400)	-29.8 -32.8	5.86 (7.33)

In this thesis, the main aim of designing, simulating, fabricating and testing of the microstrip patch antenna for multifrequency operations over the homogeneous and heterogeneous wireless networks, with enhanced bandwidth, has been accomplished. Further, some important domains of the antenna design can be explored into, for the future scope, to get a deep understanding of multiband and broadband microstrip antennas for various wireless applications. Some ideas are suggested in the subsequent section for future work to acquire superior performance multiband and multimode microstrip antenna.

7.2 FUTURE SCOPE

Although an extensive study has been carried out in this research work to design multifrequency antenna design and wideband antenna design, still there are certain areas that require attention and provide ample scope for improvement in the field of antenna design. Some such areas are briefly discussed below:

For the design of a wideband multifrequency antenna, simple parametric sweep tool, available in CST V.10 and V.14, have been used to optimize the antenna parameters. Different soft-computing techniques and even better algorithms such as Genetic Algorithms, Particle Swarm Optimization, Bacterial Foraging and Artificial Neural Network etc. might be used for optimization process leading to more precise antenna design and hence more accurate results.

Although, the use of DGS has been presented in the designed antennas for improving bandwidth, different shapes of slots with specific antenna geometry using various feeding techniques could be further experimented with; to obtain enhanced bandwidth. Also, different substrate materials with different values of relative permittivity and thickness might be used to get desired characteristics.

Size has become a major factor which needs to be taken special care of as the wireless devices available nowadays are becoming increasingly smaller in size. Therefore, to integrate

antennas within smallest possible area, further research work need to be done to obtain impressively reduced size antenna without the loss of gain and efficiency. Fractal geometry such as Sierpinski gasket, V-Koch fractals etc. could be explored. SRRs, CSRRs and DGS are also a possible candidate for future research for size reduction in antennas. As the size of the antenna element is of utmost importance, exclusive study of DGS and its frequency behavior is an attention-grabbing future problem.

The antennas designed in this thesis have considerable values for gain and efficiency which could be improved further by the use of gain and efficiency improvement techniques. The use of Split Ring Resonators (SRRs) in the patch might be a new topic for research as it is known to increase the gain along with the reduction in the size of the antenna element.

Study of SAR (Specific absorption rate) is very important in mobile devices since it indicates the amount of radiations emitted by the antenna, tolerable by the human head. So, to rule out any such health hazards, the study of electromagnetic energy radiated by the antenna and its absorption by the user's head could be another interesting field of study.

The use of Photonic Band gap (PBG) Structures, Electromagnetic Band Gap (EBG) structures, and High Impedance Surface (HIS) structures could be tested for improved filter performance in the antenna. Negative refractive index materials like Frequency Selective surfaces, SRRs, CSRRs, EBG could also be used to achieve different antenna characteristics like band stop performance and tunability of the resonant bands etc. The use of DGS may also be considered for designing notches in ultra-wideband antennas.

Mathematical modeling of the designed antennas could also be taken as a topic of further investigation. Modifications can be incorporated to implement different multi-frequency microstrip antennas with compact size, increased gain and efficiency, enhanced bandwidth and improved radiation characteristics.

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