(Design of Multiband Patch antenna using Fractal design and Defected Ground Structured for Wireless Applications)

A Thesis

Submitted in partial fulfillment of the requirements for the award of the degree of

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(Electronics and Electrical Engineering)

By

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Lovely Professional University
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DECLARATION

I hereby declare that this research work "Design of Multiband Patch antenna using Fractal design and Defected Ground Structured for Wireless Applications" has been composed solely by myself and has not been submitted anywhere. It was carried out by me for the degree of Doctor of Philosophy in Electrical Engineering under the guidance and supervision of Prof. Dr. Praveen Kumar Malik, Lovely Professional University, Phagwara Punjab, India.

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Date: 21/10/2020

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CERTIFICATE

This is to certify that the thesis entitled "**Design of Multiband Patch antenna using Fractal design and Defected Ground Structured for Wireless Applications**" being submitted by **Amandeep Kaur** for the degree of Doctor of Philosophy in Engineering from Lovely Professional University, Jalandhar is a record of bonafide research work carried out by her under my supervision at the School of Electrical and Electronics Engineering. In our opinion, this is an authentic piece of work for submission for the degree of Doctor of Philosophy. To the best of our knowledge, the work has not been submitted to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

With the tremendous growth of wireless communication application, set the way on new design specification for integrated devices which demands more compactness, low profile and cheap in cost. In wireless signal transmission, antenna plays significant role to convert electrical signals into electromagnetic waves and act as transducer at transmitter and receiver side. To reduce overall circuit dimensions for RF components, antenna miniaturisation is becoming essential to obtain optimized design for handheld wireless communication gadgets and to accomplish this PCB technology based micro-strip patch antenna becomes buzz word which gain researches attention for more compact size with good gain and bandwidth characteristics. Moreover, wireless devices like Mobile phones operates on different technologies like ISM band for Wi-Fi, Bluetooth BLE and Wi-MAX, GSM, CDMA etc. Conventional antenna mainly operates on single band of frequency but now there is need to design multiple band antenna which can resonates on different frequency band and omit the need of multiple antenna in one device. To achieve high data transmission rates, antenna must full-fill the minimum band requirements set by FCC for every wireless standard.

So, Microstrip patch antenna is highly regarded and it is the proved as the best candidate for Wireless communication applications due to several characteristics which meets the wireless communication devices requirements like light in weight, low profile, easy integration with microwave circuits and cheap in cost as fabricated using PCB technology but has some down side like less gain and bandwidth. In literature, researchers use numerous methods for micro-strip patch antenna gain, bandwidth enhancement with more compactness and multi band characteristics. In micro-strip patch antenna, multiple band characteristics can be achieved by modification to the patch structure which act as main radiator using two strategies mainly. The first one is by designing different patches for different frequencies or second approach is by increasing electrical length of patch without increasing overall antenna dimensions to achieve multi band behaviour. Second method is mainly adopted and can be accomplished using Fractal and defected ground structures.

The use of fractal structures in antenna designing has significantly impacted its use for various communication technologies. Fractal shapes are known for their space filling and self-similarity properties. Due to these characteristics, antenna minimization can be achieved by electrically increasing the length of current transmission in patch which acts as main radiator without physically changing antenna structure. Self-similarity property means, same geometry is repeated several times but with small dimensions of previous one, which leads to obtain multiple resonance to gets multi band behaviour. Further, to improve micro-strip patch antenna small gain, narrow impedance bandwidth and to supress cross-polarization defected ground structures are used due to it simple design. Etched slots or defects in the ground plane or micro-strip patch antenna are called defected ground structure and there can be single or multiples defects.

Main purpose of this thesis is to design multi band microstrip patch antenna with wide bandwidth using fractal and defected ground structures for wireless applications. Circular cut fractal antenna with U-shaped defected geometry with truncated edges and Elliptical shaped with steps cut fractal defected antenna have been proposed. The Antenna are simulated using HFSS simulator and fabricated using PCB fabrication technology. Antenna performance is analyzed in terms of return loss, gain, impedance bandwidth and radiation pattern. Proposed antenna shows multi band characteristics for wireless applications.

Circular cut fractal antenna with U-shaped defect is compact in size with dimensions 42mm x 52mm, which is fabricated on Rogers RT Duroid 5880 dielectric substrate with thickness 1.6mm and dielectric constant (ε) 2.2. Antenna resonates on frequencies 3.80, 7.01, 10.86, 11.84GHz with bandwidth 260, 330, 270 and 460MHz respectively. For proposed antenna, maximum gain achieved at these resonating frequencies are 5.52, 8.05, 5.32 and 7.78dB respectively. Antenna is simulated and fabricated results are agreement with each other.

An elliptical patch shaped fractal antenna is also simulated and fabricated on Rogers RT Duroid 5880 material with thickness 0.8mm. Antenna overall dimensions are 50 mm x 50mm x 0.8mm. Antenna shows multi band behavior and resonates on three frequency band 2.6, 6 and 8.2GHz with impedance bandwidth of 410, 1070, and 4840MHz respectively with maximum gain achieved of 5.52dB. Simulated and measured results shows that proposed antenna is used good candidate for wireless communication applications and covers different wireless standards like Wi-Fi (2.4GHz), Bluetooth version V1.0-V4.0, WLAN (2.4/5.2/5.8GHz), WiMAX (2.3/2.5/5.5GHz), Wireless Body Area Network (2.3/2.4GHz), RFID (2.4 to 2.5/5.85 to 5.925GHz), Microwave ovens (2.4 to 2.48GHz) which falls under ISM (Industrial Scientific and Medical) band applications. It also covers RADAR (2.33 to 2.74/5.4), Geostationary Satellite communication (11.7 to 12.2GHz), X-band application (8 to 12GHz), S-Band (2.3 to 2.4GHz) communication, Wireless Communication Services (WCS) 2.345 to 2.360GHz, and 4GLTE (2.3 to 2.315GHz) wireless communication standards. Proposed antenna shows multi band characteristics with wideband characteristics for wireless applications.

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Acronyms and Abbreviations

Acronyms	**Description**
2-D	Two Dimensional
2G	2nd Generation
3-D	Three Dimensional
3GPP	3rd Generation Partnership Project
4G	4th generation
5G	5th generation
AF	Audio Frequency
AMC	Artificial Magnetic Conductor
AMPS	Advanced Mobile Phone Service
AR	Axial Ratio
ARBW	Axial Ratio Bandwidth
AUT	Antenna Under Test
BPF	Band Pass Filter
BW	Bandwidth
CP	Circular Polarization
CPW	Coplanar Waveguide
CRO	Cathode-Ray Oscilloscope
CRT	Cathode-Ray Tube
CSMA/CA	Carrier Sense Multiple Access/ Collision Avoidance
CST	Computer Simulation Technology

DGS	Defected Ground Structures
DUT	Device Under Test
EBG	Electromagnetic Bandgap
EDGE	Enhanced Data for Global Evolution
EDR	Enhanced Data Rate
EIRP	Equivalent Isotopically Radiated Power
ETSI	European Telecommunications Standards Institute
FDGS	Fractal Defected Ground Structure
FDTD	Finite Difference Time Domain
FEM	Finite Element Method
FFT	Fast Fourier Transform
FHSS	Frequency Hopping Spread Spectrum
FR4	Flame Retardant 4
FSA	Fibonacci spiral antenna
FSPL	Free Space Path loss
GNSS	Global Navigation Satellite System
GPA	Ground plane aperture
GPS	Global Positioning System
GSM	Global System for Mobile
GUI	Graphical User Interface
HA	Hybrid Antenna
HFSS	High Frequency Structure Simulator
HIPERMAN	High Performance Radio Metropolitan Area Network

HORYU-IV	High Voltage Technology Demonstration Satellite-4
HPBW	Half Power Beam Width
IE3D	Integral Equation Three-Dimensional
IEEE	Institute of Electrical and Electronics Engineers
IFS	Iterated Function System
IoT	Internet of Things
ISM	Industrial Scientific and Medical
LEO	Low Earth Orbit
LHCP	Left Hand Circular Polarized
LoRA	Long Range
LPDA	Log-Periodic Antenna
LPWAN	Low-Power Wide-Area Network
LSNA	Linear Sensor Node Array
LTE	Long Term Evolution
M2M	Machine 2 Machine
MAC	Media Access Control
MIMO	Multiple input Multiple Output
MM	Metamaterial
MMOG	Multi Media Online Gaming
MNM	Multiport Network Model
MoM	Method of Moments
MPA	Microstrip Patch Antenna
MS	Meta Surface

MTA	Microwave Transition Analyzer
OFDM	Orthogonal Frequency Division Multiplexing
PAN	Personal Area Network
PBG	Photonic Band Gap
PCB	Printed Circuit Board
PHY	Physical Layer
PIFA	Planar Inverted F-Antenna
PMPA	Planer Microstrip Patch Antenna
RADAR	Radio Detection and Ranging
RCR	Cherenkov radiation
RF	Radio frequency
RFID	Radio Frequency Identification
RHCP	Right-Hand Circular Polarized
RL	Return Loss
RSL	Received Signal Level
SDT	Spectral Domain Technique
SIG	Special Interest Group
SMA	Sub-Miniature version A
SNA	Sliced Notch Antenna
SRR	Split Ring Resonator
TCDA	Tightly Coupled Dipole Array
TDMA	Time Division Multiple Access
TEM	Transverse Electric Magnetic

TL	Total Loss
TV	Television
UHF	Ultra-High Frequency
UMTS	Universal Mobile Telecommunications System
VNA	Vector Network Analyzer
VSWR	Voltage Standing Wave Ratio
WBAN	Wireless Body Area Networks
WCS	Wireless Communication Services
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
ZOR	Zeroth-order Resonator

List of Symbols

Symbol	Description
H	Efficiency
Γ	reflection coefficient
ε_r	relative permittivity
tan δ	loss tangent
λ	Wavelength
c	speed of light
f_r	resonating frequency
Z0	Characteristics Impedance
λg	Guided Wave length

CHAPTER-1
INTRODUCTION

1.1 INTRODUCTION

From last few decades, with exponential growth in the wireless communication technology and Internet services, the demand for high data rate services increased. Owing to this, the number of users rose tremendously and can be widely seen that in the future communication networks, huge traffic congestion will be experienced. To accomplish the efficient communication services, good infrastructure is the big challenge for the manufacturers and service providers to provide more capacity in the networks. Also, compactness of devices is another big issue. There are some serious challenges faced in wireless communication services like multipath fading, co-channel interference and delay spread which degrade the signal quality [1]. Numerous methods are explored by researches to maximize the efficiency of communication networks.

In the communication field, Wireless communication as shown in Figure 1.1 is the most vibrant and fastest growing technology, in which information is transmitted from one end to other end without making physical connections. Interestingly, in every communication system, to transfer information transmitter and receiver play quintessential role and can be deployed between few meters to thousands of kilometres like T.V remote and Satellite communication respectively [2]. As, no guided medium is used, so transmission and receptions of signals is achieved using Antennas.

Antenna is the device that converts electrical signal into radio waves on transmitter side and vice versa on receiver side. Also, it is one of the crucial parts in circuit designing to achieve compactness. Different types of antennas are available in the market like Horn antenna, dipole antenna, PIFA, and microstrip patch antenna etc. [3]. Nowadays, in communication systems low profile antennas are desired to achieve high performance over wide range of frequencies. Due to such reasons microstrip patch antenna are gaining much attention in this field and used widely because of their plentiful advantages like low in profile, fair cost, planar structure, high robustness, and conformability to curved surfaces, ease of installation and due to uncomplicated PCB fabrication, these are simple and inexpensive to manufacture.

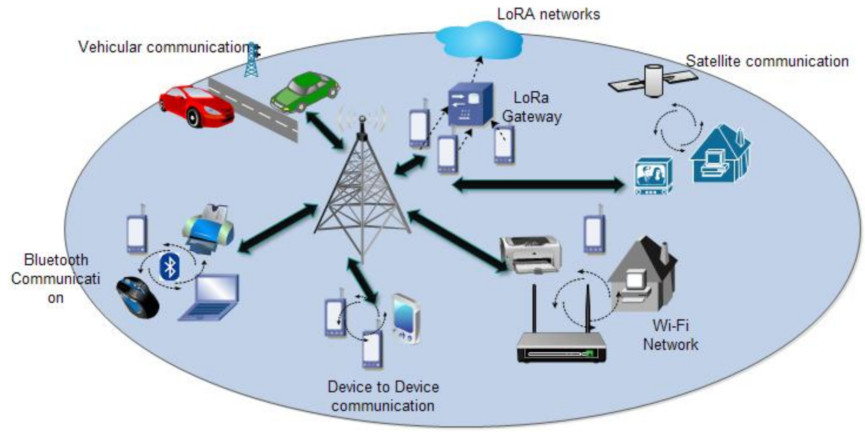


Figure 1.1: Wireless communication networks

Microstrip patch antennas are initially proposed by Deschamps in year 1953 but not come in practical existence. Practical implementation of antennas was done in 1970s by Munson and Howell due to development of PCB (Printed Circuit Board) and easily availability of dielectric substrate materials. From that time MPA gain attention on account of their numerous advantages like light weight, easy fabrication using PCB technology, cheap in cost, compact size and easy integration with microwave circuits [4]. They have been widely opted application related to civilian and military like radio-frequency identification (RFID), broadcast-radio, mobile-systems, global positioning system (GPS), television (TV), multiple-input multiple-output (MIMO) systems [5], collision avoidance in vehicles, satellite communications, surveillance systems, radar systems, remote sensing, missile guidance, and so on.

Microstrip patch antennas consist of radiating patch which act as resonating cavity, on one side of dielectric substrate and ground plan on opposite side [6]. Antenna radiating patch can be triangular, circular, square, rectangular, ring etc. as shown in Figure 1.2 below.

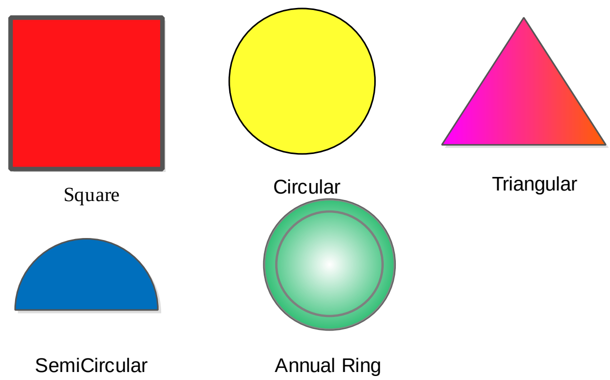


Figure 1.2: Different patch structures used for Microstrip patch antenna

1.2. WIRELESS STANDARDS

1.2.1 GSM

GSM stands for Global system for Mobile Communication (GSM), basically it is digital mobile phone standard which is developed by European institute called ETSI (European telecommunications Standards Institute). It was initially used in Finland in 1991. After that, it becomes a global standard for mobile phone communication by the mid 2010's and achieves more than 90% market share and adopted by 193 countries. GSM networks are divided into 2G and UMTS (3G) networks. 2G networks operate in frequency range 900MHz or 1800MHz and 3G networks operate in 2100 MHz frequency band [7-8]. GSM uses concept of TDMA (Time division Multiple Access). Uses are allocated different time slots, which allows 8 full and 16 half rate channels/radio frequency at data rate of 270.833Kbits/sec with frame duration of 4.615ms. Maximum power used in GSM handsets are 2watts for GSM850/900 and 1W for GSM 1800/1900.

1.2.3 IEEE standard for WLAN

WLAN stand for Wireless local area network which is mainly designed for communication between computing devices like laptops using radio waves. IEEE standard proposed for WLAN was 802.11 and initially used for infrared communication. Various IEEE802.11standards are 802.11a/802.11b/802.11e/802.11f/802.11g/802.11h/802.11n and 802.11s. First adopted standard was IEEE 802.11b that operates on frequency band 2.4

GHz ISM (Industrial and scientific) band with data rate of 11Mbps [9]. To achieve high data rate transmission 802.11g designed that operates on 2.4GHz ISM band with data rate up to 54Mbps. Afterwards second standard was defined which uses OFDM modulation techniques and uses 5GHz ISM band. It gains more attention due to high transmission data rate over small distances with suitable compatibility with devices and increased development of antennas with large bandwidth.

1.2.4 IEEE standard for WiMAX

WiMAX is formed by WiMAX forum in June 200, mainly to promote and certify interoperability and compatibility with others standards like IEEE 802.16and HIPERMAN. WiMAX delivers broadband wireless services on the IEEE 802.16 set of standards, which defines functions of the physical (PHY) and Media Access Control (MAC) layers. It works like Wi-Fi but gives more data speed over larger distance and includes more users. It uses two different models fixed 802.16d defined under 802.16a and often referred as 802.16-2004 and mobile WiMAX IEEE 802.16e [10]. Fixed WiMAX used for fixed applications like DSL with data rate upto 75Mbps. Mobile WiMAX, also called 802.16-2005, which provides cheap services compared to Cellular Services with data rate up to 15Mbps within cell radius of 2 to 4Km. It uses different frequency bands: 2.3GHz, 2.5GHz, 3.5GHz (3.4 to 3.69 GHz), and 5.5 GHz (5.25 to 5.85 GHz) as given in Table1.1.

1.2.5. IEEE standard for BLUETOOTH

Bluetooth technology is developed by Bluetooth Special Interest group (SIG) in 1998 under IEEE standard 802.15.1. It is used in Personal Area Networks (PAN) to transfer data between devices over small distances up to 30 feet using radio waves in Scientific and Medical radio bands (SIM) i.e. 2.4GHz to 2.48GHz as shown in Table1.1. It has different versions: First version 1.2 support data rate up to 1Mbps. Version 2 was 2.0+EDR with data speed 0f 3Mbps following to third version 3.0+HS which has speed of 24Mbps. Bluetooth technology uses Frequency Hopping Spread Spectrum (FHSS) multiple access method to transfer data at 1600 hopes per second through 79 different channel each with bandwidth of 1MHz.

1.2.6. LTE (Long Term Evolution)

LTE was started as a project by telecommunication body called the Third Generation Partnership Project (3GPP) in 2004. It is based on the GSM/EDGE and UMTS technologies which are used for mobile devices and data terminals to provide broadband communication services. A tremendous growth in mobile data usage and development of new applications like Mobile TV, Web 2.0, MMOG (Multimedia Online Gaming) and streaming etc. motivated 3GPP to describe LTE to achieve more reliable networks in terms of more capacity as well as speed and paved the way towards 4G mobile networks. First version of LTE was documented in Release 8 of the 3GPP specifications. The LTE wireless interface is not compatible with 2G and 3G networks, so it is operated on different radio spectrum and different frequency bands are used in different countries which need multi band mobile hence multi band antennas. Bands used are 700/1500/1700/2100/2600 MHz with flexible bandwidths 1.4/3/5/10/15/20 MHz with downlink rates of 300Mbits/s and uplink rate of 75Mbits/s [12].

1.2.7. 5G (Fifth Generation)

5G stands for 5th Generation, and this is the wireless technology for digital cellular mobile networks which deployed in 2019. Frequency spectrum of 5G technology is divided into three bands: millimeter waves, mid-band and low band. 5G millimeter is the fastest wave with speed of 1 to 2 Gb/s and uses frequency bands above 24GHz to 72GHz. 5G mid-band uses frequencies from 2.4Ghz to 4.2GHz [13-14]. This band is most widely used now, in over 20 networks, offering speed between 100 to 400Mb/s over 100MHz band. China is using 3.5GHz, while 3.3 and 4.2GHz bands are used by other countries. Low band works similar to 4G and uses similar frequency range.

1.2.8. LoRa (Long Range Radio)- IEEE 802.15.4g

In wireless communication Bluetooth technology covers very less range for local communication and consumes more power. The alternative technology used now in IoT networks is LoRa. It is new technology, specifically designed for low power and long-range wireless communication and developed by a company named Semtech. LoRa stands for Long Range Radio and used for IoT and Machine-to-Machine (M2M) networks. LoRa Alliance is the non-profit association that set standards for LPWAN (Low Power Wide Area Networks) for IoT. This technology provides range of 2-5km for Urban and 15Km for suburban area with data rates 0.3kbps to 50kbps and works on spread spectrum modulation technique to avoid interference. LoRa technology operates in ISM band 868MHz i.e. European ISM and 915MHz i.e. American ISM [15].

Table 1.1: Different Wireless standards used with frequency of operation and bandwidth

Wireless Standards	**Frequency Band of operation (MHz)**	**Occupied bandwidth (MHz)**
GSM (Global System for Mobile)	GSM-900: 890-960	70
	GSM-1800: 1710-1805	95
	GSM-1900: 1850-1990	140
WLAN (Wireless Local Area Networks)	2400-2484	84
	5150-5350	200
	5725-5825	100
WiMAX (Worldwide Interoperability for Microwave Access)	2500-2690	190
	3400-3690	290
	5250-5850	600
Bluetooth	2400-2500	100
LTE (Long Term Evolution)	1710-1755	45
	1710-1785	75
	1850-1910	60

	1920-1980	60
LoRa (Long Range Radio) in Europe, India, United States, South Korea	863-870	07
	865-867	02
	902-928	26
	920-923	03
WBAN	2360-2400	40

1.2.9. WBAN (Wireless Body Area Networks) IEEE 802.15.69

WBAN technology is used for medical and non-medical applications which supports both inside and outside communication around the human body. This is wireless technology that operates on different wireless frequency bands like 400/800/900 MHz, 2.3/2.4GHz bands for data transmission under IEEE standard 802.15.69. This technology is mainly used for wearable wireless sensor networks with wide data rates (10Mbps), low power consumption, low range and can handle maximum 256 nodes per body area in a network. It uses CSMA/CA as channel access method for channel sharing [16-17].

1.3. MOTIVATION

With tremendous growth in wireless communication technology, boost up the need for compact devices. To overcome overall dimensions of such systems, antenna optimization also becomes necessary. For wireless transmission of data at fast rates, highly efficient antennas are needed with improved performance characteristics like wideband, multi band [18], compact in size, affordable price, and straightforward to fabricate etc. Currently, the wireless devices are supporting multi communication by working on different wireless frequency standards, so multi band antenna with wideband characteristics and compact dimensions are seeking much attention of researchers. In literature, plethora of techniques are available to achieve this but fractal and defected ground structures are the best theories used to achieve such behaviour in microwave and antenna engineering field component designing. Fractal geometries posse's self-similarity and space-filling properties. Due to self-similarity property of fractal structures, multiple resonances can be achieved in antenna and it also increase the length of flow of electric current without increasing the overall dimensions of device which leads to more compact structure. Defected ground structures can any H, E, V, U shape defect in ground plane that increases antenna efficiency in terms of gain and bandwidth. Wireless communication standards like Wi-Fi, Bluetooth, Zigbee, GSM, GPS, LoRA, IoT, WiMAX, LTE/5G are most adopted standards for wireless application in field of home automation, medical, industries etc. for wireless data sharing, so, there is huge demand for multi-band antennas with good gain, wide impedance bandwidth, small size and low profile single fed [19].

Microstrip patch antennas are generally considered as narrowband devices. Antenna dimensions and performance highly depends on the frequency of operation and wavelength. But this is still a serious issue in antenna designing to obtain compact designs with respect to frequency. To deal with this problem, fractal and defected geometries can be used and further can be extended to array designing to meet minimum requirements of wireless communication systems. There are several reasons why fractal and defected geometries gain much attention in antenna designing. First, multiple copies of same design can be built up with different scaled values to design antenna with similar properties. [20-21].

Second, due to their space filling property due to which antenna space can be utilized in better way by using small scale fractal shapes [22-23]. Fractal antenna concept arises due to mixture of two different disciplines, electromagnetism and geometry. Also, one more technique that is seeking much attention now is Defected Ground Structures (DGS). Slots and defects etched upon ground plane of microwave components are called Defected Ground structures. It is opted method to enhance antenna parameters like operating bandwidth, gain, cross-polarization etc. In literature, various defected structures have been discovered and used like square, spiral, dumbbell, L-shaped, rectangular, circular, U-shaped, hexagonal, V-shaped, concentric, arrow head etc. [24-29]. Current distribution and propagation through ground plane can be controlled by properly selecting dimensions and shapes of defected structures which further controls electromagnetic waves generation and transmission through substrate material. Also, due to changes in inductive and capacitive properties of ground plane, additional frequency bands can be achieved which leads to multi band behaviour of circuits and very useful in wireless communication devices.

In this thesis, Multi band microstrip patch antennas are designed with fractal and defected ground structures for wireless applications like Bluetooth, Zigbee, Wi-Fi, LoRa, GSM, LTE etc. with frequency of operation from 1GHz to 15GHz. Two different antenna prototypes are designed and tested based on fractal and defected geometry to obtain multi band and wide bandwidth characteristic. First antenna is designed with circular cut truncated edges patch with U-shaped defected ground on Roger RT Duroid 5880 material. Four resonate frequency bands are achieved 3.93, 6.81, 10.79 and 11.64GHz with bandwidth of 140, 280, 300 and 340MHz and gain of 5.52, 8.05, 5.32 and 7.87 dB respectively. Second, elliptical shaped fractal patch with step cut defected ground antenna is simulated and fabricated on Rogers RT Duroid 5880 dielectric substrate. Antenna provides 3 resonant frequencies 2.6GHz, 6GHz and 8.2GHz with S11 co-efficient -18.18, -15.11, -16.33dB and wide impedance bandwidth achieved are 410, 1070 and 4840MHz with good gain. Proposed antenna structures are compact in size with additional features like wide bandwidth, high gain and multi band characteristics. Antenna exhibits omni-directional radiation pattern with large coverage are and found suitable for various wireless standards.

1.4. STATEMENT OF PROBLEM

It can be observed from literature survey that various techniques are proposed to enhance the bandwidth of antenna like by modifying the ground planes, meandered shorting strips, modified feeding structure, by adding parasitic elements and fractal designs. Antennas are designed in different shapes such as ellipse, circle and triangle, dipole and any other geometry. Various feeding methods are used like coaxial, strip line, aperture-coupling or proximity-coupling methods. As every antenna has its own advantages and disadvantage to use for wireless communication applications. Mainly antennas suffer from three main disadvantages:1) narrow bandwidth, 2) small gain, and 3) larger size.

1.5. SCOPE OF PRESENT WORK

Scope of present work is mainly to Design and Fabrication of Multi band Patch antenna for Wireless Communication Applications. To optimize the antenna parameters like resonant frequency, Voltage Standing Wave Ratio (VSWR), Bandwidth, return loss, directivity and gain etc. for proposed antenna using HFSS simulation software and following steps are taken to design multi band antenna using Fractal and defected ground structures.

1. Implementation and analysis of various existing antennas with different antenna parameters.
2. Design and optimization of proposed antenna for wireless applications in terms of Gain, Bandwidth, return loss etc.
3. Simulation, Fabrication, testing and validation of proposed multi band antenna.
4. Comparative analysis of simulated and experimental results of proposed antenna with existing antenna for wireless applications.

1.6. THESIS OUTLINE

This thesis reports provides detailed explanation about microstrip antenna, different method used in literature for antenna performance improvement, fractal and defected techniques used to analyse, design, optimize, fabricate and test multi band antenna for wireless applications and complete process to achieve desired goal is divided into following chapters.

Chapter-1: It provides the explanation about different wireless communication technologies used and need of microstrip patch antenna. The problem statement, aim and motivation of thesis is also explained in this chapter.

Chapter-2: This chapter presents, the overview of antenna, antenna performance parameters like Gain, Impedance, Bandwidth, Radiation pattern, Return loss etc. It also describes microstrip patch antenna structure with different feeding method used and different analysis techniques used for microstrip patch antennas.

Chapter-3: Presents extensive literature review on microstrip patch antenna used for wireless communication techniques. It provides detailed explanation about different methods and techniques used by researchers to improve antenna efficiency in terms of antenna parameters like gain, bandwidth, return loss, radiation patterns etc. and advantages and disadvantages of these methods.

Chapter-4: Explains about tools needed for antenna designing, simulations and to extract the performance parameters for antenna performance analysis. Testing tools like Vector network analyzer, Spectrum analyzer are explained in detail in terms of their working principle, types and procedure followed for antenna parameter measurements.

Chapter-5: In this chapter, details explanation of basic design techniques used for Antenna designing like Fractal and Defected Geometries are explained in details. Different types of fractal and defected shapes available in nature and used by researches in RF components designing are discussed. Also, circular cut with U-shaped Fractal and Defected Ground micro-strip patch antenna with truncated edges design methodology is elaborated with simulated and measured results comparative analysis.

Chapter-6: Explains about Elliptical patch fractal multi band microstrip patch antenna design methodology and parametric study. Antenna performance is analysed in terms of return loss, gain, bandwidth and radiation pattern to investigate antenna proposed structures possibility for wireless applications. Simulated results for proposed prototype are verified and validated by testing and measurement.

Chapter-7: In this chapter, explanation is given about conclusions drawn from this research work and suggestion are given for future research work.

Appendix: It deals with the methods and producers followed to fabricate antenna using Printed Circuit Board technology and setup used with mathematical calculations to measure antenna return loss, voltage standing wave ratio, gain and radiation pattern.

1.7. SUMMARY

This chapter begins with overview of wireless communication technology and different wireless technologies used with different frequency bands and bandwidth needed for efficient communication. Subsequently, it informs about need of microstrip patch antenna in wireless applications and it is realized that how concept of fractal and defected ground structures comes into picture for microstrip antenna performance and efficiency improvement. Brief discussion is laid on research work carried out in subsequent chapters. This chapters gives the outline of research work.

CHAPTER-2

ANTENNA OVERVIEW

2.1. INTRODUCTION

To share data effectively between two distant devices is still a constant challenge in wireless communication, beginning from smoke signals used in ancient times, to telegraphs and finally to communicate information without wires using electromagnetic signals. So, in wireless communication systems, a device is needed to convert electrical signals into electromagnetic waves effectively and that device is called antenna. In wireless devices, antenna is required at both transmitter and receiver side to couple its electrical energy to radio waves to transfer signals omitting wires through air at high speed. They provide simple means to transfer signals where other methods are not feasible. To improve quality and effectiveness of long-distance communication using different techniques to enhance data delivery is the main concern of researchers. In transmission and reception if radio waves, antenna acts as gateway at both transmitter and receiver side. Radio link quality can be improved by increasing transmission power and high receiver sensitivity to avoid interference. In this regard, antenna community plays quintessential role, to design small and multi band antennas to accomplish the strict demands of multifunction wireless devices.

2.2. ANTENNA PARAMETERS

Antenna performance is analysed on the basis of following parameters:

2.2.1 Antenna Gain: Antenna gain is defined as the ability of antenna to transmit and radiate in particular direction as compared to isotropic antenna. Directional antenna gives better performance in one direction than isotropic antenna. For transmitting antenna, gains are the factor of input energy conversion into radio waves in one direction and for receiving antenna gain defines how much radio frequency wave are converted into electrical signal. Antenna gain is basically functioning of antenna efficiency and directivity. Graphical representation of gain with respect to directivity is called radiation characteristics of antenna. Gain in terms of efficiency and directivity is given as following expression (2.1):

$$G = \eta D \qquad (2.1)$$

Here, D is directivity and η is efficiency of antenna which is unit less and lies between ($0 \leq \eta \leq 1$), and $\eta=1$ for lossless antenna. Practically gain of antenna is always less than directivity.

Gain is of two types:

(a) Power gain (Gp)

(b) Directive Gain (Gd)

Power Gain (G_p): It is defined as the ratio of radiation intensity in particular given direction to the total average power input power applied across antenna as given by expression (2.2).

$$Gp = \frac{U(\theta,\emptyset)}{Pt/4\pi} = \frac{4\pi U(\theta,\emptyset)}{Pt} \qquad (2.2)$$

Here, Pt is the total power and $P_t=P_r+P_i$, P_r is the Radiated power and P_i is the ohmic loss in antenna

Directive Gain (G_d): It is expressed as the ratio of antenna radiation intensity in given headed direction to the average antenna radiated power. It can be calculated using expression (2.3).

$$G_d = \frac{U(\theta,\emptyset)}{Pr/4\pi} = \frac{4\pi U(\theta,\emptyset)}{Pr} \qquad (2.3)$$

Directive gain is independent of radiated power and antenna losses, so maximum value of Gd is directivity of antenna as given in expression (2.4).

$$G_p = \pi Gd \qquad (2.4)$$

2.2.2 Directivity: Antenna directivity is defined as the measurement of how directional any antenna has its radiation pattern. Antenna directivity is defined in terms of decibels (dB). Radiation pattern of antenna will be more focused or concentrated in one particular direction if antenna directivity is high and will travel long distance. Omnidirectional antenna that radiates equally in all directions has 0 dB directivity. Directivity is defined in terms of antenna gain and electrical efficiency. It is maximum value of its directive gain and is represented by expression (2.5).

$$D(\theta,\phi)= \frac{U(\theta,\phi)}{Ptot/4\pi} \qquad (2.5)$$

Here, θ and ϕ are the zenith angle and azimuth angles respectively. Also, Directivity is defined in terms of ratio of maximum power density to average value of power observed in far field over S-sphere as expressed in expression (2.6).

$$D= P(\theta,\phi)max/P(\theta,\phi)av \qquad (2.6)$$

Directivity value D lies between 1 and ∞. For isotropic antenna directivity can be calculated using expression (2.7):

$$D= \frac{4\pi}{\Omega A}= \frac{4\pi}{4\pi}=1 \qquad (2.7)$$

2.2.3 Input Impedance: An antenna input impedance is defined as “the impedance presented by an antenna at its terminals or the ratio of the voltage to the current at the pair of terminals or the ratio of the appropriate components of the electric to magnetic fields at a point”. It is defined by following mathematical expression (2.8);

$$Z_{in} = R_{in} + jX_{in} \qquad (2.8)$$

Where Zin is the antenna input impedance, Rin antenna resistance and antenna reactance at the terminals is specified by Xin respectively.

How much power is stored in antenna near field, is presented by imaginary part of input impedance Xin. Rin in the resistive part of input impedance which consists of two components further, Radiation resistance Rr and loss resistance RL. The actual power radiated by antenna is the power associated with radiation resistance, and power dissipated in terms of heat is the power loss due to dielectric or antenna conducting losses.

2.2.4 Return Loss: Return loss is the function of transmitted power and reflected power in dB. It is mostly measured at the input of the coaxial cable connected to the antenna. If Pt is the source transmitted power and Pr is the reflected power than ratio of Pr/Pt is termed as return loss. Of return loss should be very small to transfer maximum power. Return loss is mainly presented in negative and should be as large a negative number [31,32]. Large negative is the value, good will be the return loss. Value for maximum power transfer the return loss should be as small as possible. Return Loss is expressed in dB as expressed in expression (2.9):

$$RL\ (\mathrm{dB}) = -20\ \log 10\ \Gamma \qquad (2.9)$$

Where | Γ | = is the reflection coefficient

2.2.5 Radiation Intensity: Radiation intensity is defined as power radiated rom antenna with respect to per unit of solid angle U that is independent on that part of the sphere surface in both horizontal and vertical planes. Antenna radiation intensity is related to beam direction and beam efficiency in that direction. It is used to measure radiation from antenna due to its independence on measurement range. Radiation intensity can be measured w.r.t isotropic antenna and given by expression (2.10);

$$\text{Radiation Intensity } U=\frac{W}{4\pi} \qquad (2.10)$$

By plotting radiation intensity with different directions radiation pattern can be achieved.

2.2.6 VSWR*:* Voltage Standing Wave Ratio parameter is used to measure how efficiently antenna impedance is matched with transmission line to deliver maximum power. To transfer maximum power between source and load, impedance of both terminals should be matched. Also, when transmission line is not properly terminated, then travelling wave is reflected back completely or partially at the termination end. So, the combination of these incident and reflected waves give rise to voltage standing waves along the transmission line. This ratio of maximum to minimum amplitude of voltage is called VSWR [4] as given in Figure 2.1 below and calculated using expression (2.11);

$$VSWR = V_{max}/V_{min} \tag{2.11}$$

VSWR is defined in terms of reflection co-efficient that defined how much power is reflected back from antenna. In terms of reflection co-efficient, VSWR can be calculated using expression (2.12);

$$VSWR=\frac{1+|\Gamma|}{1-|\Gamma|} \tag{2.12}$$

VSWR value lies between 1 to ∞. If VSWR value is small, antenna is matched properly with transmission line and more power is delivered and there is no reflection.

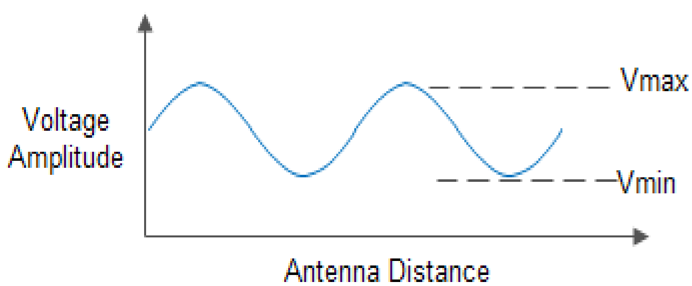


Figure 2.1: VSWR measurement along Transmission line

2.2.7 Bandwidth: It is expressed as "the range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard." It is considered as the range of frequencies on both side of cut of frequency where antenna performance parameters like input impedance, radiation pattern, polarization and beam-width should be within acceptable value with respect to central frequency.

2.2.8 Radiation Pattern: Antenna radiation pattern or far field describes the dependence of radio waves strength from antenna or other sources over angular direction [33]. Radiation patterns are graphical representation of antenna distributed power radiated from antenna if antenna is transmitting and incoming energy if antenna is receiving as function of direction angles. It can be 3-D or 2-D plot. It has three following parameters:

- **Main lobe:** It is the major or main lobe which represents the major portion of radiated energy over larger area as shown in Figure 2.2. Maximum energy exits in this portion only which indicates directivity of antenna also.
- **Side lobe:** Antenna power distributed side ward with respect to main lobe is called minor or side lobes. Most of antenna power is wasted in this region.
- **Back lobe:** Antenna power radiation lobe that is opposite to main lobe known as back lobe. Antenna power is also wasted in this lobe as it reflects energy in opposite direction.

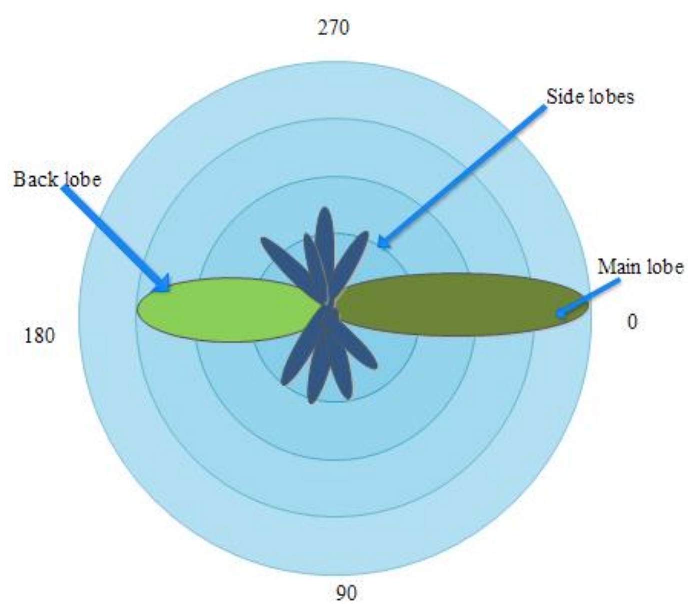


Figure 2.2: Antenna radiation pattern

In Antenna, following radiation patterns are used most commonly

- **Omni-directional pattern/non-directional pattern:** It resembles figure of eight in if observed in two-dimensional view and give doughnut geometry in 3-D view.

- **Pencil-beam pattern:** The beam has a sharp directional pencil shaped pattern.
- **Fan-beam pattern:** The beam has a fan-shaped pattern.

2.3. INTRODUCTION TO MICRO-STRIP PATCH ANTENNA

Micro-strip patch antenna gain attention in wireless communication applications these days. This antenna come in existence in 1953 and practically used in various applications in 1970's. They become highly useful due to circuit printed technology. Also, at the same time, it's less weight and simple profile make it more useful as compared to other antennas like dipole, parabolic reflector for various applications like satellite, spacecraft, and mobile applications. Micro-strip patch antenna is very simple in profile as they consist of metallic area placed above the dielectric substrate and ground plane on other side.

Micro-strip antenna patch and ground materials generally consist of materials like copper or gold. Antenna patch can be of different shapes like circular, square, rectangular, triangular, semi-circular etc. Patch and feed line used to excite antenna are photo etched on dielectric substrate material. Performance characteristics of patch antenna depends upon the dielectric material used and physical dimensions of it.

Over conventional antenna, micro-strip patch antenna has many advantages and applications. Conventional antennas are bulkier, integration problems and not able to achieve multi band operations. Due to PCB (Printed Circuit Board) technology, micro-strip antennas have planer surface, easy to integrated with microwave RF circuits, light in weight and exhibits dual and multi band characteristics. These antennas are versatile in parameters like resonant frequency, radiations and polarization. Also, different radiation patterns, modes of operation and polarization can be obtained by integrating components like diodes, shorting pins, adding loads between patch and ground plane. Instead of having numerous advantages, it has several disadvantages like narrow bandwidth, low power handling, high ohmic losses, less gain, unwanted radiations and low efficiency [33].

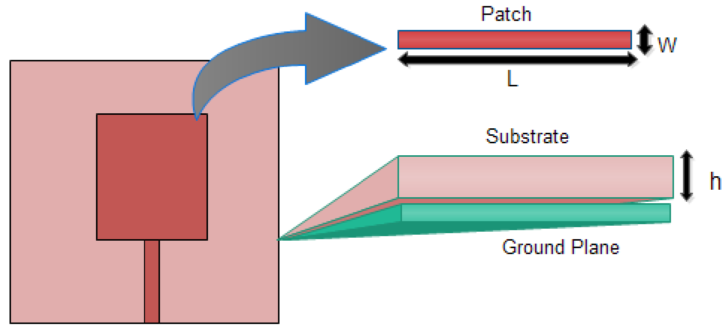


Figure 2.3: A Typical Microstrip Patch Antenna

In some application like security systems small bandwidths can be desirable but by increasing the substrate height, antenna efficiency up-to 90% can be achieved without considering surface waves and bandwidth up to 35percent can be achieved. Microstrip patch antenna mainly consist of very thin metallic strip patch (t<<λ0).

Microstrip patch antennas consist of radiating patch on one side of dielectric substrate and ground plan on other side as shown in Figure 2.3. Antenna radiating patch can be triangular, circular, square, rectangular, ring etc. The radiating patch and feed line is photo etched on the dielectric substrate.

For Micro strip patch antenna, length of rectangular patch taken is between 0.33λ0 to 0.5λ0; here λ0 is the wavelength of free-space. Thickness of radiating element patch is taken (h < λ0). Dielectric substrate thickness (t) is considered between 0.003 λ0 and 0.05λ0 with dielectric r constant of 2.2 to 12. Antenna patch is selected so that its radiation pattern remains maximum to the patch and can be achieved by properly exciting the mode of antenna [34]. Micro strip patch antenna dimensions depend upon frequency of operation, proper selection of dielectric substrate material, and dielectric constant value of material used. To get better efficiency of antenna, dielectric material with high thickness and low value of dielectric constant is needed. But it increases the antenna size, so to design compact antenna, substrate material with high dielectric constant can be used but these are less efficient and give less bandwidth. So, there is always compromise between antenna size and performance efficiency. Dielectric constant with small thickness and high ε_r value can be used for microwave circuits because tightly bound magnetic fields are needed to reduce effect of un- wanted radiations and coupling and to achieve more compactness. Path antenna analysis is done using transmission line, cavity or full wave methods. Among all methods transmission method is easy but less accurate and cavity model method is more accurate but difficult to analyse and more complex. Most accurate method is full wave methods of analysis [34]. Due to finite dimensions of patch, antenna goes under fringing effect from the edges. The amount of fringing is mainly function of antenna dimensions and substrate height. In antenna for x-y plane, fringing is function of L/h and value of substrate. Instead, of various advantages Micro strip patch antennas has some shortcomings in terms of gain and bandwidth. Researchers are mainly focusing on different techniques used to improve antenna gain and bandwidth. Applications of micro-strip Patch antenna in wireless applications is also depicts in Figure 2.4 below.

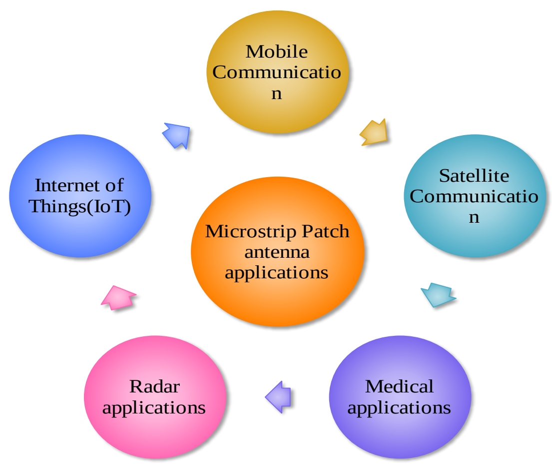


Figure 2.4: Applications of Microstrip Patch antenna in different fields

2.4. MICRO-STRIP ANTENNA FEEDING TECHNIQUES

Antenna is excited using different feeding methods to convert electrical signals to radio waves. Advantage’s, disadvantages of these feeding techniques are discussed below with detailed discretion.

(a) Micro-strip Line Feeding

(b) Probe Coupling
(c) Aperture Coupled Feed
(d) Proximity Coupling feed

2.4.1. Micro-strip line feed method: Micro-strip feed is similar to patch but with smaller dimensions compared to patch. It is simple to design and dimensions of it can be calculated using transmission line theory and impedance can be match by varying the feed position and each to fabricate. This method also has some drawbacks. By using this method, unwanted radiations and surface waves increases if dielectric substrate thickness increases, which decreases antenna bandwidth of operation (upto 2-5%). Equivalent circuit for this feeding is shunt RLC circuit gives the resonating patch frequency and series inductor represents the feed inductance of micro-strip feed line. Microstrip line feed is shown in Figure 2.5 below

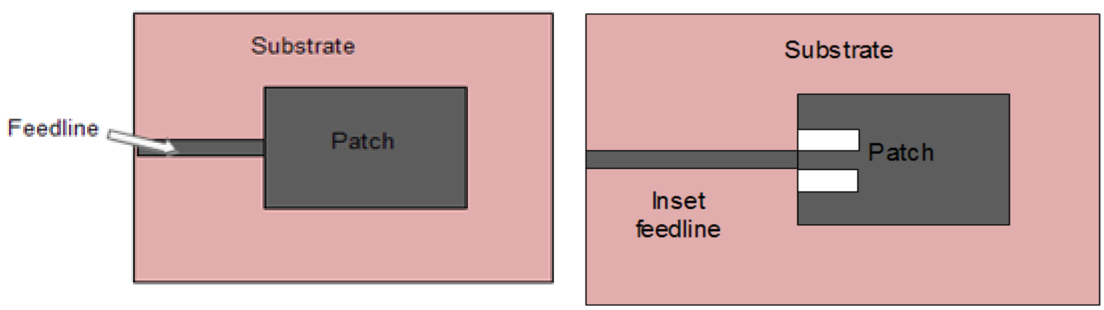


Figure 2.5: Geometry of Microstrip line fee patch antenna [35]

2.4.2. Probe Coupling Method: This method also called coaxial feeding method. Coaxial cable is used to coupled electrical signal. In this method cable inner connector is connected to patch and outer connector is attached with ground plane as represented in Figure 2.6. This method is easy to fabricated and impedance matching can be easily obtained this this. As compared to micro-strip feed line it has less spurious radiations. Like micro-strip feed line, operational bandwidth achieved is also narrow. Moreover, this method is difficult to model in antenna structures with thick substrate (t>0.02λ). Antenna losses increases while doing solder joints in designing antenna arrays and reduces reliability. Co-axial feed equivalent circuit is similar to microstrip feed method. These two methods generate dominate mode of operation for patch antenna but using these methods higher modes can also be generated which further give rise to cross-polarization radiations.

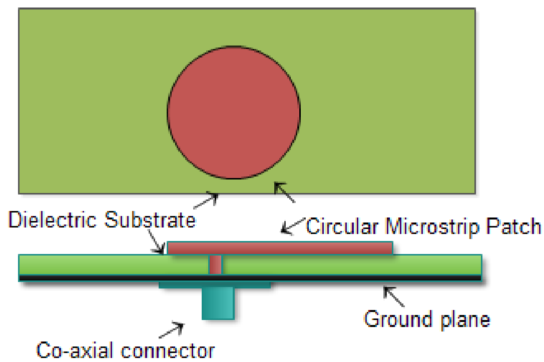


Figure 2.6: Geometry of Coaxial Probe Feed patch antenna [35]

2.4.3. Aperture Coupled Feed: This feed method uses two parallel layers of dielectric substrate separated by ground plane. Coupling is done using micro-strip feed line from bottom substrate through a small aperture from ground plane to micro-strip patch on the top substrate as given in Figure 2.7. This method makes independent optimization of feed line and radiation functions by using thin but high dielectric constant for antenna designing. Antenna aperture size is small than resonant size to reduce the size of back lobe by 15-20dB below the main lobe. As this method isolate feed and phase shift circuit electrically, so it is beneficial to use this method in micro-strip arrays. It has disadvantage also because it needs multiplayer structure that contains two substrates, so it is difficult to fabricate and increases the overall antenna thickness. It gives narrow bandwidth. The equivalent circuit diagram of this feed method looks like a series RLC circuit with inductance connected in shunt.

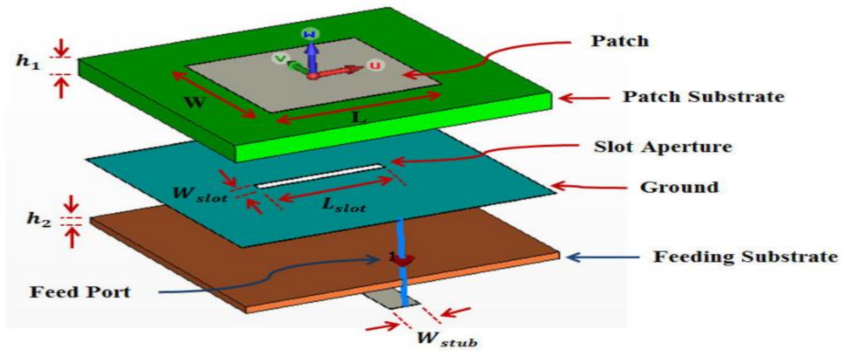


Figure 2.7: Geometry of Aperture Coupled Microstrip Patch Antenna [35]

2.4.4. Proximity Coupling feed: This method is used in antenna structures where two substrates are used. In such configurations patch is placed on the upper substrate and feed line in the lower substrate. This method has no electrical contact, so also called electromagnetically coupled feed line method as shown in Figure 2.8. In this method bandwidth can be improved by using substrate with high thickness on which patch is placed and to reduce spurious radiations lower substrate can be used with small thickness on which feed line is placed. Its fabrication is difficult because of proper alignment of upper and lower substrates. Like micro-strip and coaxial feed line methods, soldering is not needed in this method. This method gives capacitive coupling behaviour with RLC equivalent patch circuit with capacitor in series with it. Bandwidth upto 21% can be achieved with this method.

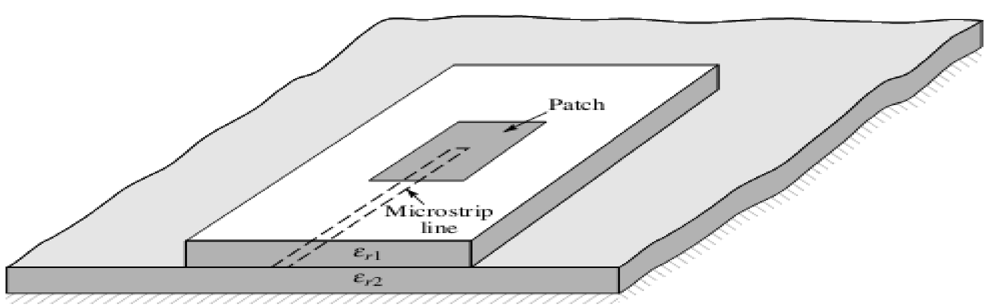


Figure 2.8: Geometry of Proximity Coupled Microstrip Patch Antenna [35]

Table 2.1: Pros and Cons of Microstrip patch antenna feeding methods

Feeding Method	**Advantages**	**Disadvantages**
Micro-strip Line	• Easy to fabricate • Impedance matching is easy by changing feed position • Spurious radiations are low	• Low bandwidth • Spurious radiation for thick substrate
Probe Coupling	• Less bandwidth • Less spurious radiations • Easy to match impedance	• Soldering needed • For thicker substrate large inductance
Aperture Coupled Feed	• With help of two substrates bandwidth and efficiency improves • No direct contact between patch and feedline	• Difficult to fabricate • Need multilayer fabrication • High back lobe radiations
Proximity Coupling feed	• Higher bandwidth upto 21% can be achieved • Effective for multiplayer substrate fabrication • Patch and feed electromagnetically coupled	• Need multilayer fabrication

2.5. MICROSTRIP PATCH ANTENNA ANALYSIS METHODS

Micro-strip antenna analysis methods are classified on the basis of magnetic current distribution (around the patch edges) and electric current distribution (on the patch conductor and the ground plane). On basis of magnetic current distribution there are three techniques:

- ·The transmission line model
- ·The cavity models
- The MNM (Multiport Network Model)

Microstrip patch antenna analysis can be done using different methods like transmission line model, full wave method and cavity model method as given in Figure 2.9. Among all these methods, transmission line analysis method is the simplest method, easy to model antenna but this is less accurate method. Cavity method is more accurate as compared to transmission line method, more flexible and provides good insight physically but more complex in nature. More versatile and accurate is full wave method. On basis of electric current distribution there are three techniques:

- The method of moments (MoM)
- The finite-element method (FEM)
- The spectral domain technique (SDT)
- The finite-difference time domain (FDTD) method

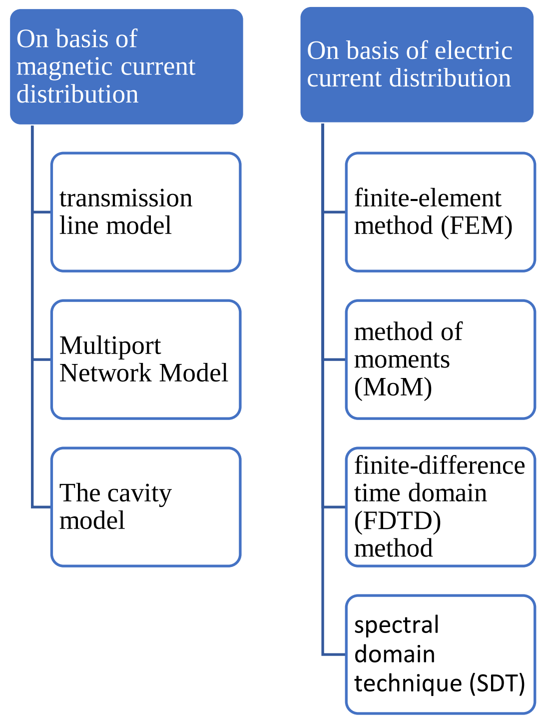


Figure 2.9: Microstrip patch antenna Analysis methods classification

2.5.1. The transmission line model: This method is simple in understanding Microstrip patch antenna performance. In this method, Microstrip patch antenna is divided into two slots with width ‘w’ and thickness ‘h’ separated by transmission line of length ‘L’. Microstrip is considered as two dielectric substrates of two different materials mainly substrate and air [35,36].

In this method electric field lines lies inside dielectric substrate mainly and some parts of electric filed is resonated in air. Due to this, this method not support actual transverse electric magnetic (TEM) transmission mode, as phase velocities are different in substrate and air. For calculation of dielectric constant fringing effect is also considered to obtain effective dielectric constant (ε_{reff}). Expressions for effective dielectric is as given below (2.13):

$$\varepsilon_{reff} = \frac{\varepsilon_{reff+1}}{2} + \frac{\varepsilon_{reff-1}}{2}\left[1 + \frac{12h}{w}\right]^{-1/2} \qquad (2.13)$$

Where ε_{reff} = Effective dielectric constant, ε_r = Dielectric constant of substrate, h = Height of the dielectric substrate, w = Width of the patch

2.5.2. Cavity model: In this method of analysis, area between the patch and ground plane of antenna is treated as cavity which is surrounded by magnetic walls and electric walls around the periphery and from top and bottom respectively. These fields are uniform along substrate thickness because thin dielectric substrates are used [36,37]. For different patch shapes like rectangular, triangular and circular shapes, fields are calculated as integration of various resonant modes of 2D resonator. Antenna effective dimensions should remain larger than physical dimensions, for that fringing fields are considered around patch periphery. Dielectric substrate loss tangent is calculated so that it incorporates conductor losses and antenna radiations. Equivalent magnetic currents are used to calculate far field and antenna radiated power around antenna periphery. The fringing field and antenna radiated power are considered only at edges not inside the cavity.

2.5.3. Multiport Network Model (MNM): This method is the extension of cavity model method [38,39]. In this method, electromagnetic fields below the patch and outside patch are modelled individually. The antenna patch is considered as 2D planer network with multiple ports located around its boundary. From 2D green's function multiport impedance patch matrix is obtained. By adding an edge equivalent admittance network, the fringing fields along patch boundary and radiated fields are calculated. After that segmentation method is used to find overall impedance matrix. Voltage distribution around periphery is used to calculate radiation fields.

These methods are used for regular patch geometries but for complex geometries following methods are used.

2.5.4. Method of moments (MoM): In this MoM method two types of currents are used for antenna modelling i.e. surface currents and polarization currents. Surface currents are used to model patch and polarization currents available inside dielectric slab are mainly used for field modelling. To formulate unknown currents of Microstrip patches, feed lines and their images in the ground plane, an integral equation is used [40]. These equations are solved using computers after converting them into algebraic equations. This method provides more exact solution because in this fringing fields outside the physical periphery of 2D patch is also considered.

2.5.5. Finite-element method (FEM): FEM method is mainly used for volumetric configurations. In this process, the area of interest is cut down into small number of finite surfaces or volume elements on basis of planar or volumetric structures to be analysed [41]. These divided discrete elements, also called finite elements can be of any properly defined geometrical structures like triangular elements for planar configurations and for 3-D configurations elements used are tetrahedral and prismatic which are more suitable for curved geometry also. In this method, integration of some basic functions is done over entire conducting patch that is divided into different number of subsections. To solve wave equations by inhomogeneous is done by dividing it into two boundary value problems, first is Laplace's equation and second with inhomogeneous wave expression with inhomogeneous and homogeneous boundary respectively [42].

2.5.6. Spectral domain technique (SDT): In this method, in plane of Microstrip patch substrate, a 2-D Fourier transform with two orthogonal directions are employed. Also, boundary conditions are applied in Fourier transform plane. The current distribution on the conducting patch is expanded in terms of chosen basis functions, and the resulting matrix equation is solved to evaluate the electric current distribution on the conducting patch and the equivalent magnetic current distribution on the surrounding substrate surface. The various parameters of the antennas are then evaluated [43].

2.5.7. Finite Difference Time Domain (FDTD): This method is highly suitable for Microstrip antennas because it can easily model various structural in-homogeneities occurred in these configurations. In this method, time and spatial grid for electric and magnetic fields are generated to find the solution. For spatial discretization, three Cartesian co-ordinates are considered to be same. With antenna boundary configuration E-cell edges are aligned and it is assumed that H-fields are located at the centre of each E-cell. Each cell keep information about characteristics of material and cells with the source are excited using suitable excitation function that propagates along the structure. Time variations of electric and magnetic fields are calculated at desired locations. The current is calculated by an integral loop of the magnetic field which surrounds the conductor, where Fourier transform provides a frequency response.

These methods, which are based on electric current distribution over the patch and ground plane conductor gives accurate results for any arbitrary shaped antenna structures but these methods are time consuming and provide less of physical understanding needed for antenna designing but can be useful to plot patch current distributions.

2.6. SUMMARY

This chapter deals exclusively with the fundamental of Antenna and Transmission line theory and antenna performance parameters with mathematical expression carried out for analysis. Further, it explains in detail about Microstrip patch antenna basic structure, its advantages and disadvantages. Also, different types of feeding methods used to improve gain and bandwidth of patch antenna with different analysis methods used in Antenna simulation software's like HFSS, CST. To sum up, this chapters laid emphasis on microstrip patch antennas.

CHAPTER-3
STATE OF ART

3.1. INTRODUCTION

With the recent developments in wireless communication systems demand for higher data rate and at very high-speed increased day by day which results in evolution of WIMAX, WI-FI, Bluetooth, UWB and mobile communication technology at high frequency bands. Personal communication devices aim to provide audio, video and data communication at very high rate and efficiently at anytime and anywhere in the world. To full fill all these requirements the communication terminal antenna must full-fill the requirements to sufficiently cover the possible operating bands. The key issue is to develop a compact and simple antenna with wideband characteristics. So various techniques to enhance the bandwidth, radiation pattern, return loss, Gain and directivity of antennas has been studied in the literature survey.

3.2. LITERATURE REVIEW

Young-Bae Jung et al. [44] describes triband antenna for Ka-K band. Author uses a Cassegrain reflector with integrated feeder for the k band to design modified hybrid antenna (HA). A microstrip antenna is used that consist of four linear sub-arrays and placed on the sub-reflector of the HA for Ku band services to provide high gain and to achieve rapid 2-D scanning ability at cheap cost for satellite applications. So, antenna is designed using a novel beam- steering through sub-reflector i.e. rotational and flat. A hexagonal structure is designed that uses feeder consist of 20 dual band horn elements those provide dual polarization also to maximise the efficiency. To reduce size, transmitter and receivers are connected with feeder horn elements. Antenna was tested for both indoor and outdoor environment and provides an EIRP of 55.2dBW and GT of 16.8dB for k band and 7.6dB for ku band.

As microstrip patch antenna has narrow bandwidth that is serious drawback of microstrip patch antenna. Author Yikai Chen et al. [45] uses concept of distributed L and C circuit to enhance bandwidth of E-shaped conventional patch antenna. In conventional E shape antenna, low inductance occurs due to probe fed, so LC circuit is used to reduce the thickness of air acting as substrate. A new resonant frequency introduced by LC circuit, near to that of E-shape increases the bandwidth of antenna without compensating the gain. Designed antenna operates on AMPS band from 824 to 894GHz frequency band. Simulation results shows that designed antenna has an impedance over 9% for Voltage Standing Wave Ratio (VSWR) over the frequency band is less than 2 but shows satisfactory performance in radiation pattern within the operated bandwidth.

Hussein Attiam et al. [46] discusses that microstrip antenna gain can be enhanced under some resonance conditions when antenna is covered with superstrate with proper distance in free space. Resonance conditions can be deduced by using proper transmission method and the cavity model to achieve the highest gain. Resonance effect can be changed by adjusting the spacing between antenna's superstrate and substrate and by varying thickness of the substrate. Depending upon these resonant lengths the permittivity, permeability and superstrate are determined and characteristics impedance can also be determined of the multilayer structure. Antenna performance is verified using simulation results and analytical methods also. From simulation results author concludes that proposed method enhances the antenna performance by 50% when compared to previous methods.

In research article [47] Ramona Cosmina Hadarig et al. proposes use of electromagnetic band-gap (EBG) structures and artificial magnetic conductors (AMC) due to their advantages use to improve antenna performance like better efficiency, high gain, and low back lobe and less side lobe levels. He designed antenna using combination of EBG with patch antenna in single layer and combination of AMC with patch antenna in two different layers. Due to more compactness and robustness antenna is compatible with plane antenna fabrication technology because it not needs via holes. Proposed antenna works in RFID 2.48GHz frequency band, also it shows better radiation properties without increasing antenna size and thickness. Proposed antenna provided bandwidth of 34MHz with EGB and of 46MHz with AMC over 23MHz for simple antenna, as well as gain improved from 4.6dB to 5.576 dB over the operating frequency band.

Feeding methods play important role as antenna efficiency also depends upon how power is transferred to the radiating element directly or indirectly. In research article [48] Soumyojit Sinha et al. describe advantages of microstrip antenna as low cost, low profile and conformal antenna. Different methods are used for antenna excitation like by coaxial probe and by microstrip line directly. Various indirect methods for excitation are also used like aperture coupling and electromagnetic coupling as there is not direct metallic contact between the patch and the feed line. Input impedance of antenna totally depends on type of feeding method used. So, author designed a rectangular patch antenna that works at 2.21 GHz frequency band using 1E3D simulator. Antenna feeding is done using probe. From simulation results antenna performs well in terms of radiation for wireless applications like mobile handheld radios, global positioning systems (GPS), radar for missiles.

To improve antenna bandwidth Y. Sung in [49] proposes printed wide slot line fed compact microstrip patch antenna with parasitic centre patch to further increase the bandwidth of conventional patch antenna. A 50ohm microstrip feed line is used to excite slot and rotated square slot resonator is considered as basic patch design. Resonator shows two frequencies i.e.f_1 low resonant and f_2 high resonant frequency. From simulation results author investigates that low resonance frequency deceases and high resonant frequency increases by placing parasitic patch in centre of rotated square slot. Simulation results show improvement in bandwidth more than 1GHz. Also proposed structure provides impedance bandwidth of 80% for 2.23 to 5.35 GHz bandwidth. Antenna covers WLAN 2.4, 5.2, 5.8 GHz bands and WiMax 2.5, 3.5, 5.5 GHz bands.

To improve microstrip antenna bandwidth a pair of parasitic patches is used by S. T. Fan et al. in [50]. Antenna dimensions taken are 37mm by 37mm, and fabricated using FR4 material with thickness of 1.6mm, relative permittivity of 4.4. To improve band, microstrip feed with 16 mm length and width 2.5 mm is used with a pair of semi-circular parasitic patches on both sides of it to provide additional resonance in the circuit. To provide strong coupling with feed line, gap of 0.5mm is maintained between patch and feed line. Antenna design is simple and easy in fabrication. Simulation results shows that bandwidth improvement is 136% for VSWR less than 2 for 2.1 to 11.1 GHz bandwidth. From simulation results the proposed antennas can be used for ultra-wideband modern wireless Communication applications.

P. A. Ambresh et al. [51] proposed a new micro-strip patch antenna with reduces size using FR4 dielectric substrate with slots for wireless applications. Proposed antenna works at two resonant frequencies 3.55 GHz and 4.99 GHz. From simulation results antenna shows 18.2% compactness for 270MHZ impedance bandwidth. Antenna shows very good performance in terms of return loss (RL) upto -36.14dB with Voltage Standing Wave ratio less than 2. Author concludes from results that antenna show better performance with linear polarization and also broadside radiation pattern is achieved with less cross polarization.

Syeda Fizzah Jilani et al. [52] proposed microstrip rectangular patch antenna with fractal design. Basically, fractal design is used to enhance the gain and bandwidth of microstrip patch antenna by implementing Star shaped patches at two sides and four corners of conventional microstrip patch antenna to overcome the limitations of low bandwidth and low gain of microstrip antenna. Antenna design is simple and easy to fabricate. Designed antenna works on 10GHz and fractal geometry enhance the gain from 5.479dB to 11dB and improves bandwidth from 550MHz to 5GHz as compared to conventional rectangular patch antenna. According to IEEE standards antenna works in X-band and Ku band. The side lobes in radiation pattern are reduced due to concept of proposed slots in design and also improve gain and directivity of antenna. Proposed antenna also used for radar, aerospace, satellites and communication systems.

Nitin Saluja et al. [53] design and fabricate planer inverted F-antenna using two folded edges based on fractal geometry which shows multi band behaviours. From proposed antenna, two frequency bands are achieved at lower and higher frequencies i.e. 2.25 to 2.863GHz and 4.81to 6.21GHz respectively. Impedance bandwidth obtained is 613MHz i.e. 25% at lower band and 1400MHz which is 26.4% at high frequency band which shows wide bandwidth. At low frequency band with centre frequency 2,4GHz maximum gain achieved is 3.8dBi and 7.2dBi for cut off frequency of 5.3GHz for high frequency band. Antenna is compact in size with overall dimensions of 19.83 x 19.8 mm2. To achieve more compactness in design, antenna patch is folded under itself. The antenna structure is best suited for Wi-Fi, LTE, WiMAX, and WLAN applications for mobile phone device.

Swaraj Panusa et al. [54] presents quad band H-slot microstrip patch antenna for WiMax applications. Antenna performance is analysed using HFSS simulator in terms of gain, return loss, radiation pattern, VSWR etc. Antenna shows multi band properties by just etching H-shape slot on patch and easy in fabrication. FR4 epoxy substrate is used with dielectric constant of 4.1 and coaxial technique is used for antenna feeding. Four frequency bands 3.41 to 3.51 GHz, 4.64 to 4.75GHz, 5.45 to 5.63 GHz and 6.38 to 6.50 GHz are covered by H-slot patch antenna. Maximum return loss is enhanced by antenna by -16.92dB at 3.46 GHz, -18 dB at 4.73 GHz, -17.50 dB at 5.55 GHz and -17.45 dB at 6.45 GHz frequencies respectively that is better enough for WiMAX applications. Radiation characteristics of proposed antenna are also good, so it can be used for multi band wireless applications also.

Lei Chen et al. [55] proposed circularly polarized wideband antenna with wide beam-width for S-band satellite communications. Author uses modified fork shaped inverted L-feed with stacked patches to improve the impedance bandwidth. To achieve wide beam-width concept of semi-open metal cavity is used. Simulation results shows that reflection co-efficient is less than -10dB, bandwidth is 30.1%, axial ratio less than 3db, half-power beam-width (HPBW) less than 100 degrees with gain of 3dbi. From experimental results antenna shows better performance in terms of circular polarization, impedance matching, and wide beam-width characteristics.

Eun-cheol Choi et al. [56] proposed a turnstile S-Band antenna using parasitic elements with cylindrical arrays and uses power divider network for feeding. Antenna performance is analysed in terms of beamwidth, gain, axial-ratio (AR), and radiation pattern. The desired frequencies can be achieved by adjusting the height, locations and number of cylindrical parasitic elements surrounding the bowtie shaped dipoles. Simulation results shows antenna beamwidth of -3dB, Axial ratio (AR) of 5dB and stable peak gain of 7.6dBi and bandwidth ranging from 2.02GHz to 2.29GHz with circular polarization. Antenna shows enhanced beamwidth, due to this antenna can be used in C–band satellite communication applications.

Jayarenjini. N et.al [57] purposes Dual Polarized micro-strip Fractal Patch Antenna for S-band applications that operates in 2 to 4 GHz frequency band for S-band. Author mainly uses the concept of fractal geometry to improve the bandwidth and to reduce isolation. Proposed antenna shows improved isolation and isolation loss is reduced by a factor of 15dB. One of the disadvantages of dual Polarized micro-strip Fractal Patch Antenna is reduced gain. The proposed antenna is used in applications like weather radars, communication satellite and wireless communications.

Mohammed N. Shakib et al. [58] proposed stacked low-profile antenna for UWB applications. Antenna contains three patches. One patch is angularly folded at 30 degrees also called bottom patch, middle patch with T-Shape and strip loaded patch as a top patch. The T-patch and angularly folded patch are combined together to achieve wide bandwidth. Author uses the shorting wall concept to minimize the antenna size further. Impedance bandwidth is improved using electromagnetic coupling between strip loaded patch antenna and T-shapes antenna. Considered dimensions of antenna are $0.12\lambda \times 0.14 \lambda \times 0.08 \lambda$, here λ is the lowest operating frequency wavelength. From simulation results author analyse that bandwidth of antenna is 107.46% for frequency band 3.1 to 10.3GHz. Antenna performs well in gain, radiation pattern and provides low delay variations in the designed frequency bands. Due to these entire advantage’s antenna is used for UWB applications.

In paper [59] Amanpreet Kaur et al. proposed a microstrip patch antenna using defected ground structure concept for wireless applications like LAN and UWB. Fractal shaped used in Sierpinski with aperture coupling feeding method. In antenna designing, author uses two layers stacked on each other of FR4 substrate material with patch contains Sierpinski fractal design on it. This complete structure further contains third layer at bottom of FR4 material, through which antenna is feeded with stub line at the bottom with ground layer on its top. To get wide antenna behaviour, cross type structure is cut from top ground layer. Designed antenna showed multi band behaviour and resonated on two different bands 4.75 to 5.38GHz and 6.8 to 7.2GHz with bandwidth of 630MHz and 400MHz respectively. Antenna has very good gain of 5.85 dB and 9.5 dB for these operating frequencies. Proposed structure works for IEEE 802.11 (5.15 to 5.35GHz) band, covers two different UWB spectrum 4750 to 5280MHz and radio astronomy frequency range from 5010 to 5030MHz. Antenna is designed and simulated using CST simulation software and tested using VNA tester.

Microstrip patch antenna gain is enhanced by M. T. Islam et al. in article [60] by using concept of parasitic patches. Antenna design consists of a rectangular parasitic strip at some distance from another rectangular strip, which contains four V-shaped slits of asymmetric structure at each corner of patch. For antenna manufacturing, Rogers's substrate material with relative permittivity of 2.2 with thickness 1.57mm is used. Antenna is circularly polarized, and provides high gain for HORYU-IV S-band Nano-satellite applications for low earth orbit (LEO). It provides return loss of -10db for 2.24 to 2.3GHz bandwidth with 3db AR and gain of 7.29dBi.

Faisel Tubbal et al. [61] studied the effect of CubSat body on antenna performance using Coplanar Wave Guide (CPW) feed, square shaped slot and Shorted patch antenna using HFSS simulator. From simulation results author concludes that performance of shorter patch antenna is better than CPW-feed antenna as shorter patch antenna provides high gain and wider bandwidth as compared to CPW feed antenna. Author again compares the performance of both antennas after re-dimensioning by shifting their resonant frequencies at 2.45GHz with help of quasi Newton algorithm to make use of both antennas in unlicensed ISM band. Proposed antenna, at frequency of 2.45 GHz for S-band simulation results shows that each modified antenna provides return loss below -10dB. Modified CPW feed antenna provides gain of 2.52dB at 2.45 GHz resonant frequency.

Author in [62] Mehr-e-Munir et al. uses concept of slots in ground for antenna size reduction and used patch slot method for multi band operation. By introducing slots in the patch also reduces the size of antenna. Antenna is fabricated using FR4 substrate with dielectric permittivity of 4.1. Results are simulated using Computer Simulation Technology (CST) simulator in term of Radiation efficiency, return loss and gain of antenna. Performance of designed antenna is compared with conventional micro-strip patch antenna for operating frequencies 2606MHz, 2807MHz, 4200MHz, 6050MHz and 7420MHz. From simulation results author concludes that slotted antenna is more compact in size as compared to conventional antenna. Due to this proposed antenna is used for S-Band, C-band and mobile applications.

Markus H. Novak et al. [63] presents tightly coupled dipole array (TCDA) an ultra-wideband antenna to support multiple satellite communication band at the same time. Antenna is very helpful in weight reduction as it replaces multiple antennas. Array is initially designed for operation across UHF, S, L and lower C-band for frequency 0.6 to 3.6GHz for easy of fabrication and more emphasis is given on dual –linear polarization. Antenna provides more spectral efficiency because intermediate frequency is reused for inter-satellite communication. Designed antenna array achieves a bandwidth of 6:1 for VSWR less than 1.8. Author presents TCDA design for operation at frequency bands like S-band, C-band, X-band and Ku bands (3 to 18GHz). From simulation results author concludes that antenna performs better with proposed design in terms of bandwidth efficiency.

Qiang Liu et al. [64] proposed double band circularly polarized (CP) microstrip patch antenna that works on 0.92 to 2.45 GHz frequency band. Proposed antenna is used for hand-held radio-frequency identification (RFID) radar applications. The antenna design contains two stacked patches further assembled with two vertical orthogonally placed probes and wideband network with dual feed. Stacked concentric patches used to generate resonance frequencies at lower and higher band. Dual feed two-way network generates signals with same amplitude and with phase difference of 90 degrees; due to this antenna covers both band 0.92 and 2.45GHz. Proposed antenna performance is compared with conventional antenna. Size of proposed antenna is 110 ×110 mm with height of 6.6 mm that is much compact than dual-band single port RFID directional Circular Polarized reader antennas. Proposed antenna is designed using PCB technology. Cost is also less. Simulation results shows return loss > 10dB, 3dB variations in gain axial ratio< 3dB for 0.91 to 0.93GHz and 2.4 to 2.57 GHz frequency band. Antenna works for both industrial scientific and medical ISM and RFID radar applications.

To improve bandwidth of basic microstrip patch antenna Ajay Thatere et al. [65] presents U-shaped structured patch antenna on FR4 substrate with two equal arms to overcome bandwidth limitation of general microstrip antenna. Under the U-shaped patch antenna on the ground surface a U-shape slot is introduced. Antenna performance is studied by analysing the performance of effect of slot size and different shapes of ground plane on antenna impedance bandwidth. With implementation of U-shaped slot maximum impedance bandwidth of 13% is obtained for 5.1 to 5.8 GHz frequency bands. From simulation results author concludes that antenna provides Voltage Standing Wave Ratio of 1.2 at desired frequency. Also, antenna size is small and simple in construction as compared to coplanar parasitic and regular stacked antennas. Due to simple construction and small size proposed antenna is highly suitable for wireless communication applications.

Suyang Shi et al. [66] propose a wideband miniaturized patch antenna with dual feed line structure. To shorten the non-radiating side of antenna element, based on concept of transversal signal interference the dual structure is used. Additional T-Shaped stub resonator is introduced in design in order to improve the impedance bandwidth. From simulation results author conclude that when compared to rectangular patch antenna, proposed antenna show 32% improvement in size reduction and 17% enhancement in bandwidth are achieved.

Pritam Singh Bakariya et al [67] present a microstrip patch antenna for multi band applications using a proximity-coupled feed. Author uses concept of slotted ground plane with proximity coupled feeding to get multi band operation. Proposed antenna consists of defected ground plane, meandered microstrip feed and truncated rectangular patch with rectangular slot. For antenna fabrication FR4 substrate is used with εr= 4.4 and thickness t= 0.8mm. Proposed antenna operates in WiMax (3.3 to 3.7GHz), Bluetooth (2400 to 2485 MHz), LTE2300 (2300 to 2400 MHz), and WLAN two bands 5.15 to 5.35 GHz, and 5.725 to 5.825 GHz. Simulation results shows that antenna performance is good in terms of gain, it provides constant gain on all operating bands and shows better radiation characteristics for operating frequency range.

In research article [68] Vandana Satam et al. proposed dual element antenna for MIMO to provide good isolation characteristics and enhanced gain by minimizing the effect of mutual coupling. Antenna is designed using Defected ground structures with 'I' shape vertical slot for 5.8GHz frequency bands used for MIMO wireless applications. Antenna is designed using FR4 substrate with dimensions 50.54 mm × 21.29 mm. MIMO antenna contains two symmetrical elements fed with insect feeding method. DGS concept is used to enhance mutual coupling. Designed antenna provides return loss of -21.71dB for wireless application and -27.95 dB for other operating bands with resonating frequency of 5.66GHz and 7.53GHz respectively. Proposed MIMO structure provides high gain of 6.05dBi. From simulation results author analyse that antenna can provide spatial diversity and also enhance data rate capacity of wireless communication systems. Antenna performs well in terms of gain and return loss.

Author B. R. Sanjeeva Reddy et al. in paper [69] proposed antenna for wireless communications with Zigzag shaped structure using microstrip antenna with defected ground. Antenna design consist of three steps: initially dual T-shaped slits are cut from opposite sides of rectangular patch, secondly, a zigzag-shaped slit is cut from patch and finally dumbbell- shaped defected ground plane with probe feeding is designed. Dual band performance is obtained using dual T-shape slits and also for better impedance matching.

Zigzag pattern is introduced to switch the resonant frequency to achieve more bands. All band frequencies got shifted to left by using a circular shaped dumb-bell structure in ground plan. Antenna operates on three resonant frequencies 2.45GHz, 5.28GHz (WLAN) and 3.5GHz (WiMax) bands. The return-loss values for achieved impedance bandwidths are enhanced significantly for these three operating frequencies. From simulation results it is analysed that return loss values increased but DGS leads to decreased gain over compactness as compared to conventional antenna. The proposed antenna has enhanced bandwidth that makes its more suitable for wireless communication applications in L and C bands.

A low-profile antenna is designed by Mingjian Li et al. in [70] for wireless applications. Author combines the concept of monopoles and slots with microstrip patch antenna to cancel effect of back radiations at two different frequencies. After executing proposed antenna, it shows uni-directional radiation characteristics over a broad band. Antenna height is only 0.035 of wavelength; here wavelength represents the central frequency. Antenna simulation is performed using HFSS and antenna provides bandwidth of 20.7% for frequencies 1.387 GHz to 1.696GHz with stable gain of 6.11dBi with unidirectional radiation pattern. This antenna prototype can be used for indoor mobile communication applications like Wi-Fi as access point antennas.

W.S. Yeoh et al. [71] present a compact size ultra-broad bandwidth, conical shaped monopole antenna which is optimized for wireless applications from Wi-Fi frequency bands to Ku band. Proposed antenna structure is highly compatible with wireless standards like Wi-Fi (2.4GHz), WiMax (2.5 to 5.5 GHz), Bluetooth v.5 and Wireless USB (3.1 to 10.6GHz). It is also suitable for radar and satellite communication applications for X-band and Ku band. Antenna consists of mechanical parts like cone and cylindrical disc. The desired structure is shaped using solid brass material and designed in such a way that it can be directly placed onto an SMA pin and flange. Proposed antenna shows maximum efficiency of 95%. The proposed conical monopole antenna provides ultra-broad bandwidth with Omni-directional radiation patterns, in a considerably small and easy to construct structure.

Falih M. Alnahwi et al. [72] proposed a switchable dual band planar ultra-wide band monopole antenna for wireless communication applications. For triggering the switch, light emitting diode is used that provides triggering pulses to a photoconductive semiconductor switch. Antenna operates in two modes depending upon ON and OFF status of switch. When switch is in off-state, proposed antenna operates in dual band /UWB mode and while in on state, the antenna shows dual band characteristic due to extended ground plane and acts as dual band antenna. From simulated and experimental analysis, it is observed that in dual-band/UWB mode, antenna covers entire UWB and 2.4GHz WLAN also, while in dual mode it covers two frequency bands WiMAX and X-band for Satellite communication. To achieve multi band and low-cost operation for proposed antenna, some tolerance is accepted in measured reflection coefficient due to the use of CdS photo resistor material as compared to CdS wafer.

Umar Farooq et.al [73] design micro-strip patch antenna for portable and multifunctional communication systems. Antenna is designed using fractal patch, E-shape slot is designed on fractal patch with first iteration and H and L-slots are combined together on the ground plane. Advantage of this design is Antenna is providing multi band response in frequency range of 1 to 8GHz with directivity range of 3.11 dBi to 5.84dBi and gain in range of -1.8 dB to -6.23 dB with good impedance bandwidth. By using this technique antenna size is reduced upto 91.72% but results for antenna gain and impedance bandwidth are satisfactory for both frequency bands. But due to small size antenna is used for various mobile phone applications and for L-Band, C-Band and C-Band applications also.

Yelei Yao et.al [74] describes an antenna that uses double-feed and stacked patch which provide circular polarization for Cube-Sat satellite applications for land S bands. Final antenna design consists of three layers, feeding network is embedded in metallic ground at the bottom of ground and dual band stacked antenna on the top. Antenna provides return loss below -15dB and axial ratio (AR) is also good less than 2dB for both Land S frequency bands. Antenna is tuneable it can work with lower and high frequencies by adjusting the length of stubs. This type of antenna design provides excellent performance, more reliable, highly stable and compact in size.

In paper [75] Yanshuai Wang et.al proposed meta-material microwave sources to reduce the size of microwave devices and to improve the electronic efficiency. Meta-materials have some properties like reverse Doppler Effect, negative refractive index and Cherenkov radiation (RCR) and due to these advantages meta-materials are used in antennas, transmission and optical applications. Author further analyse the S-band meta-material microwave sources using CST and HFSS. From the results author analyse that with 4.5 MW of output power microwave sources provides efficiency up to 90%. So, these are highly efficient materials used for antenna applications.

To reduce antenna size author Anthony Bellion et al. [76] presents circularly polarized single feed compact antenna used for Satellite S-Band applications. To reduce size of antenna author uses the concept of crossed dipoles and Artificial Magnetic Conductor (AMC). Coaxial cable with 50-ohm impedance is used to fed antenna substrate on diploes are printed on both sides. Proposed antenna covers Tele-Command band with frequency 2.025 to 2.110 GHz and Tele-Metry band with frequency 2.2 to 2.29GHz with bandwidth 17% (1.98 to 2.35 GHz). Size of complete antenna including satellite interface is 0.58 λ_{min} of diameter and 0.081λ_{min} of height where λ_{min} is the Wavelength at the lowest frequency.

Namrata D. Mahajan et al. [77] proposed patch antenna using HFSS for S–band and WiMax applications. Two antennas are designed one is circular and second is combination of two shapes circular and E-Shape using FR4-epoxy substrate with relative permittivity 4.4. Advantage of circular shape is it provides high gain with larger bandwidth and with E-Shape lower return loss is achieved. From simulation results author analyse that proposed antenna provides return loss of -19.6dB at 3.51GHz frequency and Gain of 9.13dB with voltage standing wave ratio (VSWR) of 1.2. Performance of new shape antenna is better than circular patch antenna in terms of Gain, reflection coefficient, voltage standing wave ratio (VSWR) and impedance bandwidth.

Jaypal Baviskar et al. [78] proposed Meta material (MM) lens depending upon properties of Meta Material like negative refractive index and backward wave propagation. Author uses MM lens with antenna to improve the antenna variables like bandwidth, gain, and directivity and radiation power. Author compare the performance of single patch antenna and array of 2 x2 antennas with and without using MM lens. Different patch antenna is designed for different resonant frequencies like 1.9 GHz, 2.4GHz, 3.8 GHz and 5.8GHz using MM lens with help or wires and Split Ring Resonator (SRR). Comparison is done on basis of 3D radiation plot, Polar plot, power radiation, S-parameter and power pattern plot. From simulation results author concludes that patch antenna with MM lens enhances antenna gain by 10-39%, increases antenna efficiency by 2-7.48% and improves directivity with 10-50%. MM lens also enhances antenna performance at lower frequencies marginally and at higher frequencies significantly.

Xi Chen et al. [79] proposes a circularly polarized compact micro-strip antenna for airborne communication applications. Antenna dimensions are reduced using cross slots on radiation patch and it also improves the efficiency of antenna. Proposed structure also provides wider beam-width in axial ratio (AR) radiation pattern. L-band prototype of antenna is designed and simulated. Antenna shows 97% radiation efficiency due to low loss dielectric substrate and absence of resistor feeding network. It provides impedance bandwidth of 22.4% for VSWR less than 2 and AR bandwidth reaches 6.8% for AR less than equal to 3dB. As antenna is compact in size and provides circular polarization, so it better choice for airborne communications.

Y. M. Pan et al. [80] designed wideband Metasurface (MS) based high gain, low profile filtering antenna which provides high selectivity. To feed antenna to separate microstrip – coupled slots are used at the bottom and Metasurface of antenna contains non-uniform metallic patch cells instead of uniform. Antenna provides good filtering performance by providing separation between slots with shorting via and MS antenna is designed to provide better performance at upper for o filtering. Antenna is designed and simulation results are measured at 5GHz operating frequency. Antenna performs is good in terms of gain, reflection co-efficient, radiation pattern and efficiency. Antenna shows enhanced gain of 8.2dBi within operating frequency band and 10dB bandwidth of 28.4%. No additional circuit is used for filtering and antenna shows approximately 95% efficiency.

Author Xiao Zhang et al. in research paper [81] uses concept of shorting pins to improve antenna bandwidth. He uses two different sets of shorting pins with two orthogonally diagonals on square patch radiator to enhance gain and directivity of single fed circularly polarized (CP) MPA. To enhance radiation directivity and to increase the electrical dimensions of loaded pin resonator, dominant mode of Microstrip patch antenna (MPA) can be tuned by changing the parallel inductive effect provided by shorting pins. By shifting position of pins in different way left-handed polarization (LHCP) and right-handed circular polarization (RHCP) can be changed. Two antennas are fabricated with and without shorting pins for comparison. Simulation results show that Circular polarization (CP) directivity is improved from 8 dBic shown by conventional antenna to 10.8 dBic i.e. so in total 2.8 dB increment using new design approach.

Lixun Li et al. in research article [82] proposed circular polarized triple band micro-patch antenna for Global Navigation Satellite System (GNSS) bands. Antenna works on three frequency bands 1.166 to 1.289 GHZ, 1.55 to 1.62 GHz and 2.48 to 2.5 GHz. Antenna designing done using two shorted annular shaped rings with circular array connected using via. To further enhance impedance performance at L-band, four L-probes are used for feeding antenna. Antenna performance is compared with conventional antenna; proposed antenna provides much better gain performance and operates over all GNSS bands and shows peak gains higher than 5 dBic as compared to conventional antenna.

Souren Shamsinejad et al. [83] presents 3-D cube antenna with omnidirectional radiation pattern in horizontal direction for wireless sensor networks. Structure is fabricated using RO-3003 substrate and Object Vero-Gray material. Proposed antenna is used as a transceiver of electronic circuits and wireless sensors. From simulation results author concludes cubic slotted antenna which operates at 2.45GHz with highest gain of 1.95dBi and provides bandwidth of 14% at cut off frequency of 2.49GHz. Antenna length is 33mm.

It works in ISM band at 2.45 GHz frequency band that is covered by Zigbee wireless sensor networks for monitoring.

Xi-Wang Dai et al. [84] proposed monopole patch dual-band microstrip antenna. The proposed structure consists of circularly periodic mushroom units and centre-fed circular patch antenna. Antenna provides zeroth-order resonance. Due to TM0 mode and zeroth-order resonant (ZOR) mode antenna creates magnetic currents horizontally on patch which provides low profile significance for low frequency bands. The antenna uses 50-SMA connector to provide centre feeding and designed on double layer printed circuit board (PCB). Simulation results shows that proposed antenna provides monopole like stable radiation pattern for frequency bands. Antenna shows gain of 5.1dBi and impedance bandwidth of 0.75% for low frequency bands and gain 5.8 to 8dBi and 20% bandwidth for high frequency band. As antenna is simple in design, simple profile and shows dual band behaviour, so it’s good choice for wireless Communication applications.

N. Nasimuddin et al. in paper [85] describes rectangular slotted patch antenna with 7x7 rectangular ring unit Metasurface to enhance bandwidth which is a single fed and gives circular polarization. Antenna is designed using a Metasurface with array of rectangular rings with rectangular slotted patch radiator and coaxial feed. The designed antenna provides a wide Circular polarized (CP) bandwidth ac comparison to conventional antenna. The measured results show that proposed antenna designed using FR4 substrate provides 28.3% bandwidth for 3dB axial ratio for frequency bands 3.62GHz to 4.75GHz with voltage standing wave ratio (VSWR) of 2:1 for bandwidth of 36%. Antenna prototype designing is done and tested using CST Microwave Studio and performance is compared with conventional antenna. Proposed antenna shows 70% efficiency for 3dB bandwidth.

For microstrip antenna bandwidth improvement Dong-Fang Guan et al. in [86] proposed microstrip patch array antenna using parasitically coupled patches of a 3x3. Antenna design contains nine microstrip patches to make array. Only one centre patch is excited using probe feeding and remaining eight patches act as parasitic elements. Array of four microstrip lines are used to couple energy in E and H plane, placed between parasitic elements act as feed network. Antenna is designed on a single layered substrate in form of 3x3 array element and all elements are excited simultaneously. Antenna is simple in construction, compact in size, wide impedance and excellent radiation pattern performance. From simulation results, proposed antenna provides wide bandwidth of 15.4% for 18 to 21 GHz frequency band with highest gain of 14.8dBi. Proposed antenna out performs in terms of gain and bandwidth.

M. S. Rabbani et al. [87] proposes a method to enhance gain, bandwidth and efficiency of microstrip patch antenna. Proposed design is fabricated by low cost Printed Circuit Board (PCB) method. To improve the fabrication tolerance antenna patch size is improved. Antenna performance is tested for X-band i.e. 8 to 12GHz and at 60GHz band frequencies. From simulation results author concludes that proposed antenna enhances gain by 14dB, bandwidth by 12.84% and efficiency of microstrip patch antenna by 94%. Proposed antenna is used for Wireless Personal Area Network (WPAN) and Wireless Local area network (WLAN) applications.

Zhixi Liang et al. [88] proposed dual frequency broadband two layered stacked monopole microstrip patch antenna for WLAN applications. Antenna design consists of via-loaded ring and circular patch. Via-loaded ring is on the bottom layer and circular patch is on the top layer and both are coupled fed with a common circular couple. To achieve dual bands antenna utilizes TM02 mode and TM01, TM02 and TM03 modes of via loaded ring. Antenna simulation results show that proposed antenna show resonance on lower band from 2.28GHz to 2.55 GHz and 5.15 GHz to 5.9 GHz for upper band with size of 6mm. Antenna provides gain of 6dBi in the lower and upper band of frequency.

Adrian Bekasiewicz et al. [89] proposed a surrogate assisted procedure for fast optimization of compact antenna with enhanced bandwidth. Proposed technique is very helpful to find an optimum design and be used for of high-fidelity electromagnetic (EM)-simulation models also. The method is very cost effective. Author uses concept of coarse-discretization EM simulations to represent antenna in fast way under low fidelity model design. Further combinations of frequency scaling and response correction methods are used to enhance the fidelity model. Frequency scaling is used to reduce misalignment between EM model in case of narrow band structures and correction prediction loop is used to find out optimum design at very low cost by considering all antenna parameters at same time. To implement and test this concept author uses modified patch antenna with slots in radiator based on concept of transversal signal interference. From simulation results author concludes that proposed design enhances bandwidth by 29% with antenna size of 645mm. In future size can be further reduced.

Renato Cicchetti et al. [90] proposed mushroom type dielectric resonator antenna for wireless applications with high gain. Proposed antenna design contains a hollow cylindrical DR with low permittivity and spherical shaped lens is there on top of resonator. Excitation is provided using coaxial probe method. By selecting suitable shape of reflector and lens back radiation can be reduced and high gain can be achieved more than 14dBi. From simulation results carried out using CST Microwave studio, antenna features high front to back ratio, high gain and circular radiation pattern and wideband impedance matching. Due to this proposed antenna can be used for wireless communication and satellite communication.

Marno van Rooyen et al. in paper [91] proposed a micro-strip double band antenna with improved gain for WLAN and WLAN applications using slots that operate on IEEE-802.11a/b and IEEE-802.16d standards. Proposed antenna is designed using a microstrip-fed line method to slot patch with a complimentary stub above dielectric medium. To achieve unidirectional radiation pattern concept of a reflecting ground plane is used. Antenna dimensions are 96mm × 73mm with thickness of 14 mm which provides measured gain of 9.2dBi, 7.0dBi, and 10.1 dBi. Antenna feed position optimization is done to achieve radiation efficiency more than 95% and also to minimize coupling effect between coaxial line and radiation fields. Proposed antenna shows good characteristics in terms of front-to-back ratio of the radiation patterns that make the antenna suitable for WLAN and WiMAX wireless applications.

Jian Dong et al. [92] design small sized printed multi band and decoupled dual antenna for WWAN/LTE smart phone applications. The designed antenna structure consists of two pair of bending symmetrical patterns with slotted and protruded ground with main objective to reduce the coupling between elements. The antenna structure is very simple in design and easily printed on the top side of smart phone system circuit board that occupy area of 60 × 15 mm2. Simulation results shows that for the operating bands the isolation between elements is better than 10dB. Antenna performs well in terms of diversity that makes it more suitable for WWAN/LTE smart-phone applications.

Abdelheq Boukarkar et al. in research article [93] used an approach of shorting metalized vias on one corner of radiating patch to reduce antenna size and get multi band properties by using inverted U-shapes multiple time sin patch. Both simulated and experimental results show that antenna gain peak and efficiency varies from 1.43 to 3.06 dBi and 42% to 74%, respectively. Antenna provides small size when minimum radius of enclosing sphere is considered. A proposed structure shows multi band behaviour and stable radiation pattern for all resonating frequency bands. Proposed antenna is recommended for point-to-point wireless communication applications.

Mohamed Aboualalaa et al. [94] introduce a circular dual-band antenna. Author use the concept of microstrip feedline with directly feeded circular patch. Circular patch which is inserted into the ground plane use capacitive radiation concept between patch and ground plane. Antenna radiates at 1.95 and 2.45 GHz with fractional bandwidth of 4.5 and 5% respectively. Simulation is done in CST Microwave and results shows antenna gain of 8.3 and 7.8 dBi at 1.95 and 2.45 GHz, respectively. Proposed antenna is mainly used for Wi-Fi and mobile networks energy harvesting.

Ahmed Dherar Saleh Saif Shaif et al. [95] presents Microstrip patch antenna for broadband applications using Diamond Shaped defected in antenna patch. Antenna size is 39mm×40mm and designed using FR4 substrate with ε = 4.2, height h=1.6mm and loss tangent 0.0016. Antenna is simulated at 3.6GHz and 10.35GHz simulation frequencies using Sonnet Suites version 16.52. From simulation results its analysed that returns loss

S11 parameter value is -14.63dB at 3.675GHz and -11.91dB at 10.35GHz frequency. Designed antenna gain at first resonance frequency 3.675GHz is 7.76dB and 11.04db at 10.35GHz resonance frequency. Best antenna gain is achieved at 10.35GHz frequency.

J.Zbitou et al. [96] uses the concept of Defected Ground Structure to minimize Microstrip patch antenna size and to shift resonance frequency from 10GHz to 3.5GHz without any change in original patch dimensions. For antenna designing FR-4 substrate is used with dielectric constant ε=4.4 and 1.6mm thickness. Antenna designing, optimization and simulation are done using CST Microwave Simulator. Antenna shows best performance results for WIMAX wireless applications. Proposed antenna size is 27x30 mm2. Defected Ground structure on ground plane consists of six concentric shaped rings with rectangular slot. From simulation results author analyse that proposed antenna gain increases for frequency range 2.5GHz to 4GHz and then decreases at 5GHz. Return loss is also calculated in terms of S11 parameter and its value is -10dB for resonant frequencies 3.3GHz to 3.7GHz.

Suleyman Kuzu et al. [97] designed a multi band antenna using defected ground structure and fractal structure for satellite communication. Apollonius circle that was designed as a fractal shape on the ground plane of antenna is used for frequency tuning in different bands. To tune three different frequency bands, three iterations of Apollonius circles are used. Using CST (Computer Simulation Technology) software a 2 × 2 array antenna structure is designed. Proposed antenna dimensions are 18.464mm ×18.464mm2. From simulation results author analysed that antenna dimensions are compact as compared to other antenna available in literature for same band of frequencies and also antenna performance is outstanding. Antenna return loss is measured using network analyser and simulated using CST software between 10-15GHz. S11 is below -10db for frequencies between 16.69 to 19.16GHz for manufactured. The manufactured antenna gain measured is 6.6dBi at 18GHz and 7.2dBi at the same frequency after simulation using CST software.

Author K. Wei et al. in paper [98] implemented concept of Defected Ground structures to design single feed microstrip patch antenna, to obtain circular polarization (CP). In the ground plane by further adjusting the dimensions of etched FDGS, CP radiations can be obtained. In antenna designing, total four iterations are taken. Antenna is fabricated using dielectric constant value 10, with thickness 3.18mm and loss tangent 0.0035. Antenna square patch has dimensions of 45mm and 28.6mm. Space between patch edge and feed point is taken 10.3mm. From simulation results it is analysed that impedance bandwidth of fabricated antenna is about 30MHz for 1.558 to 1.588GHz and 3-dB AR bandwidth is 6MHz for 1.572 to 1.578GHz operating frequency bands. Proposed antenna gain is from 1.7 and 2.2dBic.

Yogesh Kumar Choukiker et.al [99] designed reconfigurable antenna mainly for wideband applications based on a Koch snowflake concept. In proposed design, frequency reconfigurable property is achieved using RF PIN diodes with lumped capacitors and inductors to obtain UHF characteristics. Due to compactness of proposed antenna it can be used as an array element too. After fabrication and testing of proposed structure, three resonance bands are achieved, first: 3.34 to 4.52 GHz with 30% bandwidth; second: 2.2 to 3.4 GHz with 43% bandwidth; and third: 1.45 to 4.1 GHz with 95.49% bandwidth. First two frequency bands are different from each other but third band achieved covers frequency range of first and second band achieved. It is analysed that for proposed antenna the impedance bandwidth achieved provides continuous wideband frequency coverage from 1.45 to 4.52 GHz (103%).

Chetna Sharma et al. [100] presents a new concept based on Koch curve and implemented on Fibonacci spiral antenna (FSA) to gain more compactness in design using different iterative functions. This curve possesses semi-circular sections to maintain the symmetry with quarter circular sections of designed FSA. Due to curve properties of proposed structure, current flows very smoothly along the fractalized spiral arms as compared to conventional sharp-cornered Koch curves which provided uneven distribution of current. Implementation of second Koch curve resulted in approximately 50% reduction in size by maintaining the minimum equivalent length needed to achieve frequency operation at lower frequencies. Antenna is designed using Rogers RT Duroid 5870 substrate material with dielectric permittivity εr = 2.33. By implementing fractal geometry with two iterations, overall effective dimensions of proposed FSA reduce by 49%.

Balaka Biswas et.al [101] used different approach to design Vivaldi antenna using a natural leaf fractal structure. Proposed antenna exhibits 19.7GHz impedance bandwidth below -10dB from 1.3 to 20GHz.Proposed structure consists of two iterations of fractal leaf. By introducing 2nd iteration in design, lower operating frequencies reduced by 19% as compared to achieved with first iteration. Antenna is fabricated using FR4 material with overall dimensions of 50.8 mm by 62 mm. Proposed prototype is experimentally test in both frequency and time domain. Good wide band characteristics and radiation patterns are achieved which proves this proposed structure as good candidate for microwave imaging applications. Gain achieved is 10dBi with ultra-wide bandwidth of 175%.

Amer T. Abed et.al [102] designed MIMO antenna based on fractal geometry. Proposed antenna is compact in dimensions with overall size of 8 x 8 x 0.8mm3. To design antenna, two symmetrical radiating elements are used, which are placed on opposite side to each other to achieve spatial diversity. In total three iterations are used and with additional semi-crescent structure with scaled version of previous one and placed in cascade manner. From proposed structure, CP radiations are achieved with axial bandwidth of 2.2 to 3.2GHz which makes 24% of the entire working range from 0.1GHz to 4.3GHz. Antenna is good candidate for wireless applications like LTE/ RFID/Wi-Fi and Wi-MAX applications. Antenna provides good gain, wide AR bandwidth, diversity in terms of LHCP and RHCP as compared to existing antennas.

Tapas Mondal et al [103] proposed a new fern fractal shaped MPA antenna using an aperture coupling to obtain wide beamwidth and circular polarization. This new technique is simple in nature as compared to other methods used with similar sized patch to achieve 100-degree wide beamwidth. The proposed antenna is designed and validated experimentally for IEEE802.11y frequency band of operation. From results, it is depicted that bandwidth of 410MHz with 11.16% from frequency band 3.49GHz to 3.9GHz is achieved. For frequency band 3.62GHz to 3.71GHz, axial ratio performance is also below

3dB. Gain achieved for proposed antenna is more than 4.42dBic over the entire frequency band of operation and peak gain obtained is approximately equals to 5.16sBic. Proposed antenna can be used for various wireless standards like satellite, phone communication and vehicular applications for blind spot detection.

N. Kothari et al., (104) proposed microstrip patch antenna with U-slot structure for 5G communication. Antenna design is simple in construction and more efficient to achieve compactness, multi band and broadband behaviour. It is observed that there is inverse relation between resonant frequency and U-slot length and feed point too. Also, frequency of operation increases by changing co-axial feed point radius and slot width. Moreover, U-slot structure is used to enhance bandwidth and help in achieving multi band behaviour in antenna. Antenna is designed using Rogers RO 4350(tm) with thickness (t) =1.57mm, εr value equals to 3.66, and loss tangent value 0.004. Overall antenna dimensions are 15.8 mm × 13.1 mm × 1.57 mm. This antenna resonates at 28 GHz with gain of 4.06 dBi and voltage standing wave ratio is 1.02. RL performance of the said antenna is -20 dB. Antenna is designed and simulation using HFSS simulator software.

Kai Da Xu et al., (105) design microstrip patch antenna using different parasitic patches with main patch to obtain an equicircural triangular structure. Different resonance effects are produced using these parasitic patches to widen the antenna bandwidth. Three antennas are designed to study the effect of each patch on bandwidth. Antenna is designed using FR4 substrate material with dielectric value εr= 4.4 and thickness 1.6mm. Coaxial feeding method is used with SMA connector. Also, two shorting vias are introduced in final design to reduce the input impedance to further enhance the bandwidth. From simulation results, bandwidth of designed antenna obtained is 5.46 to 6.27GHz i.e. 13.8% without using vias and bandwidth of 17.4% is achieved from 5.5 to 6.55 GHz with introduction of vias with parasitic patches.

Amer T. Abed et al., [106] proposed circularly polarized fractal microstrip patch antenna for Wi-Fi and WiMAX applications. Final structure is designed after following five steps. Antenna is designed using FR4 substrate with εr = 4.3, tan δ = 0.027 with antenna size dimensions 18 × 18 × 0.8 mm^3. In every antenna design, patch structure design is reduced by 1/8 of original size. From simulation results antenna operates at 2.4 to 2.48GHz and 5.15 to 5.825GHz and these bands are used for W-Fi and Wi-MAX applications with gain to 0 to 1.5 dB. Antenna size is compact and gives dual band of frequency operation. Also, antenna has circularly polarization and RHCP and LHCP can be achieved using switching action between inputs.

Syeda Fizzah Jilani et al., [107] implemented concept of DGS in MIMO antenna for 5G wireless application to achieve compactness and high gain with less design complexity. Antenna patch design consists of T-shaped patch and to make antenna ground defected, five split ring slots each with width of 0.2mm are used in two iterations with proper distance from each other. Coplanar waveguide feeding method is used for 50ohm impedance matching with T-shaped patch. Antenna is fabricated on Rogers RT Duroid 5880 material with dielectric constant εr=2.2, loss tangent=0.0009 and thickness (t)=0.8mm with overall dimensions 12mm x 12mm x 0.8mm of single design. Defected ground structures are mainly used to change the direction of currents in ground of antenna to generate multiple resonating modes for antenna. This concept is further implemented in MIMO with four elements with minimum spacing of λ/2 between each patch to avoid effect of coupling. Width of each antenna in array varies from 12 to 12.7mm because width of connector used Jyebao (K864N5-00AB) is 12.7mm. Proposed antenna structure provides gain of 10.6dBi for operating range 25.1 to 37.5GHz. Antenna is further used to introduce MIMO concept and shows good isolation between adjacent elements that makes it attractive for 5G MIMO application in cellular communication.

Ali Arif et al. [108] presented a compact in size fractal antenna for wireless body area application in 2.4GHz ISM band. Patch shape used is triangular and proposed design is fabricated on vinyl polymer flexible substrate. To obtain final structure three concepts are integrated like Koch fractal geometry, DGS and meandering slits. Experimental and theoretical results are in good agreement with each other. Compared to already existing prototype, antenna is more compact in size of 0.318λo × 0.318λo × 0.004λo, with impedance bandwidth of 7.75% i.e. from 2.36-2.55GHz and peak gain of 2.06dBi with overall radiation efficiency of 75%.

Yufan Cao et al., [109] design broadband microstrip patch antenna (MPA) for wireless communication applications. Antenna patch structure consists of a square patch in centre with two mushroom type arrays on opposite side of main radiating patch. Parasitic patch theory is used to widened bandwidth of antenna. Each array contains three mushroom units and all are identical in shape and size. Antenna is fabricated using RT/Rogers 5880 dielectric substrate with εr= 2.2, loss tangent 0.0009 and thickness (h)=1.52mm. Co-axial feeding method is used. Antenna size is 32 x 20 x 1.5mm^3. Antenna results are simulated using HFSS software and it is depicted that antenna resonates between 11.9GHz to 18.2GHz with S11 below -10dB and gain value obtained over this range is from 10 to 10.5dBi. Proposed structure is suitable for satellite Ku band applications.

Kun Wei et al., [110] design microstrip patch antenna to obtain circular polarization using U shaped fractal geometry. Proposed antenna shows dual polarization characteristics, left antenna resonates in the Left-hand CP for transmitting and right antenna for receiving signals in RHCP mode. FDGS structures are used to improve antenna gain and efficiency by restoring radiation patterns. Antenna is fabricated using Taconic CER-10 substrate with dimensions 83mm x 45mm and thickness of 3.18mm, with dielectric constant εr=10. Antenna overall size is 100 x 100x 3.18mm. Three iterations of U-shaped structures are used. Results are calculated using HFSS software. Antenna resonates at 45MHz frequency band. Gain of antenna is calculated with and without using FDGS. Gain without DFGS is 2.56dBi and with using FDGS is 5.38dBic.

Zhe Wang et al., [111] design microstrip patch antenna with high gain and wide-bandwidth microstrip antenna using concept of shorting pins. Antenna patch is rectangular in shape and shorted from opposite sides. Antenna mathematical analysis is done using cavity model method. Antenna is excited using co-axial feed which is placed at distance 2.2mm from one edge. Antenna is designed on substrate with εr=2.2 and thickness=2mm. Antenna structure with size $1.29\lambda 0 \times 0.73\lambda 0 \times 0.036\lambda 0$ is simulated and designed and it is clear from results that antenna has good harmony between simulation and measured results. From simulation results, antenna operates in 5.13 to 5.85 GHz with 13.1% bandwidth with gain variation 7.9 to 9.7dBi. Also, measured results reflect that antenna has S11 below -10dB from 5.17 to 5.9GHz with gain values changes between 8 dBi to 9.7dBi. Proposed antenna has advantages like wide bandwidth, small in size, high gain and lower level of cross polarization i.e. below -25dB.

Guru Prasad Mishra et al., [112] proposed small sized microstrip patch antenna for wireless communication applications which resonates at 10GHz. To achieve antenna compactness, author uses defected ground structures below the radiating patch in the center of it. He uses Minkowski fractal shapes by adding high capacitive design for proposing the new miniaturized antenna. Overall antenna size is 0.200 × 0.150mm2, which is very small in dimensions. This antenna, provides gain of 3.2dBi and bandwidth of 270MHz over 10GHz resonating frequency. Using concept of DGS, antenna size reduction achieved is 68% with complete volume reduction of 85%. Proposed antenna structure is best suitable for movable X-band wireless sensor applications.

Xiumei Shen et al., [113] design microstrip antenna array for two elements using electromagnetic band gap structures (EBG) for 5th generation wireless communication applications. Author placed to E-shaped patch antenna close to each other with distance of 0.3 wavelength center to center with center frequency of free space. Proposed structure operates at frequency band from 26500 MHz to 29500MHz and can be used for MIMO and wireless communication systems. For antenna designing, Mushroom shaped EGB unit cell is used for simplicity which consist of square patch with metallic material and etched on dielectric substrate and connected using metal via to ground plane. Antenna structure is designed using Rogers 4003 dielectric substrate with constant value=3.55 and loss tangent (tanδ) 0.0027 with height = 0.203mm. HFSS software is used for antenna simulation and result analysis. From simulation results, its depicted that antenna provides peak gain of 7dBi by considering 1.2dB cable losses.

Ali Arif et al., [114] introduced antenna that is compact as well as low profile, mainly used for wireless on body applications. To design proposed antenna, flexible vinyl polymer material is used with dielectric constant εr= 2.20 and loss tangent of $9x10^{-4}$ and antenna is fed using insect feed line. Antenna structure consist of DGS, Koch fractal geometry and slits and makes a hybrid structure that provides improved impedance bandwidth and used for ISM application with operating frequency of 2.45GHz. Author uses fractal geometry and slits concept in antenna fabrication for increasing electrical length of antenna to achieve more compactness without increasing its overall area. Antenna dimensions are 39 x 39 x $0.508mm^3$, and it provides maximum gain of 2.06dBi with impedance bandwidth of 7.75% and radiation efficiency of 75 percent. Proposed antenna shows excellent performance in terms of simulated and experimental results.

3.3. SUMMARY

This chapter mainly deals with literature survey on Microstrip patch antenna for wireless communication applications. Chapter explain about use of basic microstrip antenna structure used for wireless standards and different methods used by researches to improve antenna performance parameters like gain, bandwidth, radiation pattern and compact size to full-fill the data transmission rate and gain needed for specific standard. From literature survey it is analysed that using CPW feed gain achieved is 2.52dG for lower frequencies. Proximity coupling feed can be used to obtain multiband operation but it is difficult to implement. In literature, antenna implemented for RFID application is very large in dimension with size of 110 x 110 x 6.6 mm3 and also some antenna mentioned in literature possess negative gain. For antenna fabrication FR4, Rogers RT Duroid etc substrate materials are used but return loss performance achieved with FR4 in not good as compared to Rogers RT Duroid. It is concluded from literature survey that there is always trade-off between antenna dimensions and performance parameters. After extensive literature survey, this research work shows the progression in work as mentioned in state of art. Also, it provides motivation to design multi band microstrip patch antenna using fractal and defected geometry to further enhance antenna performance.

CHAPTER-4

RESEARCH METHODOLOGY FOR THE RESEARCH WORK

4.1 INTRODUCTION

Antenna designing is a herculean and iterative process that involves multiple steps to achieved final design that consist of different steps like antenna software design or simulations, fabrication and testing. This chapter discusses the methods and tools used for antenna design, analysis, fabrication and testing of proposed antenna.

In simple antenna designing like dipole, process is simple and antenna current distribution in antenna structure can be easily calculated and measured with reasonable accuracy due to which it's easy for designer to calculate antenna performance parameters like Gain, Bandwidth, VSWR and radiation patterns etc. but for complex antenna structures, the current densities are difficult to calculate, so simulation tools are required to analyse antenna performance. Commercially, number of antenna design and simulations tools are available and also in open source for antenna designing and analysis. Mainly, techniques used are Finite Difference Time Domain (FDTD), Methods of Moments (MoM), and finite element method (FEM).

4.2 SIMULATION TOOL USED

4.2.1 HFSS (High Frequency Structure Simulator)

The Ansys HFSS 15 is used for designing and simulating high frequency electronic structures like antennas, RF and microwave components, filters, connectors and printed circuits boards to use in communication systems, Satellites, Radar systems, Internet of things (IoT) and other RF and digital devices. It contains versatile solvers and GUI (Graphical User Interface). HFSS gives a powerful and complete Multiphysics analysis of electronics components through interaction with Ansys thermal, structural and fluid dynamics tools to ensure their thermal and structural reliability. It is the Electromagnetic tool used for research and development and virtual prototype designing. It is standard tool used for 3D modelling for high frequency design. Professor Zoltan Cendes developed it initially developed with his students at Carnegie Mellon University in year 1990. This tool consists of combination of simulation, visualization, automation and solid modelling. This software uses Finite Element Method (FEM), excellent graphics and meshing to provide good performance. Users has the flexibility to choose the solver as per their design requirements.

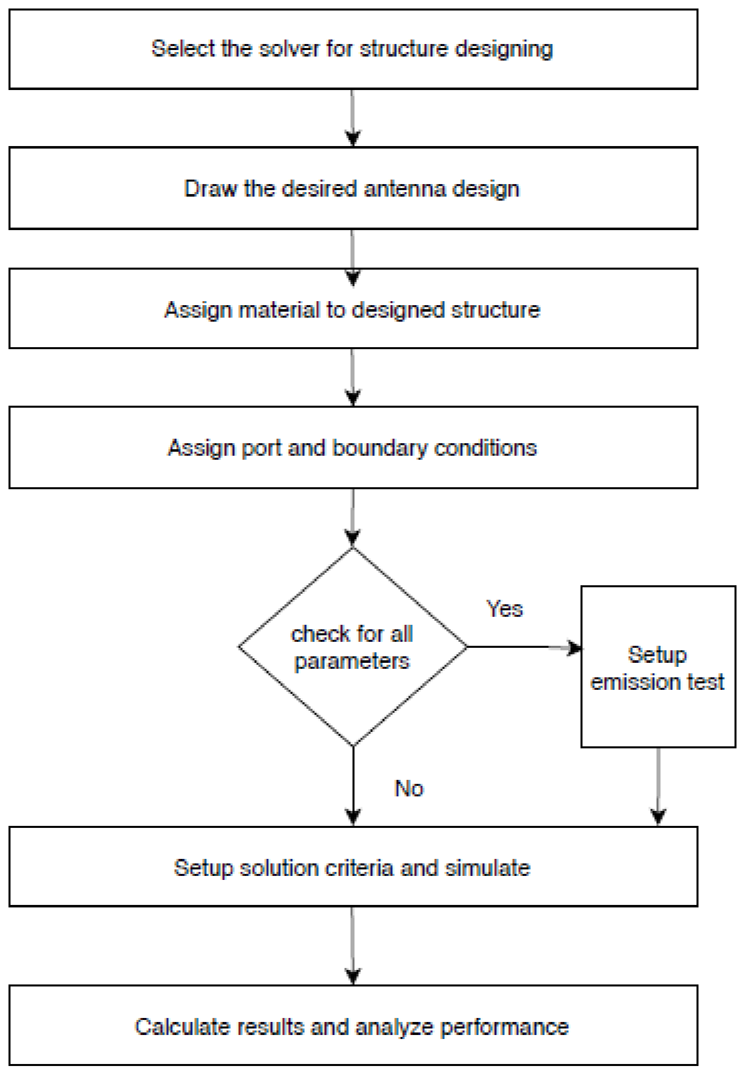


Figure 4.1: Ansys HFSS simulation procedure for Antenna designing

4.2.1.1 Structure Designing Process

The following flow chart (Figure 4.1) illustrates the step by step process to prepare antenna design and analyse its performance using HFSS tool. Initially by selecting the modeller type designer can design the geometric model. Afterword's, proper dielectric material is assigned to designed antenna structure like FR4 Epoxy, Rogers RT Duroid 5880 with desired thickness and dielectric constant. In the next steps, source (port line lumped and wave port) assigning and boundary conditions are provided like perfect_E to patch, ground and Radiations to Radiation box.

In HFSS simulator, after defining the boundary condition to all sheets and solids, a port either wave or lump is required to excite antenna structure. After structure modelling, and validation check, the structure solution is setup. After that solution frequency is assigned and frequency sweep is added to generate the solution frequency across the desired frequency range. Far field setup is added to calculate far field parameters like antenna gain and radiation patterns. After analysing the design, antenna performance parameters can be calculated in terms of S11, VSWR, Gain, 2D-3D Radiation patterns and Directivity etc. in graphical, table or smith chart form.

4.2.1.2 Antenna Design steps:

1. Create the ground plane
2. Create the substrate and assign dimensions after calculating with mathematical expressions
3. Assign dielectric material
4. Create the patch and assign dimensions to catch after mathematical calculations
5. Create feed line with proper dimensions
6. Unite the structure i.e. Patch with feed-line
7. Assign perfect_E boundary conditions to patch, ground plane
8. Assign port (Lumped or Wave) to antenna structure to couple electromagnetic energy
9. Create radiation box and assign Radiation boundary to radiation box.

4.2.1.3 Simulation and Analysis of Antenna

- To analyse the different parameters of designed antenna, the analysis setup is created first and desired solution frequency is assigned.
- ❖ **Go to HFSS Design-Analysis-Right Click-Add Solution Setup-Assign Solution frequency-provide maximum number of passes**
- After assigning the solution frequency, the next step is to add the frequency sweep which is used to generate the solution frequency across the frequency ranges.

- ❖ **Go to HFSS Design-Analysis-Right Click on Setup-Add Frequency Sweep-Select Sweep Type (Fast)-Assign Start and stop frequency with desired step size**

- After that far field radiation setup is used to analyse the gain and radiation pattern of designed antenna.
- ❖ **Go to HFSS Design-Radiation-Right Click on Radiation-Insert far field Setup-Infinite Sphere-Enter start and stop values for Phi and Theta in degrees. Execute analysis setup and compute results in terms of antenna parameters as follows:**

S11 parameters:

Go to HFSS Design-Results-Right Click-Create Modal Solution Data Report-Rectangular Report-Select S11 parameters in dB

VSWR:

Go to HFSS Design-Results-Right Click-Create Modal Solution Data Report-Rectangular Report-Select VSWR parameters in Db

Gain:

Go to HFSS Design-Results-Right Click-Create Far Field Report-Rectangular Report-Gain-Gain Total (dB)

4.2.2 Vector Network Analyzer

Vector Network analyser is used to measure the frequency response of active or passive components or networks or it is an electronics instrument that is used to measure the frequency dependent properties of device under Test (DUT) as shown in Figure 4.2. This measurement can be carried over a range of frequencies starting from a few kilohertz to hundreds of gigahertz's.

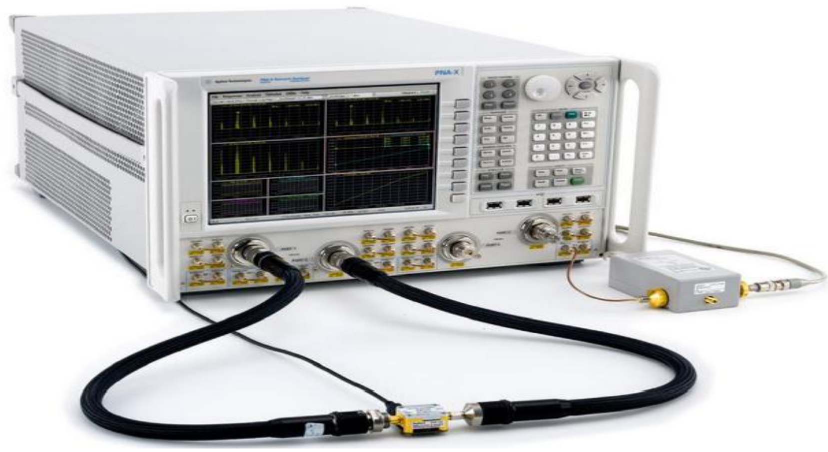


Figure 4.2: Practical two port Vector Network Analyzer

VNA measures then power going into and reflected back from a component and network at high frequencies. A signal electrical property can be analysed in terms of incident, reflected and transmitted signals, so, impedance of DUT can be calculated. The ratio of incident and reflected waves are defined in form of S parameters, also called scattering parameters. Using VNA, both amplitude and phase of frequency signals can be measured at each frequency point. Also, insertion loss and return loss of device under test can be visualized by computer used in VNA in different formats like real and imaginary, magnitude and phase and Smith chart. For S11 parameter measurement following setup as given in Figure 4.3 is considered using 2-port VNA to measure S-Parameters of DUT.

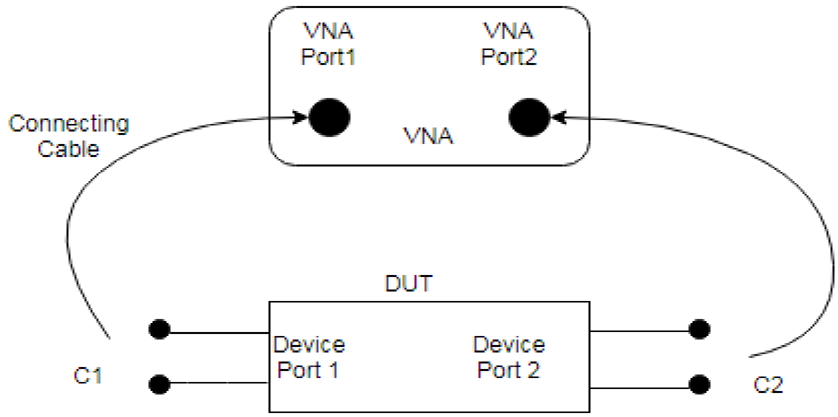


Figure 4.3: Setup for S-Parameter Measurement of DUT

Before performing measurement of device under test in VNA, it should be calibrated. Calibration means, all the undesired signal reflections, those will occur due to connecting cables and end terminals of connectors C1 and C2 as shown in Figure, must be considered and nullify. After calibration, measurement can be done. When Port1 can be used as source for RF and a1 is considered as incident voltage wave on DUT than b1 and b2 will be the reflected waves and transmitted waves through DUT respectively. Incident wave propagates from analyser to DUT and reflected wave travels in opposite direction from DUT to analyser. As, phase and amplitude of a1 is known, phase and amplitude of b1 and b2 can be measured using VNA. S-parameters gives very accurate representation of the linear characteristics of device under test, it basically describes how the device interacts with other devices when cascaded with them. Reflection co-efficient (Γ) or S11 is given as follows in Figure 4.4 and can calculated using expressions (4.1) and (4.2);

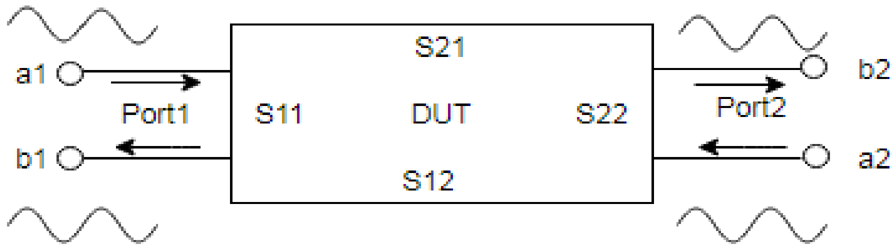


Figure 4.4: S11 co-efficient representation for 2-port network

$$S_{11} = \frac{b1}{a1}\bigg|\, a_{2=0} \quad S_{12} = \frac{b1}{a2}\bigg|\, a_{1=0}$$

$$S_{21} = \frac{b2}{a1}\bigg|\, a_{2=0} \quad S_{22} = \frac{b2}{a2}\bigg|\, a_{1=0}$$

$$S_{11} \text{ (Reflection co-efficient)} = \frac{b1}{a1} \qquad (4.1)$$

and $$\text{Transmission co-efficient (T) or } S_{21} = \frac{b2}{a1} \qquad (4.2)$$

4.2.2.1 Types of network Analyzer

Scalar network analyzer (SNA): This kind of network analyzer is used to measure the scalar amplitude properties of device under test (DUT). It is simplest type of network analyzer.

Vector Network analyzer (VNA): It is used mainly to measure more parameters as compared to scalar network analyzer of device under test. It is used to measure amplitude and phase response. It also called gain/phase meter or automatic network analyzer.

Large Signal Network Analyzer (LSNA): It is mainly used for RF networks. It is used to measure the harmonic components and non-linarites of network under test. It is also known as Microwave Transition Analyzer (MTA).

The main use of VNA is to calculates Scattering parameters of passive components including transmission cables, filters, couplers, antennas, transfers etc. VNA is also used for characterization of active devices like transistors and amplifiers using S-parameters.

VNA can be used in cable fault detection, in field of electromagnetic imaging to visualize breast tumours etc.

4.2.3. Spectrum Analyzer

In field of antenna and microwave engineering, spectrum analyzer is widely used test instrument. This test instrument, give information about signal spectrum. It measures the amplitude of an input signal with respect to frequency as per the frequency range of the instrument. It measures the spectrum power of known and unknown signals. Spectrum analyzer measures electrical signal characteristics and other signals like acoustic and optical signals spectrum can also be measured. In spectrum analyzer display, frequency is on horizontal axis and amplitude is displayed on Vertical axis.

4.2.3.1 Types of Spectrum Analyzer: Spectrum analyzer can be of following types:

(a) Filter Bank Spectrum Analyzer

(b) Super-heterodyne Spectrum analyzer

- **Filter Bank Spectrum Analyzer**

Filter bank Spectrum Analyzer are also called real time spectrum analyzer. These are used for analysing signals of Audio Frequency (AF) range and displays variations in all input frequencies. This device, initially collects the data in Time domain form and then converts it into the Frequency domain by using Fast Fourier Transform (FFT) method. Following diagram shows the filter bank spectrum analyzer.

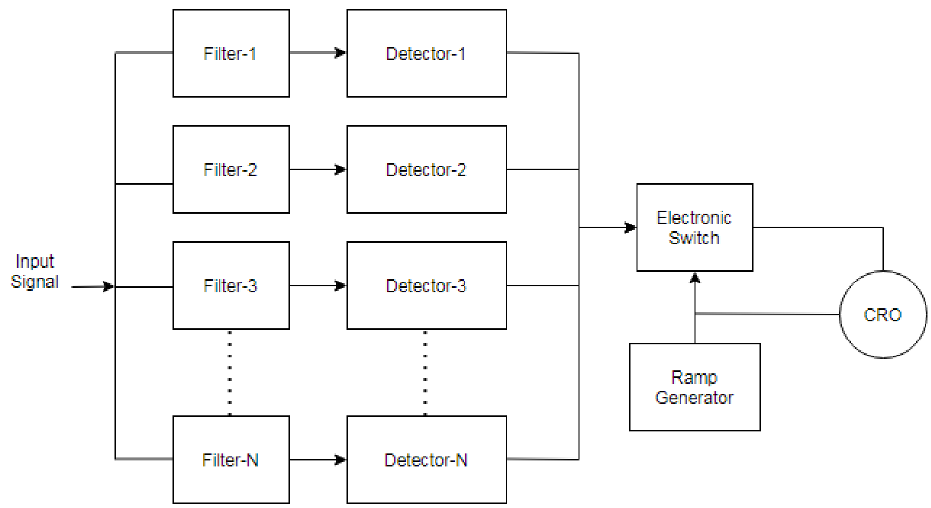


Figure 4.5: Block diagram of Filter Bank Spectrum Analyzer

It consists of a set of band pass filters (BPF) and each filter is designed to allow some particular set of frequencies. The output from each filter is passed to detector circuit following that filter circuit. Electronic switch is used to connect outputs from all detectors and further connected with vertical plate of Cathode Ray Oscilloscope (CRO) and passes the outputs in sequential manner to CRO vertical plate and displays frequency spectrum of AF signal on CRT screen.

- **Super heterodyne Spectrum Analyzer**

Super heterodyne analyzer also called sweep analyzer was the first analyzer to be used. It is used for analysis of RF frequency range; it attenuates the signal using input attenuator if the signal amplitude is very large. It allows the signal only the frequency components those are below the cut-off frequency.

The spectrum analyzer works on the super-heterodyne principle used in various radio receivers. It uses a mixer and local oscillator for frequency translation. This type of spectrum analyzer has very large scan spans due to super-heterodyne principle, even upto several GHz. Also, this spectrum analyzer can operate upto very high frequencies. Its block diagram is shown below.

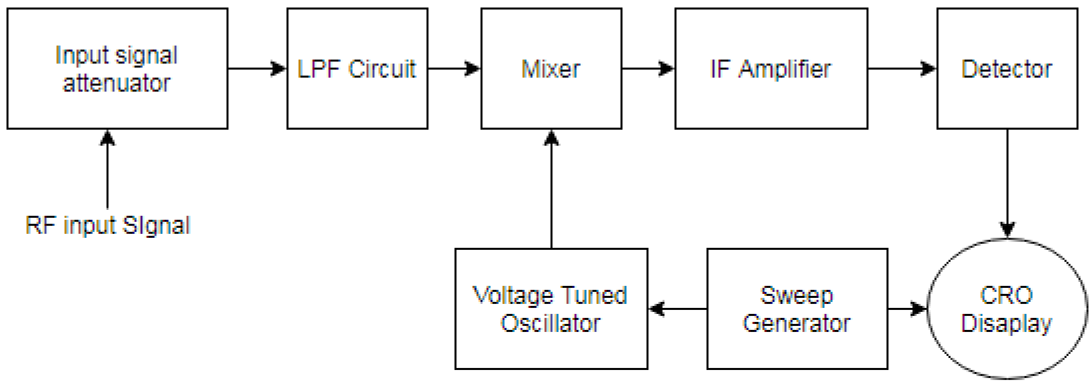


Figure 4.6: Block diagram of Super heterodyne Spectrum analyzer

The Radio Frequency signal which has to be analysed, is applied through the input attenuator and attenuated if signal amplitude is too large. Low pass filter (LPF) only passes the frequency signals which are less than cut-off frequency. Mixer circuit receives input from Low Pass filter and voltage tuned oscillator and generates the difference frequency signals. Mixer output is further amplifier by Intermediate Frequency (IF) amplifier and applied to Detector circuit that controls the vertical plate deflection of CRT tube so CRO displays the frequency spectrum of RF signal on CRT display.

Based on signal range, particular type of Spectrum analyzer can be selected.

Parameters that can be measured with spectrum analyzer.

- Return loss
- Satellite antenna alignment
- Spurious signal measurement
- Harmonic measurement

4.3 SUMMARY

In this chapter, antenna designing, simulation and testing tools are explained. Antenna structure can be designed using High Frequency Software Simulator (HFSS) and antenna designing steps are represented using flow diagram. Steps are explained to analyse designed antenna performance in terms of return loss, gain, radiation pattern using 2-D and 3-D plots. Also, antenna testing tools are used to measure antenna return loss performance, VSWR, gain and radiation pattern working principle, features and types are also explained in detail.

CHAPTER-5
CONFIGURATION OF ANTENNA DESIGN

5.1 INTRODUCTION

In this chapter, the methodology to design Multi band Microstrip patch antenna using Fractal and Defected structures for wireless communication applications using HFSS Ansoft antenna simulation software is presented. For antenna designing, transmission line design methodology is used for calculating the basic design parameters of the proposed antenna. Proposed antenna patch dimensions, ground, and feed line dimensions are calculated using antenna design expressions. Antenna basic patch selected is rectangular in shape due to its easy implementation and parameter calculation as compared to circular, semi-circular and other shapes studied in literature. For antenna designing and simulation HFSS software is used.

Microstrip patch antenna is designed using concept of fractal geometry and defected ground structure. To analyse antenna performance five iterations are taken into consideration and antenna performance in calculated using antenna parameters like Gain, Return loss (S11), VSWR etc. Initially, basic rectangular patch structure is considered and patch dimensions are calculated using mathematical expressions. Following procedure as give in Figure 5.1 is used for antenna designing.

5.2 FRACTAL STRUCTURES

Fractal antennas are widely used in the wireless communication. In conventional Microstrip patch antenna to attain multi band characteristics, fractal geometry is used. To understand the Fractal antenna, firstly we must get familiar with “What is the fractal?” It is obtained from the Latin word ‘Fractus’ which stands for broken, fracture or irregular fragments. It was discovered by a mathematician Benoit Mandelbrot. Fractal geometries are had been used in field of mathematics for a century but now fractal geometries are gaining much attention in antenna theory and microwave fields of research.

Many fractals available in nature such as Mountains and trees [120] as illustrated in Figure 5.2. Fractal shapes have created the revolution in the designing and development of multi band antennas. Numerous types of fractal geometries have been proposed by distinguished researchers for the development of wideband and multi band antennas.

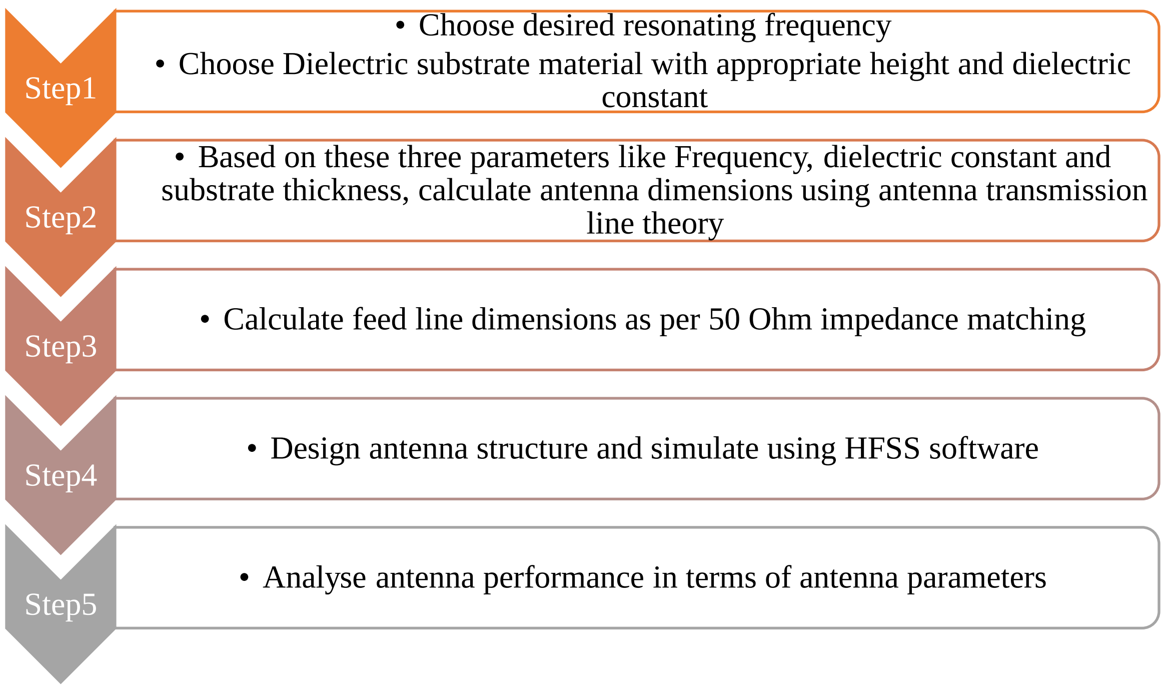


Figure 5.1: General Antenna design procedure

Fractal shapes are known for several properties like self-similarity, space-filling, infinite complexity and fractional dimensions due to which fractals in antenna field attain several advantages like compactness, multi band and wideband characteristics and improved efficiency. For antenna designing, self-similarity and space filling characteristics are widely used. To obtain sell similarity concept in fractals, infinite number of iterations can be applied using Multiple Reduction copy machine algorithm which further helps antenna to obtain multi band behaviour [121]. In antenna design circuits, size is the almost parameter, so to achieve compactness, space filling property plays essential role without changing antenna outer length it increases electrical length of antenna. These shapes are complex in nature and to exhibit more surface area in limited space, fractal geometries can be developed with recursive methods.

These properties of fractals make the fractal geometry antenna a superb structure for multi band and broadband applications [122]. Fractals can be implemented to design microstrip patch antennas, wire antennas, arrays, loop antenna, log periodic antennas or hybrid antennas. Moreover, fractals can be fabricated easily without need of any additional components on different type of dielectric substrate materials. Due to this, fractal antenna becomes more reliable and versatile for wireless application gadgets.

Figure 5.2: Fractal geometries available in Nature [120]

5.2.1 Classification of Fractal Structures

Fractal antenna are classified into following types as represented by flow diagram 5.3:

(a) Deterministic Fractals

(b) Non-Deterministic (Random Fractals)

Deterministic Fractals also called algebraic and geometric fractals. In this category, fractal designs consist of several scaled down copies of itself. Non-Deterministic or random fractals have some degree of randomness in their structure and can be compared with natural phenomenon that's why they possess statistical self-similarity.

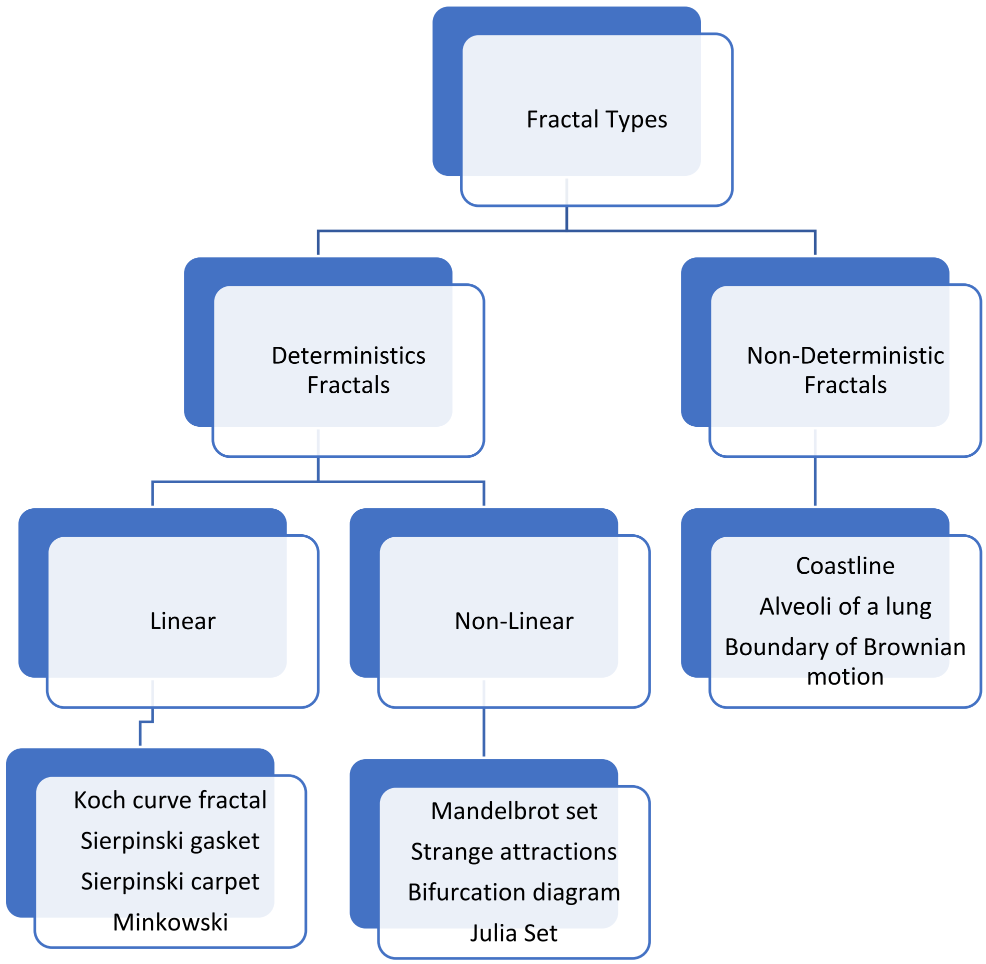


Figure 5.3: Classification of Fractal Structures on basis of Deterministic and Non-Deterministic Behaviour

5.2.3 Commonly used Fractal Geometries for Antenna designing

a. **Sierpinski Gasket:** In 1916, Polish mathematician named 'Sierpinski' proposed geometry called Sierpinski. It is also known as Sierpinski Triangle. To design fractal shape as shown in Figure 5.4, a triangular basic shape is used iteratively after inverting, scaled down and extracted from original shape to attain Sierpinski structure and repeated to obtain desired end structure. This is commonly used fractal geometry in antenna field to obtain multi band characteristics [123].

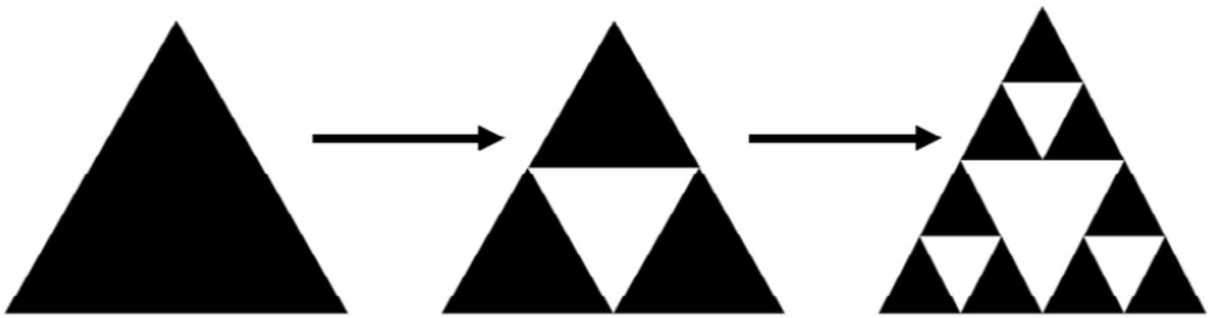


Figure 5.4: Sierpinski Gasket Fractal Geometry [120]

b. Sierpinski Carpet: The Sierpinski Carpet is developed by Waclaw Sierpinski in year 1916. It's a plane fractal and designed with help of rectangular patch. The first rectangle with dimensions of 1/3rd is extracted from the centre position of main rectangle. Square patch is used as initiator and scaled down from both x and y axis directions. The complete process is repeated to attain the final desired structure. It is the popular fractal geometry used for antenna designing and formed using IFS transformations as shown in Figure 5.5.

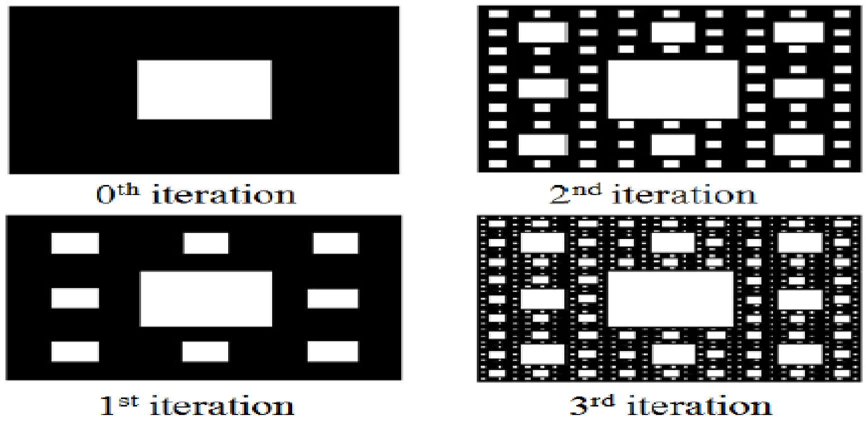


Figure 5.5: Sierpinski Carpet Fractal Structure [123]

c. Koch curves: Koch curves was developed by the Swedish mathematician Helge von Koch in 1998. Koch design is generated after breaking the straight line into three different segments x, y and z. Middle part of line is bended with angle of 60 degrees as shown in Figure 5.6 and method is repeated to achieve finite numbers of iterations for final design. This geometry is easy to design using PCB designing on dielectric substrate. To develop its generator structure, IFS algorithm can also be used.

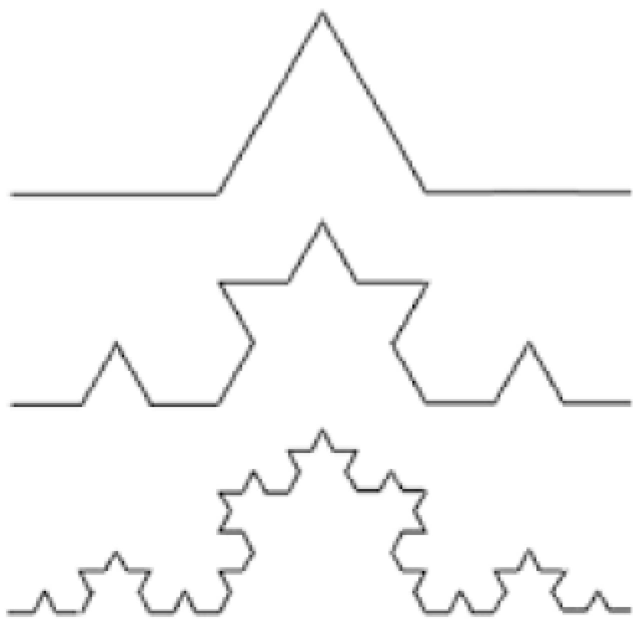


Figure 5.6: Koch curves Fractal structure [123]

d. **Minkowski curves:** This fractal geometry is discovered by a German Mathematician Hermann Minkowski in year 1907. This structure is designed using straight line as Initiator and straight line with square bend in centre is considered as Generator to attain final Minkowski curve as shown in Figure5.7. Main difference between Minkowski and Koch curve is of generator structure, in Koch curves equilateral triangles are used but in Minkowski rectangles are used. Length of rectangle considered is L3 and height is Lr3. Here L represents length of original antenna and ratio co-efficient is given by r. Antenna shows good performance in terms of resonating frequencies and radiation patterns. It helps to achieve compactness upto 24% with first iteration and 44% with second iteration and also shows multi band characteristics.

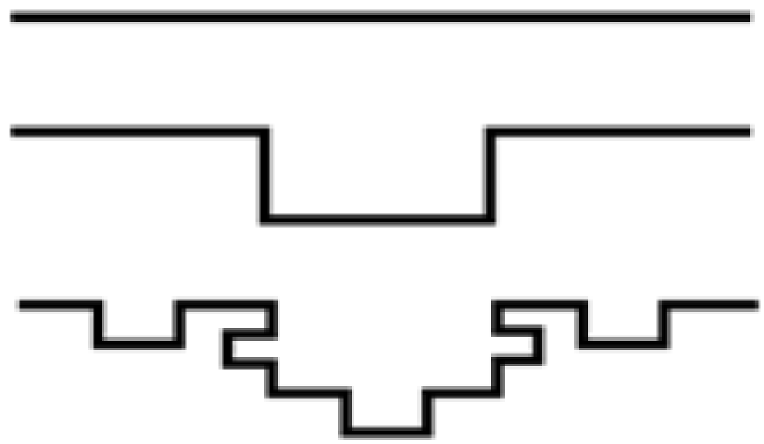


Figure 5.7: Minkowski curves Fractal structure [123]

e. **Cantor Set:** German mathematician Georg Cantor introduced Cantor set in 1883. It is generated by alternating gaps in multiple intervals and this geometry is important for set theory and dynamic systems. It can be developed by deleting the middle part of a line segment as shown in Figure 5.8. It can be used in antenna designing either in original form or after combining with other fractal shapes.

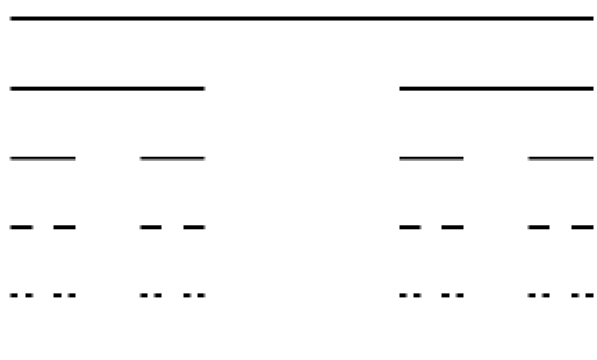


Figure 5.8: Cantor Set fractal geometry [123]

f. **Hilbert Curve Fractal:** Hilbert Curve geometry is developed by David Hilbert in 1891. In this structure each stage consists of four copies of previous design with one extra line segment as given in Figure 5.9 below. This structure is truly known for space filling property as it covers the entire area very effectively. Apart from tis, it has additional properties like self-avoidance and simplicity.

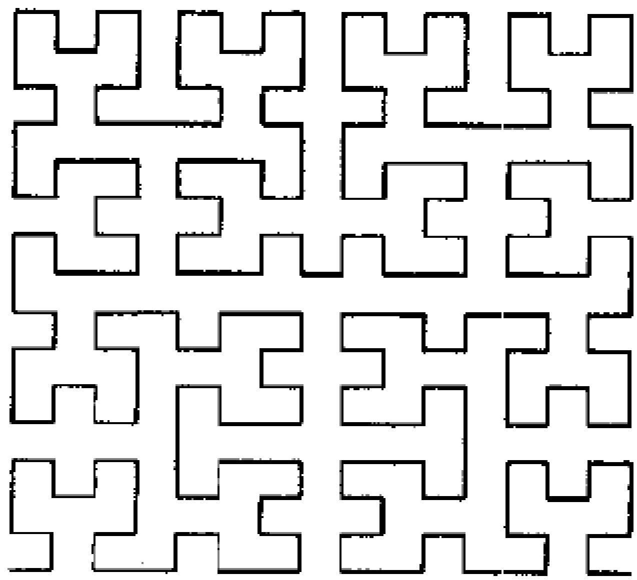


Figure 5.9: Hilbert curve Fractal Structures [123]

5.2.4 Fractals features

Fractal structures has following features:

- **Self-Similarity:** Fractals has self-similarity characteristics because they consist of multiple iterations of itself that is scaled down. Due to this antenna can operates at multiple frequencies and shows multi band behaviour. Self-similarity property of fractals geometries is used to design multi band and wideband antennas in different fields of antenna research.
- **Space Filling:** Fractals structure are known for their space filling characteristics. Fractal shapes are designed after repeating same shapes with smaller dimensions,

so due to this advantage of fractals they are considered as best designs to fill larges spaces in antenna very efficiently as compared to other designs. Fractals make large shapes to be packed into the small areas. Hence, fractal shapes are used to achieve antenna miniaturization. Space filling properties of antenna can be used in applications where antenna enlarge antenna lengths are needed with small dimensions, so fractals shapes help to increase electrical length of antenna structure without increasing overall dimensions of antenna.

- **Miniaturization:** To achieve compactness in design, researches find methods to integrate long wires to assemble sin such a way that final structure should occupy a small area [124]. Also, to obtain antenna resonance at low frequencies because according to antenna field theory, is length of electrical conductor is more than frequency of resonance will be lower due to rate of coupling between opposite currents that reduces the effective overall length of total wire and results in increase in resonance frequency.

5.2.5 Fractals Advantages and Disadvantages

The numerous positives and negatives of fractals are listed below:

Advantages

- Increase in bandwidth
- Good impedance matching
- Multi band and wideband characteristics
- Improved Voltage Standing Wave ratio
- Component matching not needed
- Provides high directivity and reduces side lobes in antenna
- Antenna can be designed using improved gain and radiation characteristics

Disadvantages

- More complexity in design

- Heavy calculations need to model these antennas.
- Antenna with higher iteration fractals are more difficult to fabricate.
  Designing the antenna prototype is expensive and leads to errors

5.3 DEFECTED STRUCTURES

In field of microwave engineering, research discovers several techniques and theories to design radio frequency and microwave components with improved characteristics. One technique that is seeking much attention now is Defected Ground Structures (DGS). Slots and defects etched upon ground plane of microwave components are called Defected Ground structures. It is opted method to enhance antenna parameters like operating bandwidth, gain, cross-polarization etc. DGS can be configurations of periodic and non-periodic structures in ground plan used to divert the current distribution which actually changes the reactive characteristics of the circuit like inductance and capacitance. In literature, various defected structures have been discovered and used like square, spiral, dumbbell, L-shaped, rectangular, circular, U-shaped, hexagonal, V-shaped, concentric, arrow head etc. [125-128]. Current distribution and propagation through ground plane can be controlled by properly selecting dimensions and shapes of defected structures which further controls elect magnetic waves generation and transmission through substrate material. Also, due to changes in inductive and capacitive properties of ground plane, additional frequency bands can be achieved which leads to multi band behaviour of circuits and very useful in wireless communication devices. The first DGS structures was discovered by Park et al. [124] as a dumbbell-shaped cells and Guha et al. [130] explains different patterns of DGS like fractal, half circle, split ring, spiral, V-Shaped etc.

These structures basically give more flexibility to microwave circuits designing and paved the way towards extensive range of applications. In yesteryears, many microwave circuits and milli-meter devices have designed to minimize the spurious harmonics, also to reduce dimensions of circuits with DGS. Various DGS printed on ground plan reported in literature are given below in Figure 5.10.

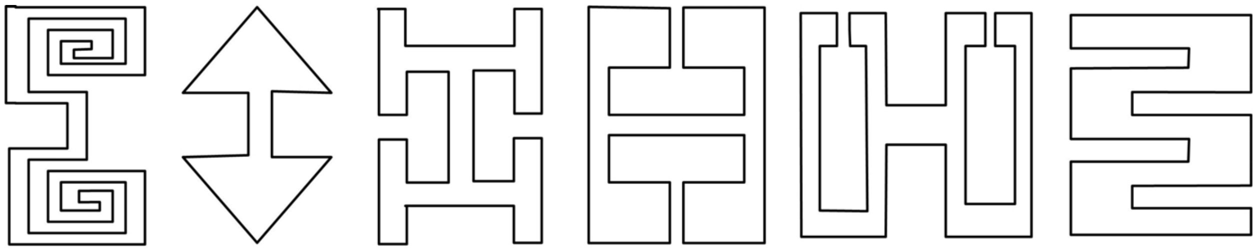


Figure 5.10: Different DGSs shapes reported in lecture [130]

5.3.1 Evolution of DGS

Initially, PBG (photonic Band Gap) and GPA (Ground plane aperture) techniques was used in electromagnetic circuit designing. Yablonovitch and John proposed, in 1987, proposed PBG [131] that utilizes metallic ground plan for microwave circuits and milli-meter-wave applications [132]. Also, GPA was used in which microstrip patch line was incorporated with a slot in centre of ground plane and mainly used for couplers and filter designing to rejection of spurious bands. PGB structure rejects some frequency bands but it’s difficult to use PGB for microwave and milli-meter wave components due to difficult in modelling because it effects numerous design parameters. With use of GPA, it is possible to change the microstrip line properties because the characteristics impedance depends upon the width of GPA. Afterwards, DGS are designed by Park by connecting two square shaped cells of PBG with thin slot.

5.3.2 Working principle of DGS

DGS is etched on ground plan of planar transmission line and can be periodic and non-periodic configurations which disturbs the current distribution that changes transmission line effective capacitance and inductance with addition of slot capacitance and inductance. DGS structure can consist of single defect i.e. unit cell or can be combination of more than one defect. Initially, DGS in planar microstrip was placed below the microstrip feed line which perturbs the EM waves. DGS comes in different shapes and dimensions depending upon the application and frequency of operation.

Unit DGS: The first DGS used was dumbbell shaped defect under the microstrip line etched on the ground plan as given in figure below with its return loss performance and used to design a filter [133]. For performance enhancement two different concepts of DGS can be used Unit cell and periodic DGS. In literature, numerous designed are discovered by researchers those are simple and complex in nature as given in Figure 5.11. These DGS structure has some advantages over initially discovered dumbbell shaped structure as follows:

(a) More compact circuit is achieved like 26.3% size reduction with help of H shaped DGS.

(b) Better return loss performance and wide bandwidth achieved for stopband.

(c) High Q factor achieved. After comparing U shaped and spiral DGS, for same resonant frequency, Q factor of U-shaped DGS is more compared to Spiral i.e. 36.05 and 7.478 respectively.

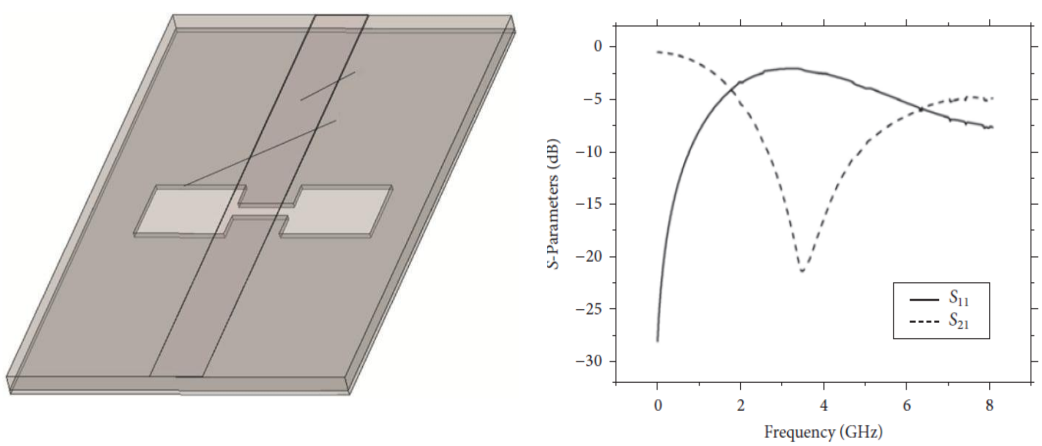
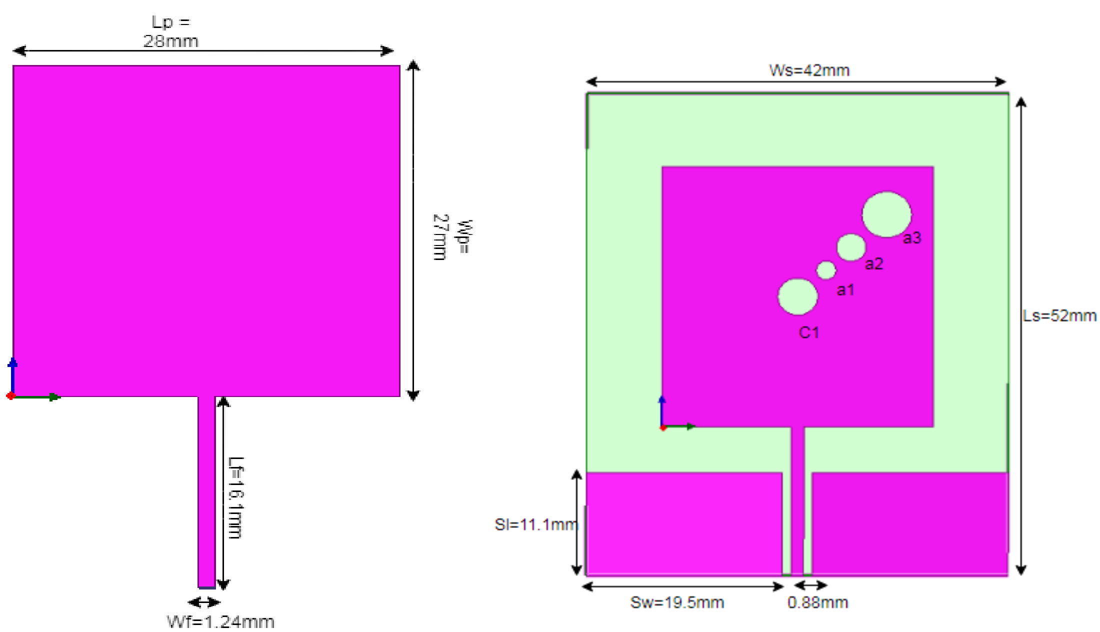


Figure 5.11: The first DGS unit: (a) dumbbell DGS unit; (b) S parameter performance [133].

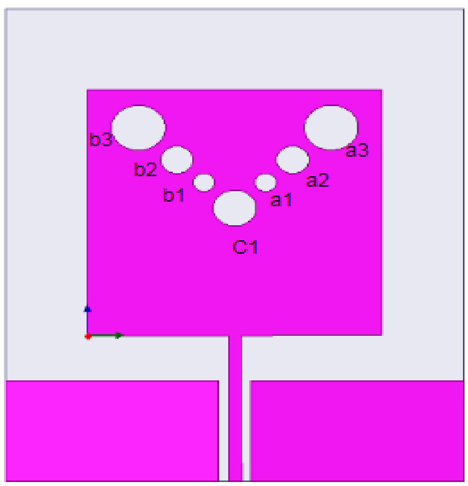
5.4 MULTI BAND CIRCULAR CUT, U-SHAPED DEFECTED GROUND MICROSTRIP PATCH ANTENNA

Proposed antenna structure is designed using Rogers RT Duroid dielectric material with thickness (t) of 1.6 mm, the dielectric constant (εr) of 2.2 and, loss tangent of 0.0009. A rectangular patch with dimensions 28mm x 27mm taken into consideration after proper calculations using transmission line theory. Also, ground plan with length and width of 52mm and 42mm used after calculation. Microstrip feed line of 16.1mm x 1.24 mm is used to provide excitation to antenna structure through the top ground plan with dimensions Lg x Wg and fed using a Lumped port with length 1.24 mm. The advantage of this feeding method is to reduce cross polarization and mutual coupling effect. A gap of 'g' is fixed between the feedline and top conductors mainly for impedance matching. To square conductors' dimensions taken are 11.1mm x 19.5mm.

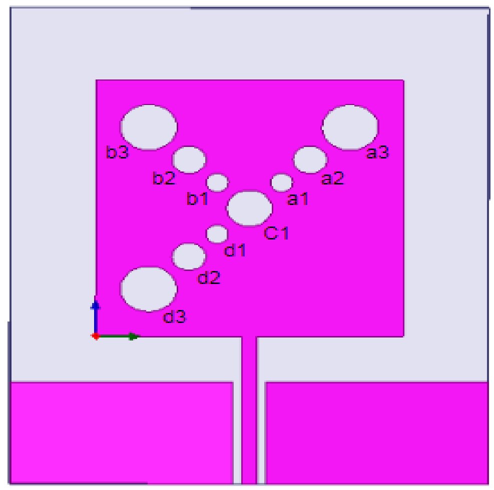


(a)Basic Microstrip square patch antenna (b) Iteration-1: Patch top view

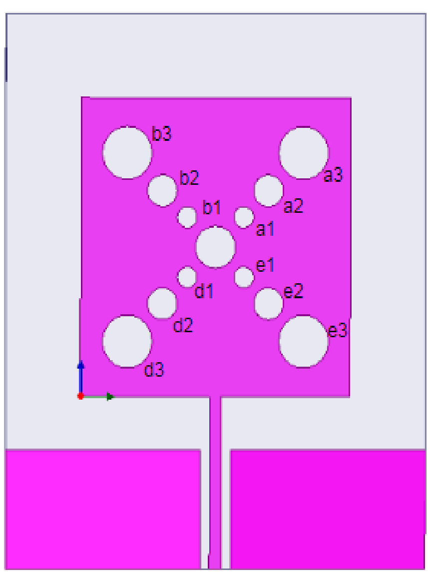
Also, the width and height of the transformer is calculated with mathematical expressions so that the impedance of the patch can be mapped with a port impedance of 50 Ohm. A circle is cut from the centre of patch with radius r= 2mm and three more circles with different radius values, as given in Table 5.1 are cut from the patch diagonally, from centre to all corner to implement the concept of fractals, as depicted in Figure 5.12. To



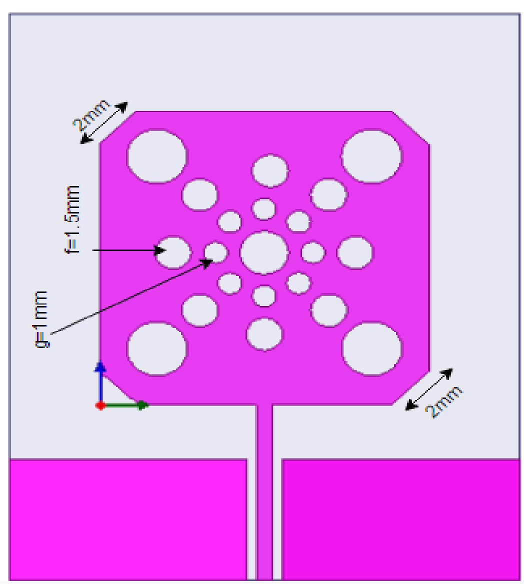
(c)Iteration-2: Top view



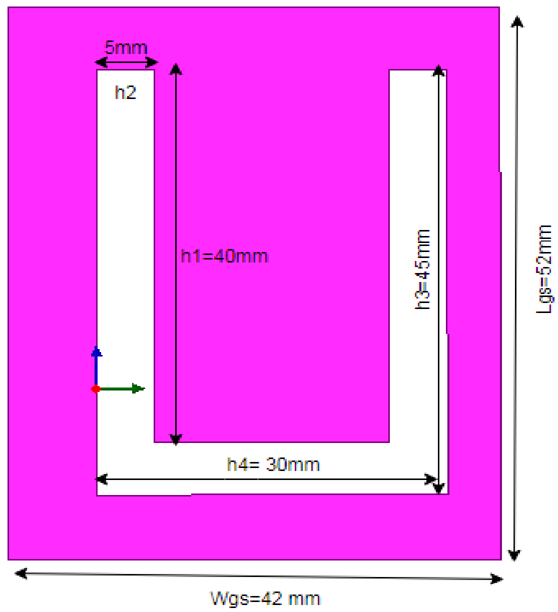
(d)Iteration-3: Top view



(e)Teration-4: Top view



(f) Iteration-5 (Final Design): Top view



(g) Defected Ground: Back view

Figure 5.12: (a) Basic design (b) Iteration-1: Top view (c) Iteration-2: Top view (d) Iteration-3: Top patch view (e) Iteration-4: Top view (f) Iteration-5: Top View (g) Defected ground used for all Iterations

implement concept of defected structures, A U-shaped slot is cut from antenna ground plane. The substrate is an essential parameter for designing of microstrip patch antenna that provides the intention of supporting the metallic resonating layers and provide physical support and strength to patch antenna. Rogers RT Duroid 5880 has uniform electrical properities over wide range of frequencies. Its laminations can be cut easily, share and shaped by machine. RT duroid material is resistant to all hot and cold solvents used in etching process for PCB designing, plating egdes and holes. Also very useful material for environments with high moisture content.

The electromagnetic analysis of proposed antenna is carried out using ANSYS HFSS simulation software that is based on Finite Element method (FEM) for antenna analysis and to obtain the fundamental characteristics such as return loss, VSWR, gain and radiation petterns.

Table 5.1: Structural Parameters of Proposed Antenna design

Parameters	**Dielectric constant**	**Substrate Material**	**Loss tangent**	**Height of substrate** (t)
Dimensions	2.2	Rogers RT Duroid 5880	0.009	1.6 mm
Parameters	Patch length (Lp)	Patch Width (Wp)	Length of Gnd (Lg)	Width of Gnd (Wg)
Dimensions	28mm	27mm	52mm	42mm
Parameters	Feed line length (Lf)	Feed line width (Wf)	Radius of center circle (c1)	Circle a1
Dimensions	16.1mm	1.24mm	2mm	1mm
Parameters	Circle a2	Circle a3	Defected ground length (Sl)	Defected ground width (Sw)
Dimensions	1.5mm	2.5mm	11.1	19.5
Parameters	U-slot width (h4)	U-slot length (h1)	U-slot thickness (h2)	
Dimensions	30mm	40mm	5mm	

To design rectangular micro-strip patch antenna resonating frequency Fr, substrate dielectric constant ε_r and height of substrate (h) should be known [134]. Antenna dimensions are calculated using the following mathematical expressions (5.1).

$$\lambda = \frac{C}{\mathrm{Fr}} \qquad (5.1)$$

Here, λ is wavelength, C is speed of light and Fr is resonating frequency.

Micro-strip patch antenna Width (W) is given by expression (5.2);

$$W = \frac{C}{2\mathrm{Fr}}\sqrt{\frac{2}{\varepsilon r+1}} \qquad (5.2)$$

Where C is speed of light ($3x10^8$m/sec)

Effective dielectric constant of the substrate is calculated using expression (5.3):

$$\varepsilon_{reff}= \frac{\varepsilon r+1}{2}+ \frac{\varepsilon r-1}{2}(1+12\frac{h}{w})^{\frac{-1}{2}} \quad (5.3)$$

Here 'h' is the thickness or height of the substrate and 'W' is the width of the antenna. Effective length of the antenna at resonant frequency is calculated as given in expression (5.4);

$$L_{eff}= \frac{C}{2Fr\sqrt{\varepsilon reff}} \quad (5.4)$$

Antenna length extension is calculated with expression (5.5);

$$\Delta L = 0.412h\left[\frac{\varepsilon reff+0.3}{\varepsilon reff-0.258}\,\frac{\frac{W}{h}+0.264}{\frac{W}{h}+0.8}\right] \quad (5.5)$$

Total length of antenna is calculated using expression (5.6);

$$L= L_{eff}-2\Delta L \quad (5.6)$$

Substrate width and length is calculated as given in expression (5.7);

$$Lg=L+6h \text{ and } Wg=W+6h \quad (5.7)$$

Height of substrate is given in expression (5.8);

$$h= \frac{0.0606\lambda}{\sqrt{\epsilon r}} \quad (5.8)$$

Feed line dimensions are calculated using expression (5.9):

$$L_f = \frac{\lambda g}{4}$$

$$\lambda g = \frac{\lambda}{\sqrt{\varepsilon eff}} \quad (5.9)$$

Radiation box dimensions can be calculated using expression (5.10);

$$\text{Axis position}= \frac{-\lambda g}{6} + \frac{-\lambda g}{6} + \frac{-\lambda g}{6}$$

$$\text{Length} = \frac{-\lambda g}{6} + \frac{-\lambda g}{6} + Lg$$

$$\text{Width} = \frac{-\lambda g}{6} + \frac{-\lambda g}{6} + Wg$$

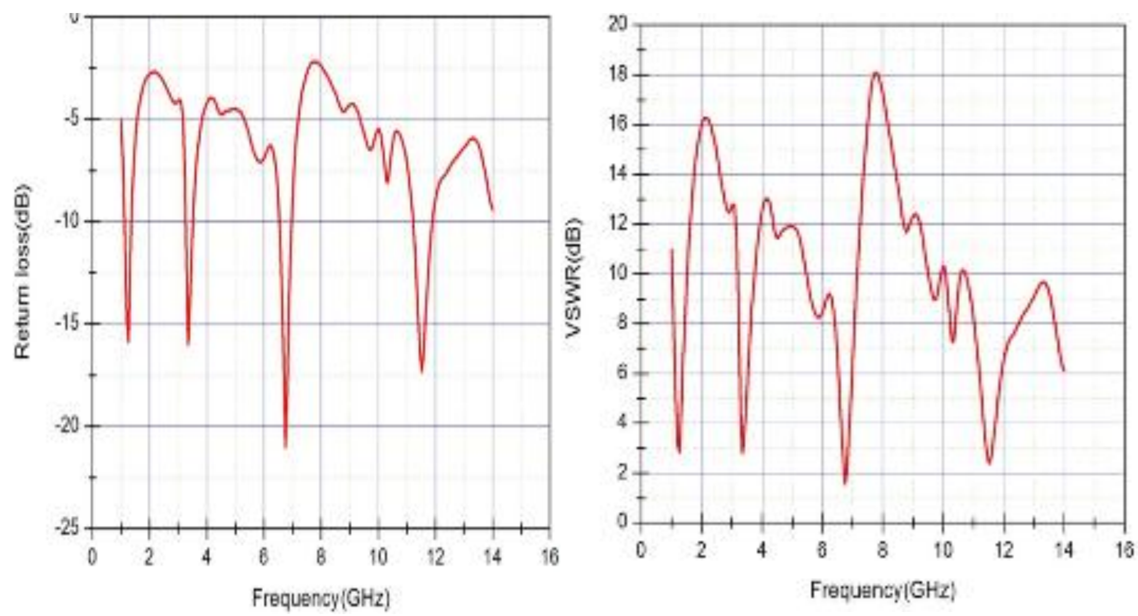
$$\text{Height}=\frac{-\lambda g}{6}+\frac{-\lambda g}{6}+h\text{g} \qquad (5.10)$$

By implementing the concept of fractals and defected in antenna designing, for every iteration performance of antenna design is observed in terms of S11 parameters, gain, bandwidth and operating frequency. Fractal geometry gives antenna design more compactness due to its self-similarity property. Also, impedance matching is better of antenna structure with antenna feedline, so that maximum signal energy is converted form voltage and current signals into electromagnetic waves. This further enhances the antenna gain and bandwidth performance, maximum gain achieved is 9.16 dB for designed antenna. In proposed antenna designing, concept of DGS is used to further improve antenna performance in terms of antenna gain and bandwidth. DGS are the shaped, those are etched on the plane ground of antenna structure. It is opted method in antenna and microwave engineering to enhance antenna parameters like operating bandwidth, gain, cross-polarization etc. In proposed antenna, U-shaped DGS is considered and used to divert the current distribution which actually changes the reactive characteristics of the circuit like inductance and capacitance. The effect of U-shaped defected structure is analysed with all iterations with length and width of 20mm x 40mm and inner gap of 5mm as given in Table 5.1 and shown in Figure 5.12(g).

5.5 ANTENNA SIMULATED RESULTS

Proposed antenna results are calculated in terms of return loss (S11), VSWR, gain for all Iterations using HFSS simulation tool from 1GHz to 15GHz. Antenna performance is analysed and compared after thoroughly comparing the effect of all iterations of proposed antenna.

Reflection coefficient is defined as ratio $\Gamma=\frac{Z_{in}-Z_0}{Z_{in}+Z_0}$ .Where Z_{in} is input impedance of the antenna and Z_0 is the impedance of transmission lines. A typical value of reflection coefficient lies in between $0<\Gamma<1$. Figure 5.13(a), shows the return vs frequency plot of proposed Antenna-1 in dB. The scattering parameter analysis is quintessential for micro-strip antenna because it represents the loss of power reflected back by antenna. As per theoretical analysis this ratio value should be zero and practically it should be less than -10dB as it complies in the design. It also reveals the operating bandwidth of antenna, extensively from graphs it is evident that antenna is resonating at four different frequencies 1.26GHz, 3.35GHz, 6.74GHz and 11.51GHz. So, from this analysis antenna shows the multi band behaviour at higher frequencies. Table 5.2 below shows the bandwidth achieved at every frequency and value of return loss.



(a) Iteration-1 VSWR Plot (b) Iteration-2: Return loss Plot

Figure 5.13: (a) Iteration-1: VSWR vs frequency plot (b) Iteration-1: Return loss vs frequency plot

The voltage standing wave ratio (VSWR) is a function of reflection coefficient (S_{11}) and it is defined as $VSWR = \frac{1+|\Gamma|}{1-|\Gamma|}$. VSWR is calculated with the help of maximum voltage of standing wave measured along the transmission line and minimum voltage of standing wave measured along the transmission line. In antenna, maximum power can be transferred only if antenna transmission line impedance matches with the load impedance.

Table 5.2: Bandwidth achieved with return loss for Iteration -1

Frequency (GHz)	Return loss(dB)	Bandwidth (MHz)
3.35	-15.98	280
6.74	-21.01	390
11.51	-17.30	590

Voltage standing wave ratio elicited and shows the impedance matching of source with load. The ideal value of VSWR should be unity. Figure 5.13(b) Illuminates the VSWR vs frequency response of proposed antenna. It is analysed that VSWR value for proposed antenna varies between 2.8 to 2.3 for different resonating frequencies from 1.26GHz to 11.51GHz respectively. Deficiency in VSWR is due to disclaimer of the extended length of patch.

Table 5.3: Frequency bands and gain achieved for Antenna-1

Frequency (GHz)	Bandwidth (MHz)	Gain(dB)
3.35	280(3.2-3.48)	2.54(1.75-3.36)
6.74	390(6.55-6.94)	5.36(4.74-5.54)
11.51	590(11.25-11.84)	4.52(4.96-3.45)

Following graph 5.14 depicts the relation between the frequency in GHz and gain in dB for the proposed design. From graph, it is clearly evident that the gain is more than 3dB between the range of frequencies 3.2GHz to 3.48GHz for Phi=360degree and Theta=10 degree. Maximum gain achieved at 3.35GHz frequency is 2.54dB.

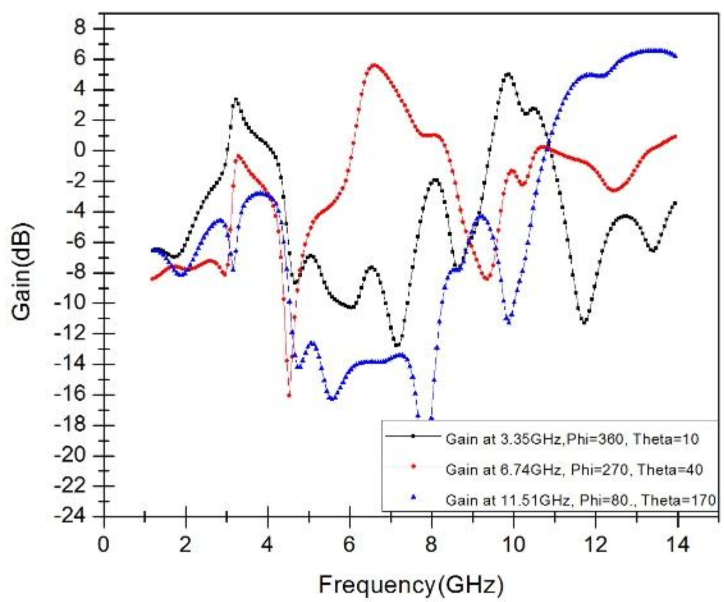
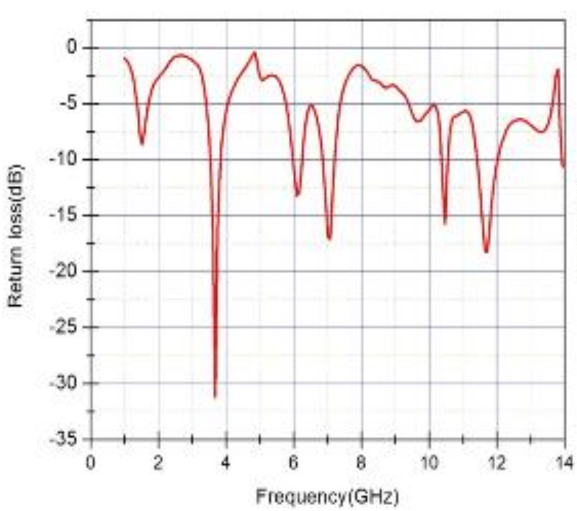


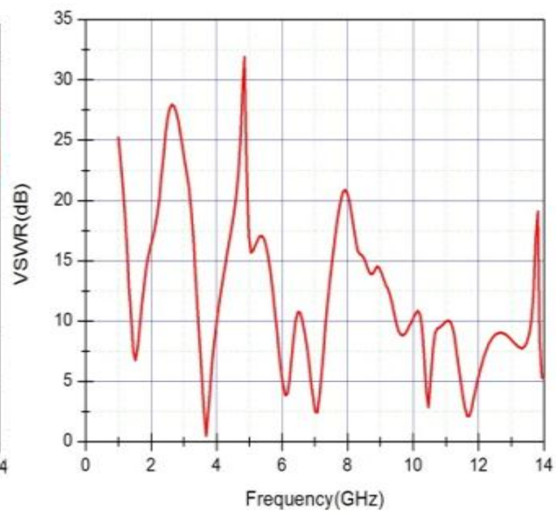
Figure 5.14: Gain of proposed antenna at different frequencies for phi and theta values

Also, it shows the gain and frequency response for proposed design for 6.74GHz frequency. The gain achieved within frequency range from 6.55GHz to 6.94GHz varies between 4.74dB to 5.54dB. At resonating frequency 6.74GHz maximum value of gain achieved is 5.36dB at Phi=40 degree. Similarly, it is analysed from Figure 5.14 that gain for frequency band 11.25 to 11.84GHz lies between 4.96 to 3.45dB and highest gain achieved is at frequency 11.51GHz that is 4.52dB for Phi=80-degree, Theta=-170degree. Table 5.3 gives relation between gain and bandwidth obtained at resonating bands achieved for proposed antenna Iteration-1.

5.5.1 Iteration-2: In Iteration-2, for proposed antenna design, three circles a1, a2, a3 are cut diagonally from top left corner towards centre of patch with radius as given in Table 5.1 to improve the resonant behaviour of the antenna. For iteration-2, patch length and width used is same as considered for Iteration-1 and same ground dimensions are used. To implement concept of fractals, patch design is modified with three more circles as shown in Figure 5.12 (c). Antenna structure is simulated using HFSS software from 1GHz to 14GHz and antenna performance is analysed in terms of antenna parameters. Dimensions for patch, ground and substrate remains same as in Iteration-1. As shown from frequency vs return loss graph in Figure 5.15(a), proposed antenna is resonating at five frequencies 3.67, 6.16, 7.07, 10.47 and 11.64GHz. Table 5.4 shows the bandwidth range of proposed antenna for these resonating frequencies. The wide bandwidth is achieved at resonating frequency 11.97 i.e. 520MHz as per requirement for 5G applications.



(a) Iteration-2: Return loss plot



(b) Iteration-2: VSWR plot

Figure 5.15: (a) Iteration-2: Return loss (S11) v/s frequency response (b)Iteration-2: VSWR vs frequency plot

Table 5.4: Bandwidth achieved with return loss for Iteration-2

Frequency (GHz)	Return loss(dB)	Bandwidth (MHz)
3.67	-31.16	480
6.16	-12.97	3960
7.07	-17.08	2440
10.47	-15.68	2880
11.64	-18.15	2150

VSWR vs frequency response for Iteration-2 is presented in Figure 5.15 (b). The theoretical value of VSWR should be unity. It is analysed that VSWR value for proposed antenna varies from 0.48 to 2.15 for resonating frequencies between 3.67 to 11.64GHz respectively. The best value achieved is at resonating frequency 3.67 i.e. 0.48.

As it is stated from theoretical concept that gain should be more than 3dB. For Iteration-2, it is analysed from graph in Figure 5.16, which gain of antenna varies between 5.3dB to 5.49dB for resonating bandwidth between 3.54GHz to 3.80GHz. For resonating frequency 3.67GHz, gain achieved is 5.47dB for Phi=130-degree, Theta=20degree. The value of gain for antenna bandwidth 6.03GHz to 6.94GHz is from 4.17 to 7.14dB as depicted from Figure 5.16 and Table 5.5. At resonating frequency 6.16GHz value of gain is 4.3dB.

Table 5.5: Value of gain for different resonating frequency bands along with bandwidth for Iteration-2

Frequency (GHz)	Bandwidth (MHz)	Gain(dB)
3.67(3.54-3.80)	480	5.47(5.53-5.49)
6.16(6.03-6.94)	3960	4.3(4.17-7.14)
7.07(7.01-7.14)	2440	8.62(7.01-8.57)
10.47(10.53-10.40)	2880	6.16(5.12-6.66)
11.64(11.45-11.97)	2150	7.48(6.98-7.35)

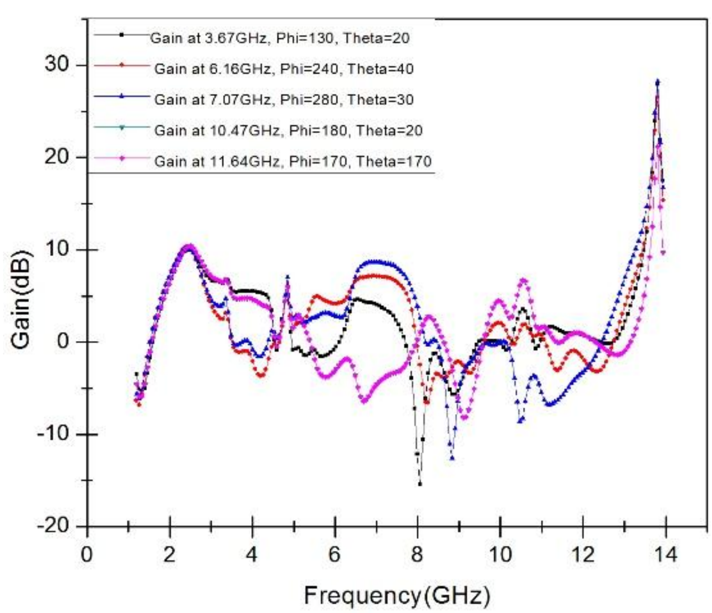


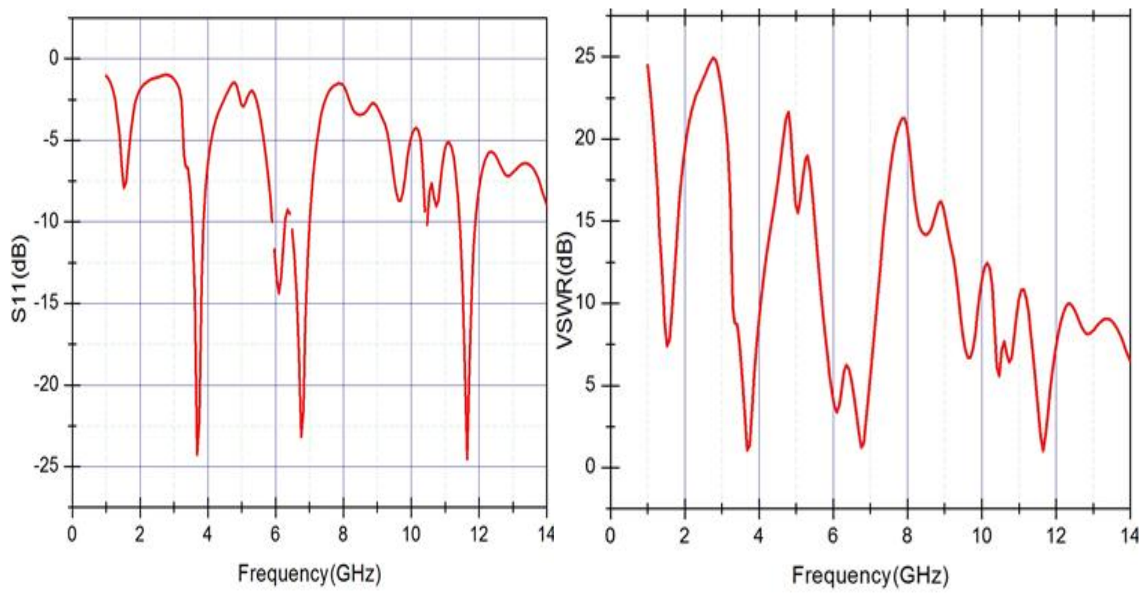
Figure 5.16: Iteration-2 gain at different frequencies

Also, as shown in Figure 5.16, for resonating frequency range between 7.01GHz to 7.14GHz, gain ranges between 7.01dB to 8.57dBfor Phi=280 degree and Theta=30degree. Value of antenna gain varies from 5.12dB to 66dB for resonating band 10.40GHz to 10.53GHz for Phi=180 degree and Theta=20degree. Similarly, gain ranges from 6.98dB to 7.35dB for frequency range from 11.45GHz to 11.97GHz respectively. It is analysed that maximum gain for proposed antenna is achieved on two resonant bands i.e. 7.07GHz and 11.64GHz, as values of gain for these frequencies are 8.62dB and 7.48dB respectively as shown in Table 5.5.

5.5.2 Iteration-3: Proposed antenna patch design for Iteration-3 is shown in Figure 5.12 (d). Antenna resonates at three operating frequencies 3.67, 6.74 and 11.64GHz with S11 values -24.27, -23.16 and -24.54 respectively as given in Table 5.6 below.

Table 5.6: Gain, S11 and bandwidth performance of Iteration-3

Frequency (GHz)	S11 (dB)	BW (MHz)	Gain (dB)	Phi (degree)	Theta (degree)	VSWR
3.67	-24.27	330(3.54-3.87)	5.27(5.4-4.95)	150	30	1.06
6.74	-23.16	460(6.48-6.94)	6.74(8.23-8.02)	280	30	1.20
11.64	-24.54	390(11.45-11.84)	7.40(7.02-7.13)	260	140	1.03



(a) Iteration-3: Return loss (b) Itertaion-3: VSWR Plot

Figure 5.17: (a) S11 v/s Frequency performance for Iteration-3 (b) VSWR vs Frequency plot of Iteration-3

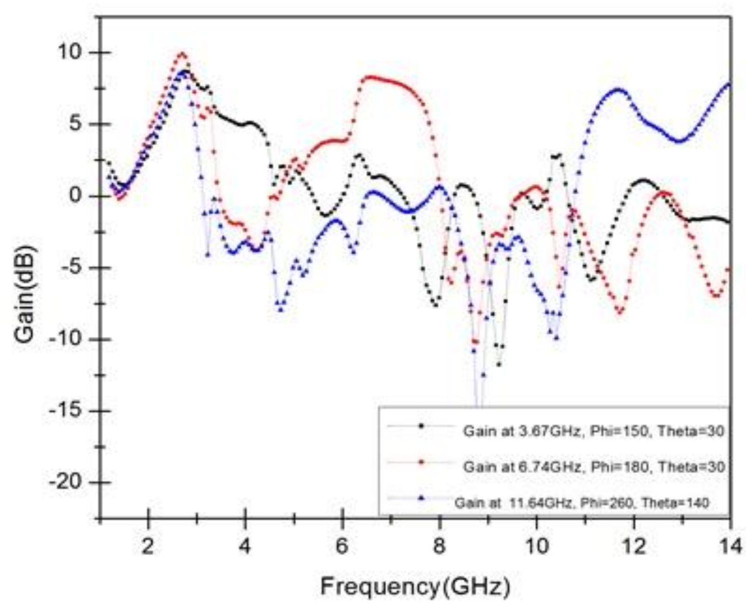
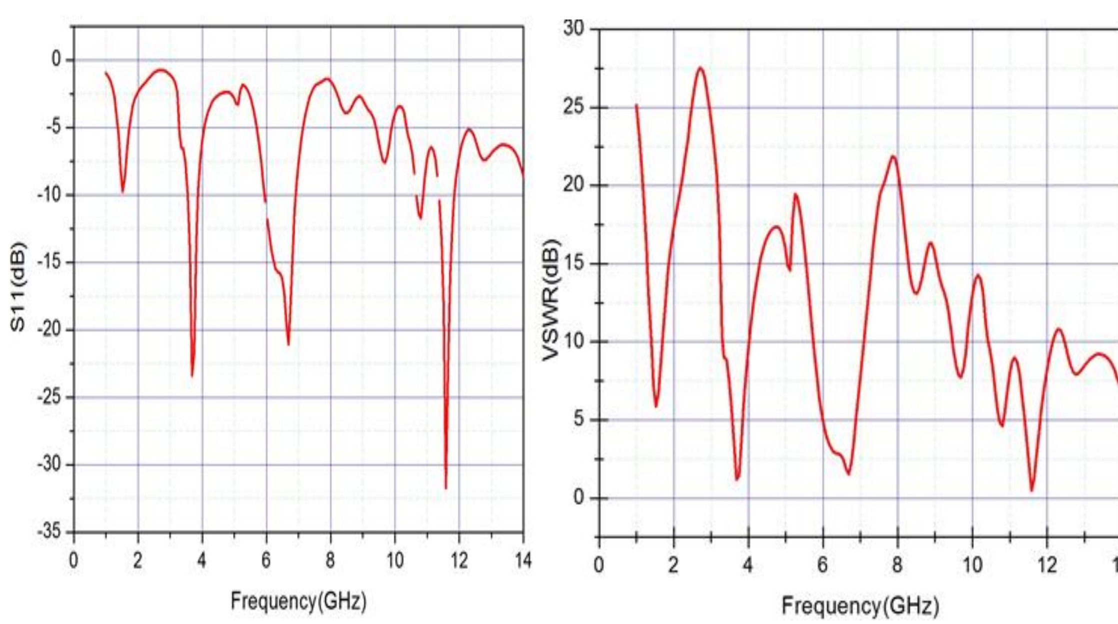


Figure 5.18: Gain at different frequency with phi and theta values for Iteration-3

5.5.3 Iteration-4: Patch design for proposed antenna in iteration-4 is as shown in Figure 5.12 (e). For Iteration-4 antenna designing, patch and ground dimension considered are same with dielectric substrate RT Duroid with thickness 1.6mm and dielectric constant of 2.2. Proposed structure return loss performance is as given in Figure 5.19 (a), it is depicted from graph that proposed structure resonates on three frequencies 3.67GHz, 6.68GHz, and 11.58GHz with S11 values -23.38, -21.03 and -31.72dB respectively. It is analysed from S11 plot that antenna shows multi band behaviour. Antenna VSWR plot is given in Figure 5.19 (b) and it is depicted that for operating band achieved for proposed antenna, VSWR performance is acceptable, as VSWR value achieved is 1.17, 1.54 and 0.45 for 3.67GHz, 6.68GHz and 11.58GHz respectively. Figure 5.20, shows simulated gain achieved for resonating frequency bands for different values of Phi and Theta. Peak value of gain achieved at 3.67GHz resonating frequency is 4.99 dB and it varies between 4.98 to 4.93dB for frequency band of operation 3.61GHz to 3.80 GHz. Maximum gain achieved is at 6.68dB i.e. 7.9dB and gain variation observed for this frequency band of operation is 4.07 to 7.79dB for frequency range 6.03GHz to 6.87GHz. For proposed antenna, gain value achieved at high frequency band 11.58GHz is 6.57dB with variations from 6.15 to 6.41dB for frequency band 11.38 to 11.84 GHz as shown in Table 5.7 for Phi 270 and theta 140 degree. For iteration-4, impedance bandwidth obtained is 190, 840 and 460 MHz for operating bands 3.67GHz, 6.68GHz and 11.58GHz respectively.



(a) Iteration-4 Return loss Plot (b) Iteration-4 VSWR Plot

Figure 5.19: (a) Return loss v/s Frequency response of Iteration-4 (b) VSWR vs Frequency plot of Iteration-4

Table 5.7: Gain, S11 and bandwidth performance of Iteration-4

Frequency (GHz)	S11 (dB)	BW (MHz)	Gain (dB)	Phi (degree)	Theta (degree)	VSWR
3.67	-23.38	190(3.61-3.80)	4.99(4.98-4.93)	120	20	1.17
6.68	-21.03	840(6.03-6.87)	7.90(4.07-7.79)	280	30	1.54
11.58	-31.72	460(11.38-11.84)	6.57(6.15-6.41)	270	140	0.45

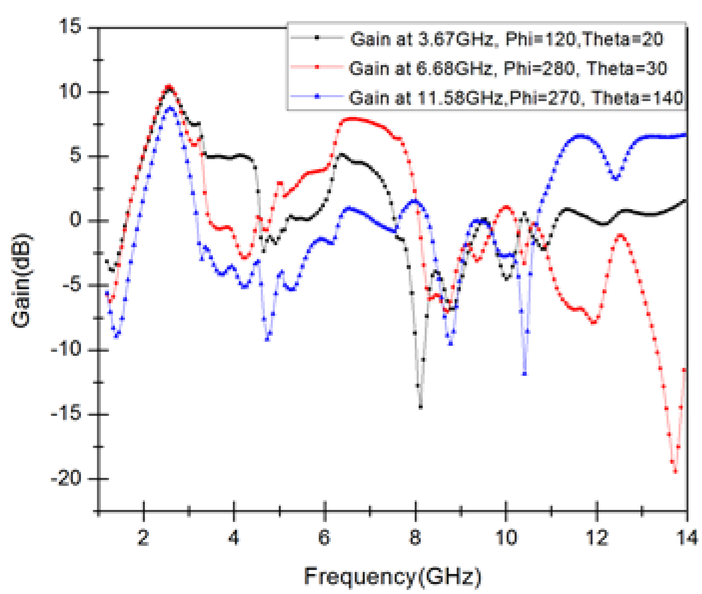


Figure 5.20: Gain at different frequencies with phi and theta of Iteration-4

5.5.4 Iteration-5: For proposed antenna design dimensions used are as given in Table 5.1 and antenna structure is presented in figure 5.12. To further improve antenna performance truncated edges concept is used and all corners are truncated with 2mm dimensions. Antenna performance is analysed in terms of antenna parameters. Antenna return loss characteristics are depicted from Figure 5.21 and it is observed that antenna resonates at four frequencies 3.80, 7.01, 10.86 and 11.84GHz with return loss values of -19.08, -29.39, -20.09 and -15.59dB. As it is depicted from return loss graph that antenna resonating bands shifted towards higher frequencies. Impedance bandwidth achieved for these cuts of frequencies are 260MHz, 330MHz, 270MHz and 460MHz respectively as given in Table 5.8. As compared to previous Iteration, it has been observed that for all resonating frequency bands, gain performance increases considerably. Proposed antenna gain performance is shown in Figure 5.23. Gain value obtained at cut off frequency 3.80GHz is 5.52dB with gain variation from 5.56 to 5.47dB for frequency band 3.93GHz to 3.67GHz. For, second frequency band of operation peak gain achieved at cut off frequency 7.01 is 8.05dB with variation between 8.17 to 7.94dB for resonating band 6.81GHz to 7.14GHz. At cut off frequency, 10.86GHz, proposed antenna gain experienced is 5.32dB which is slightly greater than gain achieved for this range for Iteration-4 but as compared to other bands of operation like 3.80, 7.01 and 11.84GHz, gain value obtained is less. Peak gain value achieved is 7.78dB for 11.84GHz cut off frequency with variations between 7.3dB to 8.18dB as given in Table 5.8. VSWR performance for proposed antenna lies between 0.58 to 2.91 which is less than 2 for lower cut of frequencies and more than 2 for high cut of frequency 11.84GHz as given in Figure 5.22.

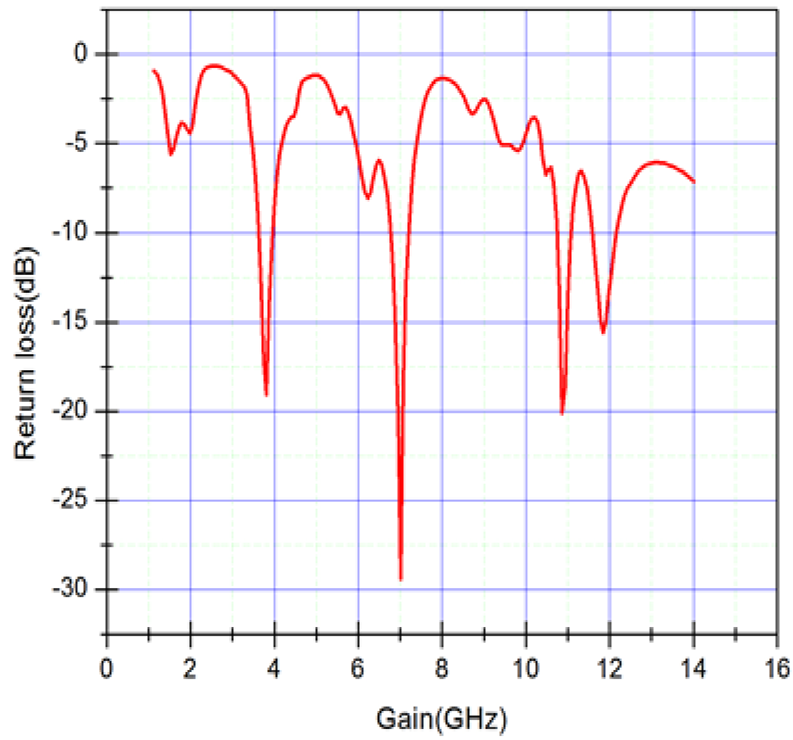


Figure 5.21: S11 v/s frequency performance of Iteration-5

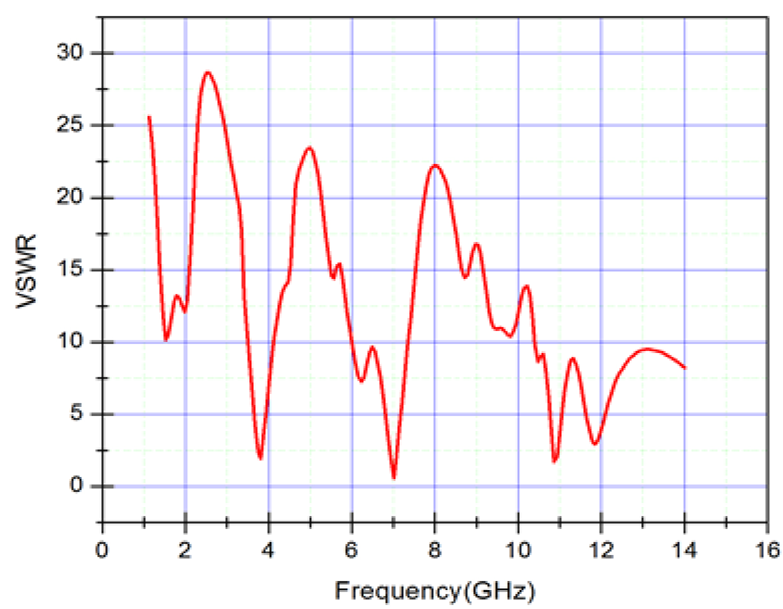


Figure 5.22: VSWR v/s frequency performance of Iteration-5

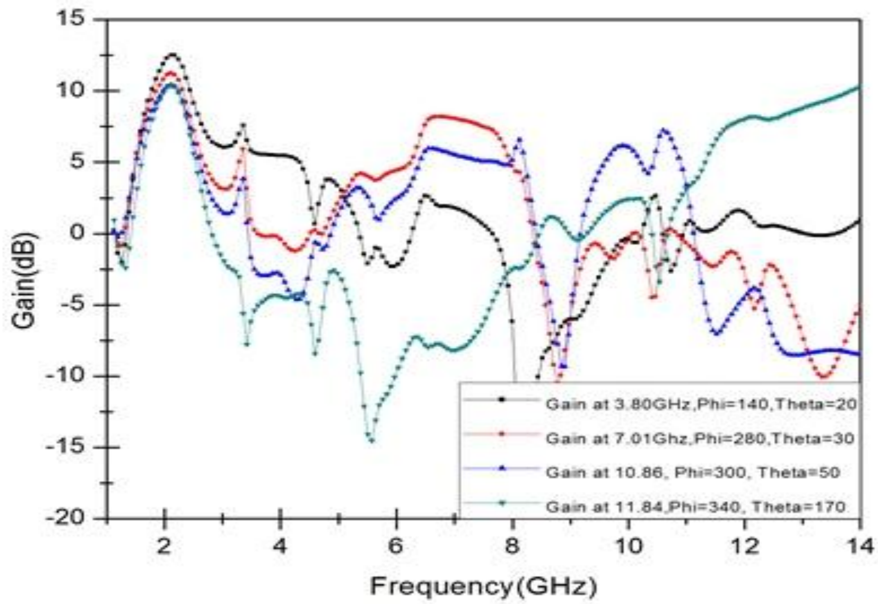
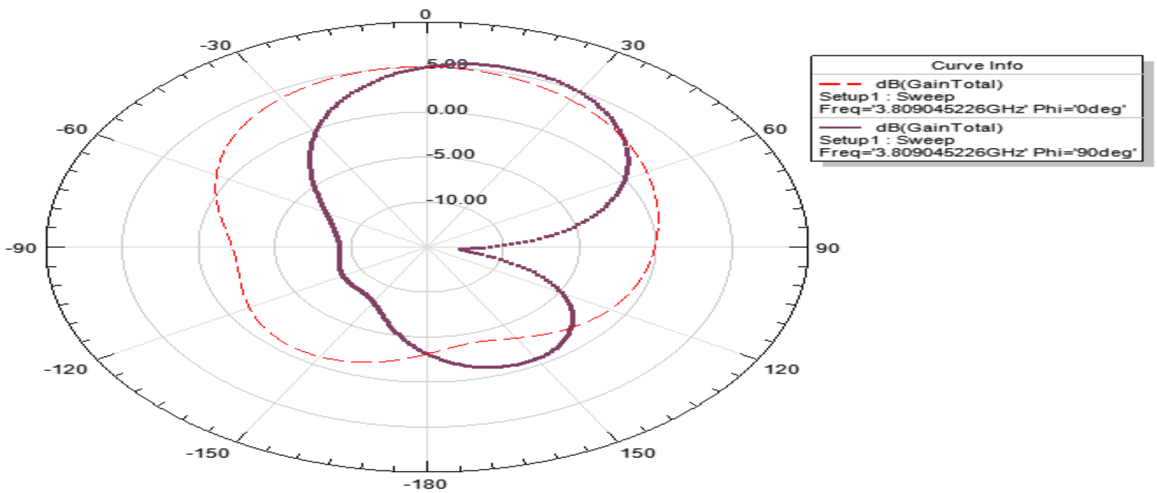


Figure 5.23: Gain at different frequencies with phi and theta for Iteration-5

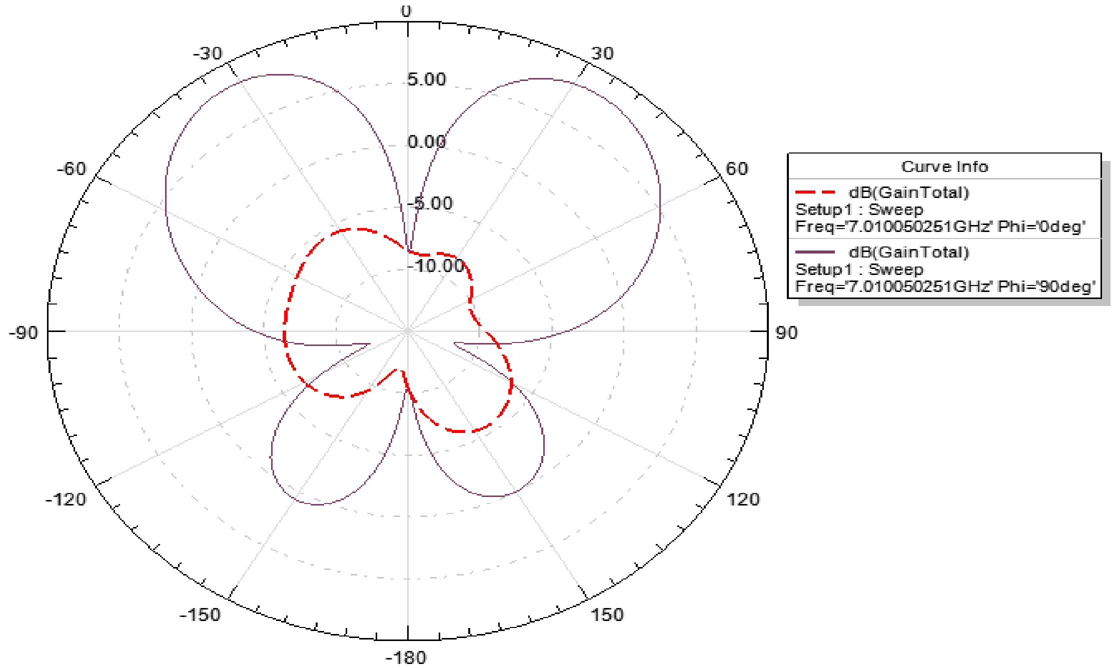
Table 5.8: S11, Gain and Bandwidth performance of Iteration-5

Frequency (GHz)	**S11 (dB)**	**BW (MHz)**	**Gain (dB)**	**Phi (degree)**	**Theta (degree)**	**VSWR**
3.80	-19.08	260(3.93-3.67)	5.52(5.56-5.47)	140	20	1.93
7.01	-29.39	330(6.81-7.14)	8.05(8.17-7.94)	280	30	0.58
10.86	-20.09	270(10.79-11.06)	5.32(6.02-1.88)	300	50	1.72
11.84	-15.59	460(11.64-12.10)	7.78(7.30-8.18)	340	70	2.91

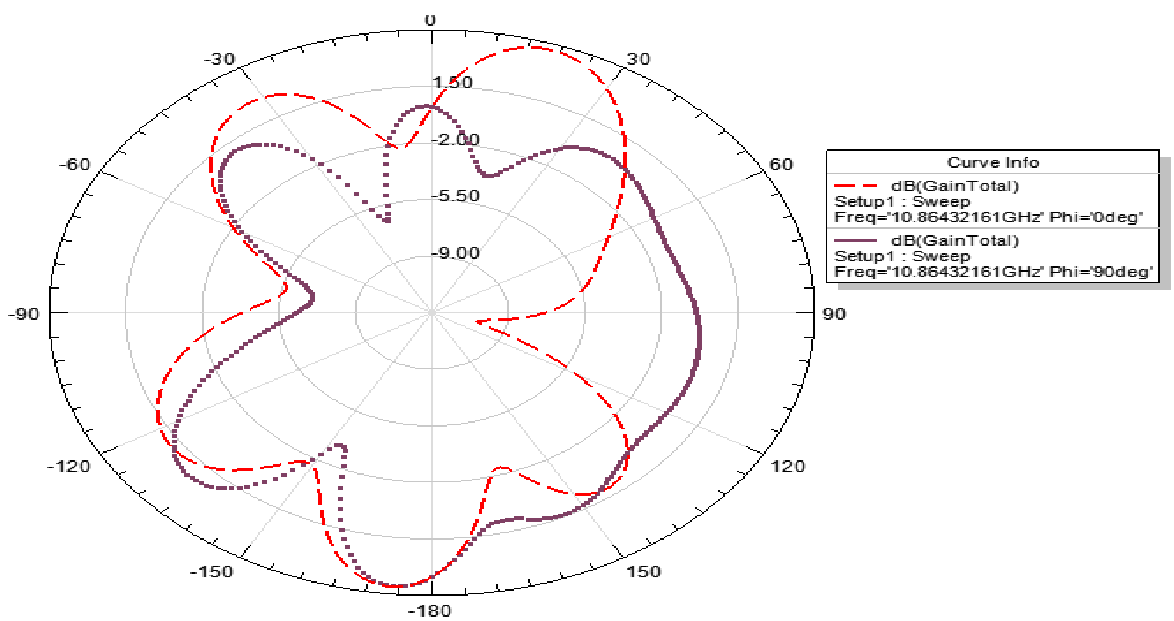
Following Figure 5.24 and 5.25 indicates the 2-D and 3-D radiation pattern for Iteration-5 at different frequencies 3.80GHz, 7.01GHz, 10.86GHz and 11.84GHz for Phi=0 and Phi= 90 degree. Antenna radiation pattern at these frequencies look like Semi-omni directional, which is acceptable with good gain.



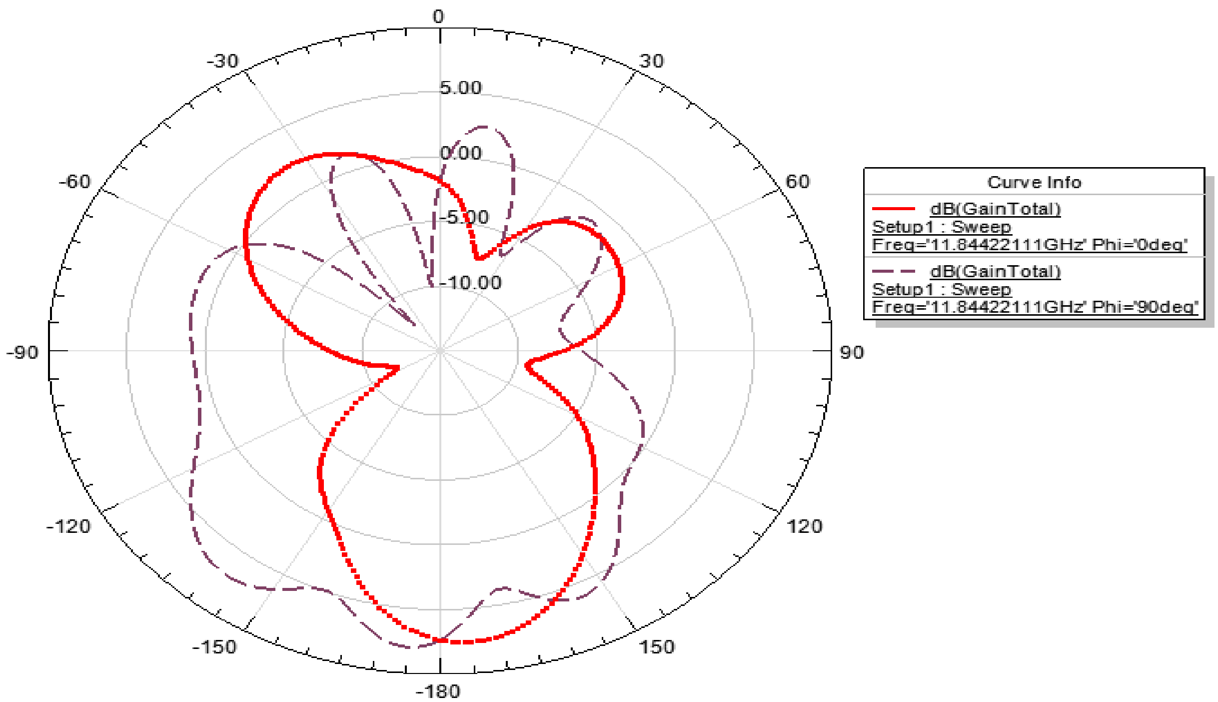
(a) Radiation pattern at 3.80GHz for phi=0 and 90 degree



(b) Radiation pattern at 7.01GHz for Phi=0 and 90 degree



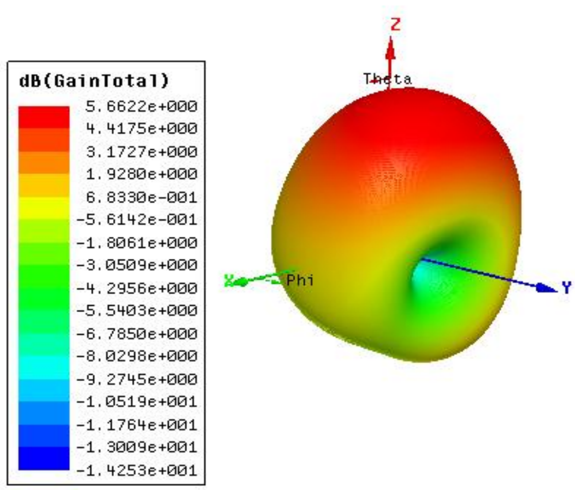
(c) Radiation pattern at 10.86GHz for Phi=0 and 90 degree



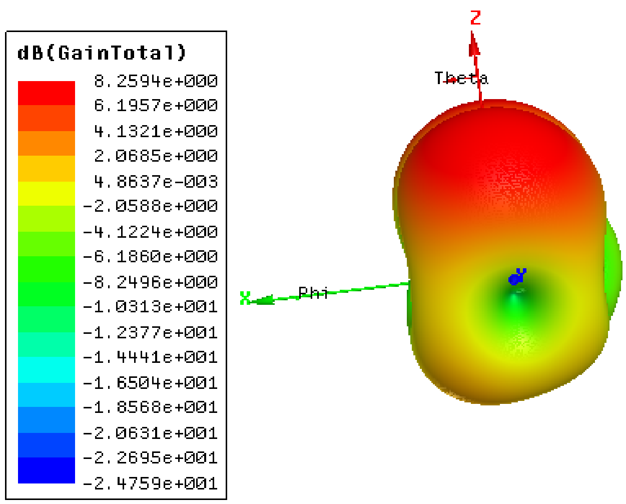
(d) Radiation pattern of Iteration-5 at 11.84GHz

Figure 5.24: Radiation pattern for Phi=0 and 90 degree (a) At 3.80GHz (b) At 7.01GHz (c) At 10.86GHz and (d) At 11.84GHz

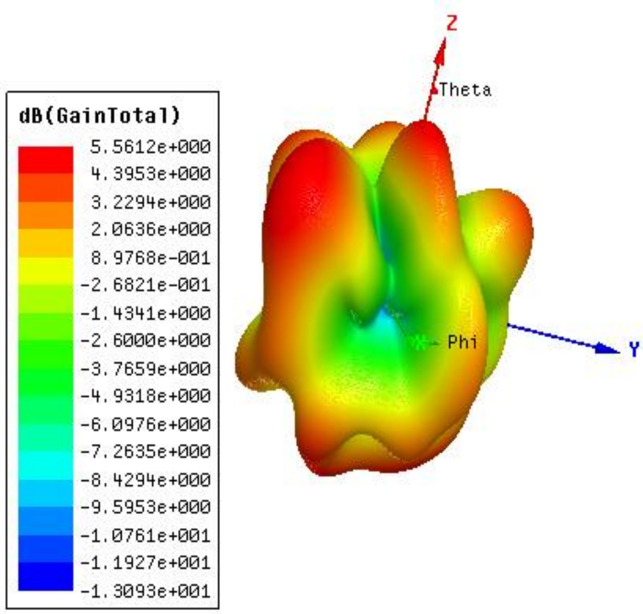
For proposed antenna, it is analysed from Figure 5.25 (a to d) that antenna gain at frequency 3.80GHz is 5.6dB, with gain of 8.25dB at 7.01GHz, 5.56dB at 10.86GHz and 8.05dB at 11.84GHz, which is good gain for wireless applications.



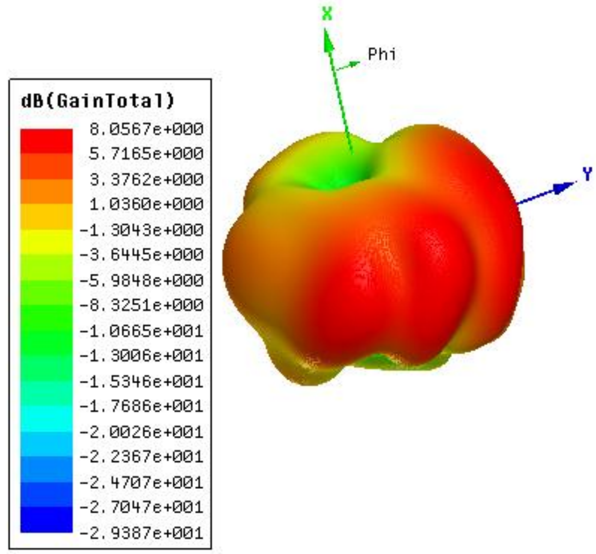
(a) 3-D Polar plot of Iteration-5 at 3.80GHz



(b) 3-D Polar plot at 7.01 GHz



(c) 3-D Polar Pot at 10.86 GHz



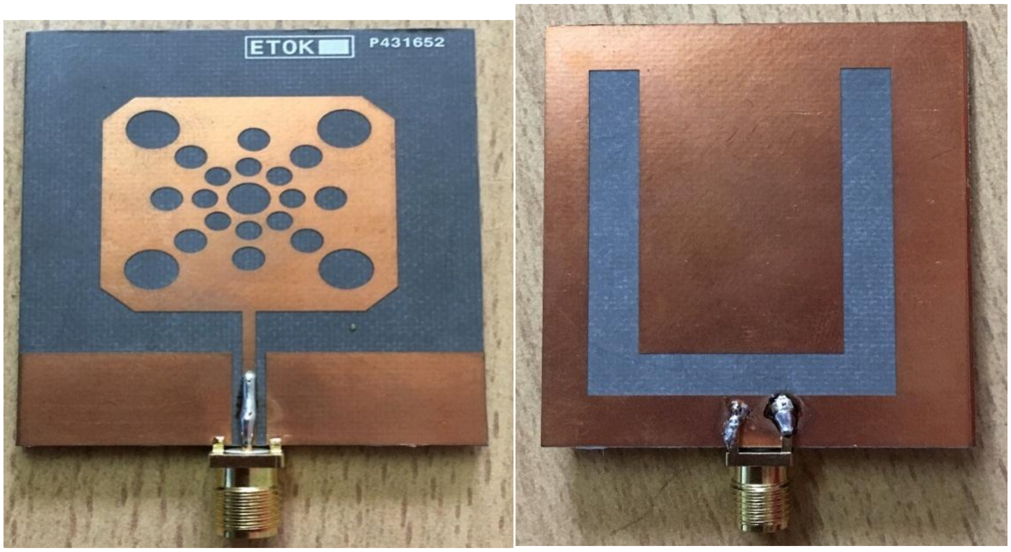
(d) 3-D Polar plot at 11.84 GHz

Figure 5.25: 3-D Polar plot at different frequencies (a) At 3.80GHz (b) At 7.01GHz (c) At 10.86GHz and (d) At 11.84GHz

5.6 ANTENNA FABRICATION

Proposed antenna structure is fabricated on Rogers RT Duroid 5880 Dielectric substrate material with thickness t=1.6mm using PCB fabrication technology. Proposed antenna prototype is shown in Figure 5.26. Antenna return loss and VSWR measurement is done using E5063A ENA series 2-Port VNA available from 100KHz to 18GHz frequency. Before testing return loss and VSWR VNA calibration is done using open, short and load test. Measurement setup used is as shown in Figure 5.27 below.

Antenna simulated and measured return loss graph is given in Figure 5.28. It is analysed from graph that simulated frequencies achieved for proposed antenna are 3.80GHz, 7.01GHz, 10.86GHz and 11.84GHz and measured return loss cut off frequencies obtained are 3.87GHz, 6.95GHz, 8.21GHz and 14.1GHz with S11 co-efficient -12.6dB, -22.6dB, -12.6dB and -11.5dB respectively.



(a) Top View (b) Back view

Figure 5.26: Proposed fabricated antenna (a) Top view (b) Back view

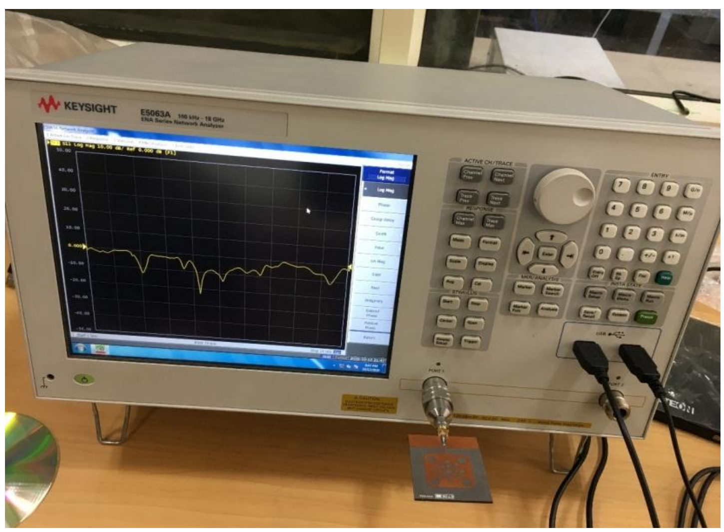


Figure 5.27: Proposed antenna return loss and VSWR measurement setup

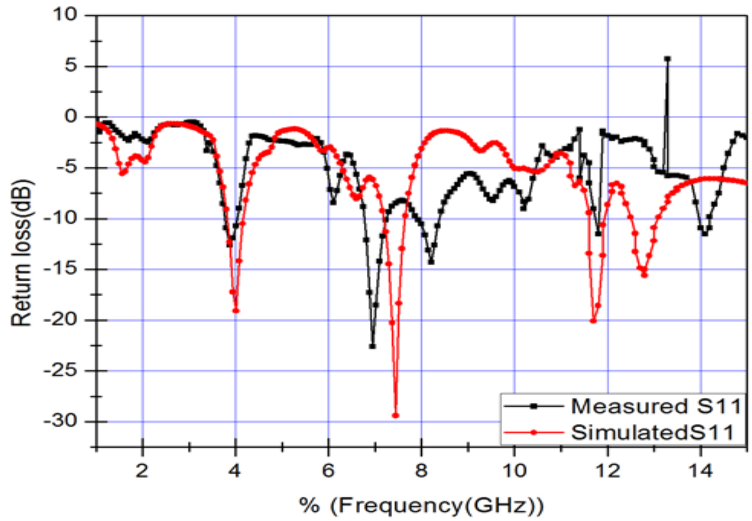


Figure 5.28: Simulated and measure return loss performance

It is evident from graph that measured return loss values are shifted on left side for simulated cut off frequency 10.86 to 8.21GHz and also frequency shift has been observed for high resonant frequencies from 11.84GHz to 14.1GHz due to fabrications losses and conductor soldering ambiguities. Impedance bandwidth obtained from measured return loss graph is 210MHz (5.23 %), 1130MHz (14.12%), 350MHz (4.19%) and 200MHz (1.40%) respectively as given in Table 5.9. Wideband is achieved for cut off frequency 6.95GHz i.e. 1130MHz from 6.81GHz to 7.93GHz. Good measurement bandwidth is obtained for proposed antenna and simulated and experimental results are in accord with each other. Fabricated antenna VSWR measurement graph is given in Figure 5.29. VSWR performance for operating frequencies 3.87, 6.95, 8.21, and 14.1GHz are 1.61, 1.16, 1.47 and 1.73 respectively which is below 2 and practically accepted.

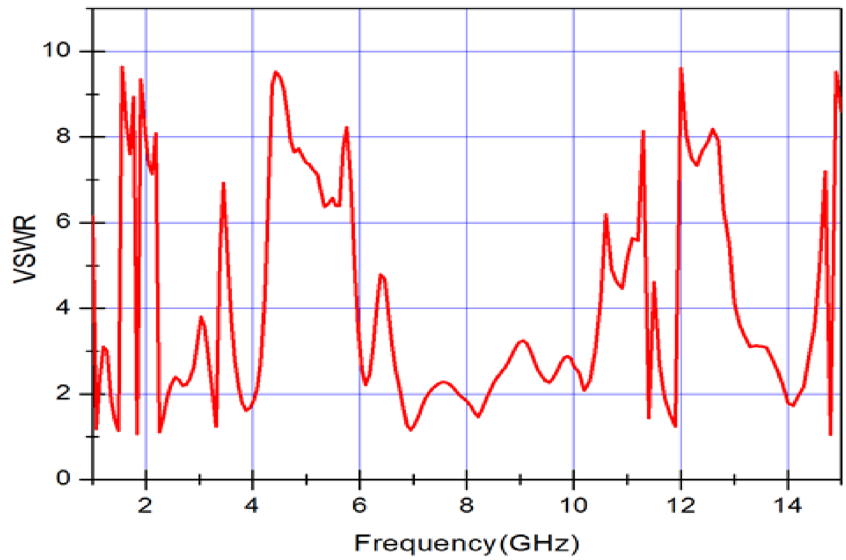


Figure 5.29: Measured VSWR performance for proposed antenna

Table 5.9: Simulated and measured return loss comparison of proposed antenna

Simulated S11				**Measured S11**			
f_L (GHz)	f_H**(GHz)**	f_c **(GHz)**	**BW(MHz)**	f_L **(GHz)**	f_H**(GHz)**	f_c **(GHz)**	**BW(MHz)**
3.93	3.67	3.80	260	3.8	4.01	3.87	210
6.81	7.14	7.01	330	6.81	7.93	6.95	1130
10.79	11.06	10.86	270	8	8.35	8.21	350
11.64	12.10	11.84	460	14	14.2	14.1	200

5.7 SUMMARY

This chapter explains about Fractal and Defected Geometries basic working principle and types. Use of Fractal structures in microwave components and antenna designing due to its prosperities like space filling and self-symmetry which increases electrical length for flow of current without changing its physical length to obtain multi band characteristics. Defected ground structures are used to improve antenna gain and bandwidth by diverting flow of current in antenna ground. On the basis of these structures, circular cut fractal patch with U-shaped defected ground with truncated edges microstrip patch antenna is proposed to achieve multi band behaviour for wireless applications. Antenna performance is observed in form of return loss, gain, VSWR and bandwidth after studying the effect of each iteration on design. Proposed antenna is fabricated and simulated and experimental performance is compared. Antenna is considered as best candidate for wireless communication applications as practically the best gain considered for all wireless applications is between 2-3dBi as per the standard bench mark and gain achieved for proposed antenna is 5.6, 8.25, 5.56 and 8.05dB at 3.80, 7.01, 10.86 and 11.84GHz frequencies respectively.

CHAPTER-6
ELLIPTICAL PATCH MULTI BAND ANTENNA USING FRACTAL AND DEFECTED GROUND STRUCTURES

6.1. INTRODUCTION

These days, many electronics devices are working on different set of frequencies for example mobile phone is needed to cover different wireless communication services like Bluetooth, Wi-Fi, GPS, 4G or LTE and 5G, so multi band antenna are in very high demand to cover all these applications in single device instead of deploying multiple antenna. In this chapter, multi band circular patch antenna is designed using fractal and defected ground structures for various wireless applications using HFSS v15.0 software and simulated from 1GHz to 15GHz frequency band of operation.

Fractal geometries possess self-similar properties and has the provision to be divided into parts that is the replica of original design with reduced dimensions. In antenna designing, multi band and broad band characteristics can be gained using self -similarity property of fractal structures and these shaped can be fit into available physical dimensions which leads for compact structures. Depending upon the fractal shape used, current flow virtual lengths increases and improves the bandwidth and radiation characteristics of antenna. Different fractal geometries considered are quadrilateral, hexagonal, elliptical, star, spiral etc. but circular and elliptical shape is chosen due to its excellent performance in gain and bandwidth. The proposed antenna consists of circular shaped patch design and final patch structure is achieved using 3 iterations of fractal geometry. Also, in proposed antenna design, instead of using full length ground plane, defected ground is used to improve antenna efficiency in terms of antenna parameters.

6.2 ANTENNA DESIGN

Planar microstrip patch antenna comprise of top layer that is called patch, bottom layer known as ground layer and dielectric substrate sandwiched between two. These PMPA can be designed by etching different structures like square, circular, elliptical, E, H, S etc. on copper layers of double side PCB. The top patch layer acts as radiator for transmitting antenna and receptor for receiving antenna, whereas the bottom PCB layer acts as ground plane which can be plane surface or defected one. In MPA, antenna radiations occur due to fringing effect between the corners of designed patch structure and the defected ground plane. Patch antenna can use different geometries to obtain resonate frequency bands for desired applications. These days' elliptical patch antenna is gaining much attention due to their circular polarization characteristics among different patch structures. For today's wireless communication systems, broadband and multiple features requirement can be only fulfilled by elliptical patch fractal antenna.

Figure 6.1, shows the proposed multi band antenna design for wireless applications. The proposed structure is designed using Rogers RT Duroid 5880 substrate material with thickness (t= 0.8mm), dielectric constant (εr=2.2), and loss tangent of 0.0009. The RT Duroid substrate dimensions are 50mm x 50mm x 0.8mm with elliptical shaped patch. To obtain impedance matching Lumped port with 50-ohm resistance is used with Y-axis and Z-axis dimensions of 3.87mm and 0.8mm respectively and microstrip feed method is used for antenna feeding with dimensions 12.94 mm x 3.87mm. To achieve more compactness in antenna design, elliptical patch with n=3 iterations is used, without changing the physical length of antenna to obtain multi band characteristics of proposed antenna structure. Defected ground plan is used to improve antenna performance parameters like bandwidth, gain and to suppress cross polarization. These structures are used to divert current distribution in ground plane to change the inductive and capacitive properties of proposed antenna. Defected ground dimensions considered are 12.7mm x 50mm x 0.8mm.

Fractal curves are characterized by two parameters: indentation factor (IF) and iteration order (IO). All of these antennas are fabricated on 0.8 mm substrates with relative permittivity 2.2, and are matched by quarter wavelength transformers. The radius of elliptical patch changes with number of iterations. As in proposed antenna design, number of iterations are increasing, the electrical length of antenna patch structure also increases without changing the overall antenna dimensions, thus different resonate bands are achieved for proposed antenna.

As compared the circular shapes, the elliptical shape has various advantages like it provides large degree of freedom and flexibility in the antenna design geometry. Other advantages of elliptical patch over circular patch are to obtain circular polarization by exciting the elliptical patch compared to rectangular and circular patch, after properly selecting the feed position of elliptical patch for 50-ohm impedance matching to transfer maximum power from source to load. Circular polarization can be achieved by positioning the feed point on a radial line with reference to the major axis. In ellipse the positive side axis gives the left-hand circular polarization (LHCP) and negative axis provides right hand circular polarization (RHCP). Moreover, elliptical patch flexibility in antenna design upto large extents by using concept of eccentricity and focal length to further fine tune antenna to get desired antenna performance. Also, in antenna design theory, elliptical patch provides more surface are for flow of electric currents as compared to circular patch for radiating.

In microstrip patch antenna, elliptical shapes are rarely used by researches due to its difficult mathematical expression and boundary conditions involved during its analysis. Regular elliptical patch used in microstrip antenna shows narrow bandwidth and gain performance, so to further enhance bandwidth and gain performance of these antenna, fractal and defected ground geometry is used. As, shown in this proposed antenna design, elliptical patch design is implemented using fractal theory with iteration factor n=3.The radiator or receptor element of proposed antenna is the fractal elliptical shaped patch structure which is fed by microstrip feed line. In proposed design, each ellipse with different radii is designed to operate on specific frequency to exhibit multi band characteristics for this antenna architecture. Final simulated antenna design consists of four Ellipses, from which the smallest inner ellipse is resonating at high frequency bands due to its smaller radiation area, whereas, the largest outer ellipse, operates at low frequency bands due to its large surface resonating area. The remaining two ellipse resonates between low cut off and high cut of frequencies to obtain wide band characteristics.

Also, considering frequency requirements for antenna operation for wireless application, antenna is designed and simulated for frequencies between 1GHz to 15GHz using HFSS v15.

6.3 ANTENNA MATEHMATICAL MODELLING

To designe proposed fractal antenna, following mathematical expressions are used. Antenna characteristics impedance is calculated using expression (6.1):

$$Z_0 = \frac{Z_{01}}{\sqrt{\varepsilon_e}} \qquad (6.1)$$

Where the characteristics impedance of the microstrip line in free space is given by expression (6.2):

$$Z_{01} = Z_0|\,(\varepsilon r=1) = 60\ln\left[\frac{F_1 h}{w} + \sqrt{1 + \left(\frac{2h}{w}\right)^2}\right]$$

And

$$F_1 = 6 + (2\pi - 6)\exp\{-(30.66h/\omega)\ 0.7528\} \qquad (6.2)$$

Antenna effective Width and Height can be calculated using expressions (6.3), (6.4) and (6.5);

$$W = w + \frac{t}{\pi}\left[\ln\left(\frac{2h}{t}\right) + 1\right]$$

$$\text{Here } H = h - 2t \qquad (6.3)$$

For $\frac{W}{H} < 1$

$$\varepsilon_{eff} = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2}\left[\frac{1}{\sqrt{1+12\frac{H}{W}}} + 0.04\left(1 - \frac{W}{H}\right)2\right]$$

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{eff}}}\ln\left(\frac{8H}{W} + \frac{W}{4H}\right)\Omega \qquad (6.4)$$

Also, $\lambda = \frac{c}{f\sqrt{\varepsilon_{eff}}}$ and $\theta = \frac{2\pi}{\lambda}$

For $\frac{W}{H} \geq 1$

$$\varepsilon_{eff} = \frac{\varepsilon_{r+1}}{2} + \frac{\epsilon_{r-1}}{\sqrt[2]{1 + 12\frac{H}{W}}}$$

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{eff}\left[\frac{W}{H}+1.393+\frac{2}{3\,ln}\left(\frac{W}{H}+1.444\right)\right]}}\ \Omega \qquad (6.5)$$

Wavelength is given by expression (6.6):

$$\lambda_g = \frac{c}{f\sqrt{\varepsilon_r}} \qquad (6.6)$$

Propagation constant can be calculated using expression (6.7)

$$\beta = \frac{2\pi}{\lambda_g} (6.7)$$

Electrical length is given by expression (6.8)

$$\theta = \text{Bl} \qquad (6.8)$$

By keeping in view this frequency of operation, to obtain dimensions of large axis of elliptical patch reverse calculation procedure is used using following formula (6.9). Diameter of elliptical patch can be obtained for low cut off frequency and high cut off frequency using following expression (6.9):

$$f_L = \frac{72}{L+r+h} \qquad (6.9)$$

Where L is diameter of radiator, h is thickness of substrate and r can be calculated using expression (6.10);

$$r = \frac{L}{2\pi} \qquad (6.10)$$

Considering a substrate with a dielectric permittivity of 2.2 and a thickness of 0.8 mm, the conventional circular antenna is presented in Figure 6.2 and fed by a 50-ohm microstrip feed line. To, calculate largest ellipse dimensions for proposed antenna on low operating frequencies as per above expressions, calculation is given in expression (6.11);

$$f_L = \frac{72}{L+r+h} \tag{6.11}$$

$$f_L = \frac{72}{65+\frac{65}{2\pi}+0.8}$$

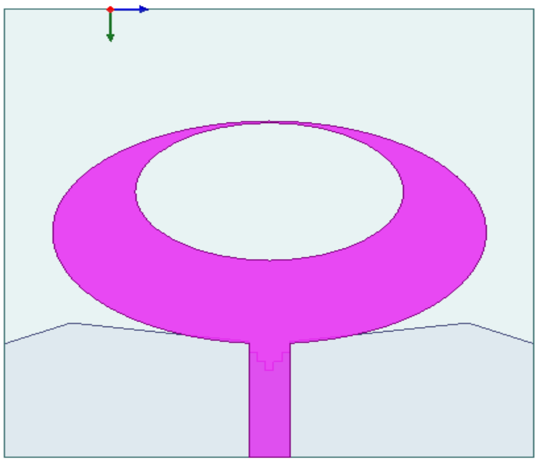
$$f_L = 0.94\text{GHz or} \approx 1\text{GHz}$$

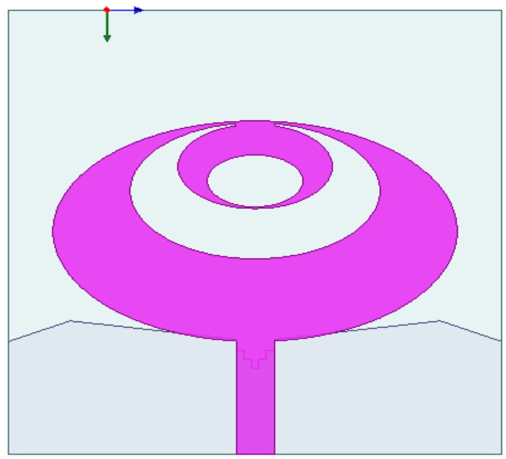
Similarly, dimensions are calculated for cut off frequency 7HGz and Higher cut off frequency 14GHz.In this antenna design procedure by adding radius of previous two ellipse, radius for next ellipse is obtained.

Table 6.1: Dimensions of proposed Elliptical shaped patch multi band Fractal and Defected Ground antenna

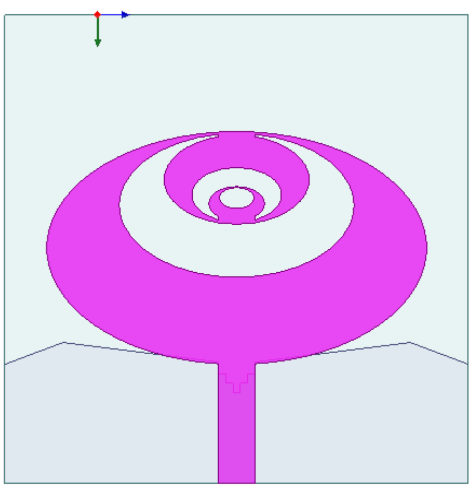
Parameters	**Dimensions (mm)**
Substrate used	Rogers RT Duroid 5880
Substrate thickness (h)	0.8mm
Dielectric constant (εr)	2.2
Ls (Substrate Length)	50
Ws (Substrate Width)	50
Lt (Transmission line length)	12.94
Wt (Transmission line Width)	3.87
E1 (Ellipse1)	12.42
E2 (Ellipse 2)	4.74
E3 (Ellipse 3)	1.81
Lg (Ground length)	12.7

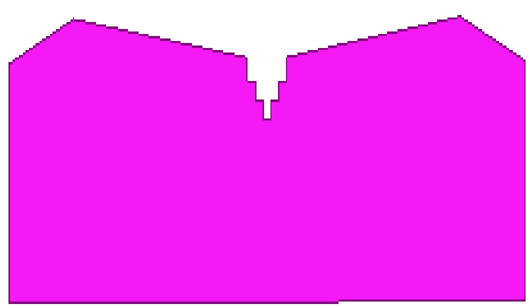
Wg (Ground Width)	50
r1,r2,r3 slots	1
s1,s2,s3 slots	0.77
h1	15.03
h2	6.25
h3	23.06
h4	5.33





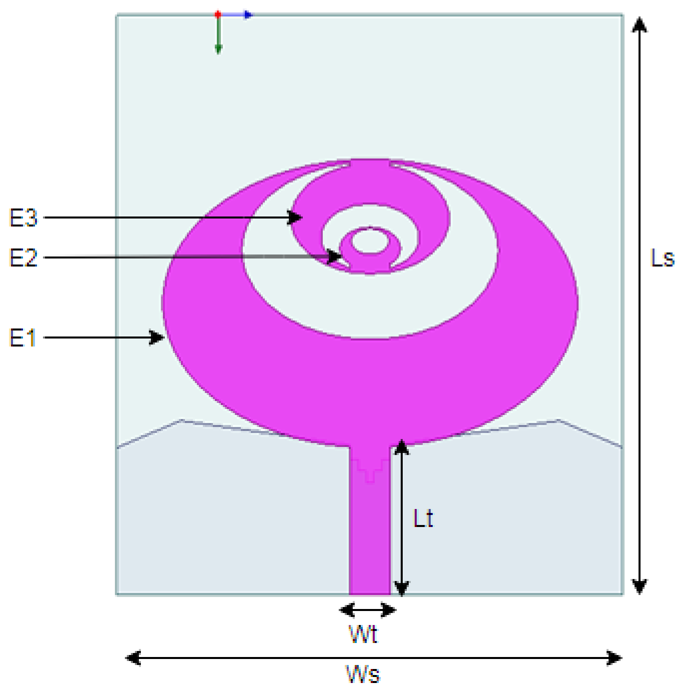
(a) Iteration-1 (n=1) (b) Iteration-2 (n=2)



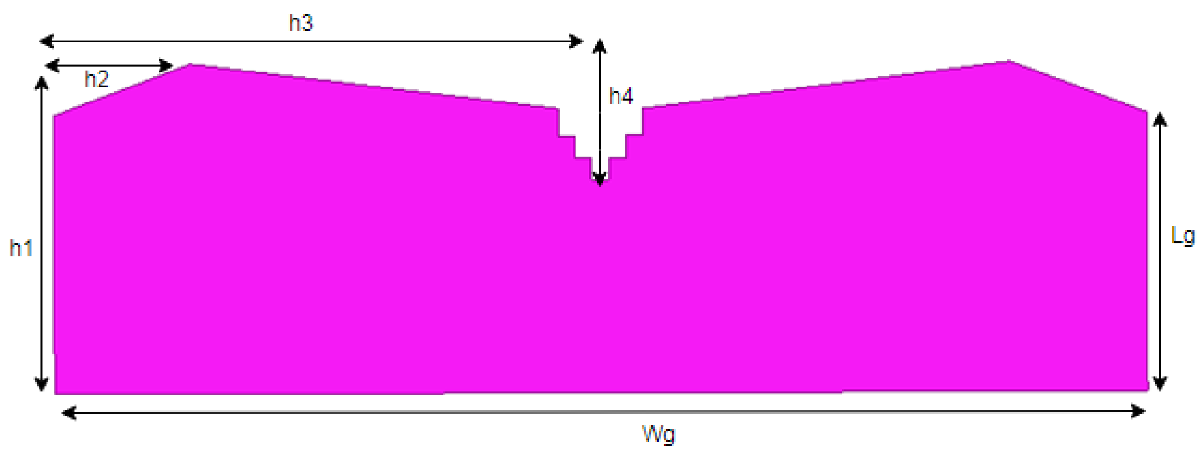


(c) Iteration-3 (n=3) (d) Defected Ground

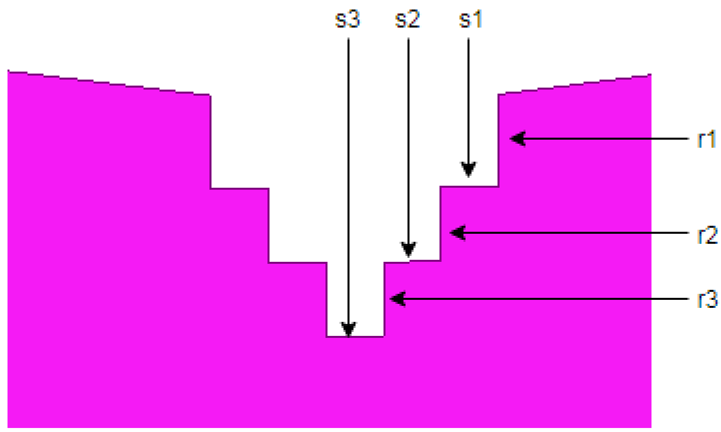
Figure 6.1: Multi band Elliptical shaped Fractal and Defected Antenna (a) Iteration-1 (n=1) (b) Iteration-2 (n=2) (c) Iteration-3 (n=3) (d) Defected Ground (back view)



(a)Final antenna design detailed dimensions



(b) Expanded view of defected ground for proposed antenna



(c) Expanded view of Defected ground slot cuts

Figure 6.2: Proposed antenna top dimensions (a) and defected ground: Back with expanded view (b,c)

To understand the working of proposed antenna in more detail, antenna current distribution analysis can be done and electric current distribution density can be observed in HFSS simulator by varying different frequencies of operation over different values of phi and theta to investigate the return loss behaviour of proposed structure. Electric and magnetic field density plots for designed antenna at resonate frequencies are demonstrated in Figure 6.3. It is depicted that the maximum current is concentrated along the edges of feedline, at the edges of elliptical patch structure and at the edges of ground plane which is responsible for obtaining multi band and wide bandwidth characteristics for proposed antenna. Also, current is distributed uniformly along the surface of elliptical patch and defected ground plane. The current distribution across edges of patch, feedline and defected ground increases its electrical length which is responsible for antenna to resonates at 2.33 to 2.74GHz, 5.46 to 6.53GHz, and 7.60 to 12.44GHz frequency bands with good return loss values.

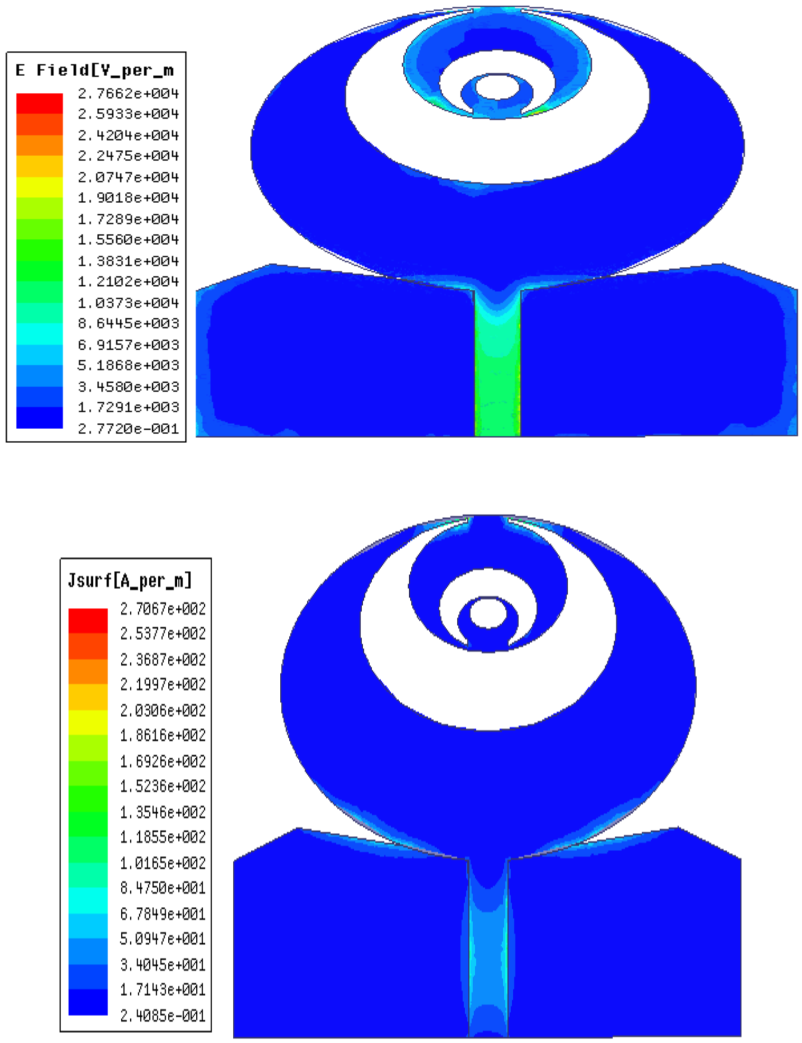


Figure 6.3: Proposed antenna E-field distribution

6.4 ANTENNA SIMULATION RESULTS

Antenna performance can be analysed by its radiation and return loss properties. Scattering parameters or reflection parameters determines how antenna is capable to radiate and receive power. It can be defined as the ratio of reflected wave form load towards source and incident wave from antenna feed point to load. This reflects the impedance matching between antenna and feed point for different resonating frequencies. Antenna radiation properties provide information related to antenna directivity, gain and density of power for frequency bands over which antenna is resonating. These parameters can be represented in terms of 2-D or 3-D graphical patterns. To analyse antenna performance, simulation is carried out using HFSS simulator from 1GHz to 15GHz prior fabrication using PCB technology. Antenna performance is analysed in terms of return loss, bandwidth, VSWR and radiation pattern.

Table 6.2: Proposed antenna simulated results in terms of S11, Gain, VSWR and Bandwidth

Frequency (GHz)	**Cut off frequency**	**Return loss (dB)**	**Bandwidth (MHz)**	**VSWR**	**Gain (dB)**
2.33-2.74	2.6	-18.18	410	1.2	3.27
5.46-6.53	6	-15.11	1070	1.4	4.37
7.60-12.44	8.2	-16.33	4840	1.35	5.52

Figure 6.4, shows the reflection co-efficient simulated performance of proposed antenna. It is depicted from graph that proposed antenna shows multi band characteristics with wide band impedance bandwidth. Antenna resonates over three frequency bands with operating frequencies 2.6GHz, 6GHz and 8.2GHz with return loss values -18.18, -15.11 and -16.33dB respectively. Impedance bandwidth achieved over respective band of operation is 14.96 % (2.33 to 2.74), 16.38% (5.46 to 6.53GHz) and 38.90% (7.60 to 12.44GHz) respectively. For achieved frequency bands of operation VSWR performance is below 2 which is acceptable and its value should be between 1 and 2 practically, VSWR is given in Figure 6.5.

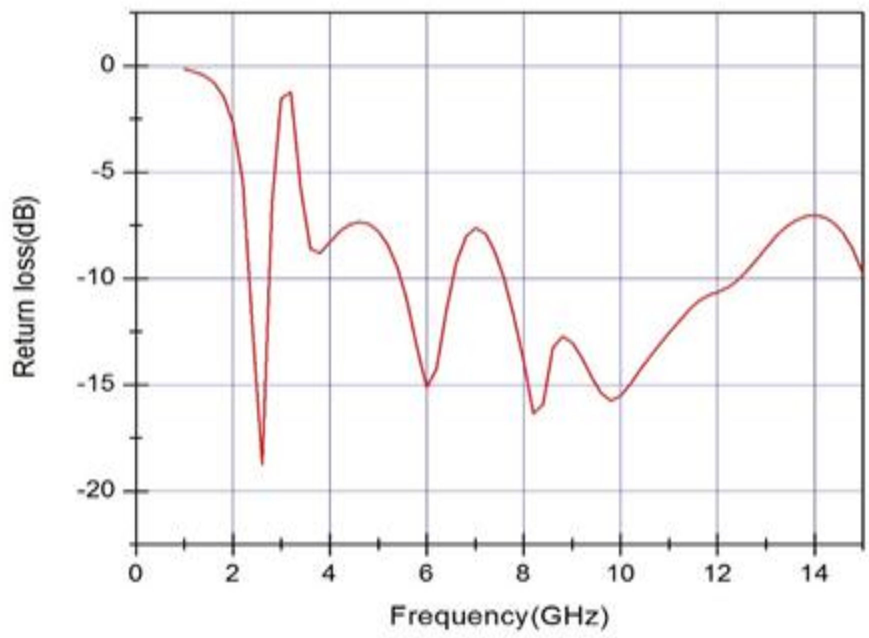


Figure 6.4: Simulated return loss performance for multi band Elliptical patch antenna

Following Figure 6.5 shows the simulated gain performance of proposed antenna. It is depicted from graph that proposed antenna gain lies between 2dB to 6dB for frequency band of operation 2GHz to 15GHz. Gain for frequency band 2.33GHz to 2.74GHz varies between 2.76dB to 3.71dB. Gain variation depicted from 3.97dB to 3.69 dB for frequency band of operation 5.4GHz to 6.6GHz and 5.56dB to 5.6dB for 7.6GHz to 12.4GHz frequency band of operation. It is observed that antenna gain for proposed structure is less on low frequencies and comparatively more at high frequencies as given in Figure 6.6. Maximum gain achieved is between frequency 10GHz to 12GHz.

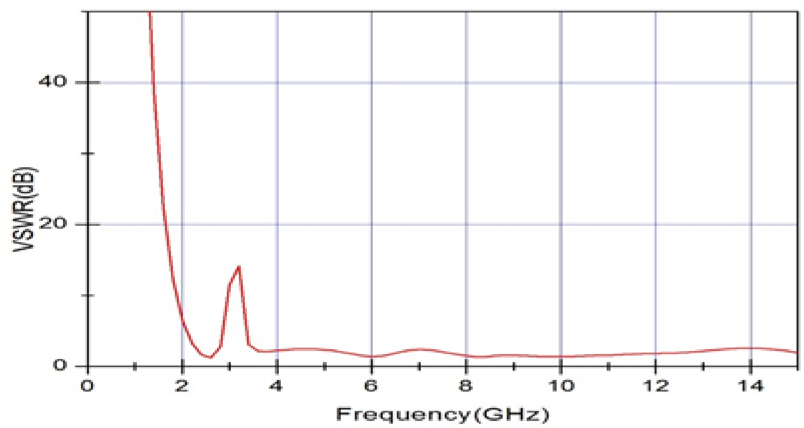


Figure 6.5: Simulated VSWR performance for multi band Elliptical patch antenna

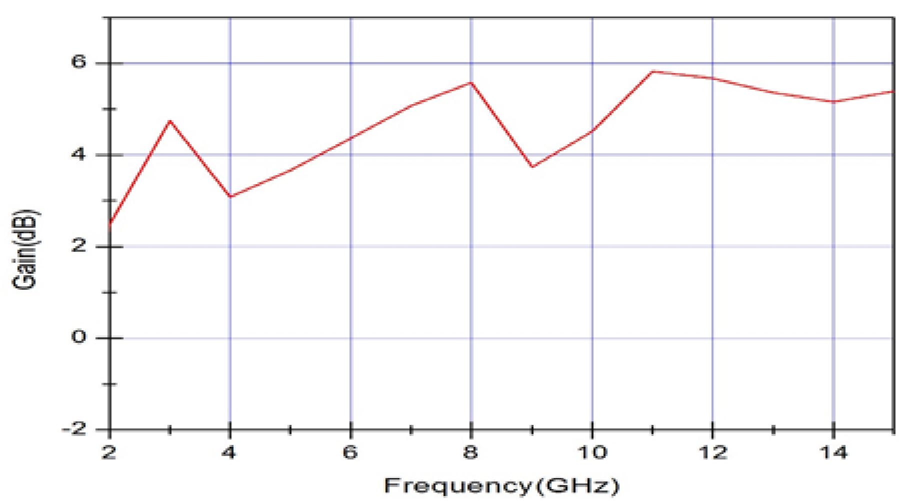
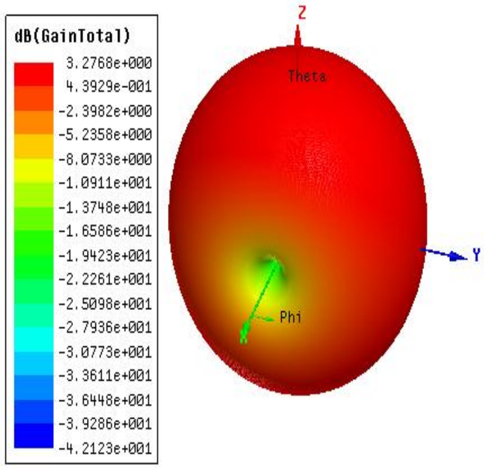
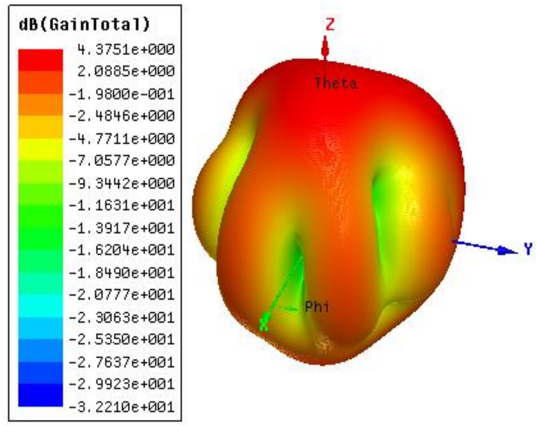


Figure 6.6: Simulated gain performance for multi band Elliptical patch antenna

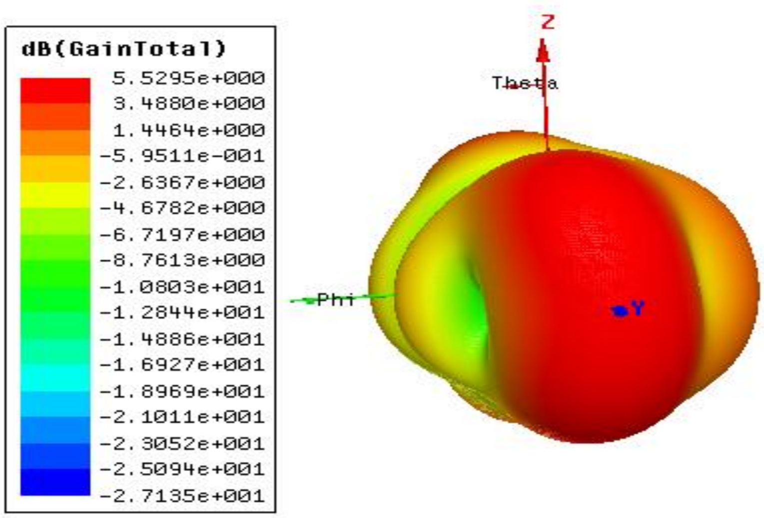
Far field radiation pattern for in terms of 3-D Polar gain plot for proposed antenna at obtained resonant frequencies 2.6GHz, 6GHz and 8.2GHz is shown in Figure 6.7 for all values of Phi and Theta. Proposed antenna exhibits high gain of 3.27dB, 4.37dB and 5.52dB respectively at these operating frequencies. 2-D Radiation pattern for proposed antenna is given in Figure at Phi-0 and Phi- 90 degree for resonating frequencies 2.6GHz, 6GHz and 8.2GHz in E-Plane and H-Plane.



(a) 3-D Gain plot at 2.6GHz

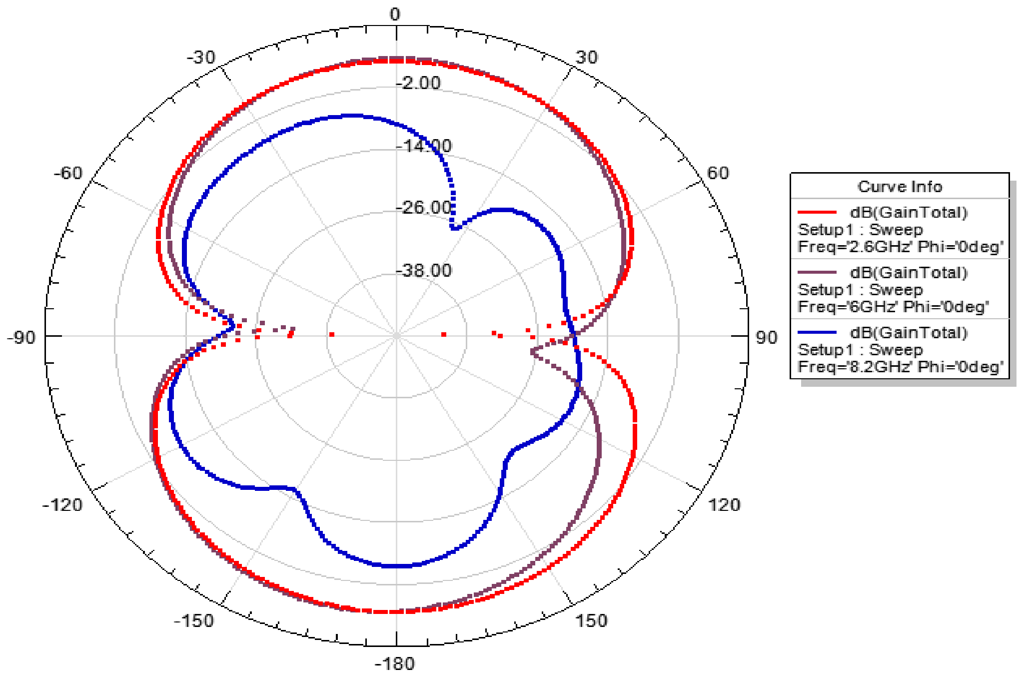


(b) 3-D Gain plot at 6GHz

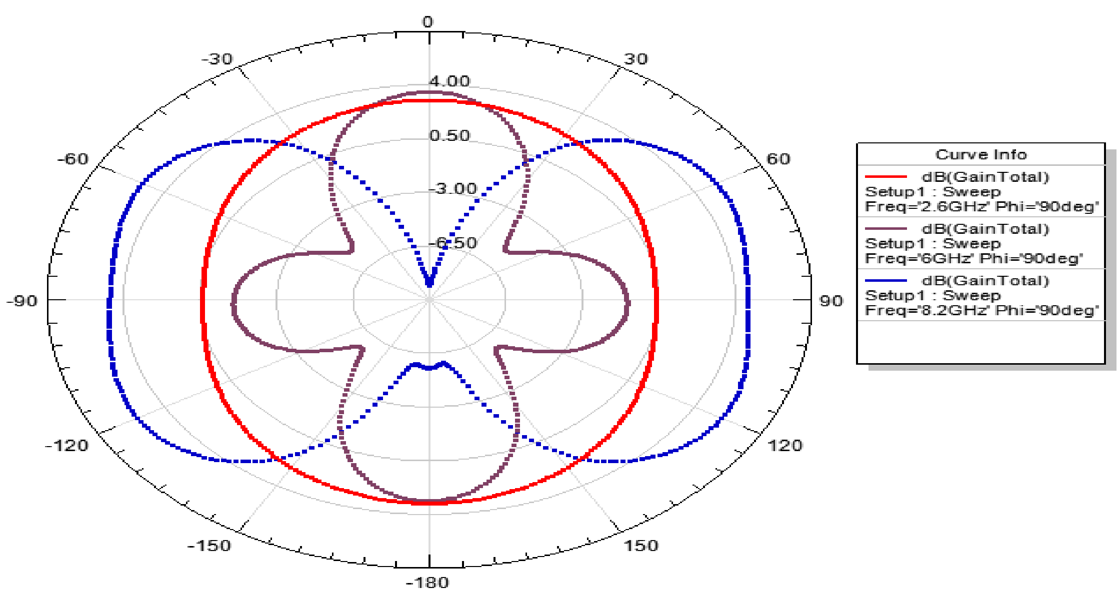


(c) 3-D Gain plot at 8.2 GHz

Figure 6.7: Simulated 3-D Polar gain plot for proposed Elliptical patch Multi band fractal and defected antenna



(a) Radiation pattern at 2.6, 6and 8.2 GHz for Phi=0 degree (y-z plane)



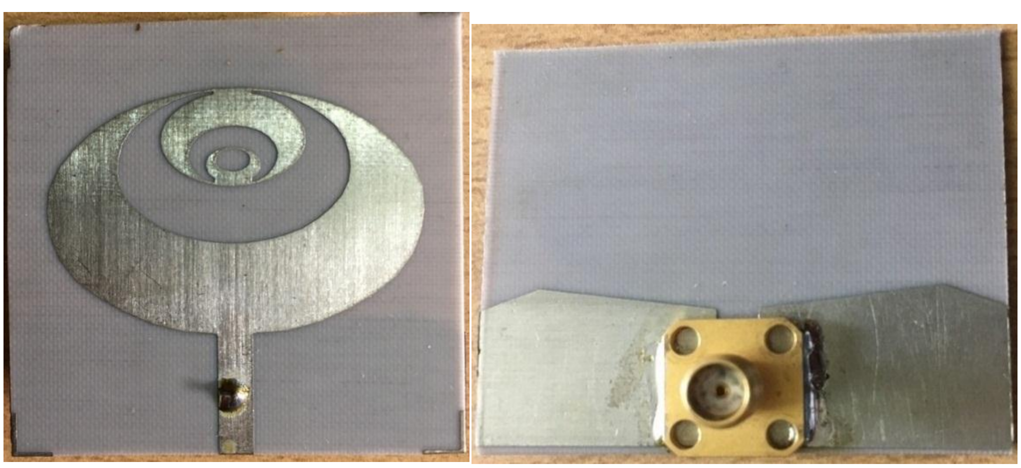
(b) Radiation pattern at 2.6, 6 and 8.2GHz for Phi=90 degree

Figure 6.8: Radiation pattern at 2.6GHz, 6GHz and 8.2GHz for (a) phi=0-degree (b) Phi=90 degree

For frequencies 2.6GHz and 6GHz, radiation beamwidth is large as compared to 8.2GHz in Azimuth plane (H-plane) in Y-Z plane as shown in Figure 6.8. Radiation pattern achieved shows semi-omnidirectional characteristics. For Phi=90 degree, at frequency 2.6GHz radiation pattern achieved is omnidirectional i.e. proposed antenna at lower frequencies is radiating in all directions with gain of 3.27dB. For resonant frequency 8.2GHz, antenna is radiating between 30 degrees to 150 degrees with gain of 5.52dB and at 6GHz major lobs are obtained at theta = 0 and -180 degree with minor lobs on 90 and -90 degree.

6.5 ANTENNA FABRICATION

After performing simulations of proposed antenna in HFSS, antenna prototype is fabricated on Roger RT Duroid 5880 Double layer PCB with copper thickness of 0.35micrometer as represented in Figure 6.9. Fabricated antenna is feeded using microstrip feedline through 4Hole Flange SMA connector by Amphenol consist of Brass and Gold plated with 50-ohm resistance and gives excellent performance between 0 to 18GHz frequency band of operation with temperature tolerance capability -55°C ~ +155°C as shown in Figure 6.9(c) below.



(a) Top view (b) Back view

(c) 4 Hole Flange SMA connector

Figure 6.9: Proposed fabricated antenna (a) Top view (b) Back view (c) SMA connector used

Fabricated antenna Return loss and VSWR is measured using Vector Network Analyzer HP-8720A with frequency band of operation from 1GHz to 15GHz. Before Return loss measurement, VNA is calibrated using Calibration Kit. Antenna return loss measurement setup and procedure are mentioned in detail in Appendix. Figure 6.10 below show the antenna measurement setup for return loss measurement.

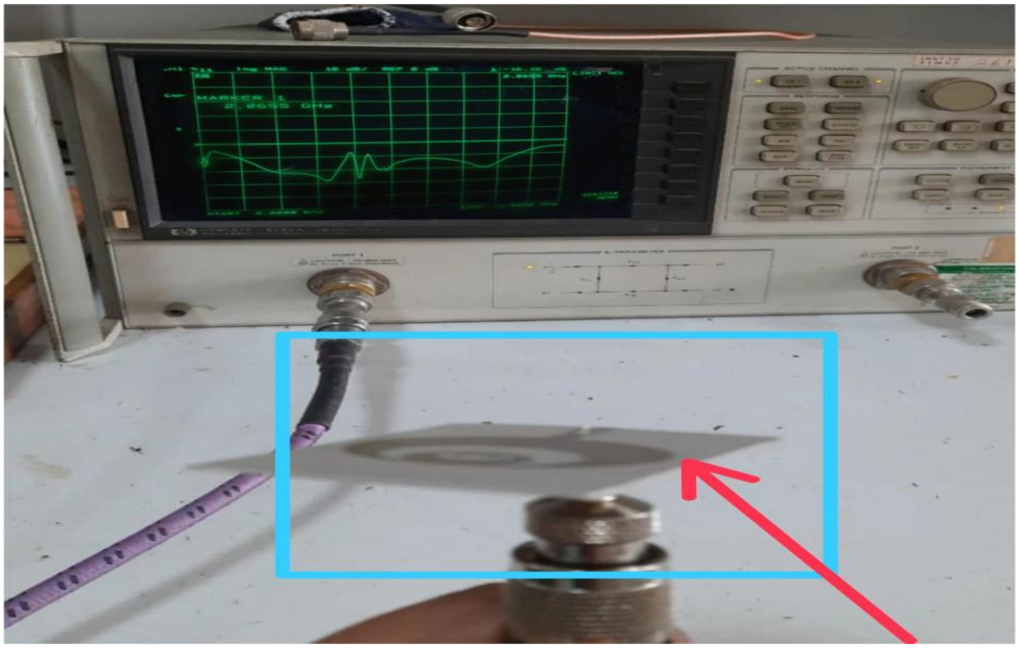


Figure 6.10: Proposed antenna Return loss measurement setup

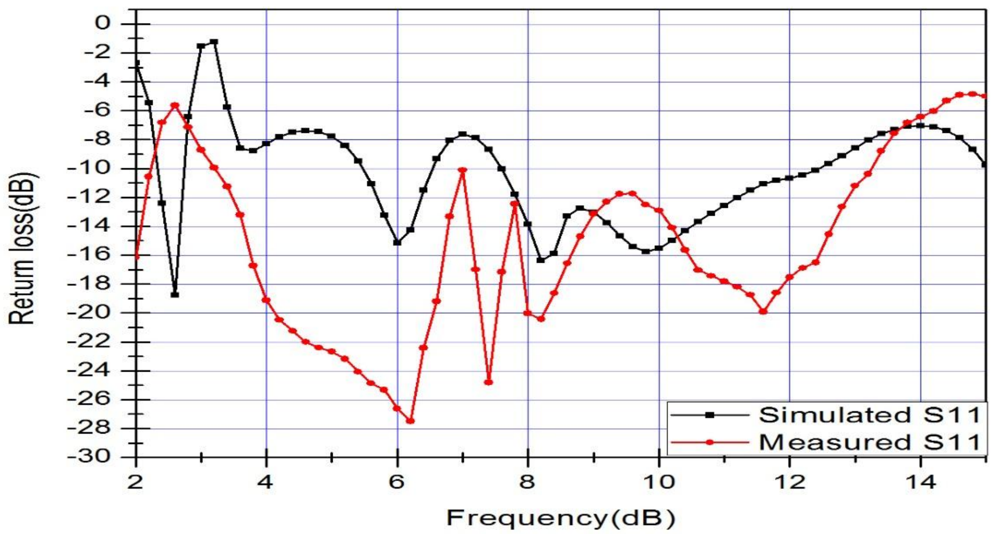


Figure 6.11: Simulated and measured return loss plot for proposed antenna

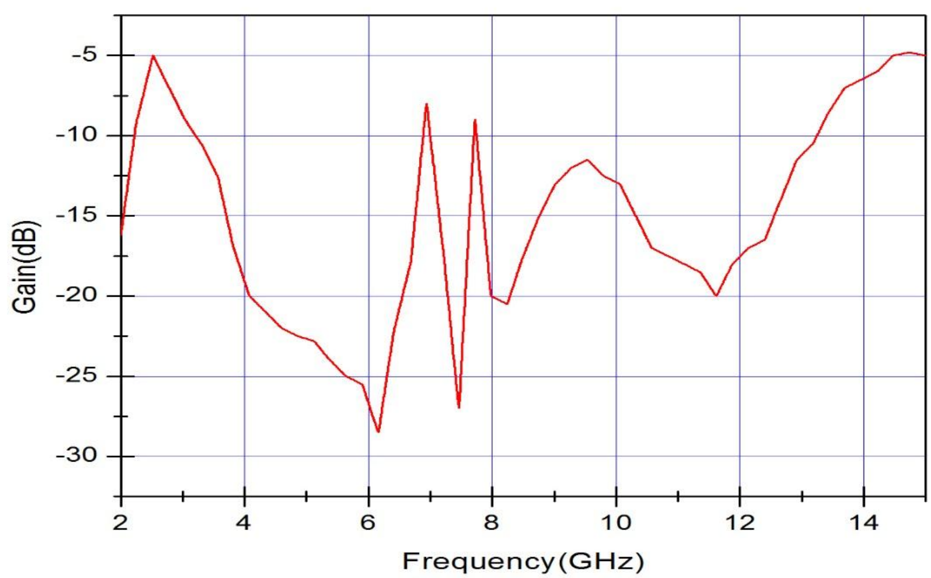


Figure 6.12: Measured return loss extended plot for proposed antenna

For proposed antenna simulated and measured return loss performance is given in Figure 6.11 and Figure 6.12. It is evident from graph that simulated and measured impedance is agreed with each other. From tested return loss characteristic, the proposed antenna is resonating between 2.2GHz to 13.2 GHz which shows antenna wideband characteristics. From Figure 6.11, it is evident that resonant frequency bands achieved with impedance bandwidth from measured results are 2 to 2.2GHz (9.09%), 3.2 to 6.8GHz (52.9%), 7 to 7.7GHz (9.09%) and 7.74 to 13.2GHz (41.36%). Antenna measurement is done with proper antenna parasitic extraction and tuning to obtain good Return loss and VSWR measurement results. Because in antenna measurement parasitic capacitance and stray capacitance effect is observed due to placement of devices with close proximity to each other and also from presence of wires etc. which leads to deviation from intended circuit outputs. So, to nullify these effects parasitic extraction is done in antenna measurement.

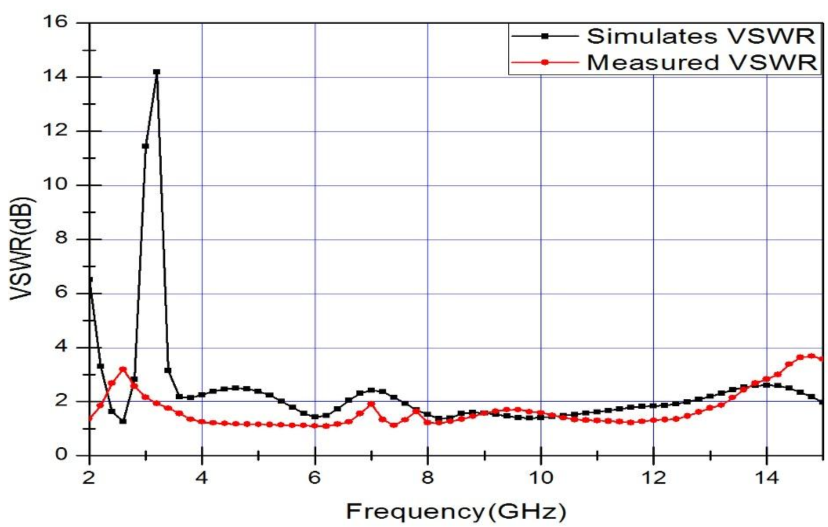


Figure 6.13: Simulated and measured VSWR performance for proposed antenna

Some mismatch and discrepancies are observed between simulated and measured results at lower frequencies due to fabricated errors, cable loss, scattering measurement environment and SMA connector quality but at the end impedance bandwidth is maintained that is the main objective of this research. Also, plot for simulated and measured VSWR is given in Figure 6.13 and both are in good agreement.

6.5.1 Antenna Gain and Radiation Pattern Measurements

Figure 6.14 shows the simulated and measured gain performance for proposed antenna. Antenna gain measurement is carried out using Reference method. To measure the proposed antenna, gain in far field environment, initially proper distance is calculated using far field formula for reference antenna and AUT (proposed antenna). Reference antenna considered is LPDA (Log Periodic Dipole Antenna). Gain measurement setup and cable insertion loss setup is explained in Appendix A in more detail. Proposed antenna gain measurement is done by using Wiltron 68147B Signal Generator and HP-8593E Spectrum analyzer. It is depicted from graph that simulated and experimental gain results are in good accord with each other for complete operating range of frequencies and more than 2dB. For fabricated antenna, value of measured gain achieved is 2.77, 3.82 and 5.2dBi at 2.6GHz, 6GHz and 8.2GHz respectively which is practically acceptable gain for wireless communication applications.

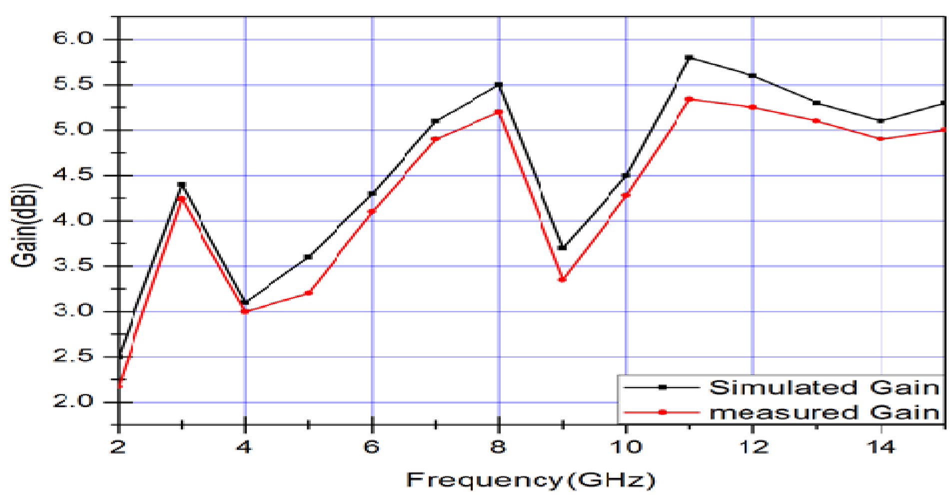


Figure 6.14: Simulated and measured gain for proposed elliptical shaped patch multi band antenna

Figure 6.15 to Figure 6.17, shows the simulated and measured radiation pattern at 2.6GHz, 6GHz and 8.2GHz in E-plane and H-plane. Radiation pattern measurement setup used is same as gain measurement as explained in Appendix A. Proposed fabricated antenna is placed in far field region with respect to reference antenna and aligned properly. Radiation pattern for proposed antenna achieved at 2.6GHz and 6GHz in dumb-bell shaped semi-omnidirectional in H-plane (y-z plane) and at frequency 8.2GHz is also semi-omnidirectional in E-plane (x-z) at phi= 90 degree.

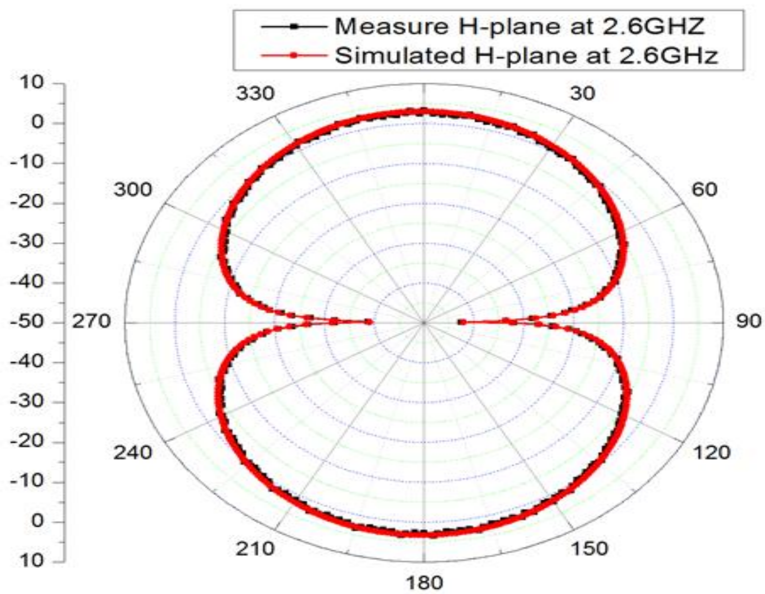


Figure 6.15: Measured and simulated radiation pattern at 2.6GHz in H-plane (Phi=90degree) for proposed antenna

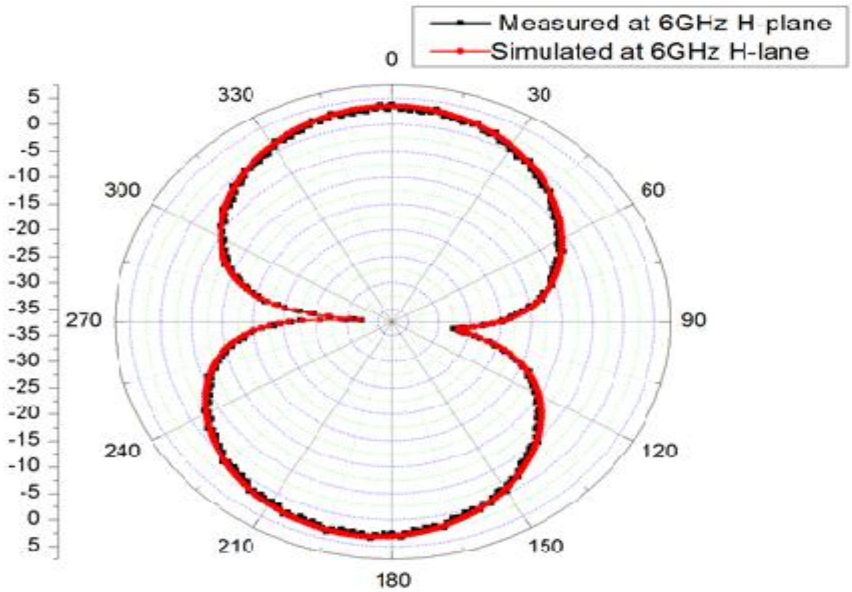


Figure 6.16: Measured and simulated radiation pattern at 6GHz in H-plane (Phi=90degree) for proposed antenna

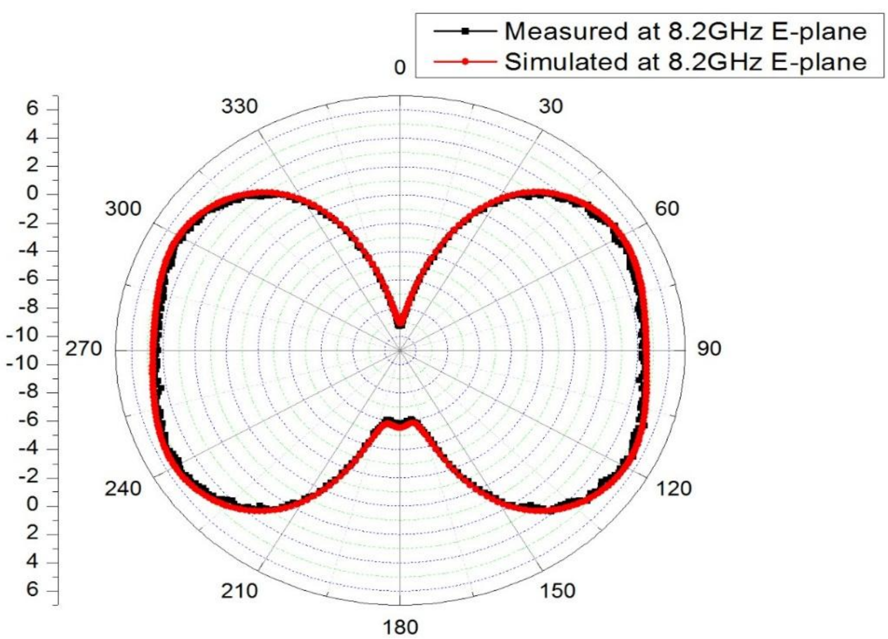


Figure 6.17: Measured and simulated radiation pattern at 8.2GHz in H-plane (Phi=90degree) for proposed antenna

6.6 PARAMETRIC ANALYSIS

Proposed antenna patch, ground and substrate dimensions are calculated using mathematical expression defined in antenna modelling to operate antenna on desired frequency band of operation. Antenna performance is also analysed and compared in terms of some parameters like by changing the substrate thickness for Rogers RT Duroid 5880 and by considering FR4 substrate material. Different thickness (t) considered are 0.5, 0.8 and 1.6 mm.

6.6.1 Effect of substrate material

Proposed antenna return loss performance is analysed using two substrate materials, those are easily available in market FR4 and Rogers DT Duroid 5880 with thickness t=0.8mm. It is depicted from figure that Rogers RT Duroid 5880 S11 performance is better as compared to FR4 with same thickness. As shown in Figure 6.18 below, RT Duroid S11 value is below -10dB for lower frequencies from 2.33 to 2.74GHz with S11 value -18.18dB at cut off frequency 2.6GHz, but for FR4 S11 values from 1 to 5GHz is not below -10dB. For FR4 dielectric substrate for proposed antenna good bandwidth of 1.7GHz and 2.91GHz is obtained from 6.43 to 8.2GHz and 12.09 to 15GHz frequency band respectively. Return loss value for RT Duroid is below -10dB from 7.6GHz to 12.4GHz frequency band that gives wide band impedance bandwidth of 4.8GHz. So, it is analysed that proposed antenna outperforms at both lower and higher cut of frequencies with Rogers RT Duroid as compared to FR dielectric substrate material in terms of bandwidth.

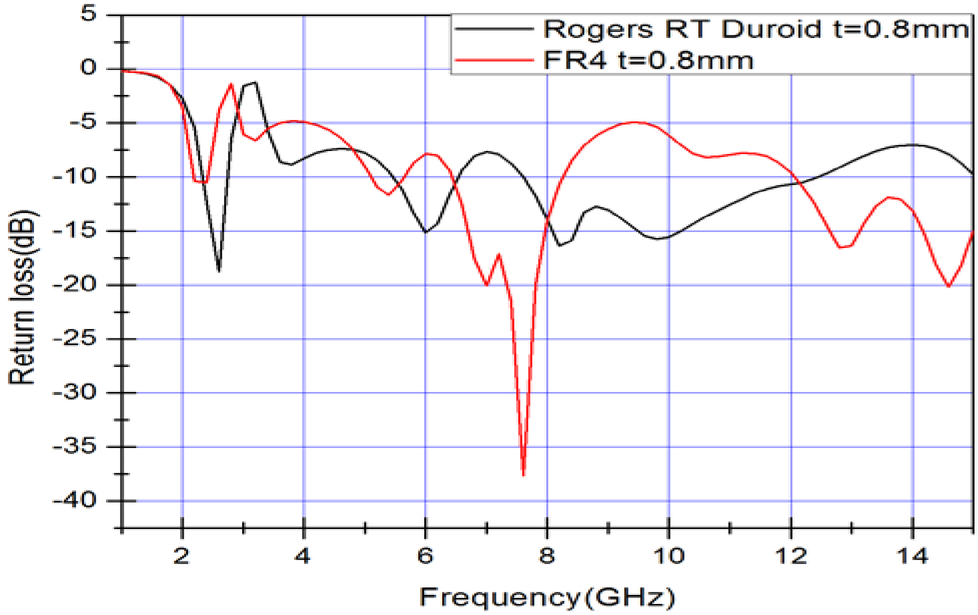


Figure 6.18: Proposed antenna S11 performance with Rogers and FR4(t=0.8mm)

6.6.2 Effect of substrate thickness

Substrate selection to obtain desired antenna performance is quintessential. It provides mechanical strength to antenna structure and effects the electrical properties of antenna as surface wave formation occurs in antenna which extracts total power for free space. For proposed antenna effect of change in dielectric height is observed on return loss performance. Dielectric thickness t= 0.5mm, 0.8mm and 1.6mm is considered for Rogers RT Duroid 5880 and performance is compared in terms of S11 parameter as shown in Figure 6.19.

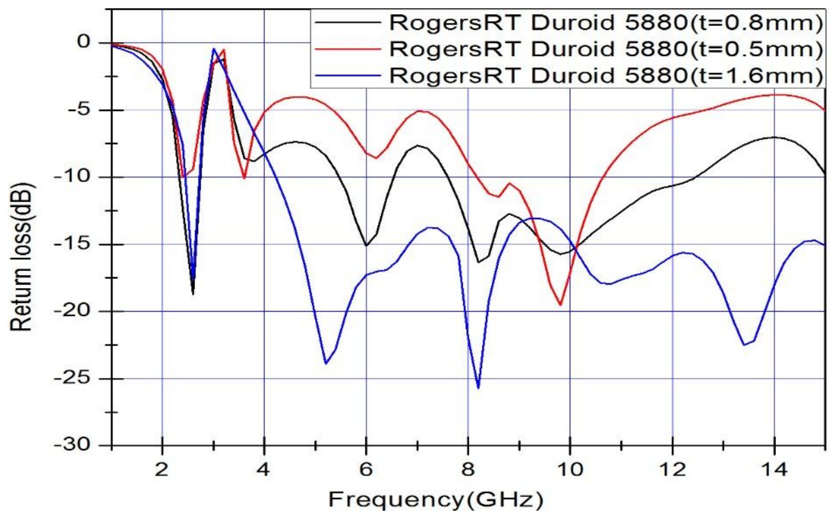


Figure 6.19: Proposed antenna S11 performance with different substrate height

6.6.3 Effect of Iterations

Following Figure 6.20 represents the effect of different iterations on return loss performance for proposed antenna. As it is depicted from diagram that with the increase in iteration, the return loss co-efficient value increase and effect on bandwidth is also analysed. Proposed antenna return loss performance is better over lower frequencies and higher frequencies as compared to Iteration-and Iteration-2. Also, Iteration-2 and 3 performs better over high frequency bands from 7.6GHz to 12.4GHz.

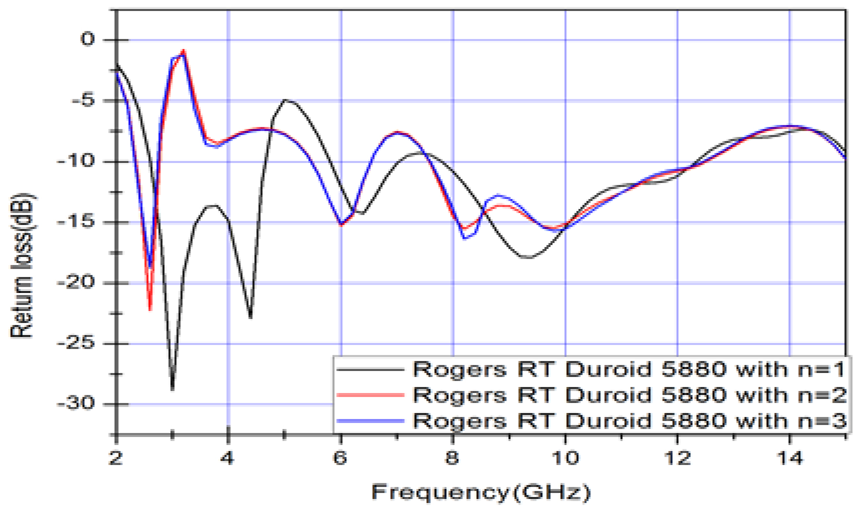


Figure 6.20: Effect of different Iterations on S11 performance

6.7 COMPARATIVE ANALYSIS

Proposed antenna shows good agreement between simulated and measured results in terms of return loss, gain and VSWR parameters. Proposed antenna performance comparison analysis is carried out with existing antenna in literature in following Table 6.3 in terms of overall antenna dimensions, achieved frequency band of operation, gain and bandwidth.

Table 6.3: Proposed antenna performance comparative analysis with existing antenna

Ref. No.	**Ant. Dimensions (mm)**	**Substrate used**	**Operating Frequency (GHz)**	**Bandwidth (MHz)**	**Gain(dB)**	**Remarks**
[59]	60 x 60 x4.8	FR4 (two layers)	4.75–5.38, 6.8–7.2	630, 400	5.85, 9.5	Large in size and use two layers of substrate
[64]	110 × 110 × 6.6	FR4(3layers)	0.911-0.933, 2.40- 2.57	20, 170	0.8, 5.9	Large dimensions, less bandwidth

[70]	138×90×6.79	Roger RT Duroid 5870	1.387-1.696	309	5.62-6.6	Large dimensions, single band
[74]	100×100 x11	Rogers RT Duroid 5880	1.4-1.6, 2-2.4	20, 40	2.3,6	Very small bandwidth and large dimensions
[85]	60×88×4.8	FR4	3.62-4.75	1130	3.4	Height is large
[91]	96×73×14	RO4003C	2.5–2.7, 3.4–3.6	30, 20	9.2, 7.0	Large dimensions, small bandwidth
[92]	95 x 60x0.8	FR4	0.74–0.965, 1.380-2.703	225, 323	0.76-4.5	Large dimension, less gain
[98]	45x45x3.18	FR4	(1.558 -1.588), (1.572 - 1.578)	30,6	1.7-2.2	Less BW and gain, use large dielectric constant(ε=10)
[99]	80x40x1.58	FR4	2.2-3.4, 3.34-4.52, 1.45-4.1	1120, 1180, 2650	2.2–2.4	Wideband, small gain and large dimensions
[101]	50.8x 62x0.8	FR4	1.3-20	19700	8	Very complex structure, large dimensions and single wideband
[108]	55 x 48 x0.58	Rogers RT Duroid 5880	2.34–2.56	220	2.36	Small, gain and bandwidth, large dimensions, single band

[110]	100 x 100x 3.18	Taconic CER-10 (εr=10)	45	--	2.56dBi (without DGS), 5.38dBic (with DGS)	Large dimensions, complex structure, high dielectric constant
[111]	100 x100 x 3.18	Taconic CER-10	1.55-1.6	50	2.38	Small gain and bandwidth, large dimensions
[115]	150x150x4	Jeans Fabric	1.78-1.98, 2.38-2.505	200, 125	---	Small bandwidth, large in size
[116]	59.5x59.9x3.7	Fabric	2.4-2.48	80	3.8	Small bandwidth
[117]	88x20x1.6	FR4	1.980-2.010, 3.40-3.50,4.94-4.99, 6.0-6.8	30, 100, 50, 80	3.23,4.3, 5.95, 4.65	Small bandwidth, large dimensions
[118]	56×44×0.80	FR4	1.7-2.92, 2.92-4.28, 5-5.98, 6.37-6.78, 7.33-8	1.22, 1.36, 0.98,0.41, 0.67	5.28	Large dimensions
[119]	60 x 30 x 1.6	FR4	2.4–2.5, 5.725–5.875	100, 150	2.2	Less Gain and bandwidth
Proposed	50 x 50 x 0.8	Rogers RT Duroid	2.33-2.74, 5.46-6.53, 7.60-12.44	410, 1070, 4840	3.27, 4.37, 5.52	Large bandwidth, compact in size, good gain

6.8 SUMMARY

In this chapter, a compact, low profile elliptical patch multi band fractal microstrip patch antenna with slotted ground plane is presented and performance is verified with help of experimental analysis. Parametric analysis is done on proposed antenna by varying substrate thickness and by changing dielectric substrate material from Rogers RT Duroid to FR4. It is analysed that antenna is outperforming on Roger RT Duroid with 0.8mm thickness. Antenna simulation and measured results are in good accord with each other. Antenna resonates on three different frequencies 2.4, 6 and 8.2GHz with bands 2.33 to 2.74, 5.46 to 6.53, 7.60 to 12.44GHz and impedance bandwidth achieved is 410, 1070 and 4840MHz respectively. Proposed antenna shows wideband and multi band characteristics. Antenna is very good candidate for wireless applications and covers frequency bands for Wi-Fi (2.4GHz) Bluetooth version V1.0-V4.0, WLAN (2.4/5.2/5.8GHz), WiMAX (2.3/2.5/5.5GHz), Wireless Body Area Network (2.3/2.4GHz), RFID (2.4-2.5/5.85-5.925GHz), Microwave ovens (2.4-2.48GHz) ISM (Industrial Scientific and Medical) band applications. It also covers RADAR (2.33-2.74/5.4), Geostationary Satellite communication (11.7-12.2GHz), X-band application (8-12GHz), S-Band (2.3-2.4GHz) communication, Wireless Communication Services (WCS) 2.345-2.360GHz, and 4G-LTE (2.3-2.315GHz) wireless communication standards.

CHAPTER-7
CONCLUSION AND FUTURE SCOPE

7.1 INTRODUCTION

With tremendous growth in wireless technology, multi band antenna becomes emerging topic of research. Multi band antenna fulfils indoor and outdoor wireless communication application requirements over differently specified frequency band of operation. Multi band Fractal and defected Microstrip patch antenna designed for Wireless communication application. Antenna is designed and simulated on HFSS simulator. Two different antenna prototypes are designed and tested based on fractal and defected geometry to obtain multi band and wide bandwidth characteristic. First antenna is designed with circular cut truncated edges patch with U-shaped defected ground on Roger RT Duroid 5880 material. Four resonate frequency bands are achieved 3.80, 7.01, 10.86 and 11.84GHz with bandwidth of 260, 330, 270 and 460MHz and gain of 5.6, 8.25, 5.56 and 8.05dB respectively. Second, elliptical shaped fractal patch with step cut defected ground antenna is simulated and fabricated on Rogers RT Duroid 5880 dielectric substrate. Proposed structure shows good agreement between simulated and fabricated results in terms of S11, Gain, Bandwidth and radiation pattern. Antenna performance is analysed after studying effect of dielectric substrate material used, height of substrate and number of iterations considered for implementing fractal geometry, on return loss performance. Proposed antenna is low profile, light in weight, small in size as compared to existing antenna. Antenna provides 3 resonant frequencies 2.6GHz, 6GHz and 8.2GHz with S11 co-efficient -18.18, -15.11, -16.33dB and wide impedance bandwidth achieved are 410, 1070 and 4840MHz with good gain. Antenna covers different wireless standards like Wi-Fi (2.4GHz), Bluetooth version V1.0-V4.0, WLAN (2.4/5.2/5.8GHz), WiMAX (2.3/2.5/5.5GHz), Wireless Body Area Network (2.3/2.4GHz), RFID (2.4-2.5/5.85-5.925GHz), Microwave ovens (2.4-2.48GHz) which falls under ISM (Industrial Scientific and Medical) band applications. It also covers RADAR (2.33-2.74/5.4), Geostationary Satellite communication (11.7-12.2GHz), X-band application (8-12GHz), S-Band (2.3-

2.4GHz) communication, Wireless Communication Services (WCS) 2.345-2.360GHz, and 4GLTE (2.3-2.315GHz) wireless communication standards.

7.2 FUTURE SCOPE

Multi band microstrip patch antenna gain much attention to fulfil demands of wireless communication application for operation on multiple frequency bands. Microstrip patch antenna suffers from some short comings like small gain and less bandwidth. In this thesis work, research is carried out to enhance gain and bandwidth of microstrip patch antenna using concept of fractal and defected ground structures to achieve high gain, bandwidth and compact size. This part explains the work that can be extended for future research work.

1. In this thesis, work is carried out on antenna gain, bandwidth and compact dimensions using fractal and defected geometry. In future, further gain can be improved using concept of array for wireless applications.
2. Antenna prototype is simulated and tested for frequencies from 1GHz to 15GHz, but its performance can be analysed on higher frequencies in terms of return loss, gain, bandwidth and radiation pattern.
3. Proposed antenna covers ISM frequency bands for WBAN applications, so Specific Absorption Rate (SAR) analysis can be done for WBAN products.

Research Publications

Published Papers

1. A. Kaur and P. K. Malik, "Tri State, T Shaped Circular Cut Ground Antenna for Higher 'X' Band Frequencies," International Conference on Computation, Automation and Knowledge Management (ICCAKM), Dubai, United Arab Emirates, pp(s): 90-94, 2020. 10.1109/ICCAKM46823.2020.9051501.
2. Microstrip patch antenna performance analysis with Defected Ground structures: A review", Journal of Emerging Technologies and Innovative Research (JETIR), ISSN: 2349-5162, January 2019.
3. Amandeep Kaur, Praveen Kumar Malik, "Microstrip Antenna Design with Truncated Edges for Bandwidth Improvement for Wireless Applications", International Conference on Recent Innovations in Computing (ICRIC-2020). (Available online in SN eproofing)
4. Amandeep Kaur, Praveen Kumar Malik, Ramendra Singh, "Planar Rectangular Micro-strip Patch Antenna Design for 25 GHz Wireless Applications" International Conference on Recent Innovations in Computing (ICRIC-2020). (Available online in SN eproofing)
5. Amandeep Kaur, Praveen Kumar Malik, "Multiband Elliptical Fractal and Defected Ground Structures Microstrip Antenna for Wireless Applications", International Journal of Communication Systems. (2nd review accepted)

Papers Communicated

1. Amandeep Kaur and Praveen Kumar Malik, "Adoption of Micro-strip Patch Antenna for Wireless Communication: Opportunities and Challenges", Journal of Electromagnetic Waves and Applications.

Patent
Published:

1.WIDE BAND MICRO-STRIP ANTENNA DESIGN FOR HIGHER X BAND, Patent ID: 1099.

In process:

1. Multiband Fractal and Defected Microstrip patch antenna for wireless applications.

Details	Id	Idea For	Title	Description	File	Remarks	Enrty By	Entry Date
View Detail	3811	Patent	Multiband Fractal and Defected Microstrip patch antenna for wireless applications	A multiband microstrip antenna is designed for wireless communication application with fractal and d	Elliptical Patch patent.doc	NA	16335	10/22/2020 12:00:00 AM

2. Multiband Microstrip patch antenna for 5G applications using Fractal structures.

Details	Id	Idea For	Title	Description	File	Remarks	Enrty By	Entry Date
View Detail	2765	Patent	Multiband Microstrip patch antenna for 5G applications using Fractal structures	Microstrip patch antenna for 5G applications	Amandeep Kaur Patent.pdf	Kindly consider	16335	1/29/2020 12:00:00 AM

Book Chapter:

1. Amandeep Kaur and Praveen Kumar Malik and Ch. Ravi Shankar, "Role of Microstrip Patch Antenna for Embedded IoT Applications", Electronic Devices and Circuit Design Challenges and Applications in the Internet of Things, ISBN: 9781771889933.

APPENDIX A

A.1 ANTENNA FABRICATION

Antenna designing process is carried out in Antenna design and simulation software HFSS. After converting the HFSS file into Gerber files antenna fabrication process starts. For Microstrip patch antenna, PCB fabrication technology is used. With the increase in fabrication demands of electronics components on smaller boards, boost-up the need of PCB fabrication technology. PCB is a board that provides the mechanical strength to components and provides connectivity between them through copper tracks. PCB can be single layer, double layer or multi-layer boards. Main components of PCB are substrate, copper layers and solder mask. Dielectric material should have low value of dielectric constant and dielectric loss to achieve good radiation performance of antenna. Selection of dielectric constant material depends on applications. Dielectric materials with thick substrate and low dielectric constant provide high bandwidth and better antenna efficiency but leads to large size structures. On contrary, material with high dielectric constant give rise to more surface waves and less bandwidth is achieved due to this. For proposed antenna designing dielectric substrate selected is Rogers RT Duroid with dielectric constant 2.2 and thickness of 0.8mm to get better antenna efficiency. RT Duroid material is also available in 0.5, 1.6, 2.4 and 3.2mm thickness. Most commonly used material is FR-4 Epoxy but it is highly lossy material, so Rogers RT Duroid material is selected for antenna fabrication. PCB board used is Double layer with copper layers of 0.35micrometer thickness on both sides.

For PCB fabrication some steps and followed. Initially, design is prepared on software than Gerber files are created. For creating Gerber files, software used is Dip Trace. It provides the complete information related to copper layers, solder mask and component notation etc. Next step is to print the PCB design using special printers called plotters. It creates a film of design also called photo negative. After preparing the blueprint of design, it is printed on the PCB using where wanted copper is kept and unwanted is removed. This process is called etching and in PCB designing Ferric chloride material is used for etching process. After removing the unwanted copper, PCB is washed with alkaline solution to further remove any leftover copper and dried. The complete PCB designing process is shown in Figure A.1 below.

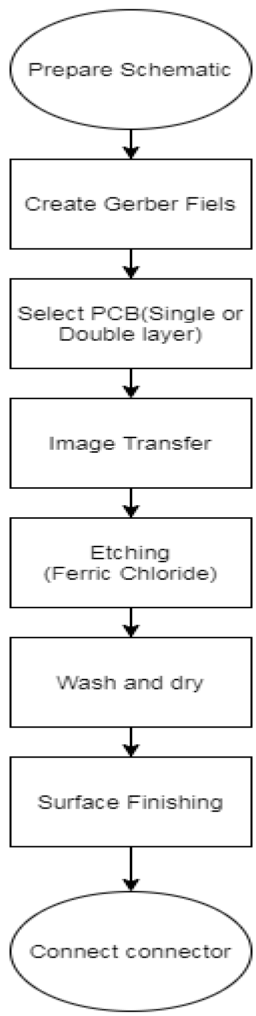


Figure A.1: PCB Fabrication process

A.2 ANTENNA TEST PROCEDURE

In practical antenna testing, after fabricating antenna using PCB fabricated technology, fabricated antenna performance is analysed in terms of Return loss, VSWR, Gain and Radiation patterns. Antenna Return loss and VSWR measurement can be done using VNA. For measurement of far field parameters like gain and Radiation Pattern Spectrum analyzer and signal generator is needed as given in Table A.1.

Table A.1: Apparatus used for Antenna parameter measurement

Antenna Parameters	Apparatus used
Return loss (S11)	VNA
VSWR	VNA
Gain	Spectrum Analyzer/ Signal Generator
Radiation pattern	Spectrum analyzer

For testing proposed antenna prototype, instruments used are given in following Table A.2 with specification.

Table A.2: Antenna testing devices used for proposed antenna performance measurement

S. No.	Instrument_Name	Company_Name	Model No	Spec.
1	Network Analyzer	HP	8720A	130MHz-20GHz
2	Signal Generator	Wiltron	68147B	10MHz-30GHz
3	Spectrum Analyzer	HP	8593E	9KHz-26.5GHz

A.2.1 Return loss/VSWR measurement using VNA (8720A)

VNA used for antenna return loss and VSWR measurement is HP8720A as shown in Figure A.2. It is high performance microwave network analyzer that covers frequency range of 130MHz to 20GHz with 100kHz frequency resolution for measurement of reflection and transmission parameters. VNA can have two ports or four ports for connection of DUT (Device under test). Before antenna measurement, VNA should be calibrated properly using calibration kit. Following steps are taken to measure VSWR for proposed antenna.

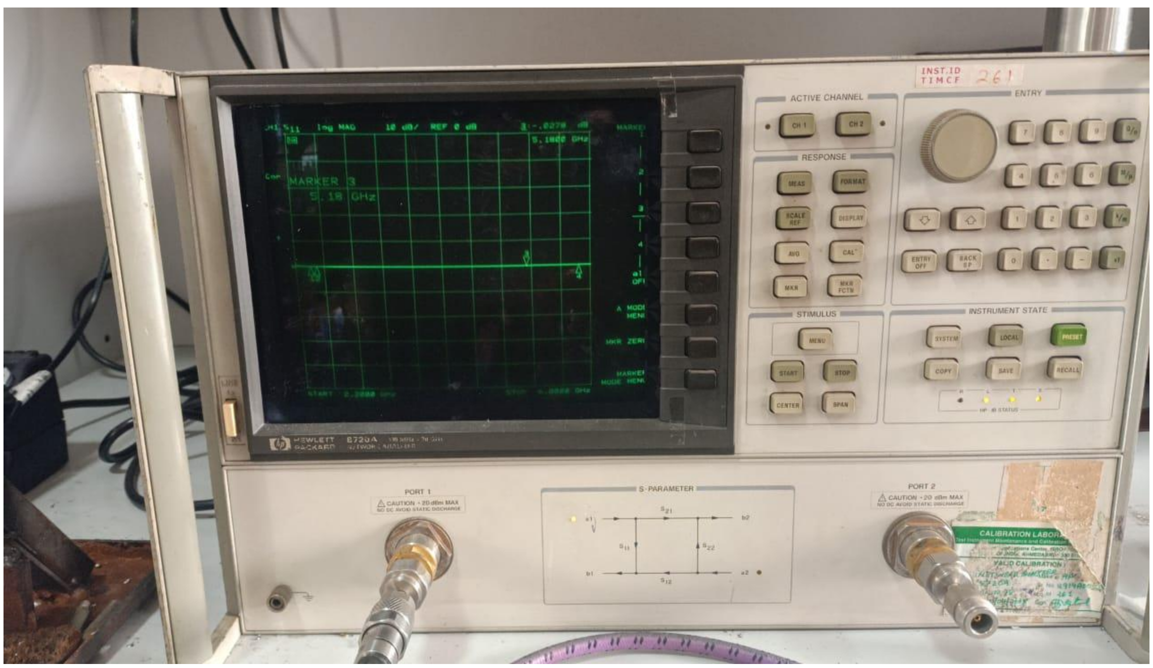


Figure A.2: VNA equipment used for proposed antenna return loss and VSWR measurement

A.2.1.1 Return loss Test procedure

1. Connect the test equipment as shown in the Figure A.3 below.
2. Switch on the Vector Network Analyzer and set the desired band of frequency means set the start frequency i.e. 1GHz and Stop frequency that is 15GHz.

3. Select S11 parameter for VSWR. Calibrate the Network Analyzer by connecting calibration module. Set the network analyzer for S11/ VSWR.
4. Connect the other end of the feeder cable to the Antenna under test (AUT)
5. Read the response in VNA over the band, which is the VSWR of the antenna
6. Note the Value of S11/VSWR.

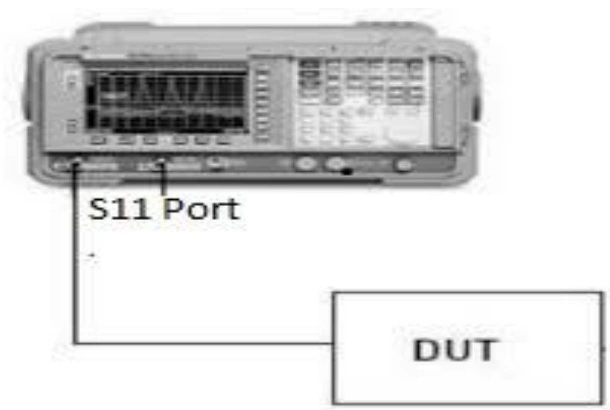


Figure A.3: Test setup for VSWR measurement

VNA port calibration can be done for frequency range between 1GHz to 15GHz using different methods like standard open, short and match load. Calibration means offset line after switching ON VNA should be aligned with Zero. After, this calibrated VNA has to connect with AUT (Antenna Under Test) with cable on VNA S11 port. Here cable used for making AUT device with VNA is LMR-400/ RG316 (Loss less cable) of length 10 meters. Fabricated antenna Return loss (S11) characteristics can be obtained by making connection of antenna with any one port of calibrated network analyzer and operating VNA in S11 or S22 mode. The graph which is display on VNA display, is observed and the frequency for which S11 value is lowest means a sharp dip is achieved on the S11 graph is called resonant frequency of cut of frequency. Return loss graph also provides information about antenna bandwidth of operation, range of frequencies for which return loss value is less than -10dB is mainly considered as antenna bandwidth. Antenna bandwidth is the range of high frequency cut off frequency and low cut off frequency below-10dB and calculated using following formula in percentage.

$$\text{Bandwidth (\%age)} = \frac{f_h - f_l}{f_c} \text{ x } 100 \qquad \text{(A.1)}$$

Where, $f_h$represents the higher -10dB point on graph, f_l denotes the lowest -10dB point on graph and fc is the cut of frequency with minimum return loss value,

`          ` A.2.2 Antenna Gain measurement

Antenna gain is the measurement of antenna power transmitted by antenna under test in a given direction. Antenna gain in given direction is expressed as the ratio of radiation intensity in given direction to the total input power. Antenna gain represents the antenna directivity and antenna electrical efficiency as expressed by expression (A.2).

$$\text{Gain} = 4\pi \frac{Radiation\ Intensity}{Total\ Input\ Power} \qquad \text{(A.2)}$$

Antenna gain measurement cab be done using (1) two antenna method (2) Reference antenna method. Proposed antenna gain measurement is done using reference antenna method. Reference antenna considered is LPDA (Long Periodic Dipole Array) wideband antenna. The AUT is placed in far field range of the reference antenna considered. Far field distance is calculated using far field formula given in expression (A.3). Antenna gain measurement is done in free space. Gain of AUT is measured with reference to the power signal received or detected by reference antenna.

$$\text{Far field} \geq \frac{2D^2}{\lambda}$$

$$\lambda = \frac{speed\ of\ light}{frequency} \qquad \text{(A.3)}$$

Here, D=Antenna length or Diameter and f= operating frequency

Both Reference antenna and AUT antenna are mounted on tunable and proper distance is maintained between them for gain measurement. Before antenna gain measurement, insertion losses are measured. Test Procedure for Insertion Loss Measurement is as follows:

1. Connect the test equipment as shown in Figure A.4
2. Switch on VNA and set the desired band of frequency
3. Select the S21 parameters for Insertion Loss (dB). Calibrate the network analyzer by connecting to Calibration module.
4. Connect both the end of connector as shown in Figure A.4.
5. Read the response in network analyzer over the band which is Insertion Loss
6. Note the Value of Insertion Loss

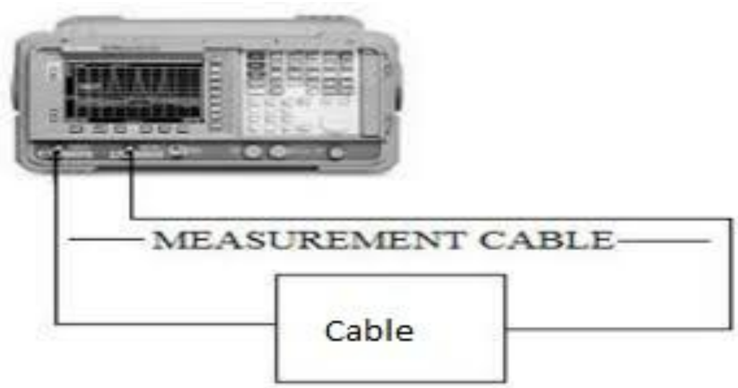


Figure A.4: Test setup for Insertion Loss measurement

A.2.2.1 Test setup for Gain Measurement

i. Distance 'D' between TX (Reference/Transmitting Antenna) and Rx (Antenna under test/receiving antenna) is 8M.
ii. Cable used is LMR-400/ RG316 (Loss less cable) of length 10 meters.

Formula:

a) Free Space Path Loss (FSPL)=92.5+20log(Freqin GHz)+20log(Distance Din KM)
b) Total Loss (TL) = FSPL+Measured Cable Loss
c) Gain:

G=((FSPL-RSL)/2) or G = Tx Power + FSPL- RSL- G(ref) (A.4)

Where G(ref)= Reference Antenna Gain in dB and RSL is Received Signal Level in dB

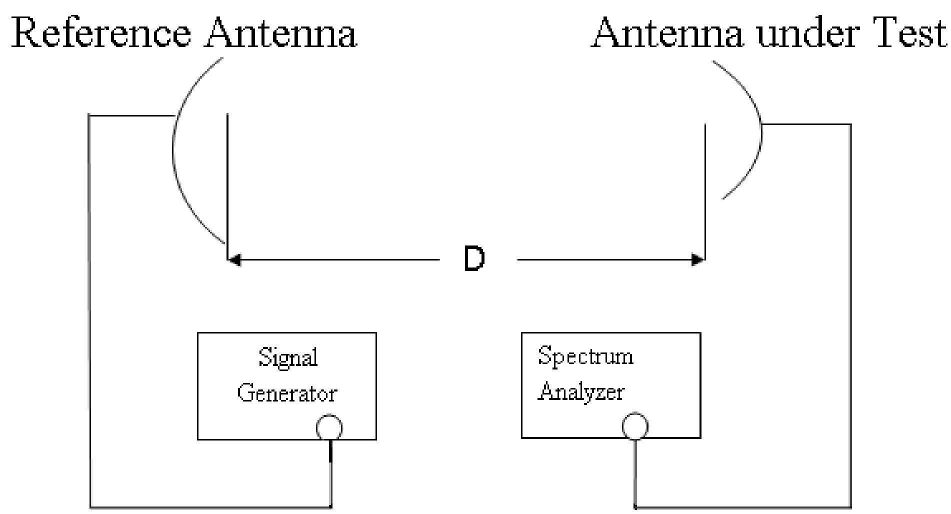


Figure A.5: Test setup for gain measurement

A.2.2.2 Test Procedure for Gain:

1) Measure the cable loss and calculate the FSPL and TL by using formula A and B
2) Connect the test setup as shown in Figure A.5.
3) Measure the RSL level from S12 Port and note the values.
4) Calculate the Gain using formula

Gain expression from Friis transmission formula is give in equation (A.5)

$$(G_t + G_r)\text{dB} = 20\log_{10}\left(\frac{4\pi R}{\lambda} + 10log_{10}\left(\frac{P_r}{P_t}\right)\right) \quad \text{(A.5)}$$

Where, (G_t)dB= gain of the Tx antenna (dB)

(G_r)dB = gain of Rx antennas (dB)

Pr = received power (watts)

Pt = transmitted power (watts)

R =Distance between antenna (m)

λ = signal wavelength (m)

A.2.3 RADIATION PATTERN MEASUREMENT

Antenna measurement setup used for Gain and Radiation pattern measurement is same. Radiation pattern of antenna represents the measurement of antenna power density transmitted in particular direction. Antenna radiation pattern measurement is carried out to analyse fabricated antenna radiation in far field region and comparison is done between simulated and measured patterns to validate antenna performance for specific application. For radiation pattern measurement, antenna under test is placed in far field region with respect to reference antenna used.

Bibliography

[1] Tapan K Sarkar, "History of Wireless", John Wiley and Sons, 2006.

[2] Theodore S. Rappaport, "Wireless Communications Principles and Practice Pearson", 2nd Edition 2002.

[3] Balanis C. A, "Microstrip Antennas", Antenna Theory, Analysis and Design, Third Edition, John Wiley & Sons, 2010.

[4] K.D Prasad, "Antenna wave and propagation", Satya Parkashan, 1983.

[5] Kin-Lu. Wong, "Planar Antennas for Wireless Communications" by Wiley Interscience, 2003.

[6] J. Q Howell, "Microstrip Antennas," IEEE International Symposium on Antennas and Propagation Society, pp(s): 177-180, Vol.10, 1972

[7]J. Barreiros , P. Cameirao, C. Peixeiro, "Microstrip patch antenna for GSM 1800 handsets", IEEE International Symposium on Antennas and Propagation Society, 06 August 2002.

[8] Yong-Sun Shin , Won-I Kwak, Seong-Ook Park, " GSM/DCS/IMT-2000 triple-band built-in antenna for wireless terminals", IEEE Antennas and Wireless Propagation Letters,Vol.3, pp(s): 104 – 107, 2004.

[9] D. Caratelli , R. Cicchetti , G. Bit-Babik, A. Faraone, "A perturbed E-shaped patch antenna for wideband WLAN applications", IEEE Transactions on Antennas and Propagation, Vol. 54 , Issue: 6 , pp(s):1871 – 1874, 2006.

[10] Xiaoxiang He , Sheng Hong , Qishan Zhang ; Emmanouil Manos M. Tentzeris, "Design of a Novel High-Gain Dual-Band Antenna for WLAN Applications", IEEE Antennas and Wireless Propagation Letters", Vol. 8, pp(s):798 – 801, 2009.

[11] L. Lu, J.C. Coetzee, “Reduced-size microstrip patch antenna for Bluetooth applications”, Electronics Letters, Vol. 41 , Issue: 17, pp(s): 944 – 945, 2005.

[12]Yong-Ling Ban , Jin-Hua Chen , Li-Jun Ying , Joshua Le-Wei Li , Yu-Jiang Wu, “Ultrawideband Antenna for LTE/GSM/UMTS Wireless USB Dongle Applications”, IEEE Antennas and Wireless Propagation Letters, Vol.11, pp(s): 403 – 406, 2012.

[13] Qian Wang, Ning Mu, LingLi Wang, Safieddin Safavi-Naeini, and JingPing Liu, “5G MIMO Conformal Microstrip Antenna Design”, Wireless Communications and Mobile Computing, Vol. 2017, pp(s):1-11, https://doi.org/10.1155/2017/7616825.

[14] Rashmitha R, Niran N, Abhinandan Ajit Jugale, Mohammed Riyaz Ahmed, “Microstrip Patch Antenna Design for Fixed Mobile and Satellite 5G Communications”, Procedia Computer Science, Vol.171, pp(s): 2073-2079, 2020. https://doi.org/10.1016/j.procs.2020.04.223

[15] Aksha Mushtaq , Sindhu Hak Gupta , Asmita Rajawat, “Design and Performance Analysis of LoRa LPWAN Antenna for IoT Applications”, IEEE7th International Conference on Signal Processing and Integrated Networks (SPIN), April 2020.

[16]PichitpongSoontornpipit, “A Dual-band Compact Microstrip Patch Antenna for 403.5 MHz and 2.45 GHz On-body Communications”, Procedia Computer Science, Vol. 86, pp(s): 232-235, 2016. https://doi.org/10.1016/j.procs.2016.05.105.

[17] Qudsia Rubani, Sindhu Hak Gupta, Arun Kumar,” Design and analysis of circular patch antenna for WBAN at terahertz frequency”, Elsevier Optik, Vol. 185, Pages 529-536, May 2019. https://doi.org/10.1016/j.ijleo.2019.03.142.

[18] Punith S, Praveenkumar S K, Abhinandan Ajit Jugale, Mohammed Riyaz Ahmed, “A Novel Multi band Microstrip Patch Antenna for 5G Communications”, ScienceDirect Procedia Computer Science, Vol. 171, pp(s): 2080-2086, 2020. 10.1016/j.procs.2020.04.224

[19] Guterman ,Moreira ,Peixeiro, “Microstrip fractal antennas for multistandard terminals”, IEEE Letters on Antennas and Wireless Propagation, Vol.3, **pp(s):** 351-354,2004. 10.1109/LAWP.2004.840253.

[20] Kuem C. Hwang, “A Modified Sierpinski Fractal Antenna for Multi band Application”, IEEE Letters on Antennas and Wireless Propagation , Vol.6, pp(s):357 – 360, October 2007.

[21] X. L. Bao , G. Ruvio , M. J. Ammann , M. John, “ A Novel GPS Patch Antenna on a Fractal Hi-Impedance Surface Substrate”, IEE Letters on Antenna and Wireless Propagation, Vol.5, pp**(s):** 323 – 326, July 2006.

[22] K. Seol, J. Jung, and J. Choi, “Multi-band monopole antenna with inverted U-shaped parasitic plane,” Electronics Letters, Vol.42, No. 15, pp(s): 844–845, 2006.

[23] R.V. Hara Prasad, Y. Purushottam , V.C. Misra , N. Ashok, “Microstrip fractal patch antenna for multi band communication”, Electronics Letters, Vol.36 , Issue: 14 , pp(s): 1179 – 1180, Jul 2000.

[24] A. B. Abdel-Rahman, A. K. Verma, A. Boutejdar, and A. S. Omar, “Control of bandstop response of Hi-Lo microstrip low-pass filter using slot in ground plane”, IEEE Transactions on Microwave Theory and Techniques, Vol. 52, Issue. 3, pp(s): 1008-1013, March 2004.

[25] C. S. Kim, J. S. Lim, S. Nam, K. Y. Kang, and D. Ahn, “Equivalent circuit modeling of spiral defected ground structure for microstrip line”, Electronic Letters, Vol. 38, Issue. 19, pp(s):1109-1110, September 2002.

[26] D. J. Woo, T. K. Lee, J. W. Lee, C. S. Pyo, and W. K. Choi, “Novel U-Slot and V-Slot DGSs for bandstop filter with improved Q factor”, IEEE Transactions on Microwave Theory and Techniques, Vol. 54, Issue. 6, pp(s):2840-2847, June 2006.

[27] M. K. Mandal and S. Sanyal, “A novel defected ground structure for planar circuits”, IEEE Letters on Microwave Wireless Components, Vol. 16, Issue. 2, pp(s):93-95, Feb. 2006.

[28] H. J. Chen, T. H. Huang, C. S. Chang, L. S. Chen, N. F. Wang, Y. H. Wang, and M. P. Houng, “A novel cross-shape DGS applied to design ultra-wide stopband low-pass filters,” IEEE letters on Microwave WirelessComponents, Vol. 16, Issue. 5, pp(s): 252-254, May 2006.

[29] D. Guha, S. Biswas, M. Biswas, J. Y. Siddiqui, and Y. M. M. Antar, “Concentric ring-shaped defected ground structures for microstrip applications,” IEEE Letters on Antennas Wireless Propagation, Vol. 5, pp(s): 402-405, 2006.

[30] Girish Kumar, K.P. Ray, “Broadband Microstrip Antennas”, Artech House, 2002.

[31] W. L. Stutzman, Polarization in Electromagnetic Systems, MA: Artech House, 1993.

[32] James, J. R., and P. S. Hall, Handbook of Microstrip Antennas, Vol. 1, London: Peter Peregrinus Ltd., 1989.

[33] Bhatacharya, A. K., and R. Garg, “Generalized Transmission Line Model for Microstrip Patches”, IEE Proceedings Microwaves, Antennas and Propagation, Pt. H, Vol. 132, No. 2, pp(s): 93–98, 1985.

[34] S. Babu, I. Singh, and G. Kumar, “Improved Linear Transmission Line Model for Rectangular, Circular and Triangular Microstrip Antennas”, IEEE Antenna and Propagation Theory International Symposium Digest, pp(s): 614–617, July 1997.

[35] Y. T. Lo, D. Solomon, and W. F. Richards, “Theory and Experiment on Microstrip Antennas”, IEEE Transactions on Antennas Propagation, Vol. AP-27, pp(s):137–145, March 1979.

[36] W. F. Richards, Y. T. Lo, and D. D. Harrison, ‘‘An Improved Theory for Microstrip Antennas and Applications”, IEEE Transactions on Antennas PropagationVol. AP-29, pp(s): 38–46, January 1981.

[37] T. Lo, and S. W. Lee, Antenna Handbook, New York: Van Nostrand Reinhold,1988.

[38]T. Okoshi, and T. Miyoshi, “The Planar Circuit-An Approach to Microwave Integrated Circuitry”, IEEE Transactions on Microwave Theory and Techniques, Vol. 20, Issue.4, pp(s): 245–252, April 1971.

[39] K. C. Gupta, and P. C. Sharma, “Segmentation and De-segmentation Techniques for the Analysis of Two Dimensional Microstrip Antennas”, IEEE AP-S International Symposium Digest, pp(s):19–22, 1981.

[40] E. H. Newman, and P. Tulyathan, “Analysis of Microstrip Antennas Using Method of Moments”, IEEE Transactions Antennas Propagation, Vol. AP-29, pp(s):47–53, January 1981, 10.1109/TAP.1981.1142532.

[41] P. Silvester, “Finite Element Analysis of Planar Microwave Network”, IEEE Transactions Microwave Theory and Techniques, Vol. 21, Issue-2, pp(s):104–108, 1973.

[42] H. F. Lee, and W. Chen, Advances in Microstrip and Printed Antennas, New York: John Wiley & Sons, 1997.

[43] T. Itoh, and W. Menzel, “A Full-Wave Analysis Method for Open Microstrip Structure”, IEEE Transactions Antennas Propagation, Vol. 29, pp(s): 63–68, January 1981.

[44] Young-Bae Jung, Soon-Young Eom, and Soon-Ik Jeon, "Novel Antenna System Design for Sat.llite Mobile Multimedia Service", IEEE transactions on Vehicular technology, Vol-59, pp(s): 4237-4247, Issue-9, 2010.

[45] Yikai Chen, Shiwen Yang, and Zaiping Nie, "Bandwidth Enhancement Method for Low Profile E-Shaped Microstrip Patch Antennas", IEEE Transactions on Antennas and Propagation, Vol.58, Issue- 7, pp(s):2442- 2247, 2010.

[46] Hussein Attia, Leila Yousefi, Omar Ramahi, "High-Gain Patch Antennas Loaded with High Characteristic Impedance Superstrates", IEEE Letters on Antenna and Wireless propagation, Vol.10, pp(s): 858-861, 2011.

[47] Ramona Cosmina Hadarig, María Elena de Cos, Fernando Las-Heras, "On the Bandwidth Enhancement of Patch Antenna Using EBG/AMC Structures", IEEE 6th European Conference on Antennas and Propagation (EUCAP), pp(s): 2853-2857, 2011.

[48] Soumyojit Sinha, Anjumanara Begam, "Design of Probe Feed Micro-strip Patch Antenna in S-Band", International Journal of Electronics and Communication Engineering, Vol.5, Issue-4, pp(s): 417-423, 2012.

[49] Y. Sung, "Bandwidth Enhancement of a Microstrip Line-Fed Printed Wide-Slot Antenna With a Parasitic Center Patch", IEEE Transactions on Antennas and Propagation, Vol.60, Issue-4, pp(s): 1712-1716, 2012.

[50] S. T. Fan, Y. Z. Yin, B. Lee, W.Hu, X. Yang, "Bandwidth Enhancement of a Printed Slot Antenna With a Pair of Parasitic Patches", IEEE letters on Antennas and Wireless Propagation, Vol.11, pp(s): 1230-1233, 2012.

[51] P. A. Ambresh, G. M. Pushpanjali, A. A. Sujata, P. M. Hadalgi, P. V. Hunagund, "S-Band compact microstrip antenna with slots", National conference on Challenges in research & Technology in the coming Decades(CRT 2013), pp(s): 1-3, 2013.

[52] Syeda Fizzah Jilani, Hamood-Ur-Rahman, Muhammad Naeem Iqbal, "Novel Star-shaped Fractal Design of Rectangular Patch Antenna for Improved Gain and Bandwidth", IEEE International Symposium on Antenna and Propagation Society (APSURSI), pp(s): 1486-1487, 2013.

[53] Nitin Saluja, Rajesh Khanna, "Design, analysis, and fabrication of a novel multi band folded edge compact size fractal PIFA for Wifi/LTE/Wimax/ Wlan application", IEEE Letters on Antennas and Wireless propagation, Vol.56, pp(s):2836-2841, 2014.

[54] Swaraj Panusa, Mithilesh Kumar, "Quad Band H-slot Microstrip Patch Antenna for WiMAX Application", International Journal of Computer Applications, Vol.103, Issue –12, pp(s):14-16, 2014.

[55] Lei Chen, Tian-Ling Zhang, Chao Wang, Xiao-Wei Shi, "Wideband Circularly Polarized Microstrip Antenna With Wide Beamwidth," IEEE Letters on Antennas and Wireless propagation, Vol.13, pp(s):1577-1580, 2014.

[56] Eun-cheol Choi, JaeW. Lee, Taek-Kyung Lee, Woo-Kyung Lee, "Circularly Polarized S-Band Satellite Antenna with Parasitic Elements and Its Arrays", IEEE Letters on Antennas and Wireless propagation, Vol.13, pp(s):1689-1692, 2014.

[57] N Jayarenjini, A.N Ali Fathima, S.Megha, C.Unni, "Dual Polarized Microstrip Fractal patch antenna for S-band applications", International Conference on Control Communication & Computing India, 2015.

[58] Mohammed N. Shakib; M. Moghavvemi; Wan N. L. Mahadi, "A low profile patch antenna for ultra-wide band application", IEEE letters Antenna and Wireless propagation, Vol.14, pp(s): 1790-1793, 2015.

[59]Amanpreet Kaur, Rajesh Khanna and Machavaram V. Kartikeyan, "A stacked sierpinski gasket fractal antenna with a defected ground structure for UWB/Wlan/Radio astronomy/STM link applications", IEEE Letters on Microwave and Optical technology, Vol.57, pp(s): 2786-2792, 2015.

[60] M. T. Islam, Mengu Cho, M. Samsuzzaman, and S. Kibria, "Compact Antenna for small Satellite Applications", IEEE Magazine on Antenna and Propagation, Vol.57, Issue-2, pp(s): 30-36, 2015.

[61] Faisel Tubbal, Raad Raad, Kwan-Wu Chin, and Brenden Butters, "S-band Planar Antennas for a CubeSat", International Journal on Electrical Engineering and Informatics, Vol.57, Issue-2, pp(s): 559-568, 2015.

[62] Mehr-e-Munir, Khalid Mahmood , "Miniaturized Microstrip Patch Antenna Using Stack Configuration For S-Band, C-Band & Mobile Applications", International Conference on Emerging Technologies (ICET), pp(s): 1-5, 2015.

[63] Markus H. Novak, John L. Volakis, "Ultrawideband Antennas for Multi band Satellite Communications at UHF–Ku Frequencies", IEEE Transactions on Antenna and propagation, Vol.63, Issue-4, pp(s): 1334-1341, 2015.

[64] Qiang Liu, Junyu Shen, Jungang Yin, Hongli Liu, and Yuanan Liu, "Compact 0.92/2.45-GHz Dual-Band Directional Circularly Polarized Microstrip Antenna for Handheld RFID Reader Applications", IEEE Transactions on Antenna and Propagation, Vol.63, Issue-9, pp(s): 3849-3856, 2015.

[65] Ajay Thatere, Dr.P.L.Zade, Dwejendra Arya, “Bandwidth Enhancement of Microstrip Patch Antenna using ‘U’ Slot with Modified Ground Plane”, IEEE International Conference on Microwave, Optical and Communication Engineering, pp(s): 408-411, 2015.

[66] Suyang Shi, Wenquan Che, Wanchen Yang, and Quan Xue, “Miniaturized Patch Antenna With Enhanced Bandwidth Based on Signal-Interference Feed”, IEEE Letters on Antennas and Wireless propagation, Vol.14, pp(s):281-284, 2015.

[67] Pritam Singh Bakariya, Santanu Dwari, Manas Sarkar, and Mrinal Kanti Mandal, “Proximity-Coupled Multi band Microstrip Antenna for Wireless Applications”, IEEE Letters on Antennas and Wireless Propagation, Vol.14, pp(s): 646-649, 2015.

[68] Vandana Satam, Shikha Nema, “Defected Ground Structure Planar Dual Element MIMO Antenna for Wireless and Short Range RADAR Application”, IEEE International Conference onSignal Processing, Informatics, Communication and Energy Systems (SPICES), pp(s): 1-5, 2015.

[69] B. R. Sanjeeva Reddy and D. Vakula, “Compact Zigzag-Shaped-Slit Microstrip Antenna With Circular Defected Ground Structure for Wireless Applications”, IEEE Letters on Antennas and Wireless Propagation, Vol.14, pp(s):678-681, 2015.

[70] Mingjian Liand Kwai-Man Lu, “A Low-Profile, Low-Backlobe and Wideband Complementary Antenna for Wireless Application”, IEEE Transactions on antennas and Propagation, Vol.63, Issue-1, pp(s): 7-14, 2015.

[71] W.S. Yeoh and Wayne S. T. Rowe, “An UWB Conical Monopole Antenna for Multiservice Wireless Applications”, IEEE Letters on Antennas and Wireless Propagation, Vol.14, pp(s):1085-1088, 2015.

[72] Falih M. Alnahwi, Khalid M. Abdulhasan, and Naz E. Islam, “An Ultrawideband to Dual-Band Switchable Antenna Design for Wireless Communication Applications”, IEEE Letters on Antennas and Wireless Propagation, Vol.14, pp(s): 1685-1688, 2015.

[73] Umar Farooq, Mehr-e-Munir, “Multi band microstrip patch antenna using DGS for L-Band, S-Band, C-Band and mobile applications”, 13th International Conference on Modern Problems of Radio Engineering, Telecommunications and Computer Science (TCSET), pp(s): 198-201, 2016.

[74] Yelei Yao, Shaowei Liao, Jianxun Wang, Kai Xue, Esmond Agurgo Balfour, Yong Luo "A New Patch Antenna Designed for CubeSat: Dual feed, L/S dual-band stacked, and circularly polarized", IEEE Journals & Magazines on Antenna and Propagation, Vol.58, Issue-3, pp(s): 16-21, 2016.

[75] Yanshuai Wang, Zhaoyun Duan, Fei Wang, Shifeng Li, Yan Nie, Yubin Gong, Jinjun Feng, " S-Band High Efficiency Metamaterial Microwave Sources", IEEE Transactions on Electron Devices, Vol.63, Issue-9, pp(s): 3747- 3752, 2016.

[76] Anthony Bellion; Kevin Elis; Stéphanie De Gaetano, "New compact S-band antenna for Nanosatellite TeleMetry and TeleCommand applications-EyeSat program", 10th European Conference on Antennas and Propagation (EuCAP), pp(s): 1-5, 2016.

[77] Namrata D. Mahajan; Kunal N. Dekate, "Design and simulation of patch antenna for 3.51GHz S-Band and WiMax application", 2nd International conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB), pp(s): 696-698, 2016.

[78] Jaypal Baviskar, Afshan Mulla, Amol Baviskar, Dinesh Auti and Rohit Waghmare, "Performance Enhancement of Microstrip Patch Antenna Array with Incorporation of MetaMaterial Lens", IEEE conference on Aerospace, pp(s): 1-10, 2016.

[79] Xi Chen, Long Yang, Jia-yue Zhao, and Guang Fu, "High-Efficiency Compact Circularly Polarized Microstrip Antenna With Wide Beamwidth for Airborne Communication", IEEE Letters on Antenna and Wireless propagation, Vol.15, pp(s): 1518-1521, 2016.

[80] Y. M. Pan, P. F. Hu, X. Y. Zhang, and S. Y. Zheng, "A Low-Profile High-Gain and Wideband Filtering Antenna with Metasurface", IEEE transactions on Antennas and propagation, Vol.64, Issue-5, pp(s):2010-2016, 2016.

[81] Xiao Zhang, Lei Zhu, "High-Gain Circularly Polarized Microstrip Patch Antenna With Loading of Shorting Pins", IEEE transactions on Antennas and propagation, pp(s):2172-2178, Vol.64, Issue-6, 2016.

[82] Lixun Li, Yangbo Huang, Li Zhou, and Feixue Wang, "Triple-Band Antenna With Shorted Annular Ring for High-Precision GNSS Applications", IEEE Letters on Antenna and Wireless propagation, Vol.15, pp(s): 942-945, 2016.

[83] Souren Shamsinejad, Franco De Flaviis, Pedram Mousavi, "Microstrip-Fed 3-D Folded Slot Antenna on Cubic Structure", IEEE Letters on Antennas and Wireless Propagation, Vol.15, pp(s): 1081-1084, 2016.

[84] Xi-Wang Dai, Tao Zhou, and Guan-Feng Cui, "Dual-Band Microstrip Circular Patch Antenna With Monopolar Radiation Pattern", IEEE Letters on Antennas and Wireless Propagation, Vol.15, pp(s): 1004-1007, 2016.

[85] N. Nasimuddin, Zhi Ning Chen, Xianming Qing, "Bandwidth Enhancement of a Single-Feed Circularly Polarized Antenna Using a Metasurface", IEEE Magazine on Antennas & Propagation, Vol.58, Issue-2, pp(s): 39-46, 2016.

[86] Dong-Fang Guan, Ying-Song Zhang, Zu-Ping Qian, Yujian Li, Wenquan Cao, and Feng Yuan, "Compact Microstrip Patch Array Antenna with Parasitically Coupled Feed", IEEE transactions on antennas and propagation, Vol-64, Issue-6, pp(s): 2531-2534, 2016.

[87] M. S. Rabbani, H. Ghafouri-Shiraz, "Improvement of Microstrip Patch Antenna Gain and Bandwidth at 60GHz and X -Bands for Wireless Applications", IET Microwaves, Antennas & Propagation, Vol.10, Issue-11, pp(s): 1167-1173, 2016.

[88] Zhixi Liang, Juhua Liu, Yuanxin Li, Yunliang Long, "A Dual-Frequency Broadband Design of Coupled-Fed Stacked Microstrip Monopolar Patch Antenna for WLAN Applications", IEEE Letters on Antennas and Wireless Propagation, Vol.15, pp(s):1289-1292, 2016.

[89] Adrian Bekasiewicz and Slawomir Koziel, "Cost-Efficient Design Optimization of Compact Patch Antennas With Improved Bandwidth", IEEE Letters on Antennas and Wireless Propagation, Vol.15, pp(s): 270-273, 2016.

[90] Renato Cicchetti, Antonio Faraone, "A High-Gain Mushroom-Shaped Dielectric Resonator Antenna for Wideband Wireless Applications", IEEE Transactions on antennas and Propagation, Vol.64, Issue-7, pp(s): 2848-2861, 2016.

[91] Marno van Rooyen, Johann W. Odendaal, and Johan Joubert, "High-Gain Directional Antenna for WLAN and WiMAX Applications", IEEE Letters on Antennas and Wireless Propagation, Vol-16, pp(s): 286-289, 2017.

[92] Jian Dong, Xiaping Yu, and Lianwen Deng, "A Decoupled Multi band Dual-Antenna System for WWAN/LTE Smartphone Applications", IEEE Letters on Antennas and Wireless Propagation, Vol.16, pp(s): 1528-1532, 2017.

[93] Abdelheq Boukarkar, Xian Qi Lin, Yuan Jiang, and Yi Qiang Yu, "Miniaturized Single-Feed Multi band Patch Antennas", IEEE Transactions on Antennas and propagation, Vol.65, Issue-2, pp(s): 850-854, 2017.

[94] Mohamed Aboualalaa, Adel B. Abdel-Rahman, Ahmed Allam, Hala Elsadek, and Ramesh K. Pokharel, “Design of a Dual-Band Microstrip Antenna With Enhanced Gain for Energy Harvesting Applications”, IEEE Letters on Antennas and Wireless Propagation, Vol.16, pp(s):1622-1626, 2017.

[95] Ahmed Dherar Saleh Saif Shaif, Ş. Taha İmeci, “Diamond-Shaped Microstrip Patch Antenna with Defected Ground Structure”, IEEE conference on Signal Processing and Communications Applications Conference, pp(s):1-4, 2017.

[96] J. Zbitou, A. Tajmouati, M. Latrach, A. Errkik, L. El Abdellaoui, “A New Design of a Miniature Microstrip Patch Antenna Using Defected Ground Structure DGS”, IEEE International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS), pp(s): 1-4, 2017.

[97] Suleyman Kuzu and Nursel Akcam, “Array Antenna Using Defected Ground Structure Shaped With Fractal Form Generated by Apollonius Circle”, IEEE letters on Antennas and Wireless Propagation, pp(s):1020-1023, Vol-16, 2017.

[98] K. Wei, J. Y. Li, L. Wang, R. Xu, and Z. J. Xing, “A New Technique to Design Circularly Polarized Microstrip Antenna by Fractal Defected Ground Structure”, IEEE Transactions on Antennas and Propagation, Vol.65, No. 7, pp(s): 3721-3725, 2017.

[99] Yogesh Kumar Choukiker and Santanu Kumar Behera, “Wideband frequency reconfigurable Koch snowflake fractal antenna”, IET Microwave Antennas Propagation, Vol. 11, No.2, pp(s): 203–208, Feb.2017.

[100] Chetna Sharma; Dinesh Kumar Vishwakarma, “Miniaturization of spiral antenna based on Fibonacci sequence using modified Koch curve”, IEEE Antennas Wireless Propagation Letters, Vol.16, pp(s):932–935, July 2017.

[101] Balaka Biswas, R. Ghatak, D.R Poddar, “A fern fractal leaf inspired wideband antipodal Vivaldi antenna for microwave imaging system”, IEEE Transactions Antennas Propagation, Vol. 65, No.11, pp(s):6126–6129, Nov.2017.

[102] T.A. Abed, “Highly compact size serpentine-shaped multiple-input–multiple-output fractal antenna with CP diversity”, IET Microwave Antennas Propagation, pp(s): 636–640, 2018.

[103] Tapas Mondal, Sandip Maity, Rowdra Ghatak, Sekhar Ranjan Bhadra Chaudhuri, “ Compact Circularly Polarized Wide-Beamwidth Fern-Fractal-Shaped Microstrip Antenna for Vehicular Communication”, IEEE Transactions on Vehicular Technology, Vol.67, pp(s):1-9,2018.

[104] N. Kothari and S. Sharma, “A 28-GHz U-slot microstrip patch antenna for 5G applications,” International Journal of Engineering Development and Research, Vol.6, Issue-1, pp(s): 363-368, 2018.

[105] K K. D. Xu, H. Xu, Y. Liu, J. Li and Q. H. Liu, "Microstrip Patch Antennas with Multiple Parasitic Patches and Shorting Vias for Bandwidth Enhancement," *IEEE Access*, Vol. 6, pp(s):11624-11633,2018. doi: 10.1109/ACCESS.2018.2794962.

[106] Amer Abed Sahab, Mandeep Singh, and Mohammad Islam, "Compact Fractal Antenna Circularly Polarized Radiation for Wi-Fi and WiMAX Communications", IET Microwaves Antennas & Propagation. Article. 10.1049/iet-map.2018.5213.

[107] S. F. Jilani and A. Alomainy, "Millimetre-wave T-shaped MIMO antenna with defected ground structures for 5G cellular networks," IET Microwaves, Antennas & Propagation, Vol. 12, Issue. 5, pp(s): 672-677, 2018. doi: 10.1049/iet-map.2017.0467

[108] A. Arif, M. Zubair, M. Ali, M. U. Khan and M. Q. Mehmood, "A Compact, Low-Profile Fractal Antenna for Wearable On-Body WBAN Applications," IEEE Antennas and Wireless Propagation Letters, Vol. 18, Issue. 5, pp(s): 981-985, May 2019.

[109] Yufan Cao , Yang Cai , Wenquan Cao , Baokun Xi , Zuping Qian , Tao Wu, and Lei Zhu, "Broadband and High-Gain Microstrip Patch Antenna Loaded with Parasitic Mushroom-Type Structure", IEEE Antennas and Wireless Propagation Letters, *Vol*. 18, Issue. 7, pp(s): 1405-1409, July2019. doi: 10.1109/LAWP.2019.2917909.

[110] K. Wei, B. Zhu and M. Tao, "The Circular Polarization Diversity Antennas Achieved by a Fractal Defected Ground Structure", IEEE Access, Vol.7, pp(s): 92030-92036, 2019. doi: 10.1109/ACCESS.2019.2927280.

[111] Z. Wang, J. Liu and Y. Long, "A Simple Wide-Bandwidth and High-Gain Microstrip Patch Antenna with Both Sides Shorted", IEEE Antennas and Wireless Propagation Letters, Vol. 18, Issue.6, pp(s): 1144-1148, June 2019. doi: 10.1109/LAWP.2019.2911045.

[112] Guru Prasad Mishra, Biswa Binayak Mangaraj, "Miniaturized microstrip patch design based on highly capacitive defected ground structure with fractal boundary for X-band microwave communications", IET Microwave Antennas & Propagation, Vol.13, Issue.10, pp(s):1593-1601, 2019.

[113] Xiumei Shen, Yujia Liu, Luyu Zhao, Guan-Long Huang, Xiaowei Shi, and Qiulin Huang, "A miniaturized Microstrip antenna array at 5G Millimeter wave band", IEEE Antennas and Wireless Propagation Letters, Vol.18, No. 8, pp(s): 1671-1675, Aug.2019.DOI 10.1109/LAWP.2019.2927460.

[114] Ali Arif, Muhammad Zubair, Mubasher Ali, Muhammad Umar Khan and Muhammad Qasim Mehmood, "A compact, Low profile Fractal Antenna for Wearable On-Body WBAN applications", IEEE

Antennas and Wireless Propagation Letters, Vol.8, Issue.5, pp(s):981-985, May 2019. DOI 10.1109/LAWP.2019.2906829.

[115] Sangeetha Velan, Esther Florence S, Malathi Kanagasabai, Aswathy K Sarma, Chinnambeti Raviteja, Ramprabhu Sivasamy and Jayaram Kizhekke Pakkathillam, "Dual-band EBG integrated monopole antenna deploying fractal geometry for wearable applications", IEEE Antennas Wireless Propagation Letters, Vol. 14, pp(s): 249-252, 2015.

[116] S. Agneessens, S. Lemey, T. Vervust and H. Rogier, "Wearable small and robust: The circular quarter-mode textile antenna", IEEE Antennas Wireless Propagation Letters, Vol. 14, pp(s): 1482-1485, 2015.

[117] A. Gupta, H. Dutt, R.Khanna, "An X-shaped fractal antenna with DGS for multi band applications", International Journal of Microwave and Wireless Technologies, Vol.9, Issue.5, pp(s):1075-1083, 2017.

[118] Hu Zhangfang, Xin Wei, Luo Yuan, Hu Yinping, Zhou Yongxin, "Design of a modified circular-cut multi band fractal antenna", Science Direct Elsevier, Vol.23, Issue.6, pp(s):68-75, 2016. DOI: 10.1016/S1005-8885(16)60072-9.

[119] Taoufik Benyetho, Jamal Zbitou, Larbi El Abdellaoui, Hamid Bennis, and Abdelwahed Tribak, "A New Fractal Multi band Antenna for Wireless Power Transmission Applications", Hindawi Active and Passive Electronic Components, Vol.2018, pp(s):1-10. https://doi.org/10.1155/2018/2084747.

[120] B.B. Mandelbort, "The fractal Geometry of Nature", San Francisco, CA, Vol.8, Issue.4, 1093.

[121] D. L. Jaggard, "On Fractal Electrodynamics", Recent Advances in Electromagnetic Theory, New York, Springer-Verlag, pp(s): 183-224, 1990.

[122] B. M. Hambly, "Fractals and the Modelling of Self-Similarity", ScienceDirect, Handbook of Statistics, Vol. 21, pp(s): 371-406, 2003.

[123] Douglas H. Werner and Suman Ganguly, "An Overview of Fractal Antenna Engineering Research", IEEE Antennas and Propagation Magazine, Vol.45, No.1, pp(s):38-57, 2003.

[124] C. Borja , G. Font, S. Blanch, J. Romeu, "High directivity fractal boundary microstrip patch antenna", IET Electronics Letters, Vol.36, Issue: 9, pp(s):778-779, 2000.

[125] C. S. Kim, J. S. Lim, S. Nam, K. Y. Kang, and D. Ahn, "Equivalent circuit modeling of spiral defected ground structure for microstrip line", Electronic Letters, Vol. 38, Issue.19, pp(s):1109-1110, Sept. 2002.

[126] D. J. Woo, T. K. Lee, J. W. Lee, C. S. Pyo, and W. K. Choi, “Novel U-Slot and V-Slot DGSs for bandstop filter with improved Q factor”, IEEE Transactions on Microwave Theory and Techniques, Vol. 54, No. 6, pp(s): 2840-2847, June 2006.

[127] M. K. Mandal and S. Sanyal, “A novel defected ground structure for planar circuits”, IEEE Letters on Microwave and Wireless Components, Vol. 16, No. 2, pp(s): 93-95, Feb. 2006.

[128] H. J. Chen, T. H. Huang, C. S. Chang, L. S. Chen, N. F. Wang, Y. H. Wang, and M. P. Houng, “A novel cross-shape DGS applied to design ultra-wide stopband low-pass filters,” IEEE Letters on Microwave and Wireless Components, Vol. 16, No. 5, pp(s): 252-254, May 2006.

[129] Park, J.-I., C.-S. Kim, et al., “Modeling of a photonic bandgap and its application for the low-pass filter design,” Asia Pacific Microwave Conference Proceedings (APMC), Vol. 2, pp(s):331–334, 1999.

[130] D. Guha, S. Biswas, and Y. M. M. Antar, Defected Ground Structure for Microstrip Antennas, in Microstrip and Printed Antennas: New Trends, Techniques and Application, John Wiley & Sons, London, UK, 2011.

[131] L. H. Weng et al., 2008. An overview on defected ground structure, Progress in Electromagnetics Research B, Vol. 7, pp(s):173–189, 2008.

[132] Debatosh Guha and Yahia M.M. Antar, Microstrip and Printed Antennas New Trends, Techniques and Applications, John Wiley & Sons, 2011.ISBN: 978-1-119-97298-3.

[133] D. Ahn, J.S. Park, C.S. Kim, J. Kim, Y. Qian, and T. Itoh, “A design of the low-pass filter using the novel microstrip defected ground structure,” IEEE Transactions on Microwave Theory and Techniques, Vol. 49, Issue. 1, pp(s):86–93, 2001.