STUDIES ON STACKED PATCH ANTENNAS FOR WLAN APPLICATIONS

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by

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Declaration

I, Amanpreet Kaur, hereby declare that the matter embodied in the thesis entitled **"Studies on Stacked Patch Antennas for WLAN Applications"** submitted to the **Department of Electronics and Communication Engineering, Thapar University, Patiala, Punjab** is the result of my Studies and research work and this thesis has been composed by me under the guidance of **Dr. Rajesh Khanna**, Professor, Department of Electronics and Communication Engineering, Thapar University, Patiala, Punjab and **Dr. M.V. Kartikeyan,** Professor & Head, Department of Electronics and Communication Engineering, Indian Institute of Technology, Roorkee , Uttarakhand. I also declare that nothing in part or full has been submitted for the award of any degree, diploma, or fellowship to any other Institute or University.

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Abstract

The need for wireless computer communications is growing day by day; with WLAN, WiMAX and UWB technologies emerging as the major technologies in this field currently. As the communication is wireless in nature, an antenna is one of the main requirements of these systems. Typically for the WLAN systems, an antenna is required at the router as well as at the computer terminal that is preferably inexpensive, compact and rugged in nature. Microstrip antennas therefore act as one of the viable choices for such systems which can be preferably designed as multiband antennas with suitable bandwidths that are capable of covering multiple wireless applications for efficient utilization of the resources. A lot of complex techniques are available in the literature that can be used to design and develop Microstrip antennas for these wireless applications; a simpler technique in this context is the use of Stacked/Multilayer Microstrip patch antennas. As the effective height of the antenna increases when multiple substrate layers are used in the antenna structure, and the resulting antenna has loosely bound EM (electromagnetic) fields and that are radiated out better into free space. This leads to an increase in the antenna bandwidth if the two substrates are of same/ close by dimensions and multiple frequencies can be radiated out if the patch antennas are of varying dimensions. Therefore the purpose of this thesis is to investigate the behavior and the design and development of Stacked Patch antennas for wireless applications like WLAN, WiMAX and UWB etc and the methods to develop Stacked Microstrip patch antennas (MSAs) that exhibit multi-frequency and a wideband behavior at these bands.

A defected ground structure (DGS) is another variation that can be incorporated into the antenna structure to enhance the existing bandwidth or get a multiband behavior from the stacked MSAs. On the basis of dimensions and shape of defect in ground plane, the protected distribution of current density in the ground plane is interrupted, leading to a restrained excitation and generation of the electromagnetic waves through the substrate layer that modify the characteristic properties of the transmission line. The shape of the defect may be changed from the simple shape to the complicated shape for getting the desired performance This concept has been used to design and develop four main types of stacked patch antennas in the current research work mainly; a simple rectangular stacked patch antenna (two layers of stacking) with improved

bandwidth, a stacked Microstrip patch antenna with an 'E' shaped defected ground structure for dual broadband operation, a fractal antenna with a cross shaped DGS for dual broadband operation and a complementary rectangular stacked patch antenna with a pie shaped DGS have been designed for the application in wireless bands of IEEE 8.2.11a/b WLAN bands, U-NII-1 ,U-NII-2/2e band, Radio Astronomy, STM band applications, UWB band from (5.28-5.8) GHz, and WiMAX wireless application bands.

All the proposed designs have been developed with a VSWR of less than 2 at their respective resonant bands of operation so that a good impedance matching allows maximum power to be coupled to the antenna from the transmission line. The designed antennas aim at getting an appreciable reflection coefficient of less than 0.33, wide impedance bandwidth, increased gain for long range applications, perfect impedance matching, increased frequency ratio and reasonable antenna size with Dual-wideband operation as the main goals of present research work. This thesis describes original work done on stacked microstrip antennas by using multiple substrate layers (up to three) in the antenna structure with an aperture coupled feeding mechanism with different types of geometries for getting multi-frequency and wideband behavior from the proposed stacked Microstrip patch antennas.

The research work starts with a thorough study of literature available in context to broad banding and multi banding of Microstrip antennas as discussed in chapter two. Chapter 3 presents the design, analysis and verification of results of a simple rectangular stacked patch antenna. A Stacked MSA with aperture coupled feeding has many parameters that can be optimized to obtain a desired behavior from this antenna. A specific design example of a stacked patch antenna at 5.4GHz with a bandwidth of 630 MHz has been considered for analysis purpose. By modifying the shape of the slot cut in the ground plane (DGS) of the aperture coupled stacked patch antenna, a dual band behavior can be achieved , which is explained in chapter 4 where the antenna is able to achieve 200MHz bandwidth at 2.53GHz and 530MHz at the 3.66GHz frequency. By incorporating fractal shaped defects in MSAs; multiband behavior can be obtained and the use of DGS with these antennas can lead to an improved bandwidth at the two bands, this is illustrated in chapter five of the thesis work. Use of complementary slotted stacked patch antennas with the help of a DGS can again lead to an improved bandwidth resulting in an ultra wideband antenna; this is explained in chapter six of the dissertation.

Chapter seven concludes the research work presented in this thesis and the future scope of the work is also presented. This entire research work is verified through analytical simulations using three dimensional Full Wave electromagnetic simulator, Computer Simulation Technology Microwave Studio Version 10.0 (CST MWS V10.0). Experimental studies and measurements have been carried out using Vector Network Analyzer (VNA) E 5071C and an anechoic Chamber operating in the range of 2 KHz to 20 GHz having a standard horn antenna with a calibrated gain of 12dBi.

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Amanpreet Kaur

Contents

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Acronyms and Abbreviations

WLANs	Wireless Local Area Networks
HIPERLAN	High-Performance Radio LAN
MBS	Mobile Broadband System
BISDN	Broadband Integrated Services Digital Network
MIMO	Multiple-Input Multiple-Output Antennas
AP	Access Point
EM Waves	Electromagnetic Waves
MSA	Microstrip Patch Antenna
ISM band	Industrial, Scientific And Medical Band
IMT	International Mobile Telecommunications
Wi-MAX	Worldwide Interoperability For Microwave Access
STM Links	Synchronous Transport Module Level Links
CST MWS V10.0	Computer Simulation Technology Version 2010.
MATLAB R2007	Math Works Matrix Laboratory Version 7
VNA	Vector Network Analyzer
RF	Radio Frequency
VWSR	Voltage Standing Wave Ratio
GHz	Giga-Hertz
RL	Return Loss
dB	Decibel
IEEE	Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunication
ISM	Industrial, Scientific and Medical
MIMO	Multiple Input Multiple Output
FIT Technique	Finite Integration Technique
FDTD	Finite-Difference Time-Domain
PBA	Perfect Boundary Approximation
ASP	Aperture Stacked Patch Antenna
FCC	Federal Communications Commission

TM	Transverse Magnetic
TE	Transverse Electric
DGS	Defected Ground Structure
UMTS	Universal Mobile and Telecommunication Systems
AR	Axial Ratio
PIFA	Planar Inverted-F Antenna
RFID	Radio Frequency Identification
CP	Circular Polarization
RF	Radio Frequency
RFID	Radio Frequency Identification
RL	Return Loss
FCC	Federal Communication Commission
OFDM	Orthogonal Frequency Division Multiplexing
ε	Dielectric Constant
GUI	Graphic User Interface
SMPA	Stacked Microstrip Patch Antenna
TEM	Transverse Electric Magnetic
TM	Transverse Magnetic
UHF	Ultra High Frequency
PCB	Printed Circuit Board
UWB	Ultra Wide Band
VNA	Vector Network Analyzer
Wi-Fi	Wireless Fidelity
3D	Three Dimensional
UNII	Unlicensed National Information Infrastructure (U-NII) Radio Band
PIFA	Planar Inverted F Antenna
GPS	Global Positioning System
SMA	Subminiature
dBi	Decibel With Respect to Isotropic
EBG	Electromagnetic Band Gap Structures

CHAPTER 1
INTRODUCTION

1.1. Introduction

Communication of information from one point to other is one of the major requirements of human race in the present era. Moreover the mobile, multimedia and computer communications have an increased role in our day to day lives for providing ubiquitous communication. This has offered new challenges to all those who are working towards the enhancement of telecomm systems for future. Apart from that, the telecom industry's main aim is to establish as many links as possible between or to the wireless terminals.

Another major challenge for the current wireless systems is to cope up with the ever increasing demand of providing high data rates. As an example, several wireless broadband systems that are expeditiously emerging to offer data rates greater than 2Mbps. Several wide band services are also being predicted for different types of end users with different needs; these may provide data rates varying from 2 Mbps to 155 Mbps. These wireless communication services offer a great deal of versatility, the terminals on the devices meant for the wireless communications can be motile (moving) or static (portable). There can be a variation in the communication scenario also; the moving speeds can be very fast sometimes when the user is travelling on a train or a car. The users may be allotted one or more channels according to their usage. The bandwidth allotted to the communication system might be locked or sometimes dynamically allotted also. The communication between wireless terminals might be done directly or it might be possible through a base station. Many other techniques can be referred to for achieving the wireless communication depending upon the user's needs.

Many wireless applications can be mentioned as making the distinction among different aspects of wide band services. The two main approaches that are emerging evidently are the wireless local area networks (WLANs) which aim at communication to computers or other compatible devices wirelessly. High-Performance Radio LAN (HIPERLAN) and Mobile Broadband System (MBS) work as a cellular system providing motility to Broadband Integrated Services Digital Network (BISDN) users [1].

A wireless LAN or the IEEE 802.11 network is a data transmission system which is devised to provide wireless network communication between computers by using radio waves rather than a wired network. The IEEE 802.11 standard enables the users to carry out WLAN computer communications in the 2.4GHz and the 5GHz frequency bands of the Electromagnetic spectrum. They are managed by the IEEE LAN/MAN Standards Committee (IEEE 802). The

802.11a standard operates in the 5 GHz band and supports a data rate of 54 Mbps, IEEE 802.11b is operational at 2.4GHz band and is backed by a maximum bit rate of 11 Mbps and the 802.11g operates at the physical layer at either 2.4GHz/5GHz and is capable of providing maximum bit rate of 54 Mbps. The IEEE 802.11n is a latest version which improves upon the previous 802.11 standards by adding multiple-input multiple-output antennas (MIMO) and many other newer features.

Figure 1.1 shows a typical WLAN system for computer communications in an area having a cellular radius of around one hundred meters.

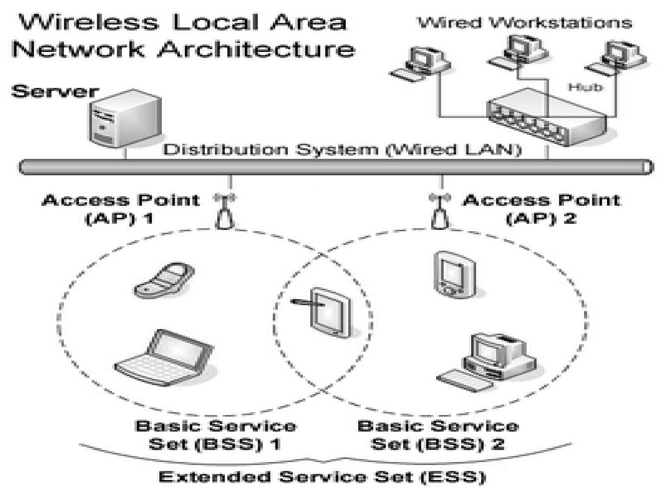


Figure 1.1: A typical WLAN network example [2]

In Figure 1.1, the WLAN network has an Access Point (AP) in the centre, which is linked to a wired network at the backbone and a number of stations are connected to this central Access Point (AP) wirelessly. These set of devices (computers and Access points) in a given area form a basic service set. There are mainly two modes of communication in this set up; centralized and a decentralized mode. In a centralized mode, communication between computer stations is actually carried beyond by the Access Points. While in a decentralized mode, the communication between two stations can take place directly without the requirement of an access Point in an ad hoc fashion.

For a centralized mode of communication between the computer stations and the access point; an antenna plays the role of a transitional device and provides a means for converting guided waves in the transmission line to free space waves in air at the transmitter side and vice versa at the receiver side. According to the IEEE, an antenna is defined as a means of transmitting and receiving EM (Electromagnetic) Waves. It is actually a transducer that converts an electrical signal to an Electromagnetic signal which is propagated out into free space. Figure 1.2 shows an antenna acting as a transitional structure (at the transmitter side) between a guided wave, flowing through a transmission line and a free space wave that is radiated out by the antenna into air [3].

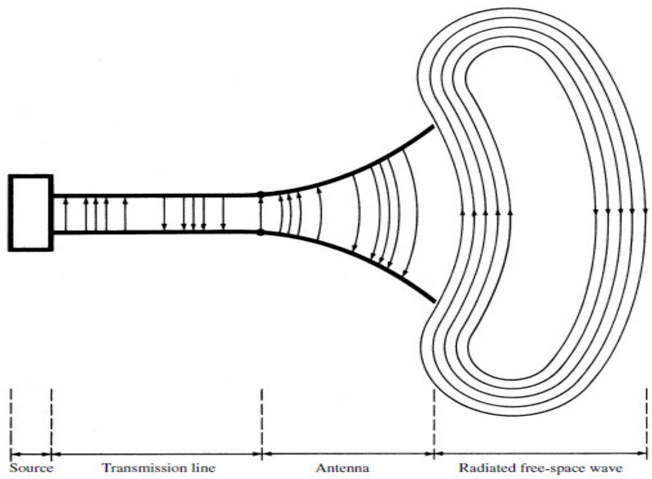


Figure 1.2: Antenna as a transitional device [3].

The main requirement of the broadband IEEE 802.11 systems is to have a good broadcast range without loss of signal quality. The range of coverage is directly correlated with the antenna performance and this fact impresses upon the importance of a good gain and a broad bandwidth antenna. A main specification of a WLAN antenna is that it should be low profile, so that is almost invisible to the user. The WLAN system coverage sometimes needs to be limited to the required areas only and since the 802.11x systems use the ISM (Industrial Scientific and Medical) bands; these are transmitted with power constraints to avoid interference. Thus it is mandatory for the WLAN system to be highly directive in order to lower the coverage in undesirable areas.

The current need of wireless communication systems, (example given as in the case of WLAN above) is to cover multiple wireless application bands within one device only. With this requirement, one can imagine a myriad of antennas required both at the base station and also on the respective device. There are additional challenges to hoist more antennas onto an already packed tower mast, or to pack the antennas into a reducing mobile terminal platform [4]. An increased demand towards the usage of multi frequency bands with one antenna on the device has therefore aroused. The main purpose of carrying out this research work is therefore to reduce number of antennas in the proposed wireless communication systems by proposing multiband antennas that support a good bandwidth at the desired resonant frequencies of operation to cover the respective data rates for those wireless applications of interest [5].

The MSA (Microstrip Antenna) satisfies almost all these requirements thus making them a them a preferred solution for WLAN and other RF systems due to their smaller physical area and ability to get concocted with the surroundings [10]. A conventional MSA is inherently a low bandwidth antenna possessing about 5% bandwidth around the center frequency of operation [3]. Several well defined techniques have been reported in the literature for achieving a broadband and multiband performance of the MSA [11-13]. Nevertheless, these approaches make the antenna structure quite complex to design and implement. These approaches also demand for a thick dielectric substrate to achieve a good bandwidth at the resonant frequency of operation.

A comparatively simpler technique to achieve a multiband and a wideband performance from MSA is to use stacked/multilayered microstrip patch antennas with aperture coupled feeding mechanism. This allows a multiband behavior of the MSA to be achieved because of stacked patches of varying dimensions and wideband characteristics at these resonant bands because of increased effective height of the antenna. This approach utilizes the fact that Microstrip patch antenna acts a resonator and the second patch is also a resonator for the respective resonant frequencies of multiband operation [14]. In case the two patch antennas are chosen to be of dimensions such that they correspond to nearby resonant frequencies, this configuration can be used for increasing the bandwidth of the MSA too[15]. The bottom patch in a stacked antenna that is fed with power is referred to as the driven patch whereas the top patch antenna which is electromagnetically coupled with the lower patch gives rise to a second resonant frequency is the parasitic patch.

Stacking multiple layers of a patch antenna also upgrades the operational characteristics of the patch antennas like gain, bandwidth, efficiency and input impedance and also reduces the phenomenon of cross polarization. It is also known that the impedance bandwidth of a MSA is proportional to the antenna’s volume calculated in terms of wavelengths. So by using two stacked shorted patches and allowing both the patches to radiate almost as equally as possible, one can achieve increased impedance bandwidth for a fixed antenna volume [15].

This Stacked antenna technique can be carried on with different feeding methods. Since the MSAs fed with aperture coupled feeding technique are low priced and have an ease of fabrication as compared to coaxially fed antennas (where the inner conductor of feed line is drilled to stimulate the patch antenna), there is a driving force towards the design of stacked patch antennas with an aperture coupled feeding mechanism. Moreover an aperture coupled feeding method has an added advantage that no interference is received from the feed network system that can interfere with the antenna's radiation pattern [16].

1.2. Motivation for Research

Mentioning specifically about the WLAN systems, a key requirement of a WLAN and other wireless systems with handheld devices is that the antenna should be of a small size, so that it is almost invisible to the user. The MSA offers an exceptional solution amongst the antennas of choice for WLAN devices due to their small occupied area and the ability to be designed to fuse into the surroundings.

These MSA's also referred to as Patch antennas, offer a great versatility in the antenna design since these are simpler and cost-effective to manufacture as compared to other antennas. By incorporating specific design techniques in the MSA, a multiband antenna with appreciable bandwidth at the desired resonant frequencies of operation can be achieved [6, 7]. Using stacked patch antennas with multiple layers of dielectric substrates and multiple antennas printed over them can be used to excite multiple resonant frequencies. The air gap between the substrates can also be varied to obtain an increased bandwidth [8, 9].

Thus the current research focuses on the study about the various broad banding techniques used for MSA's operating for WLAN and other wireless applications. Considering the advantages of stacked patch antennas over other techniques of achieving a multiband or a wideband behavior, in this thesis the stacked microstrip antennas for next generation wireless systems are considered as the main area of research. This is followed by the investigations being carried out in the field of stacked microstrip antenna design, fabrication and the experimental testing of the proposed (simulated) antenna structures as the case studies for the current research work and their analysis for any errors in measurements.

This gives an initiative for the current research work that deals with the design, simulation, fabrication and experimental verification of the results of a Stacked MSA's for

WLAN , WiMAX (Worldwide Interoperability for Microwave Access) and some more wireless applications like Zigbee, ISM (Industrial Scientific and Medical) radio band, IMT (International Mobile Telecommunications) band etc. In order to analyze the antenna's performance an acceptable amount of groundwork needs to be done in terms of literature review in the field of existing broad banding and multi banding techniques with Microstrip antennas. Study of parameters like the return loss (S_{11} in dB), radiation pattern, voltage standing wave ratio, axial ratio bandwidth and gain plots is also needed for the analysis of results.

Thus the main aim of the current research work presented in this thesis is to study the use of stacked patch antennas as a method of improving the antenna bandwidth followed by design of stacked MSAs for multiband behavior with appreciable bandwidth to cover the WLAN, Wi-MAX, Zigbee, IMT and ISM band and many other wireless applications. The antennas are fabricated and experimentally tested for verification of results also which are found to be in close approximation with the simulated ones.

These antennas are implemented as three layered stacked structures of FR4 with an aperture coupled feeding and defected ground structures (DGS).Slots and Fractal Defects are also incorporated in the antenna designs that help in allowing the antenna to achieve desired operational characteristics.

1.3. Problem Statement

The main aim of the research work is to implement stacking as a viable technique for design and implementation of antennas for WLAN scenario. The design problems of WLAN antenna domain are then considered and the antennas are optimized. One of the problem statements of the research work is to prepare an overview and study of stacked microstrip antennas for multiband operation and bandwidth enhancement [16]. For the feasibility of achieving the aim of the research work, a suitable literature survey is carried out in the field of stacked microstrip antennas for obtaining a multiband and a wideband behavior. A thorough study is done regarding the different feeding techniques used with MSA and then Stacked Aperture coupled MSA's are proposed.

In order to achieve the desired characteristics from the MSA, the ground structures of the proposed antennas are implemented with some defects and patches with fractal and complementary shapes and slots. After carrying out the necessary literature survey about the stacked MSA, the following objectives for the current research were defined.

1.3.1. Research Objectives

- To study different broad banding techniques used with microstrip patch antennas.
- To design and simulate a new optimized patch antenna for WLAN operation covering specific band of operation.
    - Parametric study of proposed antenna.
    - Fabrication and testing of the proposed antenna.
- To design and simulate a new circularly polarized stacked patch antenna with a defected ground structure covering specific bands for WLAN/Bluetooth/Zigbee/Wi-Max/ IMT band applications.
    - Parametric study of proposed antenna.
    - Fabrication and testing of the proposed antenna.
- To design and simulate a new stacked Sierpinski gasket fractal antenna with a defected ground structure for UWB/WLAN/Radio Astronomy/STM link Applications.
    - Parametric study of proposed antenna.
    - Fabrication and testing of the proposed antenna.
- To design and simulate a new complementary stacked microstrip antenna with a ‘π’ shaped defected structure for UWB, WLAN, WiMAX and Radio Astronomy Applications.
    - Parametric study of proposed antenna.
    - Fabrication and testing of the proposed antenna.
- Comparison of simulated and measured results experimentally for validation of results and applicability of the antenna in the wireless scenario.

In order to consummate the above mentioned research objectives and portray the potential efficacy of the proposed stacked multiband/wideband MSA’s, a compilation of different problems have been considered and solved. These problems are as follows.

- Effect of stacking two simple rectangular patches of same dimensions without an air gap.
- Effects of using an ‘E’ shaped DGS in a simple rectangular stacked patch antenna.
- Effects of using a feed line with a stub and a cross shaped DGS with fractal patch

antennas.

- Effects of using slots in patches such antenna that the size of lower patch antenna is approximately the same as the slot size in the upper patch leading to a complementary geometery and the use of a pie shaped DGS.
- Effects of using fractal shaped defects with stacked antenna geometery.

1.3.2. Scope

The research work concentrates on the problem recognition, simulation and parametric study for the analysis of results. Fabrication and testing of the proposed antennas for different wireless applications is also done for verification of the results. The Table 1.1 shows different bands of wireless communication for which antennas are proposed.

The proposed antennas need to possess a good return loss, a high gain and an appreciable bandwidth (as given in the table) at the respective bands of antennas operation, to fulfill the requirement of being suitable for long range applications of the respective wireless band . The antennas presented in the current research work are well suited for IMT, WLAN, Bluetooth, Zigbee, Radio Astronomy, STM (Synchronous Transport Module level) Links, UWB (Ultra Wideband) and Wi-MAX applications. Since the Stacked patch antennas are novel designs and are successfully tested for the mentioned applications, these can successfully be used for commercial applications too.

Table 1.1: Bandwidths Required at Some Wireless Application Bands

Wireless Standard	Frequency Band (MHz)	Bandwidth(MHz)
IMT (International Mobile Telecomm.)	2300-2400 2700-2900 3400-4200 4400-4900	100 200 800 500
Bluetooth	2400-2500	100
ZIGBEE	2400-2485	85
Radio Astronomy	5010-5030	200

Wireless Standard	Frequency Band (MHz)	Bandwidth(MHz)
STM Links	6000-6170	170
UWB	4750-5280	530
Wi-MAX	3400-3700	300
UNI-1	5180-5240	600
UNI-2	5260-5700	440
UWB	5280-5850	670
WLAN Standard	2400-2485 5150-5350 5725-5825	84 200 100

1.4. Methodology

- The research work starts with the study of different broad banding techniques used with microstrip antennas.
- A thorough literature survey is done regarding the design and implementation of stacked MSAs and MSA with slots and fractal shaped defects.
- The importance of using stacked patch antennas with as a method of increasing the bandwidth is then explored.
- Design problems for WLAN, Wi-MAX, Zigbee, Bluetooth, IMT band, UWB antenna domain are then considered and optimized.
- Parametric study of the antennas is done to analyze the antenna's response at different parameters like resonant frequency, return loss, gain, radiation pattern and impedance bandwidth etc.
- The simulation of proposed antenna designs is done using Full Wave Electromagnetic Simulator CST MWS V10.0 (Computer Simulation Technology version 2010).A parameter sweep option in the transient solver window that is based on the FIT simulations is responsible for carrying out the optimization of antenna parameters.
- The modeling and optimization process for patches is followed by actual fabrication and their performance evaluation is done by comparison with standard simulated results .The results are measured using a VNA (vector network analyzer) E5071C for return loss and

in an anechoic chamber (operating from 20KHz to 8GHz) for gain measurements.

- The antennas are printed using wet etching technology on a commercially available Glass Epoxy FR4 substrate with a dielectric constant of 4.4 and a height of 1.57mm.
- The comparative analysis of simulated and measured results in terms of impedance band width (return loss) and radiation pattern (in terms of gain), the simulation software Math works Matrix Laboratory Version 7 MATLAB R2007b has been done to validate the results.

1.5. Organization of Thesis

The main aim of this thesis work is to emphasize the potential applicability of stacked microstrip patch antennas for different wireless applications like WLAN, Bluetooth, Zigbee, Radio Astronomy, STM Links, UWB and Wi-MAX applications etc. The background of the research work is formed from the available knowledge gained from consulting research papers of various standard journals in the field of antennas.

Some novel antenna designs are presented in this thesis with their parametric studies presented that underline the responsibility respective antenna parts responsible for the resonant operation of the antenna. This supports/backs the theoretical concepts explained behind the respective resonant behavior of the antennas.

This research work is helpful to academia and industry personnel working in the field of microstrip antennas, so the lingual format is kept easy and understandable for reference accordingly.

The thesis work is organized into seven chapters, each chapter starts with a quick introduction of the work to be done and it concludes with the major results achieved in that chapter.

- **Chapter 1** gives an introduction about the current wireless technologies available and a need to make the devices associated with these technologies as compact as possible.

  The use of microstrip patch antennas for such applications has been highlighted. This chapter also discusses the scope of thesis work and the thesis organization too.
- **Chapter 2** deals with the basics of microstrip patch antennas and the literature survey carried out to form the foundations of the current research work.
- **Chapter 3** illustrates the use of a stacked patch antennas for bandwidth enhancement for

a conventional MSA. A multilayer antenna with two stacked patches of the same size is designed at a single resonant frequency. Investigations are carried out on the design parameters of this stacked antenna to study the effect of each parameter individually in optimizing the antenna performance. The results are verified after testing the prototype of the antenna using a VNA and an anechoic chamber.

- **Chapter 4** covers the second objective of the thesis work. A new circularly polarized stacked patch antenna with a defected ground structure covering specific bands for WLAN, Bluetooth, Zigbee, Wi-Max, IMT band applications has been designed and tested. Two patch antennas radiating at close by frequencies lead to a wideband behavior at one band and the ‘E’ shaped DGS is responsible for the second band of antenna’s operation.
- **Chapter 5** presents the third objective of the thesis work. In this chapter a new stacked Sierpinski gasket fractal antenna with a defected ground structure for UWB, WLAN, Radio Astronomy and STM link applications has been designed and tested. The fractal defects are responsible for a multiband behavior and a cross shaped DGS is used to improve the bandwidth.
- **Chapter 6** covers the fourth objective of the research work; it deals with a stacked patch antenna with two complementary shaped rectangular patches and a ‘π’ shaped defect in the ground layer giving it a defected ground structure geometery. This antenna shows an ultra wideband behavior from 5.14GHz to 5.85 GHz covering the wireless applications of UWB, WLAN, Wi-MAX and Radio Astronomy.
- **Chapter 7** draws the conclusions of the thesis work and covers the future scope of the current research work carried out in the presented thesis work.

CHAPTER 2
LITERATURE REVIEW AND PRELIMINARIES

2.1 General Introduction

The demand for wireless systems which support a high rate at a high speed is enormous. An implied need for compact and cost effective integrated antennas for handheld RF (Radio Frequency) devices is there for the rapidly expanding military and commercial wireless communications systems. In addition because of the latest developments in RF and high density microwave circuit packaging technologies used in wireless communications systems, a demand for a hand in hand development of compact and efficient antennas that can be applied to a broader range of frequencies is also there [1- 4]. Compact antennas for typical wireless applications like WLAN, Wi-MAX, Bluetooth, MIMO and IMT band applications handheld devices are thus highly in demand [18].

This has motivated the researchers to explore the field of compact printed antennas which are smaller in size, adaptable to homogeneous and unleveled surfaces. Further these antennas are demanded to be un-complicated and cheap to fabricate by applying latest photolithography techniques. These antennas should also be sturdy when seated on hard line surfaces and adaptable to Monolithic Microwave Integrated Circuit designs, when a specific patch antenna shape and its mode of operation are selected. These antennas are also very resourceful in terms of characteristics of antenna operation like the resonant frequency of operation, polarization of transmitted EM waves, radiation pattern, and input impedance [3, 18]. A microstrip antenna, as it satisfies all these requirements is an excellent candidate for application in such systems [3, 19].

These antennas are printed antennas on soft dielectric substrates, they can also be considered as smooth resonant cavities that transmit EM fields from their boundaries and help the antenna in radiation. As an example, the manufacturers of cellular communication base stations antennas usually fabricate these structures directly in the metal sheet used for handsets and position them on dielectric plates or sometimes on foam and in many more types of ways to reduce the cost of manufacturing the antenna with separate substrates and etching [19].

These antennas have an inherent disadvantage of low bandwidth (5% at the center frequency of operation); therefore numerous and well-known methods are available in the literature to improve upon their bandwidth. Some of these techniques follow the usage of thick and low dielectric constant substrates [20], a lot of impedance matching and feeding techniques can be used for bandwidth improvement [21], patch antennas with slots cut in their structure for multiple resonances [22] and parasitic patches [23] can be used to enhance the performance of these antennas.

A lot of work has been carried out regarding the increase in the bandwidth of MSA by increasing substrate thickness. As an example in [24], two small and broad-band antennas were designed, measured and characterized by introducing thick substrates with low permittivity; thus broad-band behavior of the proposed patch antennas was easily achieved by the authors. But with increase in the height of substrate layers, there is disturbance caused to the surface waves and these are eventually scattered at the substrate boundaries. This undesired emission of EM waves, lowers the gain of antenna while radiating [25].

Another method which effectively increases the radio frequency band of microstrip antenna's operation is the use of manifold dielectric layers of substrate with printed patches over them in geometry called the stacked microstrip antenna. In [26], the authors presented a variability of the conventional aperture-coupled stacked microstrip antennas which greatly improved the antenna's bandwidth and allowed bandwidths of up to one octave to be easily attained. The authors compared impedance behavior of the new proposed antenna structure with that of other wide-band microstrip antennas radiators and also introduced some matching techniques for the antenna with their relative benefits as compared to other techniques [26].

Since the aperture coupled MSA are inexpensive and easily manufacture-able in comparison to the coaxially fed antennas in which drilling is critical issue in exciting the patch (drilling point also has to be judiciously selected for impedance matching), these antennas are a preferred choice among researchers. The aperture coupled antennas on the other hand provide a better gain, radiation efficiency and impedance bandwidth as compared to the other two methods with contacting feeds. Such electromagnetically coupled antennas offer lesser VSWR and return loss as compared to antennas fed with other types of feeding techniques. Because of the above mentioned advantages of multilayer and aperture coupled microstrip antennas, these two techniques can be combined to design an aperture coupled multilayer antenna with an improved gain and bandwidth [27].

Thus Stacked microstrip antennas with a parasitic feeding method in which a ground is sandwiched between two substrate layers and an aperture is cut in the ground plane is supposed to be a good candidate for research in the field of design and development of antennas (specifically for wireless communications operating on multiple applications with handheld devices for operation).The next subsection presents the basics of microstrip antennas and an introduction to the Stacked Patch Antennas and the operation principles of such antennas.

2.2. Microstrip Patch Antenna: An Overview

A microstrip antenna is a printed antenna, with its basic geometry consisting of a very thin metallic layer (patch) placed a small fragment of wavelength (corresponding to the frequency of operation) above the ground plane. These antennas usually operate at frequencies between 1 GHz to 100 GHz [3]. Their operation can be explained by considering these antennas as planar resonant cavities that have leaking fields that flow from their edges and cause radiation [17]. Figure 2.1 shows a simple microstrip patch antenna.

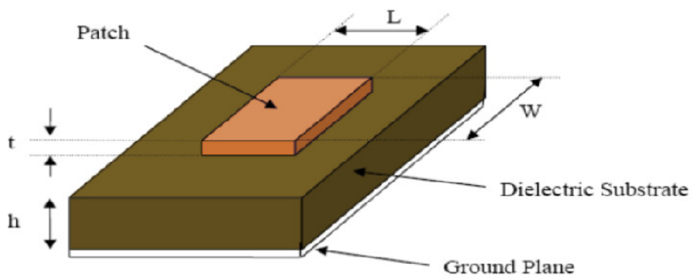


Figure 2.1: Microstrip Patch Antenna [28]

The operation of microstrip antennas can be examined with the help of fact that when these antennas are excited at the fundamental TM_{10} mode, the electric fields that are distributed on the patch surface due to excitation do not stop at the patch's boundary and extend towards the outer periphery of the antenna. These extended fields from the patch surface are called fringing fields and are radiated out by the antenna as Electromagnetic waves into free space [3, 28]. The dielectric constant of substrates affects the performance of this antenna, lower is the substrate dielectric constant that is used for making the antenna, more loosely bound are the fields and better is the radiation from the antenna. This microstrip patch usually operates such that its pattern maximum i.e. the major lobe of the antenna's pattern is normal to the patch and operates with its radiations concentrated mostly in the broadside directions. This behavior can also be cultivated by properly choosing the mode (field configuration) of excitation below the metal patch at the feed network [3]. Figure 2.2 shows a patch antenna radiating from its edges. The dimensions Length (L) and width (W) of the patch and height (h) of the substrate are chosen such that height h is far less than the operational wavelength and it is usually $0.03\lambda_0 < h < 0.05\lambda_0$. The length L of the patch element usually is given as $0.33\lambda_0 < L < 0.5\lambda_0$, where λ_0 is the free space wavelength at the frequency of operation.

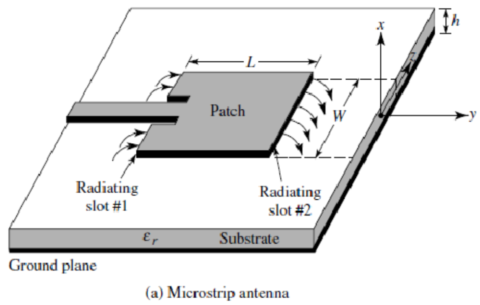


Figure 2.2: MSA radiating from its edges [3]

MSAs are gaining considerable attention these days because of the following advantages.

- They are light in weight and the volume is also quite less.
- A planar configuration which makes them conformable to the host surface.
- These are cost effective to fabricate and implement.
- These antennas can support both linear and circular polarization.
- Capable of providing multiple resonances.
- They are mechanically sturdy when mounted on solid surfaces.
- Adaptable to Monolithic Microwave Integrated circuits too.

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

- They possess a narrow bandwidth at the frequency of operation.
- These antennas have a low gain and efficiency.
- A low power handling capability approximately 20 Watts.
- Surface wave Excitation.
- Extraneous radiation from feeds and junctions [3].

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

2.2.1. Microstrip Antenna Feeding Techniques

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

- Coaxial feeding
- Microstrip line feeding; sub classified into inset feed and Edge feeding.
- Proximity feeding
- Aperture coupled feeding

2.2.1.1. Coaxial Feeding

The Coaxial feeding method consists of a coaxial wire whose intrinsic / active conductor is drilled through the antenna suitably to the patch surface and the extrinsic conductor / ground is connected to the ground layer of the patch antenna. The position of inner conductor of the coaxial cable connected at the patch can be varied to achieve effective impedance matching for the antenna. Figure 2.3 shows an example of a patch antenna fed using a coaxial connector. This method of feeding microstrip antennas is quite common as it is easy to fabricate and it presents a low level of spurious / false radiations. But it has a disadvantage that the protruding structure outside the ground plane of the coaxially fed antenna structure makes the antenna unfeasible to be used in wireless systems effectively [29].

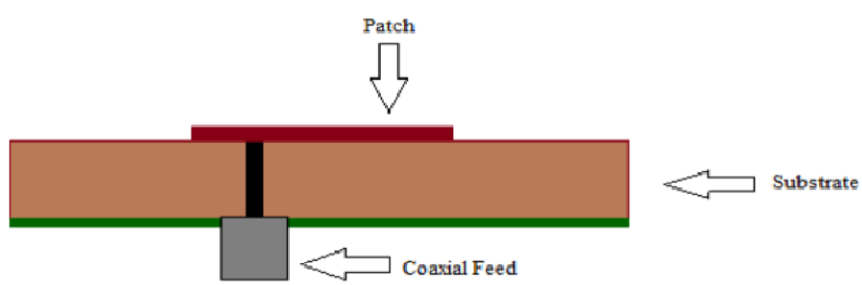


Figure 2.3: MSA fed using a Coaxial Feeding Technique [29]

Work has been done by several researchers to design and implement such antennas for different wireless applications, for example authors in [30] presented a patch antenna whose shape was a polygon with twelve sides and it was fed using coaxial feeding arrangement for applications in Wi-Fi systems. Figure 2.4 shows the front geometry of the proposed antenna.

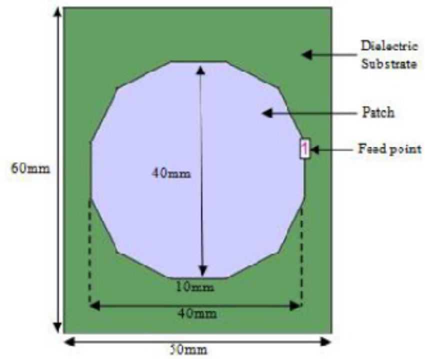
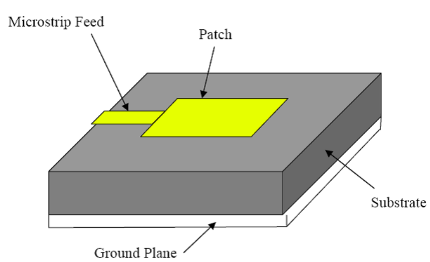


Figure 2.4: Twelve Sided Polygon with coaxial feeding technique [30]

2.2.1.2. Microstrip Feeding

In this feeding technique, a strip line adjoining the patch (of the same thickness as the patch) is photo etched on the substrate. This extends from the boundary of the substrate to the patch and its dimensions decide the impedance matching that has to be achieved for the patch antenna's operation. This feeding method is basically of two types; Inset feeding and Edge coupled feeding.

In edge coupled feeding mechanism, an electrically conducting metal layer (of the same thickness as the patch) is coupled directly to the radiating corner of the microstrip patch as shown in Figure 2.5. The conducting patch is smaller in breadth in comparison with the radiating patch.



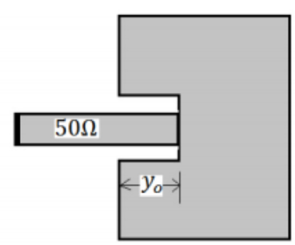


Figure 2.5: Edge feeding method [6] **Figure 2.6: Inset feeding method [6]**

Figures 2.5 and 2.6 represent the edge feeding and the inset feeding methods for microstrip antenna respectively. Since the magnitude of current flow is lower at the end of the patch and increases towards the central area of the patch; the input impedance reduces if the microstrip line is attached towards the center of the patch [6].The main advantage of this technique is its ease of implementation.

An example antenna of this feeding technique has been proposed by authors in [31]. A dual-band microstrip antenna fed using the microstrip feed line was proposed. In the patch structure, a pair of inverted L-shaped patches was patterned. The ground plane was formed of a cross shape by the authors in their design. Figure 2.7 shows the front view of the antenna.

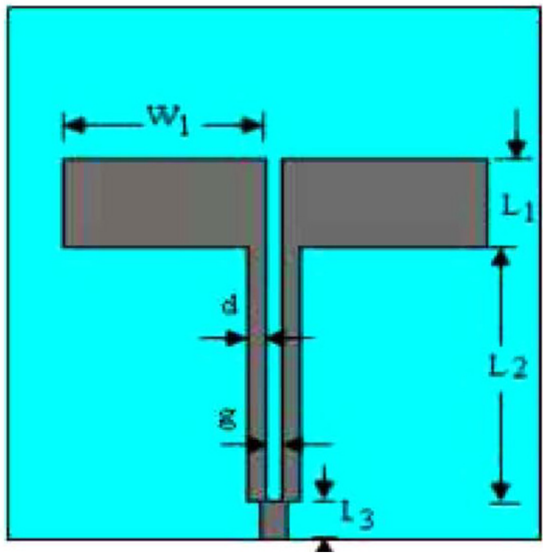


Figure 2.7: MSA fed using microstrip feeding [31]

2.2.1.3. Proximity Coupled Feeding Method

This type of feeding technique follows an electromagnetically coupled feeding mechanism(refer to Figure 2.8) ; here the patch antenna is parasitically coupled to the feed network where the transmission line is sandwiched in between the ground plane and patch which are printed on two separate substrates. Coupling of fields takes place from the transmission line to the metal radiator patch. Since the overall height of antenna increases, this technique of feeding MSA is quite beneficial and it leads to an increased bandwidth by around 21% as compared to other feeding methods [3]. An example of this kind of antenna is presented in the literature by authors in [32] where a stacked Sierpinski gasket fractal antenna with proximity feeding is proposed that gives an enhanced bandwidth of 64 MHz at the 2.4 GHz frequency band and offers a bandwidth of 500 MHz at the 5.8 GHz WLAN bands. Figure 2.9 shows the proposed design by the authors; the designed antenna was optimized up to second iteration of sierpinski gasket fractal to achieve the desired results [32].

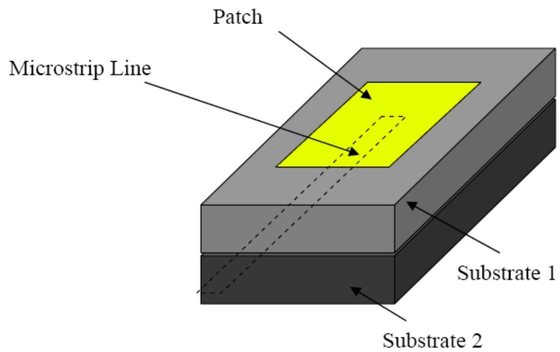


Figure 2.8: A Proximity Coupled Antenna [32]

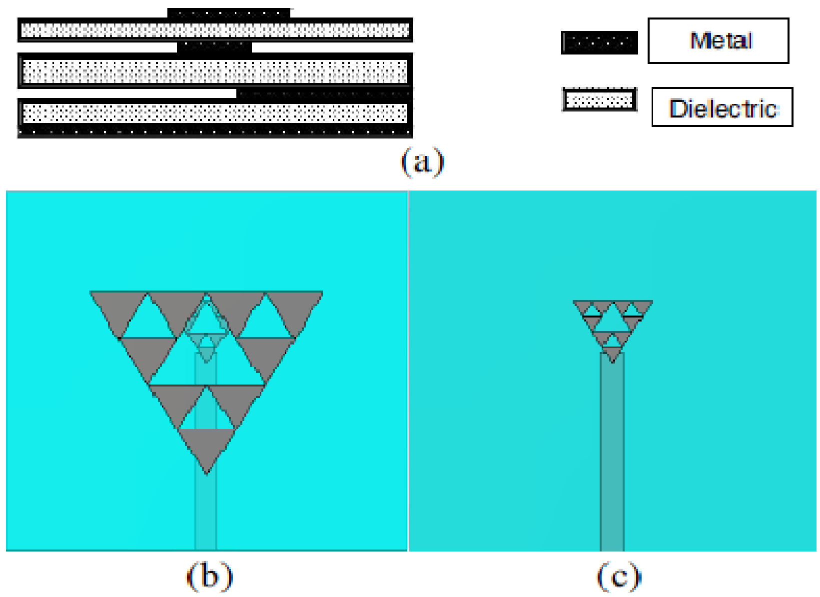


Figure 2.9: Sierpinski gasket MSA with proximity feeding [32]

2.2.1.4. Aperture Coupled Feeding Method

The aperture coupling method of feeding MSA consists of a metal ground plane sandwiched between two layers of substrates. On the upper substrate layer, a patch is printed and on the base of the lower substrate, a microstrip feed line is formed. The energy from the feed network is coupled to the patch through a slot in the ground plane that separates the upper and the lower substrates. This arrangement helps in optimizing the antenna's output by optimizing the feed structure and the radiating patch independently. To obtain a good bandwidth and low spurious fields from the antenna, a high dielectric constant material is used for the lower substrate (with feed line) and thick low dielectric constant material for the upper substrate (with patch printed over it) usually. The ground layer that is in between the upper and the lower substrates also helps in isolating the feed from the radiating element and minimizes interference of spurious radiation to obtain polarization purity of the results [3]. Figure 2.10 shows the basic layout of an aperture coupled microstrip patch antenna. For such structures, the dimensions of the slot can also be optimized to achieve a good bandwidth at the resonant frequency of operation.

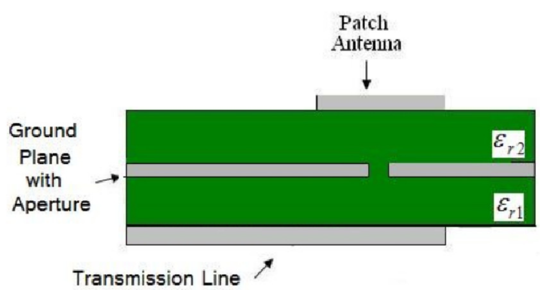


Figure 2.10: Aperture coupled MSA [4]

An example antenna of the work done in the field of aperture coupled microstrip patch antennas has been presented by authors in [33]; the authors proposed a rectangular antenna structure that had a U shaped feed line and the ground plane was projected with two slots for electromagnetic coupling. The radiating antenna and the ground layer in the design were separated by a material with low dielectric constant and an air gap. This antenna was able to achieve a bandwidth from 5.3 GHz –13.2 GHz. Figure 2.11 shows the proposed antenna by authors with a U shaped feed line.

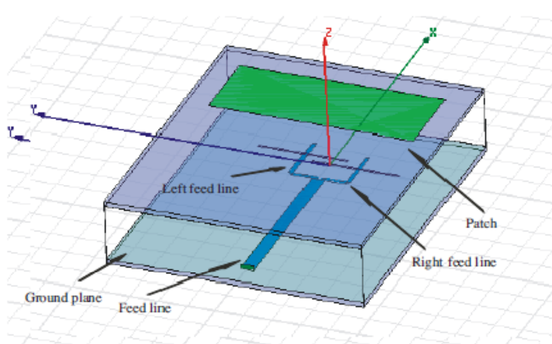


Figure 2.11: MSA with an Aperture coupled feeding and a U shaped feed line [33]

Out of all the mentioned feeding techniques with microstrip antennas, proximity feeding and aperture coupled feeding techniques are supposed to be the best ones as they provide enhanced bandwidth and are easy to model and fabricate. Table 2.1 shows the comparison of all the four feeding techniques and because of the inherent advantages of aperture coupled feeding mechanism, this technique is followed with designed MSAs in the current research work.

Table 2.1: Comparison of Different Feeding Techniques of MSA [6]

Characteristics	Microstrip Line Feed	Coaxial Feed	Aperture Coupled Feed	Proximity Coupled Feed
Spurious feed radiations	Quite Much	Higher	Less	Least
Reliability	Better	Very Poor due to soldering joints	Great	Great
Ease of fabrication	Uncomplicated	Complicated as Soldering and drilling needed a specific impedance matching point	Easy but alignment required	Alignment required here too.
Impedance Matching	Simple to achieve	Simple to achieve	Simple to achieve	Simple to achieve
Bandwidth(achieved with impedance matching)	2-5%	2-5%	13 %	21%
Polarization purity	Better	Less	Good	Best

There are numerous other methods too that increase the bandwidth of these microstrip antennas. A simple preferred choice amongst all other available techniques [21-26] is to increase the effective height of the antenna, which can be achieved by using thick dielectric substrates. Alternatively, multiple layers of the available substrate can be used for making the antenna with an increased bandwidth. Because of the advantages of an aperture coupled feeding technique over other methods, multilayered patch antennas with aperture coupled feeding technique are preferred by most researchers.

The bandwidth of a planar antenna can be represented by the equation (2.1) given as

$$B=\frac{VSWR-1}{\frac{Q}{\sqrt{\varepsilon_e}}}4f_0\,h, \qquad (2.1)$$

Where Q- is the quality factor

f_0 is the center frequency of the band

ε_e is the effective permittivity

h is the thickness of microstrip antenna

Since the height of the antenna is directly related to its bandwidth, a multilayer antenna in which the height of the antenna increases with the number of layers used is a less complicated method of increasing its operational bandwidth. In order to further improve the operational bandwidth of the antenna, stacked MSA structures have been introduced that are explained in the next section.

2.2.2. Aperture Coupled Stacked Microstrip Antenna

An Aperture coupled method of feeding MSAs was first proposed by David.M. Pozar in 1985 [16]. A multilayer /stacked microstrip antenna is an aerial or an antenna that comprises of multiple dielectric layers with antennas printed over them. With this method of feeding antenna, a wide operating bandwidth can be obtained. The primitive condition for obtaining satisfactory results in such antennas is to optimize the parameters of the multilayer that are printed. Figure 2.12 shows a stacked microstrip antenna with aperture coupled feeding mechanism.

As mentioned in section 2.2.1.4, this method of feeding microstrip antenna offers a lot of parameters for antenna optimization like the aperture dimensions, ground plane dimensions, feed line and dimensions of the patch also which can be optimized to obtain a wide operating bandwidth and a multiband behavior. Figure 2.12(a) shows a stacked microstrip antenna with aperture coupled feeding mechanism. Figures 2.12 (b) and (c) show the equivalent circuits of the stacked patch antenna when two resonant patches are stacked above each other.

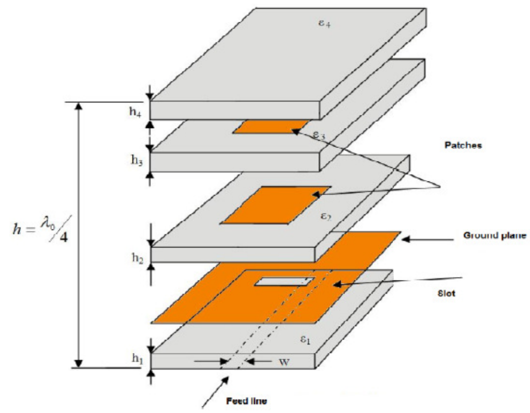
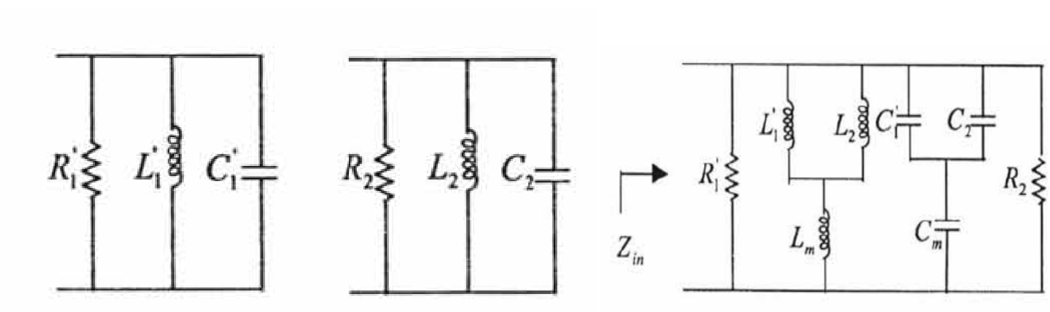


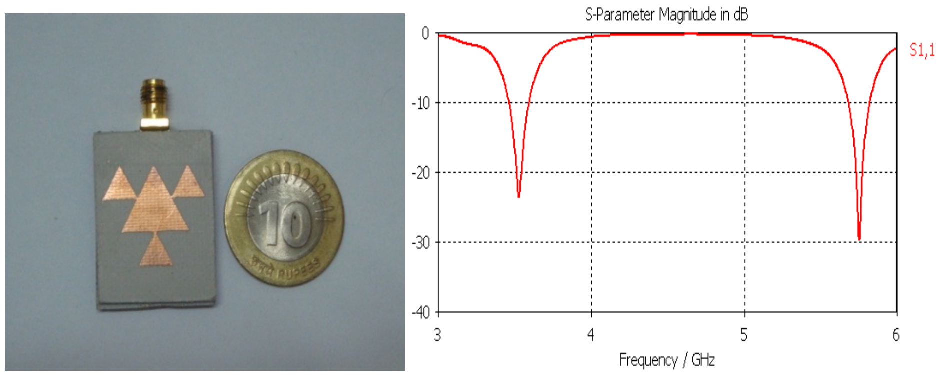
Figure 2.12(a): An aperture coupled antenna with multiple layers [29].



(b) (c)

Figure 2.12(b): The equivalent circuits for two patches individually and Figure 2.12(c): equivalent circuit of the stacked patches [53]

A large amount research work has been done in the past is available in the literature that focuses on the usage of Aperture coupled stacked microstrip antennas for different wireless applications. A typical antenna of the same kind for WLAN applications has been proposed by authors in [34]. The authors proposed a stacked Sierpinski gasket fractal antenna with a complementary structure that was made from an equilateral triangular shape resonator in a stacked layer structure, to obtain dual-band resonance for Wi MAX and WLAN wireless operations. The antenna was optimized by taking iterations up to the second stage. The substrate used for antenna design had a permittivity of 3.38 for all the antenna layers. Figure 2.13(a) shows the fabricated model of the proposed antenna and Figure 2.13(b) shows the impedance bandwidth of the antenna.



(a) (b)

Figure 2.13: (a) Stacked microstrip antenna for WLAN applications [34] (b) Its impedance bandwidth [34]

2.2.3. Antenna Analysis Parameters

When microstrip antennas are designed, simulated, fabricated and tested for measurement of their performance; a few parameters are required for their performance evaluation. These are briefly mentioned and explained in the further subsections.

2.2.3.1. Impedance Bandwidth

The bandwidth of an antenna is the spectrum of frequencies for which the antenna performance, corresponding to some specific trait, certifies to a given standard value. This property could be radiation pattern, antenna's polarization, beam width, side lobe level and gain, axial ratio, return loss, impedance characteristics etc.

Typically the range of frequencies over which antenna maintains an acceptable value of VWSR (Voltage Standing Wave Ratio) around the center frequency (practically a VSWR of less than equal to 2) is called the impedance bandwidth of the antenna. This can also be expressed in terms of return loss which relates to reflection coefficient ' Γ'. For a satisfactory performance, this corresponds to the range of frequencies for which the antenna return loss is less than -10dB and is termed as the Impedance bandwidth of the antenna. Broadband antennas use the ratio of upper to lower frequency for expressing their bandwidth. For example, an 8:1 bandwidth shows that the upper frequency of the radio band is 8 times greater than the lower frequency of the band. Narrowband antennas use percentage bandwidth which is expressed as a percentage of the frequency difference (upper minus lower) over the central frequency of the radio band for expressing antennas bandwidth conforming to any specific standard [3, 6, 20]. The expression that represents the percentage bandwidth (BW) of an antenna around a center frequency is given by equation (2.2) as

$BW = 100 X (F_h-F_l)/F_c$ ………………………………………………………………..(2.2)

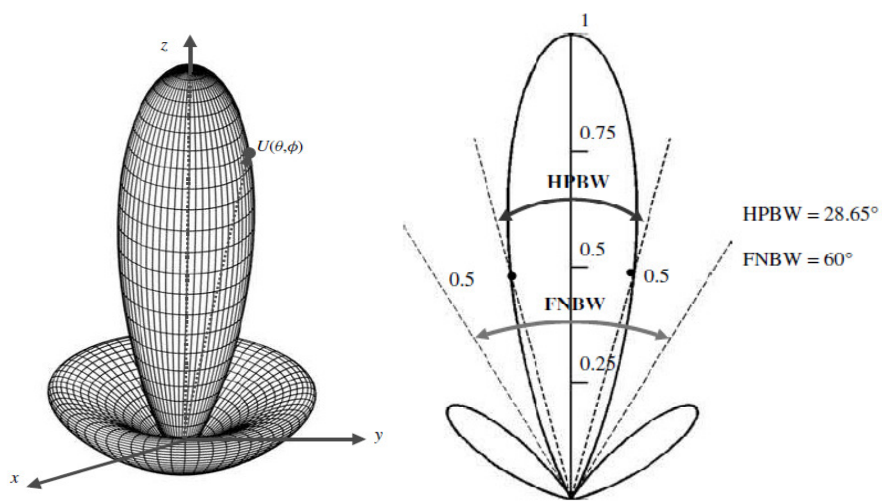
where F_h is the upper frequency of the band

F_l is the lower frequency of the band

F_c is the center frequency of operation.

2.2.3.2. Radiation Pattern

A three dimensional graphical representation of antenna radiation characteristics like power density (power pattern), field strength (field strength pattern), phase (phase pattern) or polarization (polarization pattern) as a function of space coordinates in the far field of the radiating antenna is called the radiation pattern of the antenna. It can also conveniently be represented as a 2D (dimensional) figure as the elevation and azimuthal polar graph patterns of the antenna. These polar graphs in the elevation plane and azimuthal plane can be used to determine the half power beam width and Side lobe level of the antenna's radiation pattern. Figures 2.14(a) and (b) show the radiation pattern of a half wave dipole antenna (in 3D and Front view whose radiation intensity is given by U (θ) = Cos^2(θ),where θ is the angle of observation [3]



(a) (b)

Figure 2.14(a): 3D Radiation pattern and the front view (b) Front view showing Half Power Beam width on the pattern [3]

2.2.3.3. Antenna Half Power Beam Width

The angular separation between those two points on the major lobe of radiation pattern of the antenna where power has fallen to half of the maximum value is called the Half Power Beam Width of the antenna. An antenna that intends to cover a broader geographical coverage area should possess more HPBW in order to allow radiations in the major lobe to spread to a larger area. Figure 2.14(b) shows a half power beam width of 28.65 degrees on the major lobe of the antenna's radiation pattern [3, 6].

2.2.3.4. Side Lobe Level

The ratio of proportion of power in first side lobe to that in the major lobe of antenna's radiation pattern (side lobe is any other lobe in the radiation pattern apart from the major lobe) is called the Side lobe level of the antenna. Usually most of the antenna and RADAR applications require a side lobe level of -30 dB and even less [3,6].

2.2.3.5. Voltage Standing Wave Ratio

Voltage standing wave ratio is a measure of the amount of reflections received at the source because of impedance mismatch between source and load that leads to formation of standing waves along the transmission line. For maximum transfer of power ideally from source to load, their impedances should be matched so as to give a reflection coefficient of zero ideally. The reflection coefficient when measured in terms of source and load impedances is given in equation 2.3 as

$$\Gamma = (Z_L - Z_0) / (Z_L + Z_0) \qquad \text{(2.3(a))}$$

and the VSWR in terms of reflection coefficient is given by equation 2.4 as

$$VSWR = \left(\frac{1+|\Gamma|}{1-|\Gamma|}\right) \qquad \text{(2.3(b))}$$

The range for VSWR can go from 1 to infinity but practically a VSWR of less than 2 is supposed to be satisfactory for a good performance [35].

2.2.3.6. Return Loss

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

The mathematical expression is given by equation (2.4) as

$$RL\ (dB) = 10 \log_{10} P_{inc}/P_{ref} \qquad (2.4)$$

When there is perfect matching between antenna and the source, Γ = 0 and RL = -infinity dB, which indicates no reflections back to the source, while on the contrary, Γ = 1 has a RL = 0 dB, for a case when all the incident power gets reflected to the source. A VSWR of 2 is supposed to be good for practical applications as this represents a RL of -10 dB [36].

2.2.3.7. Polarization

The direction of orientation of electric field vector of the EM waves radiated by the antenna refers to the polarization of that antenna. If the electric field vector is aligned along only one plane it is called liner polarization, this can be horizontal or vertical depending upon the direction of orientation of the electric field vector. If two orthogonal components of electric field are transmitted by the transmitter such that one is horizontal and the other is vertical with same magnitudes, the extremity of the electric field vector traces a circle and that type of polarization is called circular polarization. In case the extremity of the E field vectors traces an ellipse (when the two electric field vectors are unequal), it is called elliptical polarization.

A microstrip antenna is a linear broadside radiator, by careful design the antenna can be made to transmit circularly polarized waves so that the orientation of transmitter and receiver does not affect the communication system's performance [3, 37]. Figure 2.15 shows a typical circularly polarized microstrip patch antenna. The axial ratio of a circularly /elliptically polarized antenna is the ratio of the major to minor axis of the circle /ellipse. For a circularly polarized antenna the Axial ratio is 1 (appx.) or 0 dB (decibel) and for elliptical polarization, it is greater than 1 dB. Figure 2.16 shows a polarization ellipse with major and minor axis. Equation 2.5 gives the mathematical expression for axial ratio as mentioned below.

$$AR\ (dB) = 10 \log\left|\frac{Emax}{Emin}\right|^2 dB \qquad (2.5)$$

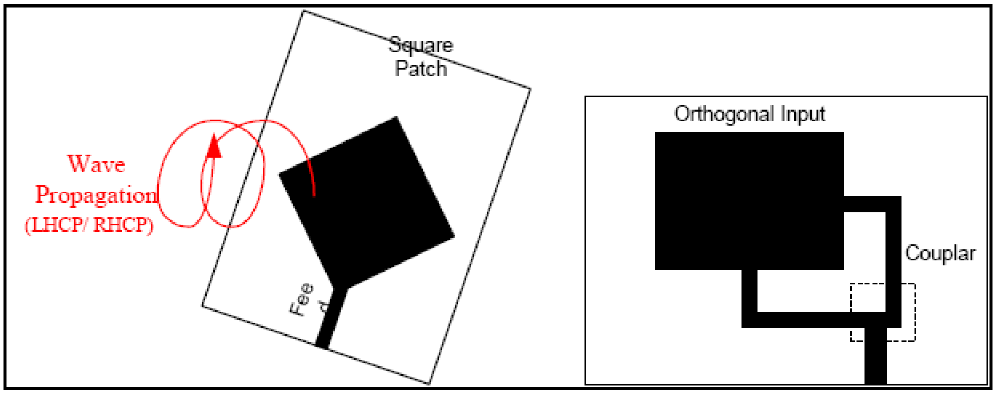


Figure 2.15: Circularly polarized MSA [37]

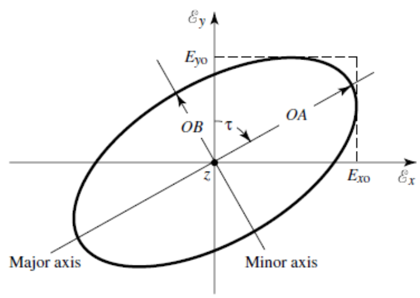


Figure 2.16: Polarization ellipse [3]

2.2.3.8. Axial Ratio Bandwidth

When an antenna is circularly polarized, the ratio of its major to minor axis gives the axial ratio of the antenna. The range of frequencies for which the antenna possesses a specific axial ratio is called its axial ratio bandwidth of that antenna. For example a 1dB axial ratio bandwidth corresponds to all the frequencies which posses an axial ratio below 1dB for that antenna.

2.2.3.9. Current Distribution

When an aperture coupled MSA is excited, there is a large flow of current over the surface of the microstrip line, this high frequency current that leads to the generation of Electromagnetic waves that are conjoined to the patch from the slot in the ground surface. The maximum current that streams on the respective part of the patch antenna supports the view of that part being responsible for a respective resonant operation of the MSA (As the respective part of the patch will radiate maximum that has maximum current flowing over it). Additionally the larger current loops are responsible for lower frequency of operation and the smaller current loops are responsible for higher frequency of operation. In an aperture coupled Stacked MSA; the aperture in the ground plane, Width of feed line and the distance between the substrate layers are the parameters that can be used to optimize the amount of current flowing on the patch thereby leading to increased radiations. Thus the antenna's efficiency and bandwidth can be improved accordingly [36].

2.2.3.10. Antenna Gain

The gain (G) of any antenna is described as the amount of power concentrated by the antenna in a given direction with respect to the total input power fed to the antenna. This defines the directional capabilities of the antenna keeping in account the efficiency of that radiator. Typically the Gain of any radiating antenna which is by default measured in the direction of maximum radiation is described as the proportion of the power per unit solid angle in the given direction to the power that would be obtained if the power input to the antenna is radiated isotropically. When the direction is not stated, the power gain is usually found out along the direction of maximum radiation. Mathematically it is can be expressed in terms of equation 2.6.

$$G = 4\pi \text{ X } \frac{\text{Radition intensity in the desired direction}}{\text{Total input power to the antenna}} \quad \ldots\ldots(2.6)$$

The gain and directivity (D) of an antenna are related by the efficiency of the antenna and mathematically, it is given as:

$$G = e_{cd} D, \quad \ldots\ldots(2.7)$$

Where e_{cd} is the efficiency of the antenna that considers the reflection, conduction and dielectric losses of the antenna in computing the overall efficiency of the antenna and D is the directivity of the antenna that is the amount of power delivered by the antenna along the direction of maximum output to the power distributed by antenna isotropically [3].

2.2.3.11. Antenna efficiency

The proportion of output power obtained from the antenna out of the input power fed to the antenna is called its radiation efficiency. The output that is obtained from the antenna is affected by

- Reflections to the source because of the impedance mismatch between the transmission line and the antenna.

- I^2R losses i.e. the Heat losses in terms of conduction and dielectric losses.

In general the total efficiency of the antenna is given as

$\eta_o = \eta_r \eta_c \eta_d$……………………………………………………………..…………………(2.8)

where η_0= Total antenna efficiency (dimensionless)

η_r= Antenna reflection(mismatch) efficiency = $(1 - |\Gamma|^2)$;Γ being the reflection coefficient.

η_c= Antenna conduction efficiency (dimensionless).

η_d= Antenna dielectric efficiency (dimensionless).

Antenna Efficiency can also be described in terms of radiation efficiency which is the proportion of power radiated by the antenna to the total power input to it [3, 6].

2.2.3.12. Input Impedance

The input or drive point impedance of an antenna is explained as the ratio of voltage to current (alternatively the magnitude of Electric to Magnetic field vector) measured at the input or drive point of the antenna. This is denoted mathematically as

$Z_{in} = R + jX$ at the input terminals; where $X = X_l + X_c$ is the sum of inductive and capacitive reactance. In order to have the VSWR at the drive point less than 2, the input impedance should be matched to the impedance of the coaxial cable and SMA connector which is 50 ohms [3]. The MSA that satisfy an appreciable level of the above mentioned qualities can be utilized for various commercial and scientific applications as listed in the next section .

2.3. Utilization of Microstrip antennas

Microstrip antennas have been a preferred choice amongst the communications industry because of the inherent advantages of being light weight, small in size, cost effectiveness, robustness etc. Some of the major applications of these antennas are mentioned as below [38].

- Cellular communications
- Wireless Local Area Networks.
- Radio Frequency Identification Modules.
- Worldwide Interoperability for Microwave Access (Wi-Max).
- Satellite Communications.
- Military applications like Missiles.

- Zigbee.
- Bluetooth applications.

2.4. Method of MSA analysis: Transmission-Line Model

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

The radiation from a MSA can be explained by considering fringing effects that are described as follows

Fringing Effects

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

Fringing actually increases the electrical length of the MSA and allows the microstrip line to appear longer electrically as compared to its real dimensions of the antenna. Since some of the Electromagnetic waves penetrate into the substrate and some are detached to the air. In order to account for the fringing effects, an effective dielectric constant ε_{reff} is introduced that is given by equation 2.10.

For W/h > 1, Figure 2.17(a) and (b) show the effect of fringing that makes the antenna look longer than its physical length [3].

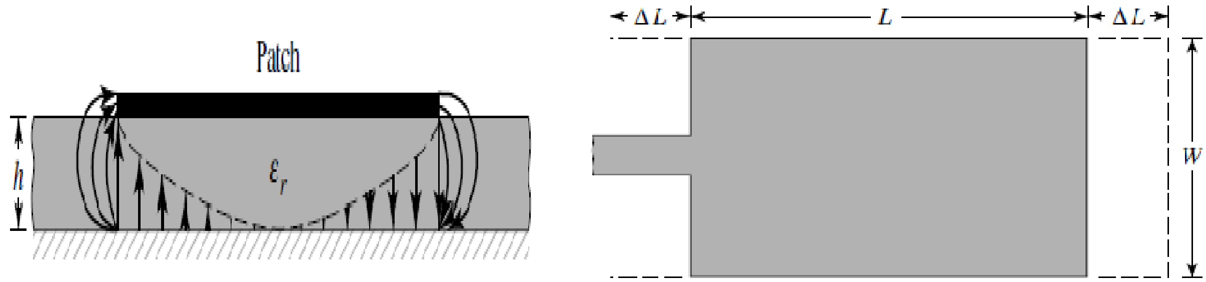
$$\varepsilon_{reff} = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2}\left[1 + 12\, h/w\right]^{-1/2} \quad \text{.....(2.10)}$$

where ε_{reff}= Effective dielectric constant

ε_r = Dielectric constant of substrate

h = Height of dielectric substrate

W = Width of the patch



(a) (b)

Figure 2.17(a) Side view of patch antenna showing fringing fields (b): Top view of antenna shows extended length of the patch by ΔL [3]

Thus the dimensions of the patch across its length have now been increased on each side by a length ΔL that is presented empirically by Hammerstad [39, 40]

$$\Delta L = 0.412h \frac{(\varepsilon_{reff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{reff} - 0.258)\left(\frac{W}{h} + 0.8\right)} \quad (2.11)$$

The effective length L_{eff} of the patch therefore becomes

$$L_{eff} = L + 2\Delta L \quad (2.12)$$

The effective length of the patch taking fringing effects into account, for a given resonant frequency is also given by [41] as

$$L_{eff} = \frac{c}{2f_o\sqrt{\varepsilon_{reff}}} \quad (2.13)$$

In general the resonant frequency for any TM_{mn} mode of a rectangular microstrip patch antenna, is presented by James and Hall [40] as

$$f_o = \frac{c}{2\sqrt{\varepsilon_{reff}}}\left[\left(\frac{m}{L}\right)^2 + \left(\frac{n}{W}\right)^2\right]^{\frac{1}{2}}, \quad (2.14)$$

where 'm'and 'n'are the number of half wave cycles of magnetic or electric fields along L and W of the patch in the TM (Transverse Magnetic) or TE (Transverse Electric) mode of operation respectively. For effective radiation from the antenna, the width W of the patch is given by Bahl and Bhartia in [6] as

$$W = \frac{c}{2f_o\sqrt{\frac{(\varepsilon_r + 1)}{2}}} \quad \text{(2.15)}$$

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

In order to design and simulate microstrip antennas for Wireless applications with desirable qualities for the current research work, full wave analysis of the microstrip antennas is done using Computer Simulation Technology Microwave Studio version 2010. The next section deals with the full wave antenna analysis procedure and the use of CST MWS V.10 for the same.

2.5. Full Wave Analysis of Antennas

The full wave analysis of the antennas uses FIT (Finite Integration Technique) to evaluate the fields radiated by an antenna under consideration, this method was proposed by Wieland in 1977. The FIT (Finite Integration Technique) technique mentions the matrix equations for the electromagnetic integral quantities in terms of built in properties of Maxwell's equations and explains the Maxwell's equations on a grid space. This allows the FIT to be very remarkable from a theoretical point of view also. Different types of grids like Cartesian or general non-orthogonal are available with the FIT technique which gives it an added advantage.

The discrete grid equations that are obtained with the FIT in time domain are similar to the discrete equations derived with the classical Finite - Difference Time-Domain (FDTD) methods. The difference between the FIT and FDTD is that FIT is applied to the integral form of the field equations, FDTD (as a subset of the finite integration method) is applied to the differential form of the concerning Maxwell curl equations. Theoretical links between FDTD and the FIT approach have been realized by researchers and can be found in [42]. A comparative study on different Time Domain methods was also presented in [43]. According to the available research in this regard, the Finite Integration technique can be considered to be in good agreement with the FDTD techniques. A widely used software tool based on FIT is the CST Microwave Studio.

2.6. Computer Simulation Technology Microwave Studio 2010 Software

CST MWS offers exact, competent and computational solutions for electromagnetic design and analysis of antennas and other microwave components. The 3D EM simulation software is user-friendly and it enables the user to choose the most fitting method for the design and optimization of RF and microwave devices operating in a wide range of frequencies.

CST MWS operation principle is established on the FIT method that allows the user to select among the time domain and the frequency domain approach for antenna analysis, depending upon the requirement. Even though Eigen mode and frequency domain solvers are available within CST MWS; the transient solver is the most frequently used module as it measures the broadband conduct of electromagnetic devices in one simulation run with a consistently admirable frequency resolution. The designing of curved structures in CST MWS is done using the Perfect Boundary Approximation (PBA) technique and the modeling of thin perfectly electric conducting sheets is done with the Thin Sheet technique. The software tries to overcome the typical difficulties that are encountered with canonical FDTD methods.

The current research work utilizes the hexahedral mesh type for the analysis of these microstrip antennas in CST MWS. The software has an automatic mesh generator that identifies the important points inside the antenna structure (fix points) and locates mesh nodes there. The user also has a liberty that he can manually add fix points on the structure and control the number of mesh lines in each coordinate (in context to the specified wavelength). The analysis in this research work uses an automatic direct meshing without any local settings by the designer [44, 45].

All the antennas in the research work presented are planar in nature and are simulated using the hexahedral mesh settings and time domain solver; the boundary conditions are open space as the antenna is a radiating structure in free space. Before starting with the case studies of the research work carried out, a thorough literature survey was done in the field of MSA with aperture coupled feeding and stacked geometry. This is presented in the following sections.

2.7. Background

A lot of research has been going on in the field of microstrip antennas because of its ingenious nature [45]. The applications of these antennas are sometimes limited because of their narrow bandwidth (BW). Consequently, a lot of researchers are working in this field to increase the bandwidth of these antennas. A great deal of work is available in the literature that focuses on the measures to increase the bandwidth of these antennas. Regrettably, the bandwidth of the antenna through various techniques that was obtained was usually 15-18 % at the center frequency of operation only.

A few frequently used techniques to increase the operational band of a planar antenna are mentioned as:

• Tuning frequency planar radiators.

• Dual frequency transmitters.

• Multilayer structures [46].

From the mentioned techniques, the one which is focused in the current research work is a multilayer antenna which is a radiator that comprises of multiple dielectric layers with antennas printed over them. These stacked antennas can be fed using a lot of feeding techniques. Aperture coupled feeding method that was suggested by David.M. Pozar [16] is a preferred one for feeding multilayer antennas as it gives an increased bandwidth of the antenna by around 70% as compared to other feeding methods [6]. From the historical perspective, these antennas were introduced by S. D. Targonski, R. B. Waterhouse and D. M. Pozar in 1998; the authors presented a foundation work for the design of ASP (aperture stacked patch) microstrip antennas. The resonators in the proposed antenna presented a greatly improved bandwidth as compared to the other aperture-coupled microstrip elements [41].

In 1998 Nasimuddin and Chen presented a broadband microstrip antenna with three layers of substrate having a combination of low, high and low dielectric constant substrates. The antenna was fed using a microstrip feed line to obtain an ultra-wideband operational behavior. The authors used parasitic patches and microstrip line feed to get an impedance bandwidth of 46.9% and directive gain 5.2 dBi at bore sight across the antenna's bandwidth [47].

In 1999, Rod B. Waterhouse proposed stacked patch antennas for the devices in which photonic and microwave devices have to be directly consolidated with the antenna .The antenna also had a stacked structure with a low dielectric constant substrate used for the patch and a high dielectric constant material used for the feed line. The proposed antenna was able to achieve a 25% bandwidth with such a configuration [48].

In 2001, J. Bartolit, Z. Sipus, N. Herscovicis proposed shorted patch antenna to obtain compact design for broadband applications. It consisted of a quarter wavelength shorted patch with tilted top patch and a coaxial feed with circular polarization was successfully achieved [49].

In 2001, another aperture coupled dual frequency broadband microstrip antenna with stacked elements and reactive loading and was presented by **J. Anguera, C. Puente, and C.**

Borja [50]. The authors presented a rectangular patch antenna structure that was reactively loaded with a stub placed along one of the radiating edges.

In March 2003 Jaume Anguera, Gisela Font, Carles presented a multi frequency microstrip patch antenna comprised of a driven patch and multiple parasitic elements placed below the driven patch. The antenna was featured with a multi frequency behavior (five operating band) and with a good gain [51].

In 2006, RSA Raja Abdullah, D. Yoharaaj, and Alyani Ismail presented miniature, light weight, easily fixable and broad bandwidth antenna that had two layers and an air gap between them for wireless applications. The effect of air gap was observed on the antenna's performance. A bandwidth enhancement of more than 11% was achieved in this case [8].

Another work of the same kind was proposed by **K. Shambavi in 2007 [52]**. In the presented antenna design, two identical square patches were stacked to increase the gain and bandwidth that is required for WLAN applications. The antenna was proposed with an air-gap of 9 mm that resonated at 2.45 GHz showing a gain of 8.05 dBi. The bandwidth achieved was 12.72% with 2: 1 VSWR.

In 2008 J. A. Ansari, P. Sing et al, **in [53]** proposed a stacked antenna with patch having a U slot .This antenna was stacked with an H-shaped parasitic antenna. Typically a bandwidth at the lower and upper resonance of 3.66% and 10.25% respectively was achieved using this stacked patch geometry.

In 2009 M. A. Matin, B. S. Sharif, C. C. Tsimenidis in [54] presented the experimental study of Broadband stacked microstrip antennas for an impedance bandwidth of 60.2%. This was achieved using an E-shape and modified half-E shape radiating patches for improved impedance bandwidth.

In 2010 H. Tiwari and M. V. Kartikeyan in [55] proposed a novel type of stacked microstrip patch antenna in which fractal shaped defects were abraded from the patch sheet. The antenna was designed for dual band operation at the WLAN 2.4 GHz and 5.8 GHz frequency bands and size reduction for both the stacked patches was also achieved.

In 2011 Dan Sun and Wenbin Dou [56] proposed a stacked proximity-coupled microstrip antenna with a cavity backing. In this antenna, as opposed to the conventional proximity-coupled/cavity-backed microstrip antennas; the lower patch and the cavity of the antenna produced the coupled resonances and this helped in achieving an impedance bandwidth over one octave.

In 2012 Trivedi, R.D., Dwivedi, V. in [57] presented the effects of patch rotation on stacked patch antennas. The authors presented stacked rectangular patch designed to operate in the C-band. This antenna had a bandwidth of 527 MHz for VSWR < 2.

In 2014 Mendhe, S.E. , Kosta, Y.P. in [58] presented a compact, simple and gap coupled broadband microstrip patch antenna. Impedance bandwidth of approximately 71.7372% with constant gain in specified bandwidth with good cross-polarization characteristics was achieved.

In 2015 Pravin R. Prajapati, Amalendu Patnaik and M. V. Kartikeyan [59] presented a Yagi Uda antenna with a plus shaped fractal slot. The antenna was circularly polarized. To suppress undesirable higher modes, a dumbbell-shaped defect was cut from the ground layer. A DGS in this case caused the reduction in antennas gain which is overcome by using a Yagi Uda shape.

In order to achieve a deep vision into the introduction of microstrip antennas and Stacked microstrip antennas in specific; a review of the MSAs, Stacked MSA, their feeding methods a research work has been carried out in the field of Stacked / Multilayer microstrip patch antennas and a few research gaps that have been found from the literature survey are listed in the next section.

2.8. Research Gaps

- Work is presented in the literature regarding the use of identical patch antennas with multiple substrate layers for a broadband operation; the variation air gap between the two substrates can be optimized to achieve best results.
- Stacked antennas are available in literature with coaxial feeding and microstrip feeding techniques, analysis can be done with different feeding techniques to propose that an aperture coupled antenna outperforms all other types of feeding methods.
- The use of spiral and Vivaldi antennas for UWB operation has already been proposed. Slot antennas for multiband operation have also been presented, but a multilayer antenna with simple rectangular patches and a Defected ground structure for WLAN, Bluetooth, ZigBee, Wi-Max and IMT Band applications covered simultaneously in a single antenna

is an open area for research.

- A Multilayer antenna usually increases the volume of the resulting antenna structure but the overall surface area remains the same, size reduction for multilayer antennas is another area of research.
- Fractal antennas and antennas with Defected Ground Structures have been presented in the literature for a multiband operation, an antenna with fractal defects and a defected ground structure in a single structure for multiband operation with broadband behavior at all the multiple resonances is an open area of research.
- Antennas with thicker substrates show an improved return loss, so a high dielectric constant substrate is preferred for microwave circuits and a low dielectric constant substrate for antennas. In aperture coupled antennas, the upper substrate of low permittivity and lower substrate of high permittivity can be chosen and analysis can be done in terms of improvement of the antenna results.
- Not much work is available in the literature for UWB generators like circle, elliptical and triangular geometry with conventional fractal geometry like Sierpinski and Koch in SMSA. Research can be done in this field to propose a new stacked fractal antenna for UWB applications.
- Slotted Multilayer microstrip patch antennas for UWB applications is also a new area of research to increase the gain of antenna and allow it to be suitable for long range applications.
- Circularly polarized antennas have been designed in the literature by the use of rhombus shaped patches, some specific feeding mechanisms etc, this gives an open opportunity of research in the field of design and implementation of circularly polarized antennas with some other techniques too.

These research gaps form the foundations for defining the research objectives for carrying out the current research work mentioned in this thesis. Based on the literature survey carried out in context to stacked multiband antennas exhibiting broadband behavior at each of their bands to support a high data rate, following advantages of stacked microstrip antennas are defined in the succeeding section.

2.9 . Advantages of Stacked microstrip Antennas

- **Multi frequency Antenna**

  For a microstrip antenna with multiple stacked patches having unequal sizes, each patch antenna excites a separate resonant frequency and thus can lead to a multi frequency behavior of the antenna [20].

- **Convenience in Antenna Optimization**

  For a stacked aperture coupled microstrip antenna, since there is a lot of choice available to the designer in terms of parameters to optimize the antenna’s performance like dielectric constants of the multiple substrate layers, patch sizes, air gap between dielectric layers, offset between centers of patches, feed location etc, these SMSAs offer an added advantage to achieve desired characteristics [20].

- **Constant surface Area**

  Stacked antennas offer the same surface area as compared to the coplanar antennas which lead to an increased surface area for the same results approximately [20, 60]. An increase in effective height of the antenna takes place and that gives positive results and enhances its performance.

- **Improved bandwidth**

  As the effective height of a stacked antenna increases, it results in more loosely bound fields that are radiated out more effectively. This increases the bandwidth of the antenna by 18 to 67% with aperture stacked patches as compared to a probe fed stacked patch antennas [20, 61].

- **Suitable for Array applications**

  Since the phase center of radiation patterns of a stacked antenna remains symmetrical over its operation band, the stacked antennas are well suited for array applications [20, 61].

- **DGS Incorporated in Stacked Antennas**

  If the ground structure of the antenna is made defected in its configuration i.e. a specific shaped slot is cut from its geometry depending upon the design equations, the resulting antenna has a reduced size, reduced crossed polarization and reduced level of harmonics in its output [62-64].

In order to carry out the research work defined in the research objectives in chapter 1, literature survey was executed in the field of multiband and broadband antennas in addition to the study of stacked microstrip patch antennas. The following subsection covers the various broad banding and multi banding techniques that were studied in this regard.

2.10. Techniques for Bandwidth enhancement and Multi frequency operation

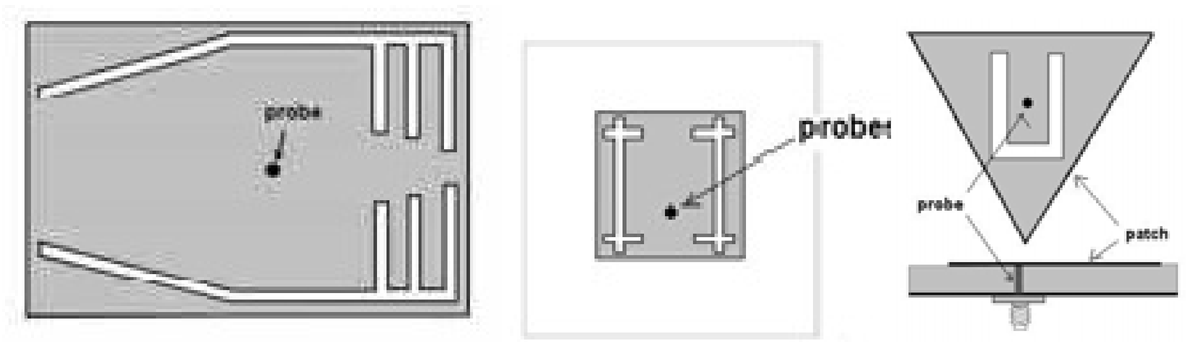
The traditional microstrip antennas have a geometry which has a metallic patch printed over a dielectric substrate that is grounded and it operates as a resonant cavity element. The major shortcoming of these antennas is their low bandwidth which restricts their use in some wireless applications. Sometimes, a multi frequency operation is also the main requirement of communication systems; therefore the main challenge for antenna engineers is the improvement of the bandwidth with the multifrequency operation.

The impedance bandwidth of a MSA is based mainly upon the height and the electrical permittivity of the dielectric substrate that is used for the antenna design. A thick substrate is easy to implement with MSA but the thickness of the substrate poses some problems in the installation of the antenna with other microwave circuits. It causes some more problems such as the wave propagation at the surface and the input impedance having a large inductive image part, which makes its resonance unfeasible. Thus, the substrate should be chosen with an optimized thickness and the bandwidth should be improved using supplementary methods. Some of the most common and effective of techniques for this are

- Using slots of different shapes on the patch surface.
- Cutting narrow or wide slits at the boundary of the microstrip patch.
- Utilization of stacked, shorted patches.
- Use of extra microstrip resonators [69-98].

2.10.1. Slot Loaded Patch Antennas

In the technique of cutting slots from the patch, certain shapes are chipped off from the microstrip patch corresponding to a specific resonant frequency of operation. If the two frequencies are close enough, it leads a wide bandwidth at that frequency of operation. The slots that are cut can be of a number of shapes like toothbrush as shown in Figure 2.18(a) [65], cross shaped Figure 2.18 (b) [66], or U-shape in Figure 2.18(c) [67].



(a) (b) (c)

Figure 2.18(a): Toothbrush shaped slots (b) Cross shaped slots (c): U shaped slot in the patch [67]

The main criterion that affects the multiband and broad band behavior of the antenna is the Slot Length, its width and its position in the patch surface. The width of the slot is preferably chosen to be less than the length of the slot for the desired performance in terms of resonance. As an example, in the U shaped slotted patch antenna, the higher resonant mode is sensitive to the length variation of the horizontal slot, whereas the lower resonant mode strongly depends upon the perimeter of the U-slot [68].

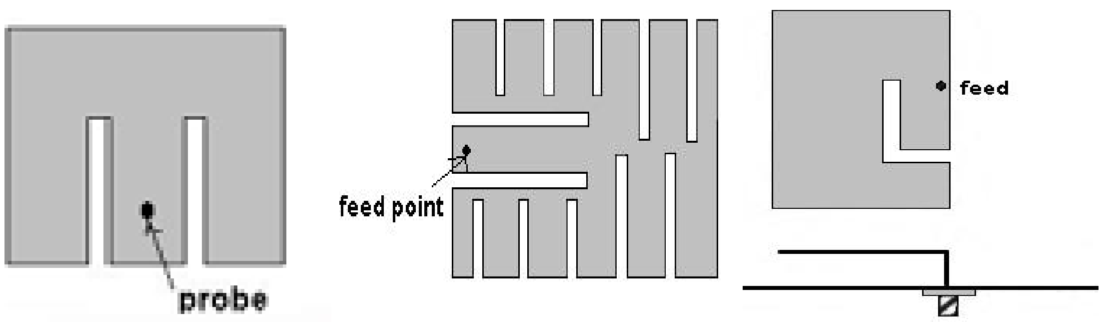
2.10.2. Slit Loaded Patches

Multiband and broadband behavior can also be achieved by cutting a slit at the patch boundary. As an example, the E shaped patch formed by cutting slits at the patch boundary, this technique can be applied to the antennas with rectangular, circular or triangular patches. Figure 2.19(a), (b) and (c) show three such significant designs that have been worked upon in literature [69-71]. By cutting an L or Half U shape slit along the patch surface, the antenna can be regarded as two connected resonators of different sizes. If their resonances are close enough, they give a wideband behavior else they show multiple resonances [68]. If a rectangular patch with a folded slit or L-shape slit is cut from the patch as shown in Figure 2.19 (a) & (b), then the resultant antenna configuration so formed can be considered to be comprised of two coupled resonators of distinct sizes [68].

Referring to the Figure 2.20; the geometry shows two rectangles; the smaller rectangle of dimensions $L_2 \times W_2$ resonates at the higher of the specified frequencies and the larger rectangle of dimensions $L_1 \times W_1$ resonates at the lower frequency of antennas operation [72]. Since the height of antenna is inversely related to the antenna's resonant frequency of operation, the lower L_f and the upper H_f operating frequencies of the proposed structure design can be found from the equation 2.16 and 2.17

$$f_L \cong \frac{c}{4(L_1 + W_1)} \qquad (2.16)$$

$$f_H \cong \frac{c}{4(L_2 + W_2)} \qquad (2.17)$$



(a) (b) (c)

Figure 2.19(a): Rectangular slit loaded antenna, (b) Meander shaped multi slit antenna (c) half U slit antenna [68]

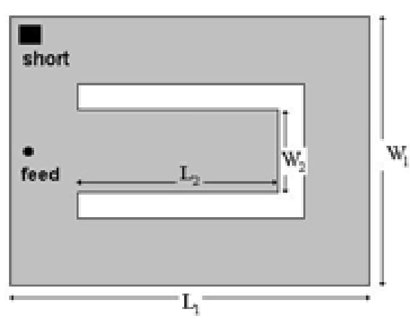


Figure 2.20: U shaped slot in the patch [72]

2.10.3. Ultra Wideband Antennas

UWB antennas are the ones that possess a fractional bandwidth greater than 0.25. According to Federal Communications Commission (FCC) this limit can be 0.2 also. Equation 2.18 gives the equation for fractional bandwidth, in mathematical form as

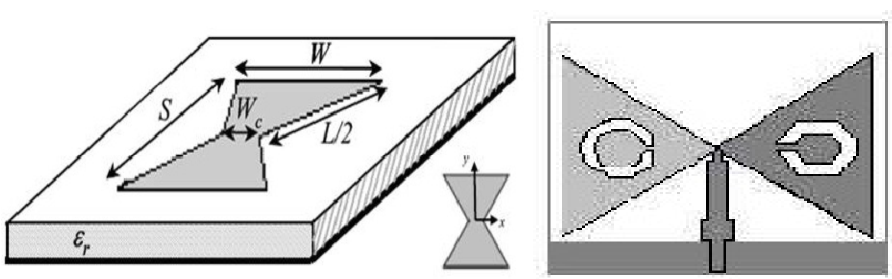
$$\text{Fractional BW} = \frac{2\ Fh - Fl}{Fh + Fl} \qquad (2.18)$$

where F_h and F_l are the upper and lower frequencies in the band respectively.

Some most frequently used antennas in this class are the spiral shaped antenna, the tapered slot, the antipodal tapered, as the Vivaldi antennas, the stacked patch antennas and bowtie shaped antennas. As an example a bow tie antenna is elaborated in the further sections as follows.

Bow Tie Shaped Antennas

Another type of patch configuration that can be used for antenna's multifrequency operation is the bowtie shaped antenna and if the multiple frequencies are chosen to be close enough, the antenna shows a wide band antenna behavior. A Bowtie microstrip antenna has an advantage that for the same resonant frequency of operation, they offer a smaller sized antenna. A basic bowtie shaped microstrip antenna is as shown in Figure 2.21(a) and (b). The bowtie shaped printed geometry has been derived from the modification of a rectangular patch using the calculations of the resonance frequency in terms of the geometrical and material parametric values [73].



(a) (b)

Figure 2.21(a): A typical Bow Tie shaped antenna (b): Bow tie antenna with slots [73]

A bow tie antenna incorporated with slots can be used for multi-frequency applications too as can be seen from Figure 2.21(b). The first step in designing this type of antenna is to select the approximate measurements of the sides of the triangle according the first operation frequency. The resonant frequency according to any given TM_{mn} mode of operation of an equilateral triangular microstrip antenna is given by equation 2.19 as

$$f_r = \frac{2C}{3\alpha\sqrt{\varepsilon r}}\sqrt{(m^2 + mn + n^2)} \quad \text{.....(2.19)}$$

Where c is the velocity of light

m & n are the number of half wave cycles of magnetic fields along the length and width of patch

α is the side of equilateral triangle

ε_r is the effective dielectric constant

In the second step of the designing six sided polygon slots is carried out, these bow tie that are embedded in to the bow patches give the antenna a dual band operation.

2.10.4. Stacked Antennas

The height of substrate layers in a multiple layered structure antenna is one of the most important factors affecting the bandwidth of the whole radiating antenna structure as mentioned in equation no 2.12. A typical SMSA (Stacked Microstrip Antenna) is shown in Figure 2.12 with multilayer configuration. Because of the inherent advantages of these antennas, they are a preferred choice for the current research work presented. These stacked antennas can have many geometries ranging from simple rectangular patches to fractal shapes and different types of slotted shapes too as explained in the further subsections of the chapter.

2.10.5. Fractal Patch Antennas

Fractal patch antennas are a new class of radiating elements inspired from the amalgamation of the two theories of Electrodynamics and Electromagnetics. The majority of fractal antenna structures are printed antennas that have a small size, low profile and cost and offer a multiple band output. They can be easily fed and their behavior could be easily optimized by suitably modifying their structure. These can be suitably designed to provide a high gain, with multiple - band behavior and radiation patterns characteristics with a low side-lobe level.

These Fractal shapes can be of two types; deterministic and random. Deterministic fractals are generated from multiple scaled down and rotated copies of the original generator using a specific algorithm and Random fractals contain characteristics of randomness that allow simulation of a natural phenomena.

The basic fundamental of a fractally designed microstrip antenna is to generate, and initiate a radiating element. For the deterministic fractal antenna, the final antenna structure can be made by repetitive application of the generating element with a specified scaling factor. This process can be implemented by using two main techniques. In one technique, the generator is repetitively added as a scaled version of the main generator in such a way that the entire size of antenna gets larger from stage to stage in making the final antenna structure. In the second technique, a priori is made of the final antenna size, this is then occupied with scaled down version of the generator to occupy the given space.

The most popular efficient fractal geometries for antenna design, available in the literature are the Koch fractal, the Sierpinski gasket or carpet fractal, the Hilbert fractal, the Minkowski and the Square Curve fractals [68].

Sierpinski Fractals

A most popularly used fractal antenna concept is the Sierpinski fractal which is a self similar structure [61]-[69]. A lot of Sierpinski fractal like the Sierpinski Gasket / Triangle, the Sierpinski Carpet / rectangle, the Sierpinski Pentagon and the Sierpinski Hexagon have been proposed in the literature. The carpet and the gasket fractals are supposed to be the most efficient of all. A Sierpinski gasket can be made by using an equilateral triangle as the generator of the antenna as shown in Figure 2.22(a). Then in order to make the final antenna, triangle with vertices that are located at the midpoints of the sides of the original triangle is cut from it. After the subtraction, three equal triangles are left on the antenna structure, each one being half of the size of the original one as given in Figure 2.22 (b). Then remaining three triangles are also cut from the structure as shown in Figure 2.22(c) to get the final radiating structure. The order of iterations is decided by the optimization of antenna. As can be seen from the Figure, in each stage of fractal making, the same generator that is scaled down by a factor is removed from the original structure. The design equation 2.17 is used for an equilateral triangle designing as the generator of the Sierpinski gasket fractal [75, 76].

As an example, of the stacked fractal antennas, the authors in [34] presented a stacked complementary Sierpinski gasket antenna. This geometry was formed with an equilateral triangle as the generator and then fractal shapes of the same type, scaled down by a factor were extracted from the patch radiating surfaces. The fractal order of 2nd degree was carried out with Sierpinski Gasket that led to longer current paths on the patches which helped in a size reduction at the operation frequencies of 3.5GHz and 5.8GHz respectively. A size reduction of about 3.5% and 26% for 3.5 GHz band and 5.8 GHz band respectively observed for the proposed antenna.

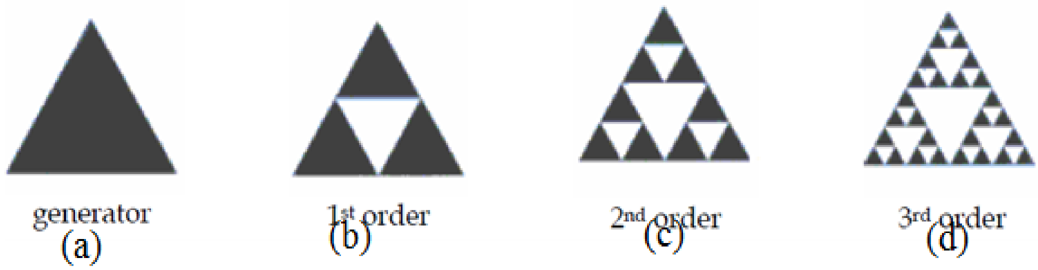


Figure 2.22 (a), (b), (c), (d): show the four stages of iterations in a Sierpinski gasket fractal antenna [34]

Square Curve Fractals

Another fractal shape that can be used to design multiband antennas is a square shaped fractal antenna. A rectangular ring is used as the generator for this type of fractal and thus the curves of the various stages for this type are closed curves. The geometry of fractal building that is followed here is based on increasing the size of the ring by addition of scaled rings of same type at the corners of the rectangle; the size attained by these antennas is still less as compared to other types and it also allows these antennas to exhibit an increasing gain.

The design process for these antennas thus starts with the selection of the size of the generator which is a rectangular ring with side length L as shown in Figure 2.23(a). At the next step of the repetitive process, the four corners of the square ring are added to the generator, till the design gets optimized for multiband as well as wideband behavior (refer tofigure 2.23(b) and (c)[77].

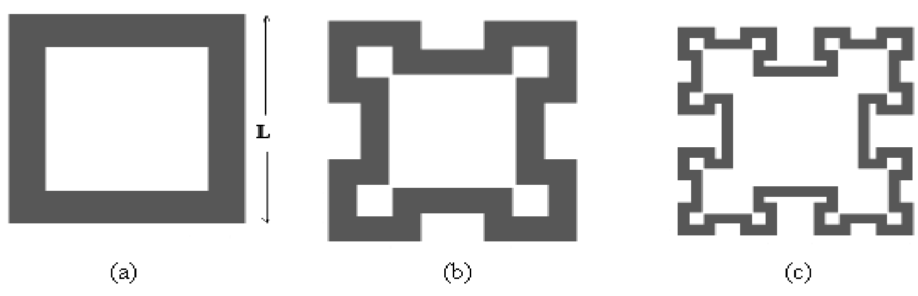


Figure 2.23: The generator and two iteration stages of Square Curve fractal (a)-(c) [77]

In order to improve the performance of these stacked fractal antennas or any other shape antennas; some specific shaped defects are etched out from the ground plane thereby making it a defected ground structure. The next subsection elaborates the concept of these structures used in the ground plane of the antenna.

2.10.6. Defected Ground Structures

DGS is an etched slot from the ground plane of the microstrip antennas structure. It is motivated by the study of Photonic Band Gap (PBG) materials to change guided wave properties. A DGS can be realized by making one or a few PBG etched shapes in the ground plane. The shape of DGS slot can be modified from a simple slot to a more complicated shape. The DGS structure may be found in both 1D and 2D forms also. Some common shaped DGS that are etched in periodic form from the ground plane of microstrip antennas is shown in Figure 2.24(a) and Figure 2.24(b). These Figures show a dumbbell shaped DGS and its LC equivalent circuit which can be used to give a specific resonant frequency of operation [97]. If a resonant frequency obtained from this DGS used in an antenna is a second resonance apart from the antenna's own resonant frequency, the antenna operates as a dual frequency antenna and by choosing the second resonant frequency to be close to the existing resonant frequency of the antenna, a broadband operation can be obtained.

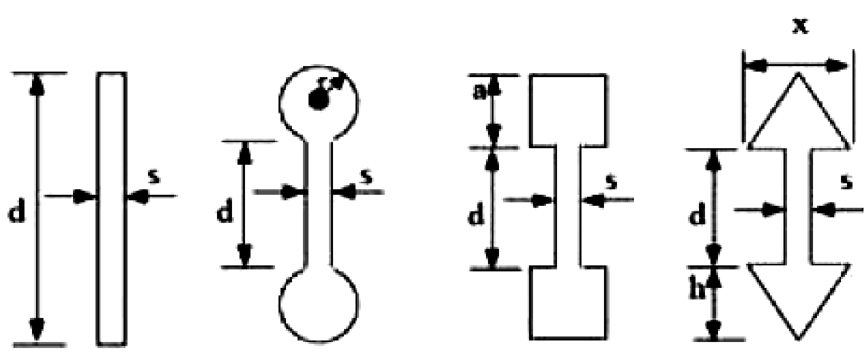


Figure 2.24 (a): Some common DGS shapes [97]

Different shapes of DGS structures, such as rectangular [78, 79], square [80], circular [81, 82], dumbbell [83, 84], spiral [85], L shaped [86], concentric ring [87], U-shaped and V-shaped [88-90], hairpin DGS [91-92], hexagonal DGS [93], cross shaped DGS [94] and combined structures [95-96] have appeared in the literature. A DGS offers many advantages to the existing antenna design, apart from providing a wideband and a multiband behavior; it helps in microstrip patch antenna size reduction, harmonics reduction, cross polarization reduction and mutual coupling reduction and also helps in enhancement of its radiation properties. A DGS can also be used to overcome the effect of Surface waves. The surface waves arise when antenna is radiating and a part of the total available radiated power of antenna gets captured along the substrate surface because of its permittivity to the Electrical signals. It can thus clip out the total available power for antennas radiation from the space wave thereby reducing the antenna's gain, efficiency and bandwidth. For antenna arrays also, the surface waves affect the mutual coupling between array elements [98].

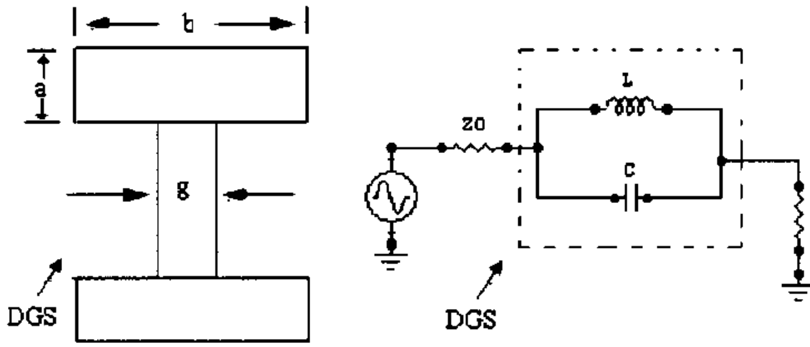


Figure 2.24 (b): A typical dumbbell shaped DGS and its equivalent structure [97]

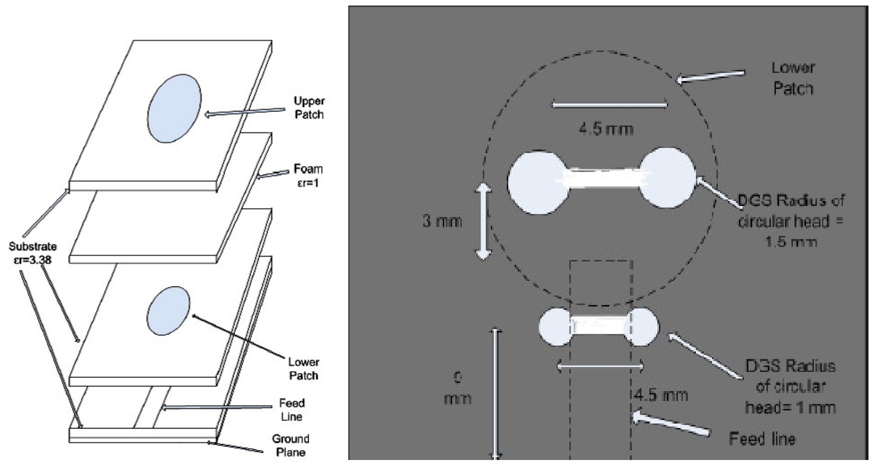
A typical Dumbbell shaped DGS unit cell is represented in Figure 2.24(b). It can be equivalently represented by a LC circuit as shown in Figure 2.24(b). The proposed DGS structure is fully described by two Parameters; the engraved lattice dimension and the gap distance between the vertical arm of the DGS shape [98]. The inductance and capacitance of the equivalent circuit of the DGS are given by equations 2.20.

$$L = \frac{1}{4\pi^2 fo^2 C} \text{ and } C = \frac{fc}{2Zo} \cdot \frac{1}{2\pi\left(fo^2 - fc^2\right)} \quad \ldots\ldots(2.20)$$

where f_0, f_c and Z_0 denote the resonant frequency, cut off frequency and characteristic impedance of microstrip line above the DGS.

As an example of the investigations done in the design of antennas with DGS, a stacked microstrip antenna with a proximity feeding technique and a DGS was presented by authors in [98]. Figure 2.25(a) and (b) shows the antenna structure that consisted of two circular stacked patches with a dumbbell shaped Defected ground structure that enhanced the impedance bandwidth by 204%, achieved a size reduction in the area of both circular patches by 58% on an average and an increase in radiation efficiency by 30.7% and also improved VSWR by 17%. The simulated antenna exhibited 6.24 dB gain at 5.53 GHz operating frequency and had a bandwidth

5.20GHz to 5.94 GHz, which satisfied two licensed bands (5.25-5.85 GHz) and (5.725-5.8 GHz) [98].



(a) (b)

Figure 2.25: (a) Stacked antenna with circular patches (b) view of ground plane with DGS [98]

2.11. Latest Advancements in the Field of Stacked Microstrip Antennas

A few latest advancements in the field of stacked microstrip antennas that was taken as the foundation for carrying out the current research work about the design and analysis of stacked microstrip antennas with defected ground structures, with fractal shapes and slots in patch antennas respectively are as mentioned in the following subsection.

2.11.1. Literature Review on Stacked Fractal Antennas

Fractal antennas can lead to multi frequency behavior with a reduced antenna size; researchers have used this concept in the stacked antennas to design a stacked fractal antenna for wireless applications**.**

In 2006 Mazlina Esa et al proposed Fractal Antenna with a square shape that was used for enhanced Bandwidth for WLAN applications. This paper presented the design of a fractal microstrip antenna with multiple layers and an air gap between two substrate layers. The antenna was operational between 5.15 GHz and 5.825 GHz. This antenna was found to perform well in terms of improved bandwidth, beam width and low cross polarization, its size was also small [99].

In 2006 Jaume Anguera et al, proposed Broadband Triple-Frequency microstrip Patch Radiator, this antenna was designed by taking the Combination of a modified Dual-Band Sierpinski gasket Fractal and a Monoband antenna and it was able to achieve a triple-frequency band with broadside radiation patterns observed. Sierpinski gasket fractal was responsible for the dual band and because stacking of dual band Sierpinski gasket antennas over the monoband antenna, broadband characteristics were obtained [100].

In 2009 A.S. Elkorany et al presented a paper on a stacked MSA with an Ultra wideband operation. In his design the upper patch that was stacked had a larger dimension than the excited / fed patch and an impedance bandwidth of about 2.5:1 was achieved between the frequencies 5.6GHz - 14.2 GHz when the excited patch and stacked one were co-centered [101].

In 2010 H. Tiwari and M. V. Kartikeyan presented a multilayer Patch Antenna with defects that were Fractal in Shape. The antenna was designed for dual band operation at the two WLAN bands with operation frequencies of 2.4 GHz and 5.8 GHz and size reduction for both the stacked patches was achieved due to the use of fractal shaped defects [55].

In 2013 Vilenskiy Artem and Kletsov Andrey presented a paper on Ultra-Wideband Signals Radiation by Linear Arrays of Aperture Stacked Patch Antennas. A low-profile stacked Ultra-Wideband microstrip antenna was investigated as a radiator of ultra - wideband radio pulses with 50% relative bandwidth. Low permittivity materials such as Rogers RO 4003, Teflon and foam were used for antenna implementation. Linear antenna arrays designed on the basis of proposed stacked patch elements were investigated. Frequency-domain analysis demonstrated very good array elements matching and negligible mutual coupling. Transient radiated pulses were simulated for different observation angles in the antenna E-plane, energy patterns and fidelity factors were calculated. Time-domain results evidence small radiated pulse degradation and high fidelity factor values for broadside directions were observed [102].

In 2014 Kirti Inamdar, Yogesh P. Kosta and Suprava Patnaik proposed multilayer meta material Microstrip antenna optimized for broadband and multifrequency operations . Figure 2.26 shows the structure of the antenna with multiple layers. It was shown that the proposed antenna exhibited negative values of electrical permittivity and magnetic permeability region of interest for antenna's operation. The negative parameter bandwidth obtained with the Criss-Cross structure was 33.33% and when the proposed Criss-Cross Meta material structure used for designing a rectangular MSA, the antenna showed a multi frequency operation and an increased bandwidth by about 86% and an increased gain by around 2 dB was achieved. The antenna had a coaxial feeding mechanism to achieve the desired characteristics [103].

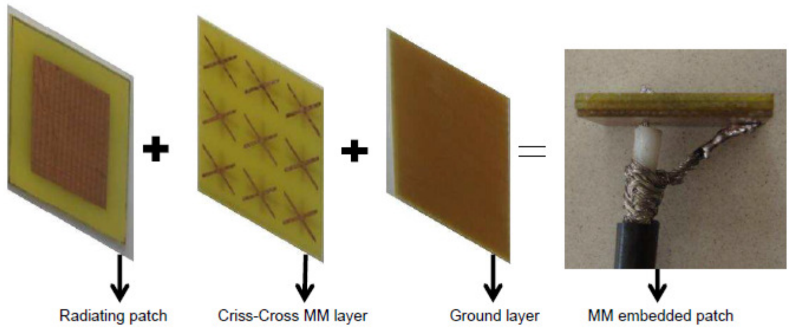


Figure 2.26: Multilayer antenna with Criss cross shaped Meta material structure [103]

2.11.2. Stacked Microstrip Patch Antennas with Defected Ground Structures

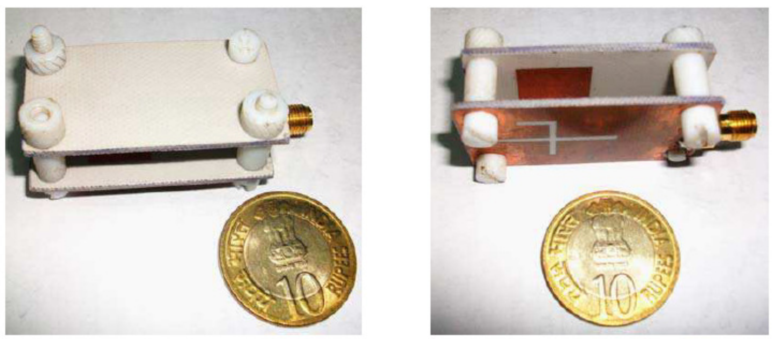
A defected ground structure when used with microstrip patch antennas leads to the reduction in size and harmonics of the antenna, the cross polarization and mutual coupling are also reduced. Many researchers have worked in the field of stacked Microstrip antenna and incorporated defected ground structures in a stacked Multilayer Microstrip antenna to achieve desired results.

In 2008 Ridho Chayono, Misao Haneishi, and Yuichi Kimura proposed a 2 dimensional Defected Ground Structure layer that was placed between the two patches of stacked circular microstrip antenna geometry. The antenna was fed using an inductively slot-coupled CPW structure. A DGS slab was imprinted on the lower side of the upper substrate. In addition, the upper patch antenna was embedded with a half-ring slot. The antenna produced a triple band output with an impedance bandwidth of 3.9% at 109 MHz, 2.8% at 86 MHz, and 2.8% at 119 MHz [104].

In 2010, Jyoti R. Panda and Rakhesh S. Kshetrimayum proposed monopole MSA that had a compact microstrip line feed network. The antenna was implemented with single and dual band-notched function UWB communication systems. The ground had a defected structure by etching two symmetrical L-shaped slots from it, which were responsible for the proper impedance matching, thus provided the full operational bandwidth for the UWB systems. The antenna could find its application in the Wi-MAX, C-band and WLAN operating bands respectively [105].

In 2010, J. X. Liu, W. Y. Yin, and S. L. proposed a new DGS that gave better results than a dumbbell or a cross shaped DGS as it had better slow-wave effect. The proposed DGS was then used in the design of a proximity coupled antenna for its miniaturization. The size of the developed antenna was about 68% smaller than that of the conventional one [106].

In 2011, A. K. Arya, A. Patnaik, and M. V. Kartikeyan presented a novel study on the on the modified broadband stacked MSA with different DGS structures in detail. A Skew shaped DGS was cut from the ground layer of a proximity coupled antenna and its effects were observed on the antenna performance which led to an increased bandwidth and reduction in the size of the antenna [107]. Figure 2.27(a) and (b) show the top and side view of the proposed antenna.



(a) (b)

Figure 2.27: (a) Top view (b) Side view of the stacked antenna with skew shaped DGS [107]

In 2012 Avisankar Roy, Sunandan Bhunia presented a MSA with square and triangular shaped defects in the antenna's ground plane. This resulted in a dual frequency, rugged microstrip patch antenna with enhanced bandwidth. A 31% improved antenna bandwidth for Wi-MAX application by using a defect in the ground plane was obtained for this case [108].

In 2013 Ather, S.N.Verma, R.K. Singhal, presented a rectangular microstrip antenna that had truncated corners and was used for wideband applications. The antenna was a multilayered structure with a defected ground and had slots embedded into the patches for increasing the antenna bandwidth. The bandwidth before adding the slot in the ground structure was 29.7% and after incorporating the slot in the ground plane of a stacked truncated rectangular micro strip antenna had an increase of 63.65% for frequencies ranging from 2.72GHz to 5.26 GHz. The antenna was designed at FR4 glass epoxy substrate and was fed by a coaxial feeding technique. A Specific modified stacked patch antenna with broadband application and dual band frequencies of operation due to the single skew-F shaped defect which was cut from the antenna's ground plane and a size reduction was also achieved for this antenna [109].

In 2015 Vidyadhar S Melkeri , S L Mallikarjun, P V Hunagund presented microstrip patch antenna that was designed for 2.4GHz frequency band. For the antenna size reduction and bandwidth enhancement, an H-shaped DGS with microstrip patch antenna (MSA) was used. The design of DGS (defected ground structure) was analyzed for different dimensions of H-slot and achieved optimized dimensions. The simulation process was done using High Frequency Structure Simulator (HFSS) software that is based on Finite element method of approximation. The Proposed antenna could easily find its application in wireless LAN protocols such as Bluetooth, IEEE 802.11 and in 2.4GHz ISM Band [110].

Circularly Polarized Stacked Patch Antennas

Circularly polarized antennas have also been a preferred choice amongst wireless engineers. The main reason behind this fact is that in the communication equipment being used for transmission and reception at the receiver side, a circularly polarized antenna can allow the user to receive both horizontally and vertically polarized transmitted signals. Thus the receiver alignment with respect to the transmitter does not disturb the performance of the communication system. A few research studies of stacked antennas with circular polarization have been presented below.

In 2004 K. Ghorbani and R. B. Waterhouse presented a wide-band, circularly polarized printed antenna that used an aperture fed multilayer patch antenna geometry. The feeding mechanism with an orthogonal feed and a cross shaped slot in the ground plane for aperture coupling of the antenna was responsible to provide a circularly polarized behavior. This printed antenna was able to provide a bandwidth of 52% and an isolation of 39dB between the excitation ports over the given frequency range. The gain of the antenna achieved was around 7.4 dBi [111].

In 2007 A. A. Serra, P. Nepa, G. Manara, G. Tribellini also proposed a multilayer antenna with circular polarization and wideband characteristics of the patch. The antenna was able to operate in frequency range from 1920MHz to 2170 MHz, from 2400MHz to 2484 MHz, and from 2500MHz to 2690 MHz for the UMTS (Universal Mobile and Telecommunication

Systems) band, ISM band and the new UMTS extension band respectively. The antenna was tested and the results were in close proximity with the simulated ones [112].

In 2007 Nasimuddin, Karu Esselleand A. K. Verma proposed a circularly polarized stacked patch antenna; the feed network of this structure was C type in nature that helped in achieving circular polarization. Authors presented a step by step method to optimize the Axial Ratio (AR) bandwidth. In the antenna structure, the main patch antenna and the coupled patch were of same size. The separation between the two patches was optimized to achieve a directive gain of 8.82 dBi, 3-dB Axial Ratio bandwidth of 14% was achieved and the polarization was elliptical in nature [113].

In 2008 J.S. Roy and M. Thomas presented a proximity coupled circularly polarized antenna, where the radiating patch was loaded by a V-slot. The variation of performances of the antenna with the change of stub length dimension and corner truncation dimension were reported in their research paper which were important information for proper design of the antenna [114].

In 2008 Yang, S. S Lee, K. F Kishk A. A, & Luk K. M also presented a single fed circularly polarized antenna by using a patch with truncated corners**.** An improvement in the axial ratio bandwidth was observed with a patch having truncated corners. A U-slot or L-probe was used to affect the impedance matching of the antenna. Because of truncated structure, the antenna was circularly polarized and the authors reported an axial ratio bandwidth (< 3 dB) of about 14% within the impedance matching band when the substrate thickness was used as about 0.2 times the free space wavelength [115].

In 2011 Sitao Chen, Xiaolin Yang, Haiping Sun proposed a parasitic patch antenna with circular shape. A circular shaped slot was cut from the centre of the patch and two rectangular holes on the boundary were placed over the former patch to improve the impedance bandwidth and the axial ratio (AR) bandwidth. The simulated impedance bandwidth for -10 dB return loss was 11.9% at the center frequency of the band from 1.485GHz -1.675 GHz. The 3-dB AR bandwidth was 8.5% from 1.525-1.660 GHz at the center frequency of operation [116].

In 2013 Nan Chang and Jyun-Ming Lin presented a Multiband Circularly Polarized Stacked microstrip Antenna where by stacking a sot-ring a proper distance above the patch, traveling current along the periphery of the slot-ring was formed and the axial-ratio bandwidth was optimized by varying the size of the slot-ring and the size of the ground plane. Through this simple method, 3- dB axial-ratio bandwidth of 9.8% centered at 915 MHz is achieved for RFID (Radio frequency Identification) use [117].

In 2015 Dinesh K. Singh, Binod K. Kanaujia et al presented a Multiband Circularly Polarized Stacked microstrip Antenna. The Circular Polarization (CP) over the multiband was achieved by corner truncation and embedding slits and inclined slots on a three layered antenna structure. The proposed antenna presented a wideband performance with an impedance bandwidth of 52.13% in the frequency range of 4.85GHz to 8.27 GHz, while 3 dB axial ratio bandwidths in five CP bands are 0.51%, 4.54%, 0.33%, 0.83% and 1.29% in the frequency range of 5.12GHz to 5.15 GHz, 5.45 GHz to 5.70GHz, 5.90GHz to 5.92 GHz, 6.25 GHz to 6.31GHz and 7.68GHz to 7.78 GHz, respectively. Figure 2.28(a) - (d) show the snapshots of the stacked circularly polarized antenna's top, middle and bottom layers [118].

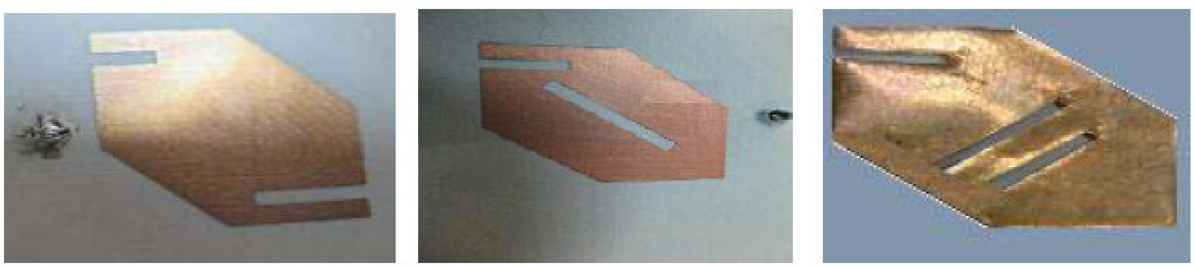

(a) (b) (c)

Figure 2.28(a) view of top (b) middle and (c) bottom layer of the stacked antenna with tapered structure [118].

2.11.3. Stacked Microstrip antennas for Ultra wideband

The researchers and industry are finding great interest in the Ultra wideband technology because it is also an unlicensed frequency band ranging from 3.1 to 10.6 GHz for commercial communication applications. This UWB technology got a major breakthrough especially in 2002 when the US Federal Communication Commission (FCC) allowed the endorsement of using the mentioned band as an unlicensed band [119]. It can serve many wireless services like fast internet access, video telephony, faster video/music download as well as digital voice services and the power consumption for this band is also low. The energy of UWB signals gets spread over a large frequency band, the maximum power available to the antenna as part of UWB system is of the order of 0.5mW according to the FCC spectral mask [120].These features make the UWB a favorable technology for future communications.

These UWB antennas can be of two types; UWB DS UWB and Multiband OFDM (Orthogonal Frequency Division Multiplexing) antennas. In the MB (multiband) OFDM technique, the 3.1GHz to 10.6GHz band is further divided in 14 sub bands of 528 MHz each. The design of antennas for the MB-OFDM ultra wideband technology sometimes requires only one or more bands to be covered by the antenna [121].

In the context of designing Stacked microstrip antennas for UWB applications; **in 2007 [122] Matin M.A. Sharif, B.S. Tsimenidis, C.C,** proposed a stacked rectangular microstrip antennas with U shaped slots .It was observed that the addition of a second U slot layer over the existing patch added another resonant frequency to the antenna close to the original one provided a wider bandwidth of operation. The dimension of the top patch was optimized to achieve ultra wide bandwidth. A 56.8% impedance bandwidth was achieved using this structure. The antenna could operate from 3.06 GHz to 5.49 GHz and the radiation patterns were found to be relatively constant throughout the band.

In 2008 Nasimuddin and Z.N. Chenthe presented multilayered ultra-wideband (UWB) MSA with five dielectric layers. The antenna comprised of an active patch radiator with five electromagnetically coupled patch radiators. The antenna could achieve good gain and a broad bandwidth behavior because of the multi layered structure. Authors measured a 10 dB return loss bandwidth of 48% with bore sight gain of 5.0 dBi for this antenna [123].

In 2009 Elkorany, A.S., Sharshar, A.A. , Elhalafawy, S.M. presented a new type of ultra wideband multilayered MSA. In the offered design, the upper patch had larger dimensions than the directly energized one. An impedance bandwidth with VSWR < 2 of around 2.5:1 was achieved between (5.6 - 14.2) GHz when the excited patch and stacked one were co-centered at (0, 0) point. The impedance bandwidth was improved to a ratio of 3:1 in the frequency range 5.6GHz -17.2 GHz when the upper patch center is shifted to (3, 3 mm) [124].

In 2011 Baskaran Kasi, Chandan Chakrabarty presented a simple and compact ultra-wideband (UWB) MSA with a rectangular slot. The antenna was fabricated using a tapered rectangular patch with microstrip feeding structure and ground plane was truncated in its structure. The proposed antenna was etched on an FR4 board with a wholesome precise structure. This antenna presented an UWB from 4.1 to 12GHz [125].

2.11.4. Multi frequency Stacked Microstrip Antennas with Slotted Structure

As discussed in sections 2.6(a) and 2.6(b), slots can be incorporated into microstrip antennas for wideband and multiband operation of these antennas. Using slotted stacked microstrip antennas gives an added advantage in terms of increase in the resonant frequencies and the bandwidth at each band.

In 2003 P.K. Singhal et al presented a two layer square shaped microstrip patch antenna with probe feeding to the lower patch. The patch structure was slotted to enhance the antenna's bandwidth and an input impedance bandwidth of 6.1GHz for VSWR < 2 was observed for the proposed antenna [126].

In 2009 J. A. Ansari, N. P. Yadav, P. Singh, and A. Mishra presented the study of a patch antenna with a half U slot with shorting wall. The parameters of the antenna significantly depended on the groove and notch measurements. The percentage bandwidth of the proposed antenna was found to be 21.59% at the center frequency of operation. The half power beam width of the antenna was reported to be 90 degrees at the central frequency of 2.6 GHz [127].

In 2009 D. K. Srivastava, J. P. Saini, and D. S. Chauhan presented a slotted antenna with a wide operational band. The antenna structure was rectangular H shaped with a slotted structure of U shape. The width of slot, its length of side arm and the length of base arm of U-slot were liable for optimizing the resonant frequencies of antenna's operation. Also the notch length of notch used and width of H shaped parasitic patch and separation between the two patches were optimized for getting the same results. Optimization of these parameters gave an impedance Bandwidth of 44.5% [128].

In 2010 Harshvardhan Tiwari and M.V. Kartikeyan presented a U slotted stacked microstrip antenna fed using coaxial and coplanar waveguide feeding techniques. Authors also used the Particle swarm optimizer for optimizing the required antenna parameters. The antenna was able to cover the IEEE 802.11b and IEEE 802.11a WLAN standards at the 2.4 GHz band and 5.8 GHz band. The bandwidths at the 2.4 GHz band were around 135 MHz with a gain of 8.668 dB and at the 5.8 GHz band were around 270 MHz with a gain of 8.694 dB respectively [129].

In 2011 Koray Sürmeli & Bahattin Türetken presented a multilayered U-slotted rectangular microstrip patch antenna that was excited using coaxial feeding method. The antenna geometry comprised of two layers with a dielectric constant combination of high ε for lower layer and a low 'ε' for upper layer dielectric material combination. The dielectric constants of are 3.27 and 1.07 were used respectively for the antenna design. The antenna measured a return loss bandwidth of about 52.94%, centered about 3.4 GHz. The antenna was well suited for the proposed wireless applications [130].

2.12. Conclusions

This chapter presents an introduction to the basics of microstrip patch antennas, their operation principles and the different feed networks that can be connected to excite this antenna. The advantages of aperture coupled feeding method over other methods of feeding allow these antennas to be a preferred choice for the current research work. A literature review in the field of stacked microstrip antennas is presented and the research gaps are then found out.

In accordance with the objectives defined for the research work to be performed in the field of stacked microstrip antennas, a literature survey has been presented corresponding to the design, simulation and experimental testing of stacked patch antennas for the wireless applications of WLAN, Wi-MAX, UWB, Radio Astronomy and STM link applications using DGS, fractal shaped patches in the SMSA and slotted SMSA forming a complementary geometry.

CHAPTER 3
Design and Studies of a Simple Stacked Patch Antenna for WLAN / UNII-1 and UNII-2 band Applications

The main aim of this chapter is to illustrate the design of stacked microstrip antennas with an aperture coupled feeding mechanism. It also aims to illustrate the use of multiple layers in a MSA geometry that helps in improving the antenna performance in terms of resonant frequencies of operation and also the bandwidth at that specific resonant frequency of operation. Since the unlicensed wireless bands have a lot of applications like in the ISM band; the WLAN, Wi-MAX, Zigbee, Bluetooth etc, the current research work concentrates on the design and development of stacked microstrip patch antennas for WLAN, Wi-MAX and many other indoor wireless applications. In order to deliver a high data rate in these bands, an enhanced bandwidth is the main requirement which is kept as the target while designing antennas for the proposed wireless applications in the current chapter.

In this chapter a thorough study of the performance evaluation of a stacked MSA for WLAN application is also done. A study on variation of its various design parameters has been presented. A compact single band microstrip patch antenna is therefore designed, fabricated and tested on the readily available FR4 substrate (with a dielectric constant of 4.4, a height of 1.57mm and a loss tangent of 0.0024), for IEEE 802.11a WLAN and UNII band applications. The bandwidth of this proposed antenna can be increased by a simple and a convenient method of using a two layer stacked structure. This structure has an identical parasitic patch on the upper substrate layer designed as the driven patch antenna. An aperture coupled method of feeding the microstrip antenna that gives an increased bandwidth by around 21% is used with the existing antenna structure for desired performance [16].

In order to illustrate that a stacked aperture coupled antenna offers a liberty among a lot of parameters for performance optimization to the researchers, the parametric analysis of the performance of this stacked aperture coupled antenna by variation of various antenna dimensions (of the stacked aperture coupled geometry) is also carried out. The parametric study shows the variation in the output in terms of return loss, impedance matching and impedance bandwidth when the respective dimensions of different antenna parts are varied.

The organization of the chapter is as follows; section 3.1 discusses the general introduction to a stacked MSA with its equivalent circuit and the operation mechanism. The design of a simple aperture coupled MSA at the resonant frequency of 5.4GHz is then presented. Section 3.2 explains the antenna geometry and the simulation results of the antenna, section 3.3

explains the investigations that are carried out on the design of stacked aperture coupled microstrip patch antennas by the parametric variations of various antennas dimensions and section 3.4 gives a validation of the simulated results based on the experimental testing of the antenna.

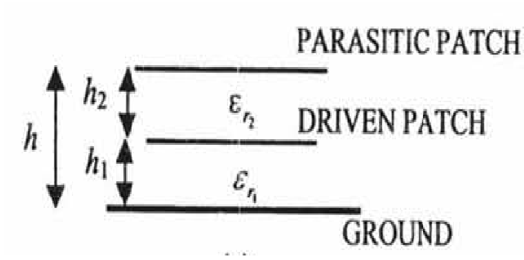
3.1. Introduction

An Aperture coupled stacked microstrip antenna offers numerous advantages to an antenna designer in terms of availability of the optimization parameters [1]. A lot of work is thus available in the literature that concentrates on the design and application of these antennas for specific wireless applications [16]-[20]. Based on the literature survey done in this regard, the design, simulation, parametric analysis and experimental testing of a stacked MSA with aperture coupled feed for WLAN applications are presented in this section.

The proposed aperture coupled SMSA in its basic geometry consists of three dielectric substrate layers of FR4 with an electrical permittivity of 4.4 each. The basic geometry of a stacked MSA is shown in Figure 3.1(a). Three layers of substrates viz. upper, lower and middle. can be seen. The Upper and middle layers are single sided PCBs and lower layer is double sided PCB. On the upper side of the top substrate layer (parasitic layer); a patch antenna of any shape defining the resonance and bandwidth of a particular band is printed. On the top of middle layer a driven patch antenna printed, giving it a stacked geometry. This antenna is fed using a feed line printed on the bottom of third (lower) substrate (ground layer). The top of this lower layer has a metallic layer printed over it and a slot is etched out from the ground giving it an aperture coupled SMSA configuration. The aperture slot is cut orthogonal to the feed line. The equivalent circuit of two patch antennas individually is as shown in Figure 3.1(b).The RLC equivalent circuit of the antenna obtained by stacking two patches one above the other is shown in Figure 3.2 [53]. This stacked geometry offers many features that are helpful in optimizing the antenna as mentioned below.

- The two stacked substrate layers (upper and lower) can be selected to be of different dielectric constants. Usually the preference is to have the lower substrate with a high dielectric constant and upper substrate with a low dielectric constant to avoid any spurious waves which degrade the antenna's performance.

- The increase in the number of substrate layers is a factor that can be used to optimize the performance in terms of bandwidth of the radiating structure.
- Upper and middle dielectric layers can be directly stacked one over the other or there can be an air gap maintained between the two. The height of this air gap can be optimized to get a desired antenna performance.
- A stacked antenna with an aperture coupled feed can be optimized in terms of three parameters for a good impedance bandwidth; the aperture length and width, feed line dimensions and the ground plane dimensions.
- The patch antennas can be of different shapes to excite multi frequencies from the antenna; alternatively these multi frequencies can also be selected close to each other so as to excite a wideband.
- By judiciously choosing the antenna geometry or the feed geometry, the antenna can be made as a circularly polarized one, so that it radiates two orthogonal electric field components in far field of antenna's radiation.



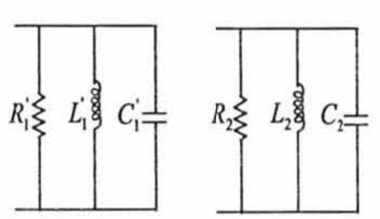


Figure 3.1(a): Stacked Patch antenna [4]. **Figure 3.1(b): Equivalent Circuits of the two patch antennas[4].**

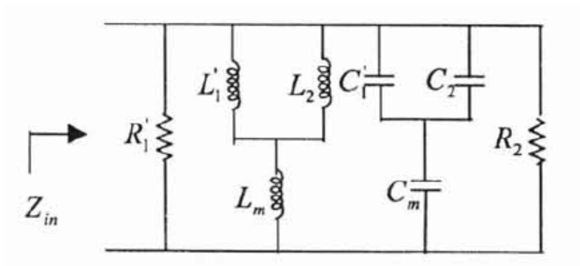


Figure 3.2: Equivalent circuit of a stacked patch antenna with two dielectric layers [4].

Because of its simplicity and its ease of application, this type of SMSA has been the choice of researchers and a lot of work is available in literature that concentrates on the design and development of these antennas for different wireless applications.

3.2. Stacked Patch Antenna Geometry

The designed antenna is a wide band stacked rectangular microstrip antenna with three dielectric layers (refer to Figure 3.3). The proposed antenna has been simulated, fabricated and tested for WLAN, ISM and UNII band applications. The stacked structure gives an enhanced measured bandwidth of 640 MHz. The designing of the stacked rectangular patch antenna is done by taking the reference of transmission line model (refer to section 2.4). Using the equations 2.10, 2.13 and 2.15, the effective dielectric constant, the effective length and width of the rectangular patch antenna for a specific resonant frequency are chosen respectively. Then another patch of identical dimensions printed over the substrate layer of same dimensions (as the driven patch) is stacked over the existing driven microstrip patch antenna. The feeding method used to excite this antenna is an aperture coupled feeding, therefore it has a ground layer with a slot on the top of lower substrate and a feed line its bottom. The dimensions of feed line are optimized to allow the antenna to be matched to a SMA (subminiature) connector having an impedance of 50 ohms. Figure 3.3 shows the detailed layout of the proposed antenna and Figure 3.4 shows each layer of the antenna with its explicit parts labeled and their values mentioned in Table 3.1.

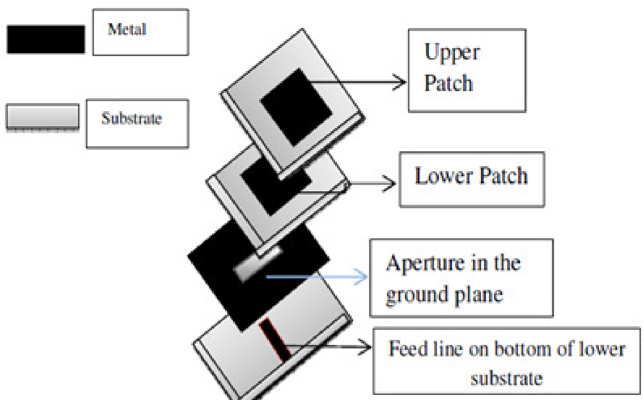
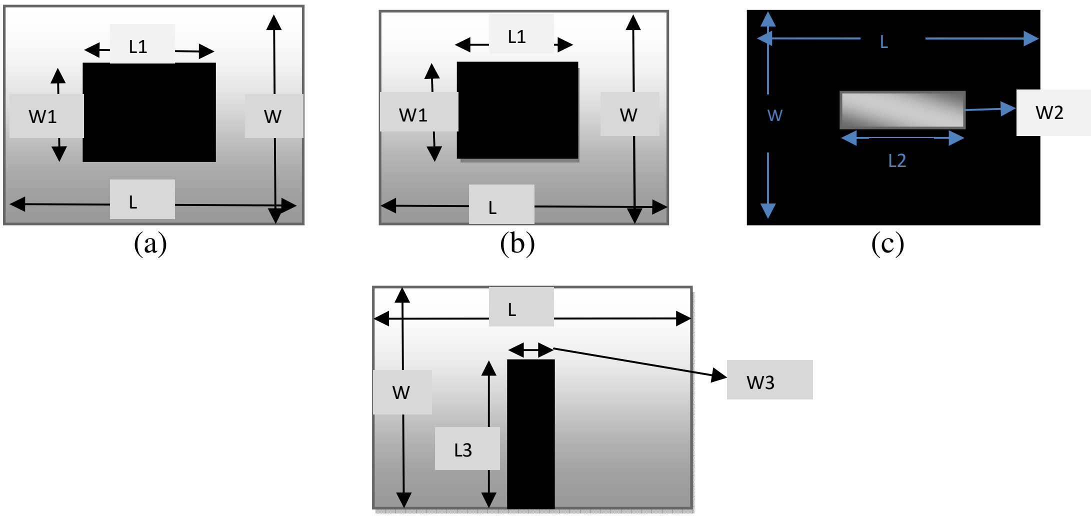


Figure 3.3: Perspective View of the Proposed Antenna



(d)

Figure 3.4: (a) Top substrate layer with patch, (b) Middle substrate layer with patch, (c) Ground with an aperture on lowest substrate (d) Feed line on the bottom of lowest substrate

The proposed antenna possesses overall dimensions of 2.5cm X 2.2 cm X 4.8mm with patch length and width of (L1 X W1) 14mm X 9.10 mm. The feed line is designed with dimensions of (L3 X W3) 14mm X 2mm to allow the antenna to get matched to an input impedance of 50 ohms and the aperture slot in the ground plane has dimensions of (L2 X W2) 7.6mm X 2.4mm. Table 3.1 mentions the parametric details of the antenna.

Table 3.1: Parametric Details of the antenna

Antenna parameter	Values in mm
L	25
W	22
L1	14
W1	9.10
L2	7.6
W2	2.4
L3	17.17
W3	4

3.3. Simulation Results

The proposed antenna was simulated using CST MWS V.10 software. This is GUI (Graphic User Interface) friendly software which is based on FIT Techniques. The antenna designing is done using a hexahedral mesh settings and perfect boundary approximations. This designed antenna's simulated results obtained using the in CST MWS V.10 software in terms of return loss, gain, radiation pattern, VSWR and Current distribution were found and are discussed in the succeeding sections.

3.3.1. Impedance Bandwidth

The S_{11}(dB) results plotted on Y axis with respect to frequency on X axis helps in analyzing the set of frequencies radiated by the antenna for which antenna shows a reflection coefficient of around 0.33 or a VSWR less than 2. Figure 3.5 shows the S_{11}(dB) plot of the antenna against frequency, it can be seen from the plot that the antenna shows an impedance bandwidth of 473 MHz from 5.13GHz to 5.603GHz i.e. 8.75% bandwidth at the center frequency of operation. This allows the antenna to be suitable for the wireless applications of WLAN from (5.15 to 5.35) GHz, UNII-1(Unlicensed National Information Infrastructure radio band) from (5.18-5.24) GHz (ISM band).

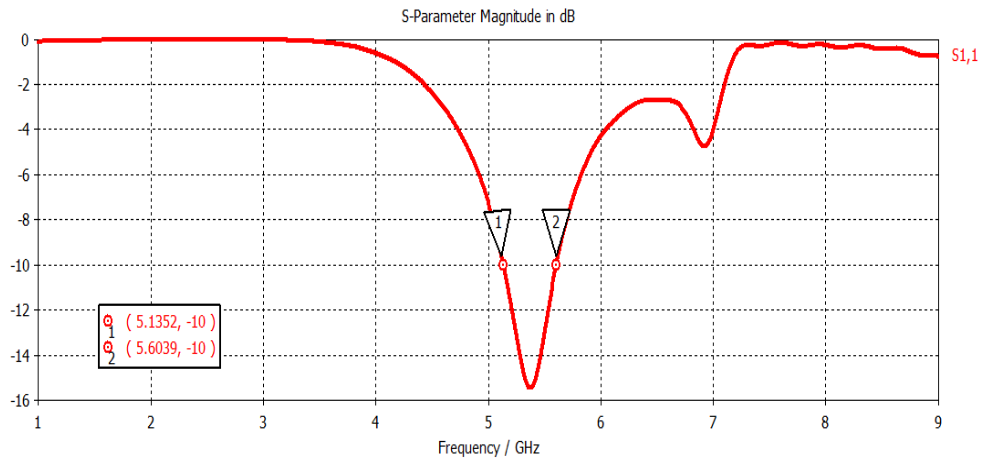


Figure 3.5: S_{11} (dB) plot of the antenna

3.3.2. VSWR

For maximum transfer of power from source to the antenna, the feed line must be matched in its impedance to the antenna connector, therefore the reflection coefficient at their joining point should be zero ideally, but practically a reflection coefficient of 0.35 and less is considered to be optimum. This corresponds to a VSWR of less than 2. Figure 3.6 shows the VSWR plot of the proposed antenna. The antenna shows a VSWR of 1.4 at the central resonant frequency of 5.38GHz.

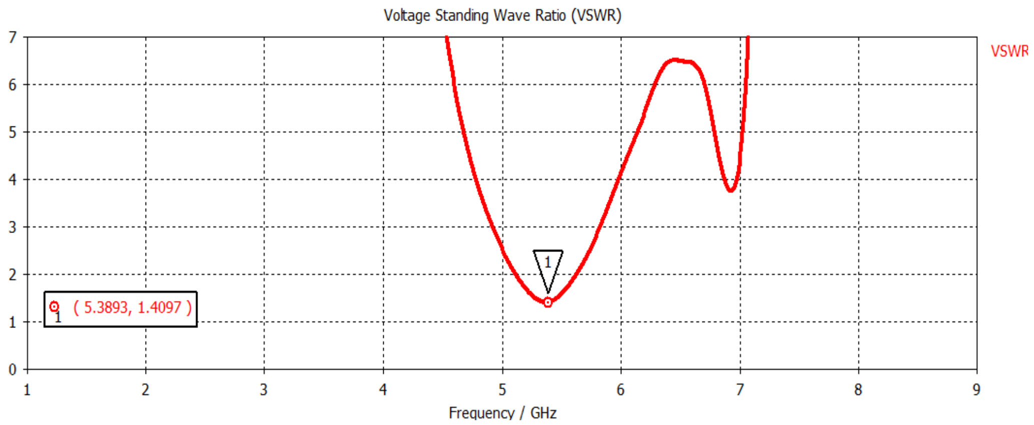


Figure 3.6: VSWR plot of antenna at 5.38 GHz

3.3.3. Gain

The 3D gain plot of the antenna plotted in far field is shown in Figure 3.7. The gain of an antenna shows how much energy it can concentrate in a given direction as compared to the total input power to the antenna, showing the range of antenna in far field. Figure 3.6 shows that the antenna possesses a good gain of 6.56 dB at the frequency of 5.4 GHz. A gain of 5dB or more is considered to be good enough for indoor wireless applications, thus making the antenna suitable for short range indoor wireless applications.

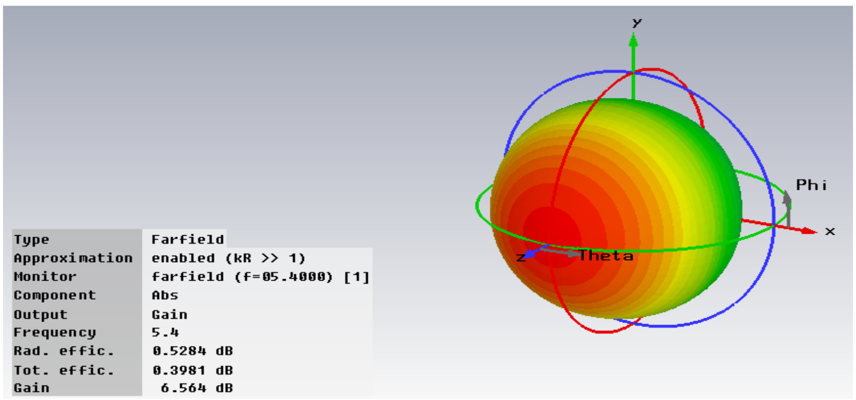
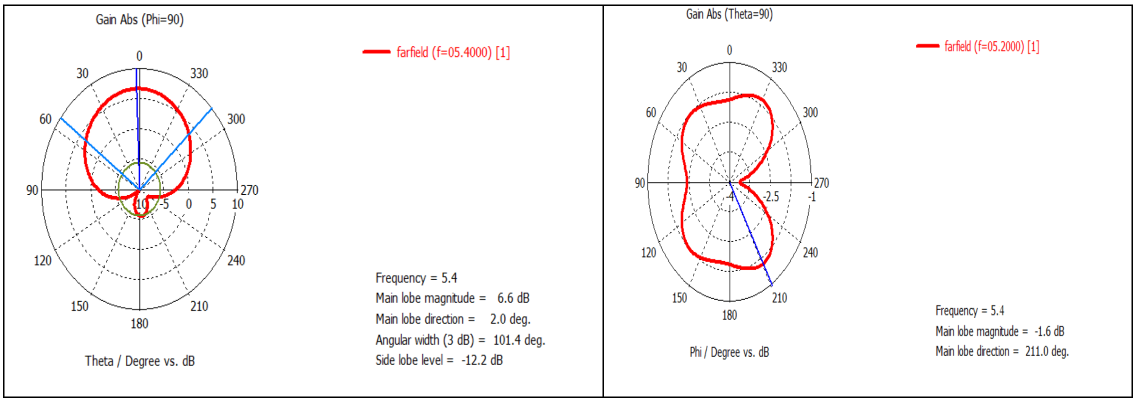


Figure 3.7: 3D Gain plot of antenna at 5.4GHz

3.3.4. Radiation Pattern

The polar plots of the 3D radiation pattern of the antenna in far filed indicate the beam width , side lobe level and direction of pattern maxima in the elevation plane and the azimuthal plane of the antenna. The polar plots in the elevation and azimuthal pattern views of the antenna are shown in Figures 3.8(a) and (b). The antenna has a major lobe in the E plane along 2 degrees and a half power beam width of 101.4 degrees and a side lobe level of -12.2dB. The radiation pattern shows that the antenna has nearly Omni directional pattern in the E plane thereby allowing a good coverage to be obtained in all directions in the XY plane (if z is the direction of propagation of EM signals).



(a) (b)

Figure 3.8 (a) & (b): E and H plane views of antenna's radiation pattern at 5.4GHz

3.3.5. Current Distribution Results

The stacked microstrip antenna structure was excited using the feed network to see the distribution of energy over its various structural parts. This helps in analyzing that in what capacity, a specific part of the antenna is responsible for the given resonant frequency of antenna's operation. Figures 3.9(a), (b), (c) and (d) show the distribution of current on the upper patch, middle patch, ground plane and feed line respectively. It can be seen that a peak current of 63.1A/m is maintained over the aperture in ground plane at 5.4 GHz, this allows maximum power to be electromagnetically coupled to the patch antennas. The upper and middle patches have peak current amplitude of 16.5A/m and 40.0 A/m over their surfaces respectively that helps in increasing the bandwidth of the antenna at the desired frequency band. The driven patch radiates well at 5.4 GHz and the parasitic patch radiates almost 50% of that of the driven patch, thereby allowing the antenna to exhibit broadband behavior at 5.4GHz.

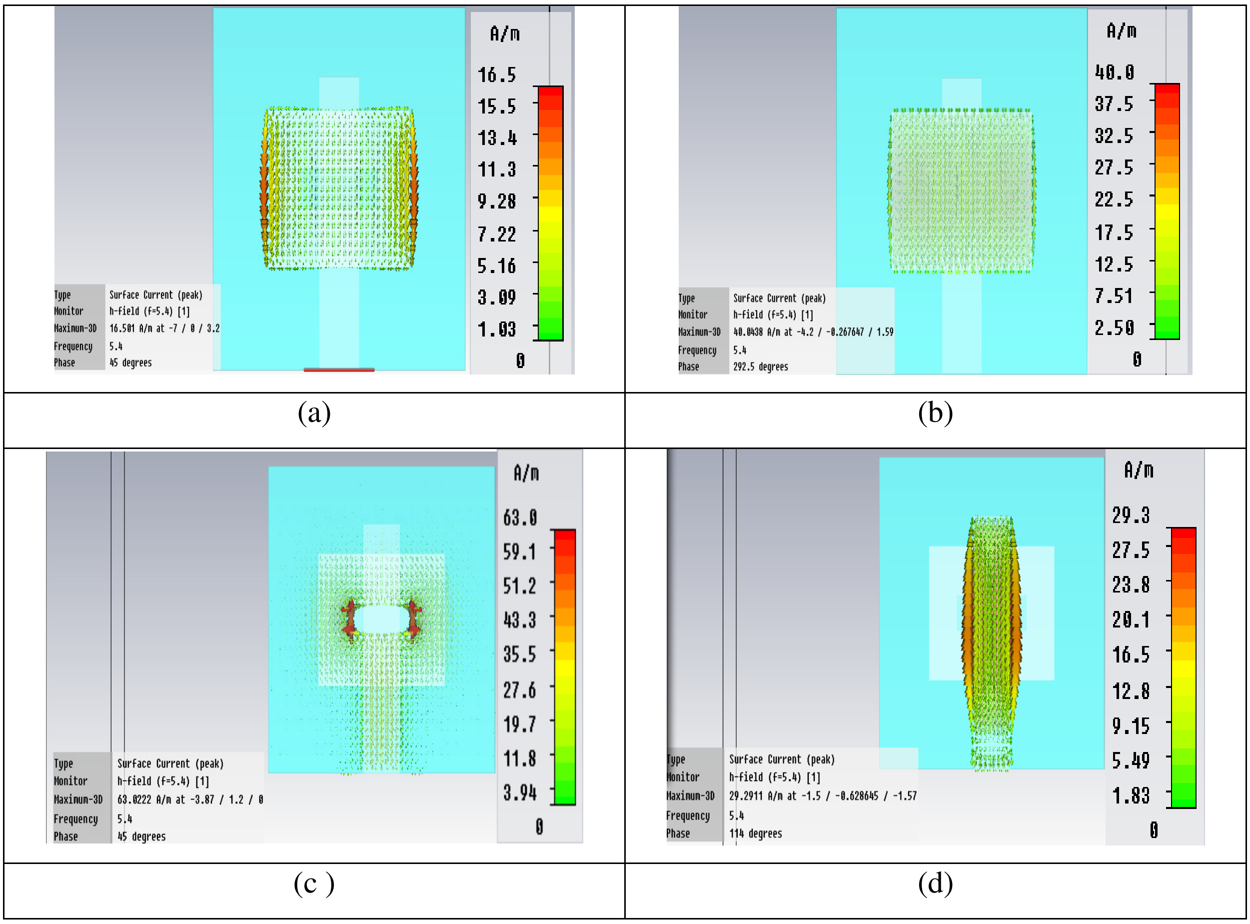


Figure 3.9: Current distribution on the (a) Top Patch (b) Middle Patch (c) Ground and (d) Feed line respectively

3.4. Parametric Analysis of the Antenna

An aperture coupled stacked patch antenna offers many parameters to the antenna designer that can be optimized to get a wide band operation; in this section each parameter is individually varied to see its effect on the performance of the proposed antenna in terms of return loss, impedance matching and impedance bandwidth.

3.4.1. Variations in the width (W1) of the driven patch antenna

The patch antenna width i.e. the radiating edges in a rectangular patch mainly affects the resonant frequency of the antenna's operation. In the proposed antenna, the patch width (W1) was changed to see the affect of this variation on resonant band of operation. Figure 3.10 shows the shift in the resonant band with the change in patch width from 7.1mm (-3.55 to 3.55) mm to 11.1mm, (-5.55 to 5.55) mm.

Table 3.2: Effect of change in patch width on the resonant frequency

Width (w1) mm(-x to x) mm	Resonant Frequency(GHz)	Bandwidth (appx.)MHz
7.1	6.3	500
9.1	5.4	473
11.1	4.8	100

It can be concluded from Figure 3.10 and Table 3.2 that the resonant band of operation gets shifted to right or left of the desired resonant frequency by increasing or decreasing the width of the rectangular patch. The bandwidth of the resonant band also reduces when the patch width is reduced and it improves with increase in patch width. Since the desired wireless applications demand a resonant frequency of 5.4GHz, the optimized width of the patch dimensions selected were 9.1mm (-4.55 to 4.55)mm.

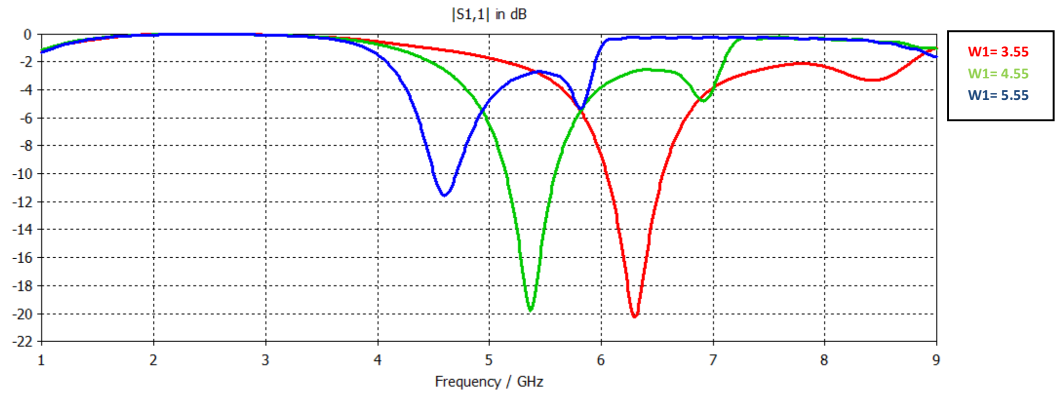


Figure 3.10: Effect of change in patch width

3.4.2. Effect of Variation in width (W2) of Aperture slot

The aperture in the ground helps in allowing EM waves to be electromagnetically coupled to the patch antennas. A rectangular aperture that is orthogonal to the feed line usually helps in achieving that. The aperture slot width is also varied to observe the effect of this variation on the antenna's performance. As can be observed from the Figure 3.11, there is a change in the antenna's S_{11} (dB) value at the resonant frequency with variation in the slot width. This suggests that the impedance matching is affected with change in dimensions along Y axis of the aperture. Referring to the Table 3.3, the aperture length dimensions with minimum S_{11} (dB) value (best impedance matching) are chosen as the optimized dimensions for the currently designed stacked aperture coupled antenna. Therefore in this case, the optimum value of the width is chosen to be 2.5mm (-1.25 to 1.25) mm.

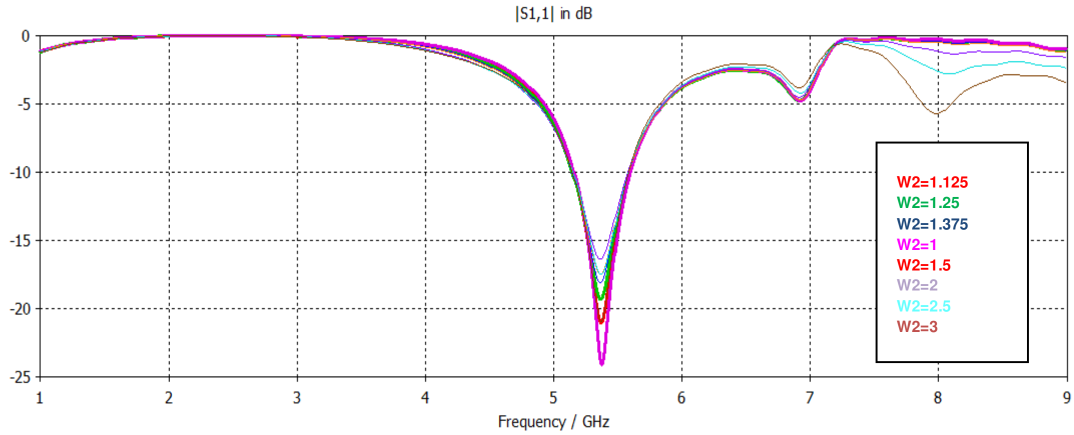


Figure 3.11: Effect of change in aperture slot width W2 on the antenna's performance.

Table 3.3: Effect of change in aperture length on impedance matching

Aperture length (-x to x) mm	Resonant Frequency (GHz)	S_{11}(dB)
6	5.38	-24
5	5.38	-22
4	5.38	-22
3	5.38	-20
2.75	5.38	-20
2.5	5.38	-18
2.2	5.38	-22

3.4.3. Effect of Variation in length of Aperture slot

The length of Aperture slot can also be optimized to get a desired operational behavior from the antenna. Figure 3.12 and Table 3.4 shows how a change in the aperture length affects the S_{11} (in dB) values and the operational bandwidth at the resonant frequency of operation. The aperture length is seen to affect the bandwidth of antennas because it helps the EM fields to get coupled from the feed line to the radiating patches. It is observed from the simulated results in Figure 3.12 that as the aperture length is decreased or increased from the optimized value, the antenna's resonance changes and at some dimensions it does not resonate at all. It is observed from Table 3.4 that a decrease in the aperture length from the optimized value causes the bandwidth to decrease and increasing the aperture dimensions beyond the optimized value changes the resonance of the antenna. Thus an optimized value of 7.74 mm (-3.87 to 3.87) mm was chosen for the aperture length dimensions (L2) for the current antenna design.

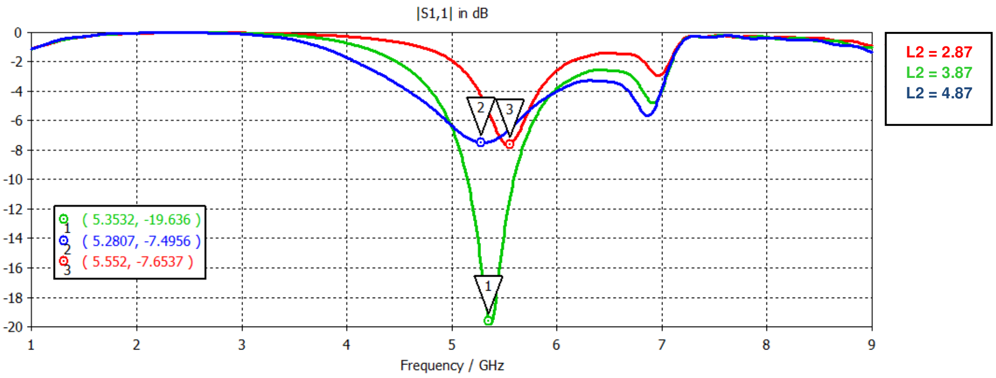


Figure 3.12: Effect of change in aperture length

Table 3.4: Effect of Change in aperture length on resonant frequency

Aperture length (L2)mm	Resonant Frequency (GHz)	Bandwidth (appx.) MHz
5.74	5.55	200(at S_{11} value of -6dB
7.74	5.4	500
9.74	5.28	400 (at S_{11} value of -6dB)

3.4.4. Effect of Variation in width of Feed line (W3)

The feed line of the antenna is responsible for supplying current throughout the antenna parts . The dimensions of the feed line are optimized so that the input impedance of the antenna matches with the impedance of a subminiature connector that connects the supply cable to the antenna feed line. A change in feed line width leads to a change in the impedance matching of the antenna at the resonant frequency band. It also leads to a slight shift in the resonant frequency and the bandwidth obtained at that frequency band. Figure 3.13 shows the effect of change in the feed line width from 3mm to 6mm. Referring to Table 3.5; it is observed that the best antenna performance was obtained with a feed line width of 4mm. Thus 4mm (-2mm to 2mm) is chosen to be the optimized feed line width for the antenna's desired behavior.

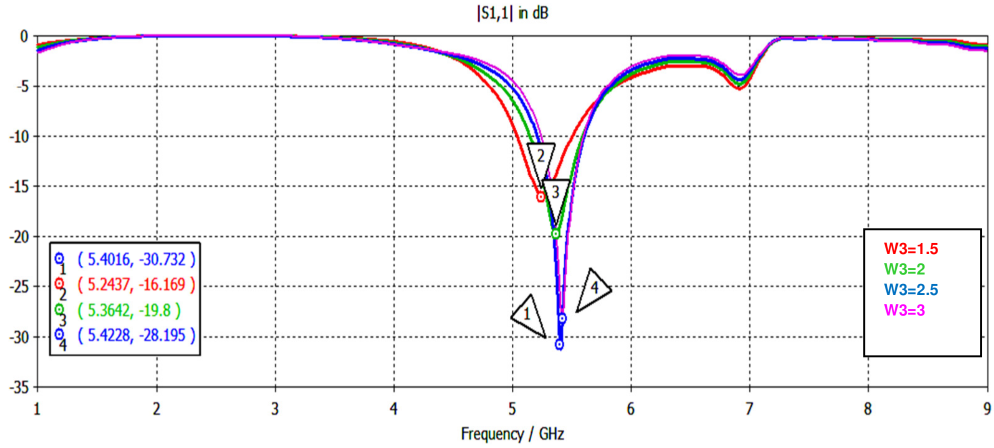


Figure 3.13: Effect of change in antenna's feed line width

Table 3.5: Effect of change in feed line width on resonance and imp. matching

Feed line width , W3 (-x to x) mm	Resonant Frequency (GHz)	S_{11}(dB)
6	5.40	-33
5	5.42	-28
4	5.36	-29
3	5.24	-26

3.4.5. Effect of Variation in Length of antenna's Feed line (L3)

Ideally the feed line length should be from the patch edge up to the point where patch center lies but this can also be varied for getting an input impedance of 50 ohms matched at the respective resonant band. The feed line length in this case was varied to see the variation in output response of the antenna. Figure 3.14 shows the effect of parametric variation of feed line length of the antenna, it can be observed from Table 3.6 that the S_{11}(dB) values are varied as the length of feed line is varied, thereby showing a change in impedance matching at the antenna's resonant frequency. The optimized value of 13.04mm (- 6.57 to 6.57) mm from the patch edge was chosen as the optimized length of the feed line.

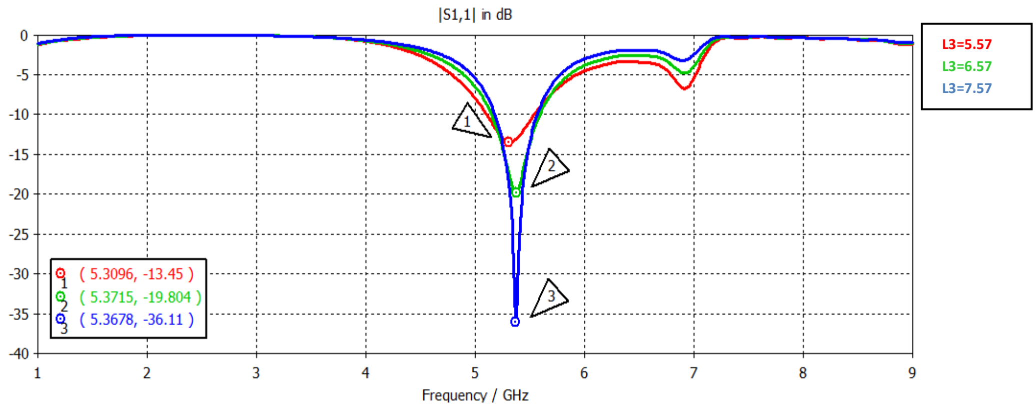


Figure 3.14: Effect of change in feed line length

Table 3.6: Effect of change in feed line length on impedance matching

Feed line length L3 (-x to x) mm	Resonant frequency	S_{11}(dB)
5.57	5.4	-15
6.57	5.4	-20
7.57	5.4	-36

3.4.6. Effect of variation in Ground Plane Dimensions

The ground plane of the antenna can be reduced along the X and Y axis to allow more fringing of fields so that these fields are loosely bound and are radiated better and the antenna gives an optimized performance in terms of its impedance bandwidth. To illustrate this, Figure 3.15 shows the variations in ground plane dimensions of the antenna along Y axis to observe the change in response from the S_{11}(dB) plot. It can be observed that the best results are obtained for the current case with the length of the ground chosen as 22 mm (-10.56 to 10.56) mm which are same as that of the substrate width also. After optimization, the antenna was fabricated using wet etching technology and tested using a Vector Network Analyzer and in an anechoic chamber for validation of results. The next section presents antenna fabrication process and its testing.

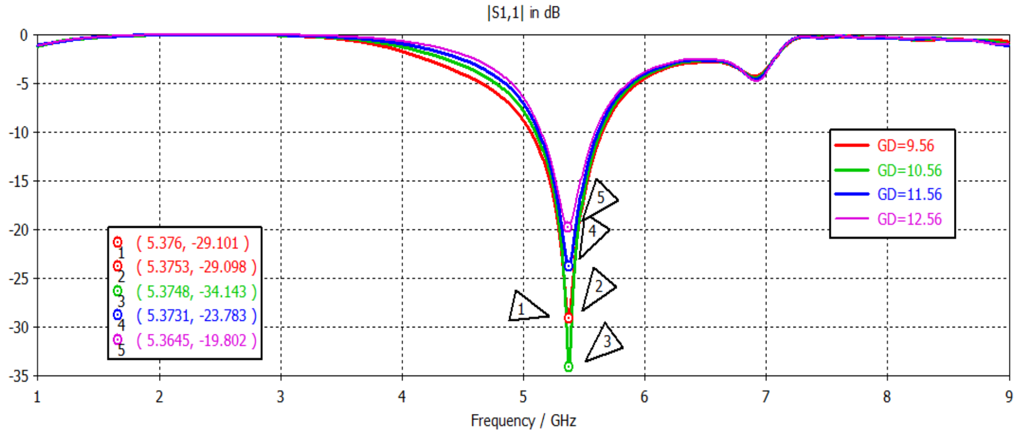


Figure 3.15: Effect of change in ground plane length

3.5. Antenna Fabrication and Testing for Validation of Results

The proposed antenna with all the optimized parametric values as mentioned in Table 3.1 was fabricated using the wet etching technique on the easily available FR4 dielectric slab with an absolute permittivity of 4.4, a thickness of 1.57mm and a loss tangent of 0.0024. The various steps that are carried out in the fabrication process are highlighted in Figure 3.16 which shows the flow chart of steps that are carried out to fabricate the final antenna.

Figures 3.17(a), (b) and (c) show the snap shots of the back view of antenna with feed line, assembled antenna with three substrate layers of FR4, the view of ground plane with an aperture slot respectively. The fabricated antenna was tested for validation of its results on a vector network analyzer; (Agilent's E5071C) operating in the frequency range of 9 KHz to 8.5GHz. Figure 3.18(a) shows the snap shot of VNA while testing the antenna for its S_{11}(dB) results.

Figure 3.18(a) shows the snap shot of the VNA screen when the fabricated antenna was tested for S_{11} (dB) results. Figure 3.18(b) shows the comparison of simulated and measured results of the antennas S_{11} (dB) results plotted in MATLAB for the justifying the correlation between the two results obtained. It can be seen from the Figures that the antenna has a measured impedance bandwidth of 640 MHz from 5.06 to 5.70GHz thereby covering the wireless applications of WLAN from (5.15 to 5.35) GHz , UNII-1(Unlicensed National Information Infrastructure radio band) from (5.18-5.24) GHz and UNII-2 bands(5.26-5.70) GHz . (The UNII-1 and UNII-2 bands come under the category of ISM bands). This makes the antenna practically suitable for the suggested wireless applications. The measure impedance bandwidth is found to be more than the simulate one because of the minute air gap that might be present between substrate layers of the antenna while physically assembling it.

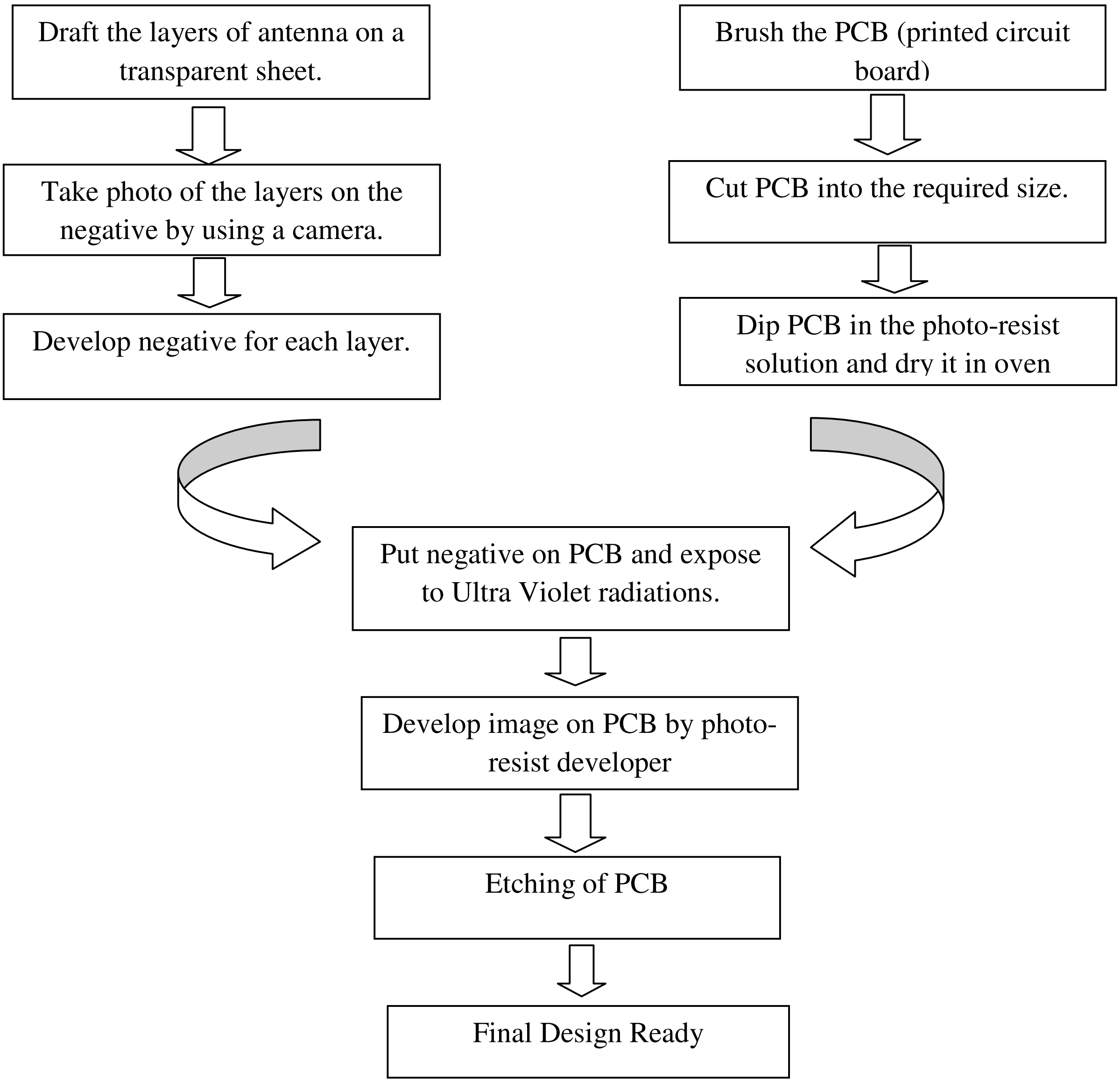
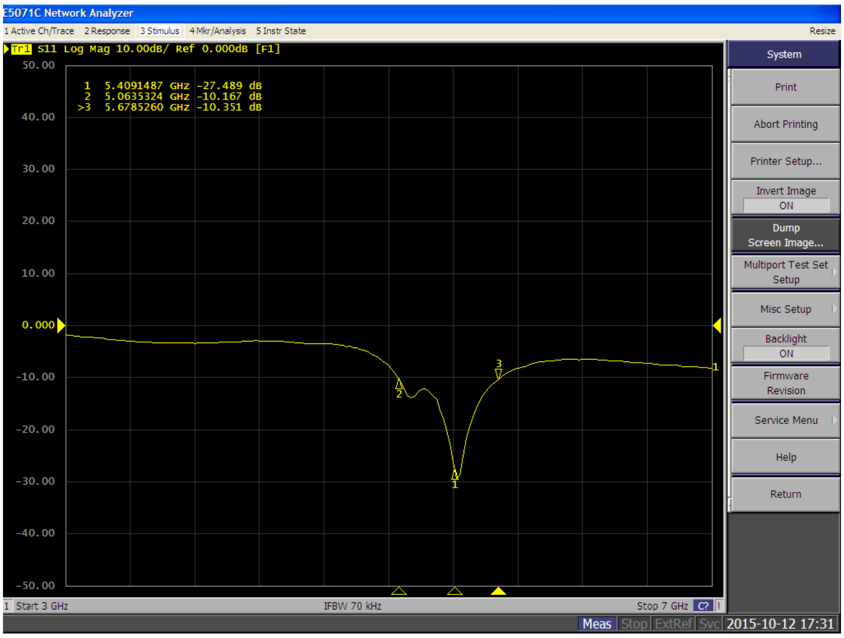


Figure 3.16: Flow Chart of the Fabrication Process of Antenna

(a)	(b)	(c)

Figure 3.17 (a): Back view of antenna, 3.15(b): The assembled antenna with three substrate layers, 3.15(c): View of the ground layer of the antenna



Figures 3.18 (a): Snap shot of the VNA when antenna was tested for S_{11} (dB) results

The antenna was also tested for gain measurements in an anechoic chamber operating at a frequency range from 2 KHz to 20 GHz. This chamber has a standard horn antenna with a calibrated gain of 12dBi. It provides an ideal environment that is free of reflections for the testing of antennas. The comparison of simulated and measured values of antenna's gain pattern along the elevation plane and azimuth plane are as shown in Figures 3.19(a) and (b).

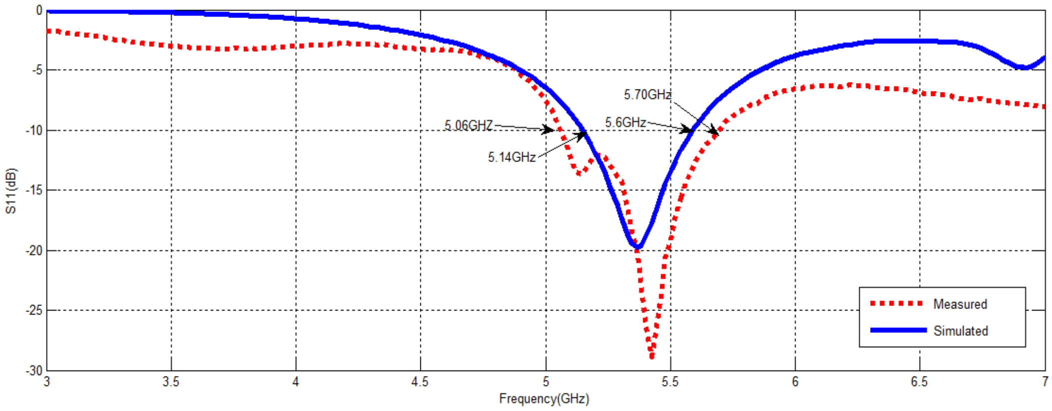
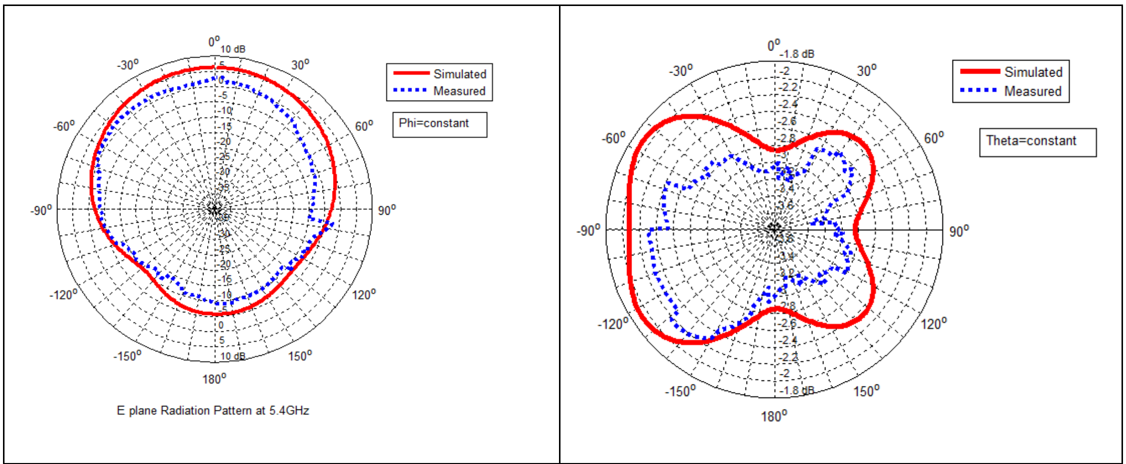


Figure 3.18 (b): Comparison between simulated and measured S_{11} (dB) results of the antenna



(a) (b)

Figure 3.19 Comparison of: (a) E (Elevation) and (b) H (Azimuthal) plane patterns of the antenna at 5.4GHz respectively.

The polar plots of the measured radiation patterns can be seen to follow the simulated ones closely but a few variations that are seen in the H plane pattern arise mainly because of the inaccuracies of alignment of the three substrate layers, soldering connections and measuring low gain values in a low noise environment. The possible reason for these variations in the measured results could also be because of some air gap that might arise between the three substrate layers while stacking multiple layers one above the other. On an average a variation of 1 to 1.3 dB can be seen in the simulated and measured results that can be verified from the Figure 3.20 that shows the comparison between the simulated and measured gain values in the frequency band from 5 to 6 GHz.

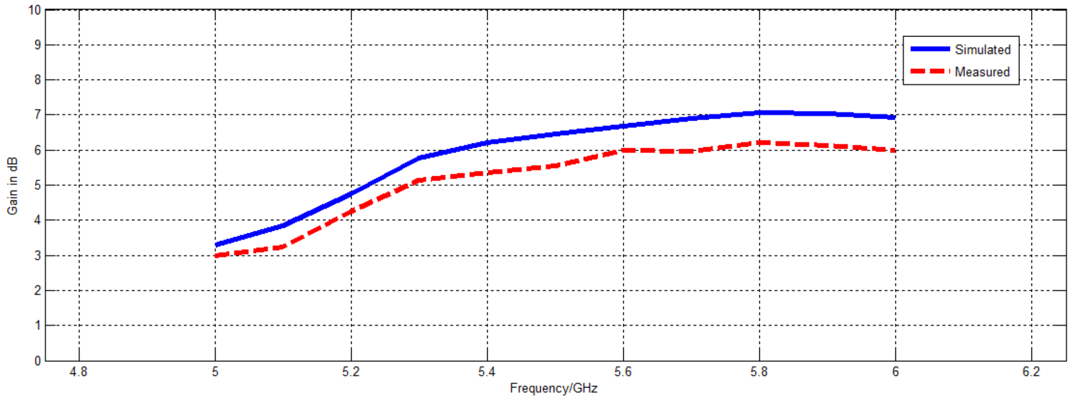


Figure 3.20: Comparison between Simulated and Measured gain at 5-6 GHz

3.6. Conclusions

A three layered aperture coupled SMSA with stacked identical patches having no air gap between them is presented in this chapter. The antenna is matched to an input impedance of 50 ohms and shows a VSWR of 1.4 at the central frequency (5.38GHz) of the band.

The main aim of this chapter is to illustrate the use of stacking as a simpler and an efficient method for improving the antenna's impedance bandwidth. With the proposed stacked structure, the antenna is able to achieve a measured bandwidth of 640 MHz i.e. around 11.8% bandwidth at the central frequency of operation. The antenna dimensions were optimized for the desired behavior using a parameter sweep option in CST MWSV.10 software. In this context, the parametric analysis of the different antenna dimensions is also presented to emphasize upon the optimization of the antenna's output based upon variations of dimensions of the different antenna parts.

The antenna has a compact structure with dimensions of 2.5cm X 2.3cm X 4.8mm and it is fabricated using wet etching technology. This SMSA is tested using a VNA and an anechoic chamber for its applicability to wireless applications of WLAN (5.15-5.35) GHz, ISM band (5.18-5.24 GHz) and UNII-2 bands (5.26-5.70 GHz). It shows good gain characteristics of around 6.5dB that allow it to be applicable to the indoor wireless applications for which it is proposed.

In conclusion, the research work presented in chapter emphasizes on the use of stacked microstrip patch antennas for improving the bandwidth of the existing aperture coupled antenna without using any complex geometry and therefore impresses upon the usage of such antennas for the current research work. The next three chapters present the design, analysis and experimental illustration of three main types of stacked microstrip patch antennas that include a simple rectangular stacked patch antenna with an E shaped DGS, fractal shaped stacked antennas with cross shaped DGS and complementary/slotted stacked patch antenna with a pie shaped DGS.

Chapter 4
Design and Analysis of a Stacked Dual Wide Band Circularly Polarized Microstrip patch Antenna with Defected Ground Structure for Wi-MAX/ WLAN / Bluetooth / Zigbee and IMT Band Applications

In this chapter, a novel dual broad band, dual polarized microstrip patch antenna with a three layered structure having an 'E' slotted ground layer leading to Defected Ground geometry is presented. The main goal of this chapter is to show the effect of stacking two unequal sized patch antennas, whose dimensions are selected such that two close by resonant frequencies are excited. The resonant frequencies of the two patch antennas are close to each other, thus leading to a wideband behavior. The chapter also aims to show the effect of DGS that can lead to the second resonant band with an enhanced bandwidth. The proposed structure is fed by an electromagnetically coupled method called aperture coupling with a feed line having an orthogonal stub. The feed line that has an orthogonal stub attached to it can allow the antenna to transmit circularly polarized waves. The antenna design and simulation is done using CST MWS V.10 with hexahedral mesh settings and perfect boundary approximations.

The antenna has been proposed for Wireless Local Area Networks (WLAN), Bluetooth, Worldwide Interoperability for Microwave Access (Wi-MAX), Zigbee, and International Mobile Telecommunication band (IMT) applications. The recommended antenna structure has a compact structure with dimensions of (L X W X H) as 4.85cm X 4.03cm X 5.01mm. It shows a dual wide band because of the fact that two patch antennas provide one resonant band of operation and the defected ground structure provides the second resonant band. The antenna also shows a circular polarization because of the structure of the feed network.

The organization of this chapter is as follows; section 4.1 gives an introduction to the need for such antennas and related work in this regard, section 4.2 mentions the basics of antenna design in CSTMWS V.10 and the simulation results obtained, section 4.3 mentions the parametric study of the antenna and section 4.4 mentions the comparison of fabrication and testing results obtained for the validation and application of proposed antenna in the current wireless scenario.

4.1. Introduction and Related Works

The WLAN technology has been one of the most promising technologies for computer communications in the unlicensed wireless band**.** The antennas needed for WLAN applications require a good bandwidth to support a high data rate. Additionally, if the antenna is a multiband antenna; it is capable of covering multiple wireless applications in a single device. Thus a demand for multiband antennas has led researchers to design and propose more and more multiband antennas to meet the current needs of these communication systems. As an example, the authors in [131] proposed a triple band PIFA (Planar Inverted F antenna) antenna for WLAN and GSM applications.

Another such work related to multiband antennas was proposed by authors in [132]. A compact, small sized antenna was presented that consisted of structure in which three inverted S shaped and C shaped grooves were embedded into a rectangular ring, the antenna thus achieved a Penta band behavior with a good impedance matching and wideband characteristics. Many other related research work for multi frequency wideband antennas for antennas operating for WLAN and Wi-MAX bands are reported by authors in [52], [135]-[137],[108].

In order to support a high data rate at all the resonant bands of an antenna, a good bandwidth is one of the main requirements. Another major requirement is the ease of fabrication and design of these antennas for their implementation in the current wireless scenario. These characteristics are easily available with stacked antennas. In this context, the authors in [133] proposed multilayer patch antenna with an air gap between the layers for WLAN and Wi-Max applications. This structure was fed with power using a microstrip line feed. The antenna had a defected ground structure with a circular defect. The antenna was able to achieve Dual band characteristic at 2.55 GHz and 5.25 GHz with compactness in design of 36% for the proposed applications [133].

Another work that was presented by researchers in literature was based on the usage of dual polarized multiple layered patch antennas in [134], authors proposed a circularly polarized multi frequency antenna for GPS receivers. Coaxial probe feeding was used to feed this three layered antenna. The geometry of the antenna had a slit and symmetrical I-slot which presented triple frequency bands for GPS (Global Positioning System) operations. Many other circularly polarized antennas are reported in the literature in [115]-[118].

Since a multi frequency broadband antenna with circular polarization is required for covering the desired wireless applications of WLAN, Bluetooth, Zigbee, Wi-MaX and IMT band using a single antenna, the current research work focuses on the design of a dual wideband antenna using a stacked rectangular patch structure with an 'E' shaped slot in the ground layer of this antenna structure.

Circular polarization is achieved from this antenna by the use of a stub that is in quadrature with the feed line. This helps in exciting the patch antenna as the energy gets coupled to the patches because of the ‘E’ shaped aperture slot in the ground plane (using the aperture coupled feeding mechanism).

4.2. Antenna Geometry and Design

The proposed stacked patch structure is designed upon a glass epoxy Flame retardant 4 (FR4) substrate with a relative permittivity of 4.4. This antenna is capable of providing a dual wideband behavior from 2.39GHz - 2.64GHz with an impedance bandwidth of 250MHz (centered at 2.51GHz) and from 3.39GHz -3.76GHz with an impedance bandwidth of 370MHz (centered at 3.57GHz) respectively.

The antenna structure consists of three substrate layers of FR4 with the top layer and the middle layer having rectangular patches printed over them. The dimensions of the two rectangular patches are defined from the transmission line model using equations 2.10 to 2.15 (section 2.3) to determine the length and width of the patch antennas.

The measurements of the patches are chosen such that the higher frequency band of antenna’s working is gained by piling up two rectangular patches. These patches differ in size from each other by around 9% are piled up one over the other to give an enhanced bandwidth of operation. (Dimensions of lower patch are 9% shorter than the top patch). The resulting antenna structure is energized using aperture coupled feeding. As a result the two antennas radiate two frequency bands in close proximity of each other and their combined effect gives an improved bandwidth from 3.39GHz to 3.76GHz. Figure 4.1 shows the stacked antenna arrangement; the antenna has three substrate layers (each of FR4 with ε_r= 4.4, thickness h =1.57 mm and a dielectric loss tangent of 0.0024) and all the printed metallic layers of thickness 0.035mm.

The resulting antenna structure is fed by a parasitic feeding method in which the patch antenna gets its supply from the feed line though a slot in ground plane. The feed line is on the base of lowermost substrate, the dimensions of this feed line are judiciously selected so that the antenna input impedance matches to the impedance of a sub miniature connector (SMA) connecting the feed line and the coaxial cable of impedance 50 ohms. A rectangular stub is connected in quadrature to the feed line; this allows the antenna to radiate circularly polarized waves (as both the vertical and horizontal components of electric field are provided by the feed line to the antenna).

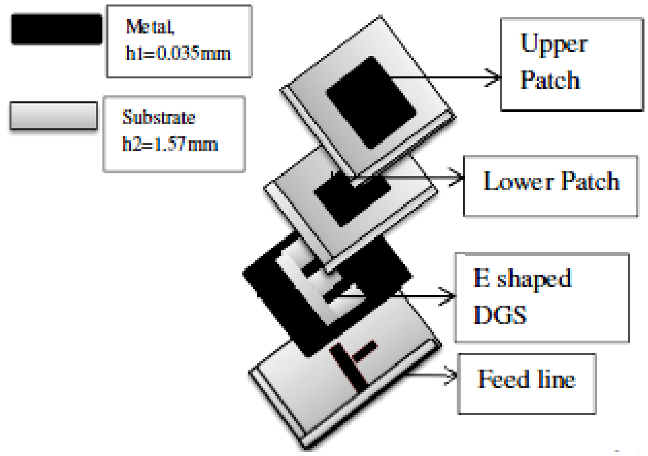


Figure 4.1: The perspective view of the antenna with three substrate layers

The ground plane of this antenna has an aperture slot that is modified to an 'E' shape with asymmetrical length of the three 'E' arms thereby giving it defected structure geometry. This is achieved by etching a groove of 'E' shape from the ground layer of optimized dimensions so as to excite the second resonant band from the antenna. The equivalent circuit of a DGS can be considered as equivalent to a parallel LC resonant circuit (as explained in section 2.9.e) whose resonant frequency (f_r) is given by equation 4.1 as

$$f_r = \frac{1}{\sqrt{2\pi LC}} \quad \ldots\ldots(4.1)$$

where L and C are given below [97].

$$L = \frac{1}{4\pi^2 fo^2 C} \text{ and } C = \frac{fc}{2Zo} \cdot \frac{1}{2\pi\left(fo^2 - fc^2\right)}, \quad \ldots\ldots(4.2)$$

and f_c, Z_0 *and* f_0, represent the cut off frequency, characteristic impedance of microstrip line above the DGS and the resonant frequency of working. Thus knowing the parameters of the dimensions of the specific shaped groove in the ground layer, the respective resonating frequency of operation because of it can be decided. Thus it is the defected ground structure that serves the job of showing the second resonant frequency band from 2.29GHz - 2.64GHz. This allows the current antenna structure to be resonant at the two mentioned frequency bands.

The general design steps in the designing of the antenna are mentioned as follows.

i) The dimensions of rectangular patches are calculated according to the transmission line model equations taking into account, permittivity and thickness of the substrate FR4 [3].
ii) Feed network is optimized in its dimensions of length and width using parametric sweep in the CSTMWS V.10 software.
iii) The dimensions of the 'E' shaped slot in ground are computed according to equations (4.1) and (4.2) to obtain the second resonant radio band of operation [97].
iv) Optimization of the parameters of 'E' using the parameter sweep option in the software to cover the mentioned wireless applications.

The optimized antenna has an upper patch that is rectangular in shape with measurements of (L_1 X W_1) as 19mm x 18.8mm imprinted on the top substrate layer. Figure 4.2 shows the detailed structure and the dimensions of the proposed structure. A comparatively shorter rectangular patch of dimensions (L_2 X W_2) as 17.2mm x 17.2mm is printed on the middle substrate layer is shown in Figure 4.3. The metallic ground layer of the antenna is a reduced ground plane with dimensions of (X_1 X Y_1) as 36mm X 29.65mm has an 'E' shaped slot etched from its surface (Figure. 4.4). The length of 'E' shaped DGS slot is (W_6) 9.5mm and the dimensions of the lower 'E' sub arm is (L5) 9.85mm (Figure 4. 4). The lower longer side of the 'E' arm is 11.95mm and the middle 'E' arm is (L4) 8.85mm long. The feed line of dimensions (L_7 X W_7) 3.3mm x 26mm is engraved on the baseline of lower substrate with a horizontal stub/tag of measurements (L_8 X W_8) 6.09mm x 1.6mm attached orthogonally to it (Figure.4.5). The antenna radiates circularly polarized signals when it is excited since the vertical feed line provides the vertical component of the electric (E) field and the horizontal stub provides the horizontal component of the E field thereby making the antenna circularly polarized in nature. The comprehensive dimensions of all the structural details of antenna are also mentioned in Table 4.1.

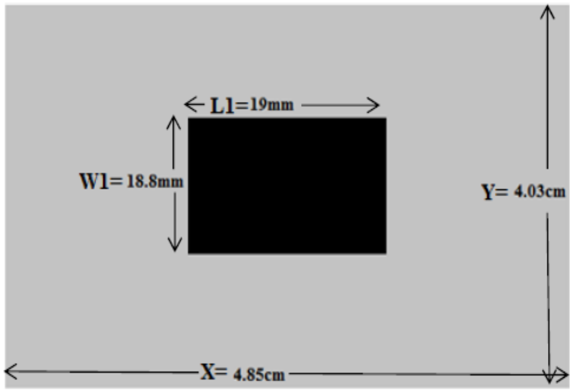


Figure 4.2: The top rectangular patch

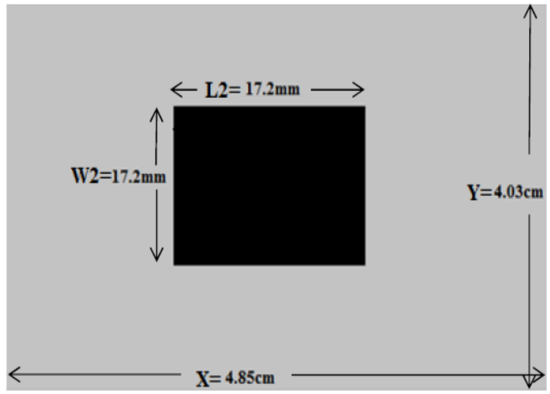


Figure 4.3: Lower rectangular patch

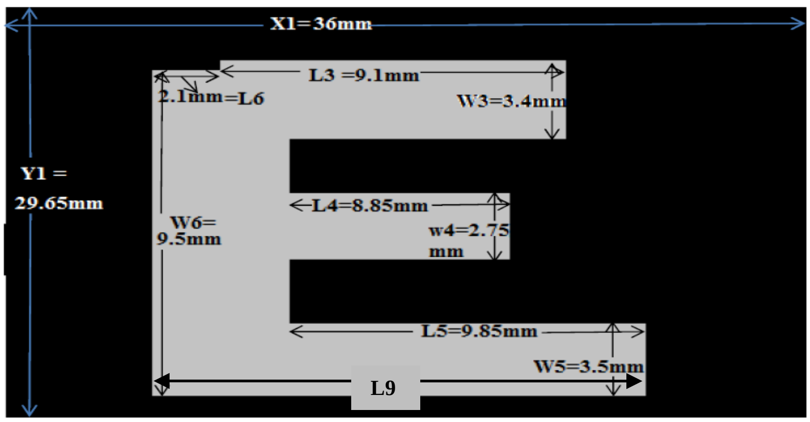


Figure 4.4: Reduced ground plane with an E shaped Slot (DGS)

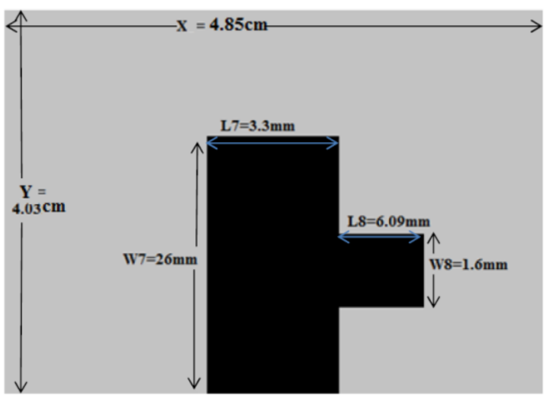


Figure 4.5: Feed line with an orthogonal stub on the backside of bottom substrate

Table 4.1: Design Parameters of the stacked antenna

Parameter	Dimensions in mm
L_1	19
W_1	18.8
L_2	17.2
W_2	17.2
L_3	9.1
W_3	3.4
L_4	8.85
W4	2.75
L5	9.85
W5	3.5
L6	2.1
W6	9.5
L7	3.3
W7	26
L8	6.09
W8	1.6
X	48.5
Y	40.3
X1	36
Y1	29.65

4.3. Simulation Results

The proposed antenna structure was simulated in CSTMWS V.10 and the results obtained in terms of impedance bandwidth, VSWR, current distribution, radiation pattern, gain and axial ratio bandwidth are discussed in the succeeding subsections.

4.3.1. Impedance bandwidth

The antenna behaves as a dual band antenna showing a impedance bandwidth (impedance matched at 50 ohms) from the frequency range of 2.39GHz - 2.64GHz showing a bandwidth of 250MHz (with a centre frequency of 2.51GHz) and a bandwidth of 370MHz ranging from 3.39GHz -3.76GHz (centered at 3.57GHz). Figure 4.6 shows the S_{11} (dB) plot of antenna with S_{11} (dB) shown on Y axis against the frequency shown on X axis. The two operating bands have a frequency range corresponding to S_{11} (dB) value of -10dB from 2.39GHz -2.64GHz and 3.39GHz -3.76GHz. Further the minimum S_{11} (dB) values are found to be -33dB and -25dB at the two lower and upper frequency bands respectively. The upper band ranging between 3.39GHz - 3.76GHz is due to the two stacked rectangular microstrip antennas of varying dimensions and second band of operation from 2.39GHz - 2.64GHz is due to 'E' shaped slot that is etched from the ground plane. The additional advantage to the bandwidth enhancement is offered by the aperture coupled feeding method used with the antenna.

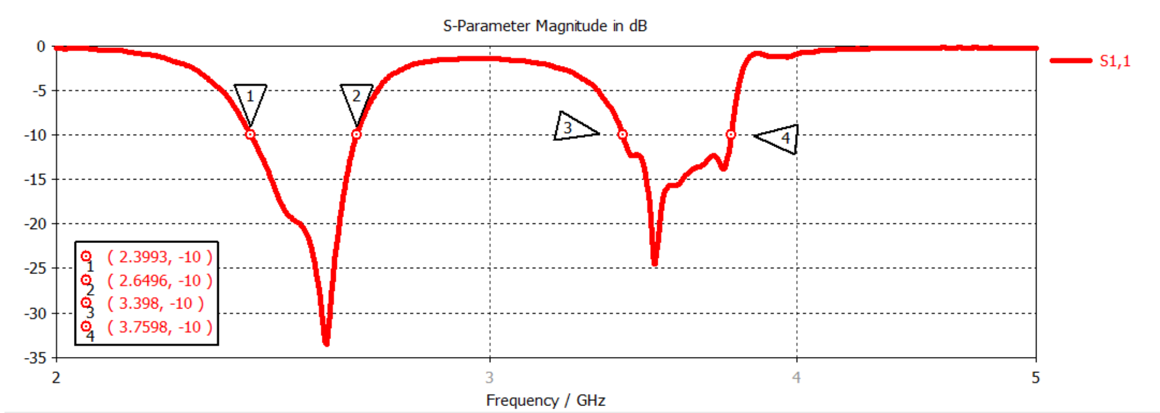


Figure 4.6: Simulated S_{11} (dB) Plot Showing Impedance Bandwidth

4.3.2. Axial Ratio Bandwidth

The proposed antenna transmits circularly polarized waves, i.e. it radiates two (approximately equal in magnitude) components of the electric field vector, one horizontal and one vertical such that their resultant trajectory in far field traces a circle. The feed line that is capable of energizing the antenna is provided with an orthogonal stub, thus the currents that are fed to the antenna are in phase quadrature, and radiate EM fields that have two orthogonal E field components.

The range of frequencies which possess an axial ratio less than a predefined standard value confirm as Axial Ratio (AR) Bandwidth of the antenna. Figure 4.7 shows the simulated 1dB AR bandwidth for the presented antenna, axial ratio bandwidth of 320MHz from (2.2GHz - 2.52GHz), AR bandwidth of 520MHz from (3.18GHz - 3.7GHz), an AR bandwidth of 200MHz from (3.9GHz - 4.1GHz), AR bandwidth of 800MHz from (4.3GHz - 5.1GHz) is exhibited by the proposed antenna. The antenna is thus capable of transmitting two components of electric field at the two proposed wireless bands of 2.39GHz - 2.64GHz and 3.39GHz - 3.76GHz

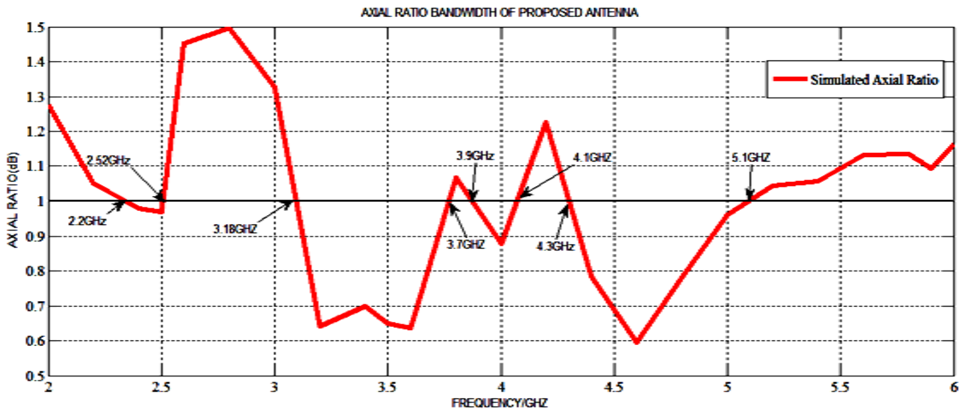


Figure 4.7: Axial Ratio bandwidth of the proposed antenna

4.3.3. VSWR Plot

The VSWR (Voltage standing wave ratio) defines the quantum of the amount of impedance matching between the antenna and the transmission line connected to it from the source. Figure 4.8 shows the VSWR plot of the antenna, it is observed that the antenna shows a VSWR of 1.22 and 1.39 respectively at 2.51GHz and 3.57GHz as the center frequencies of the two bands. Since a VSWR of less than 2 is considered to be optimum for RF applications, the designed antenna fulfils the requirements of conjugate matching.

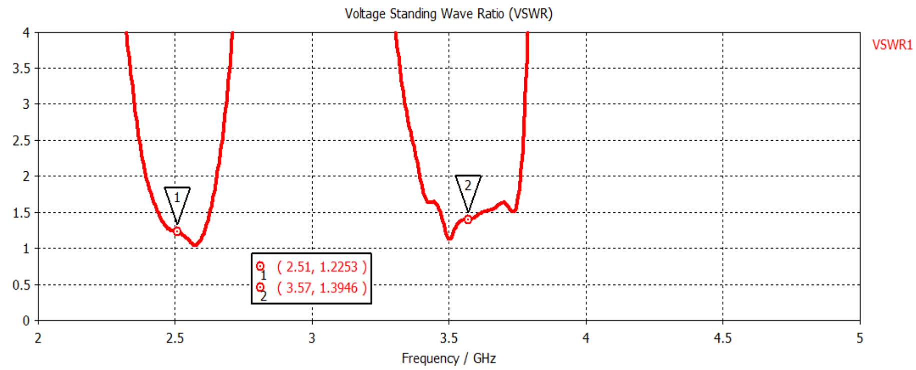


Figure 4.8: The VSWR Plot of the Antenna at 2.51GHz and 3.57GHz

4.3.4. Current Distribution

The proposed MSA was energized with a power stimulus of 1 Watt in CST MWS V.10 software, to observe the distribution of energy on the various parts of the antenna structure at the two centre frequencies of the two RF bands radiated by the antenna (for VSWR < 2) and also to support the theoretical statements about the claim of a respective parts of antenna being responsible for a specific resonance. Figures 4.9(a) and 4.9(b) show the distribution of current on the ground layer of the proposed MSA in contrast to the distribution of current on the surface of upper rectangular patch at the central frequency of upper resonant frequency band at 2.51GHz. Figures 4.9(a) and (b) depict the maximum current distribution of 108.4A/m on the E shaped slot in comparison to the upper rectangular patch antenna with a current distribution of 14.2A/m at the central frequency of 2.51 GHz (lower band). This leads to a conclusion that the 'E' shaped slot in ground layer is responsible for exhibiting a resonant frequency band from 2.39GHz – 2.64GHz .This can also be concluded from the parametric analysis of antenna given in the next subsection.

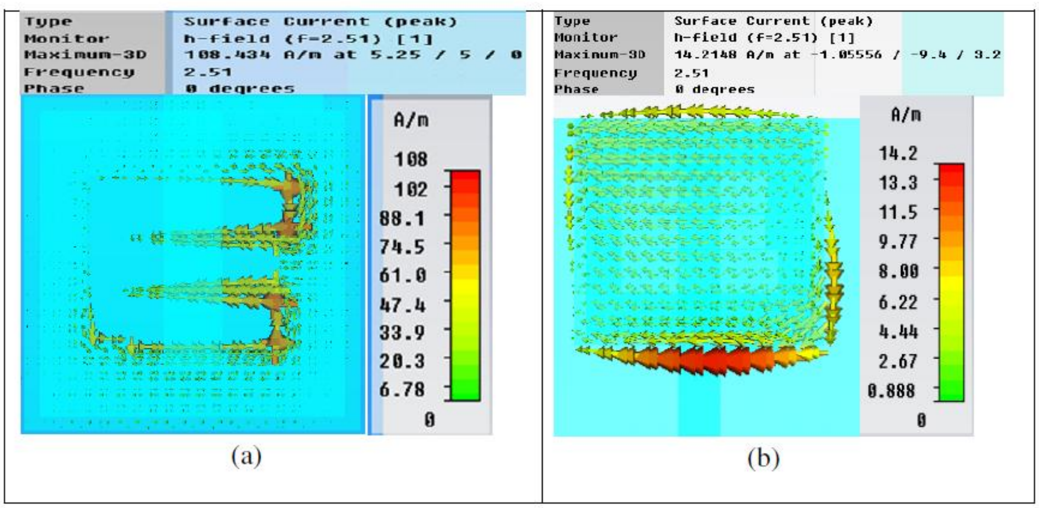
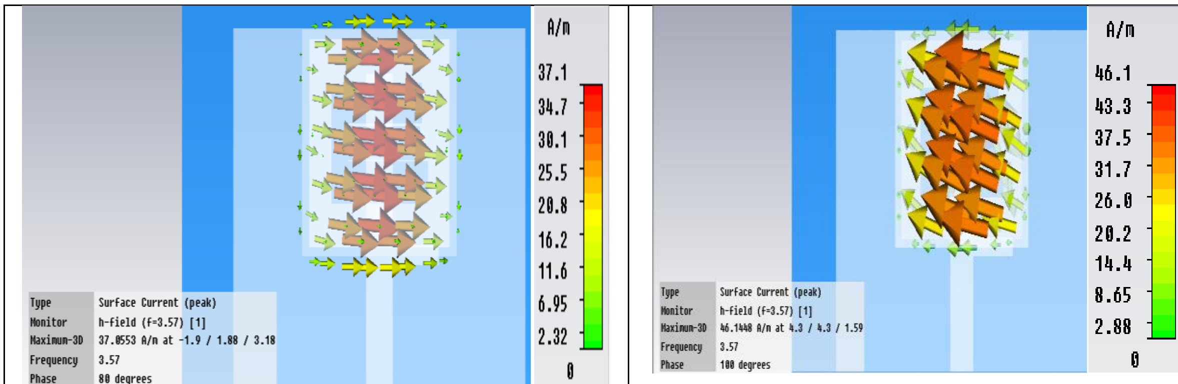


Figure 4.9: (a) Current distributions on Ground and (b) Upper patch layers of the antenna at 2.51GHz respectively

The current distribution on the top and middle antenna layers was observed at the central frequency of upper band i.e. at 3.57GHz. Figures 4.10(a) and 4.10(b) show the distribution of current on the patch antennas lying on top and middle substrate layers at 3.57GHz. The respective part of the antenna that has a maximum distribution of current over its surface at the resonant frequency is considered to be responsible for maximum radiation of EM waves. It is observed that the maximum concentration of energy takes place on the patch doublet at 3.57

GHz. The top and middle rectangular patch antennas show a current of 37.1A/m and 46.1 A/m respectively over their surfaces and are thus helpful for exhibiting an operational band from 3.39 GHz - 3.76GHz. It is also observed that the current distribution on rectangular patch antenna pair is circularly polarized since both the linear components (orthogonal to each other) of electric field are provided by the feed line.

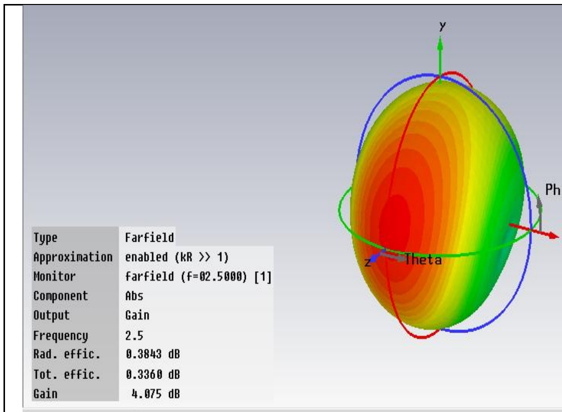


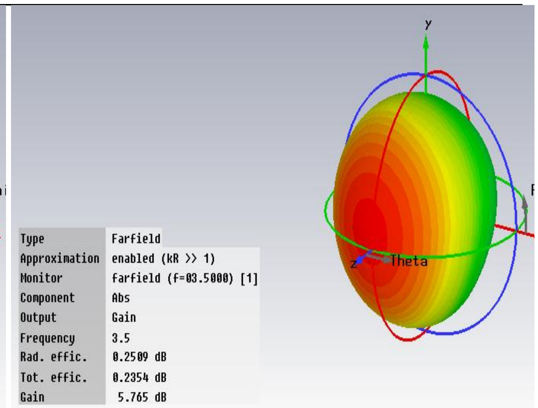
(a) (b)

Figure 4.10: Current distribution on the (a) Upper patch and (b) Lower patch antennas at 3.57 GHz

4.3.5. Gain

A high gain antenna is desirable since it is a directional antenna capable of covering long distances in terms of its range. Figures 4.11(a) and (b) show the simulated gain plots of the antenna showing a gain of 4.07dBi at 2.5GHz and a gain of 5.765dBi at 3.5GHz respectively (at the center frequency of the upper and lower wireless bands of antenna's operation). Hence the proposed antenna is able to concentrate its maximum power in a given direction so and it is able to focus the power towards a larger distance in terms of range. Thus this antenna can be successfully applied to the proposed wireless services of Wireless Local Area Networks in either computer terminals or the access points, for Bluetooth services in mobile handsets, tablets, handheld laptops, robotic systems etc for Zigbee applications to create a small Wireless personal area network like usage in traffic management systems and some consumer and industrial equipment. It can be utilized in Wi-MAX for providing high data rates over a little larger distance and International Mobile Telecommunication bands for broadband wireless access.





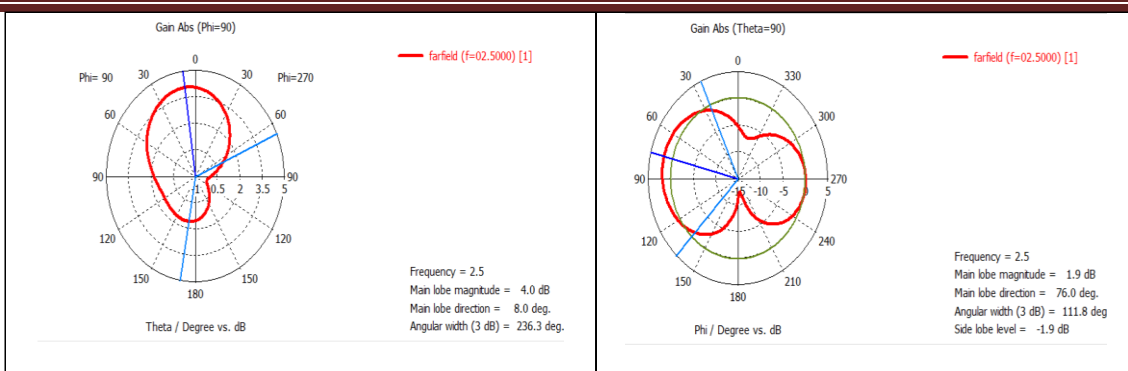
(a) (b)

Figure 4.11(a): Gain plot of antenna at 2.5GHz **Figure 4.11(b): Gain plot at 3.5GHz**

4.3.6. Radiation pattern

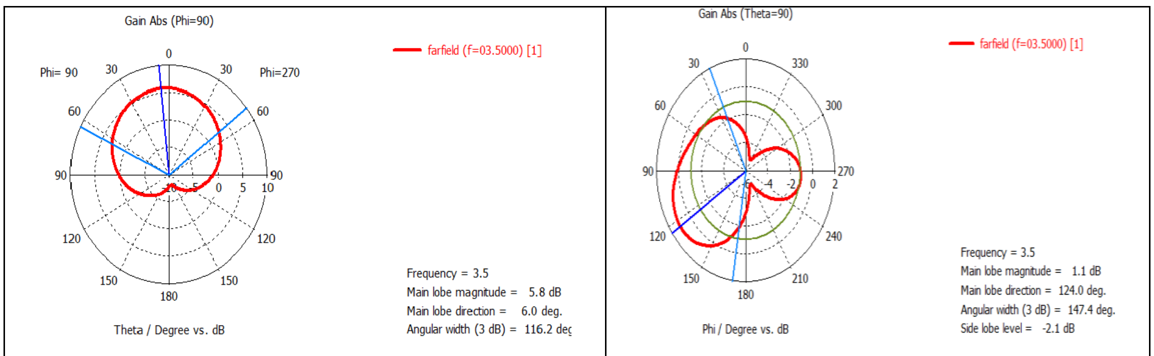
In order to practically use the antenna for a wireless application, some parameters like the direction of major and minor lobes of the antenna's pattern, to determine the angular width / beam width of the antenna's major lobe to allow it to fit to a specific coverage sector and also to find out the side lobe level of the antenna while radiating so as to remove unwanted radiations to avoid interference; the polar plots of the antennas in the elevation and azimuthal plane are important. Figures 4.12(a) and (b) show the antennas Elevation and Azimuthal views of the radiation pattern at 2.5GHz. As it can be observed from these figures, the antenna has a major lobe (in elevation plane) towards θ equal to 8 degrees, with a half power beam width of 263 degrees and a side lobe level of -1.9dB.

Figures 4.13(a) and (b) represent the elevation and azimuthal radiation patterns of the antenna at the center frequency of the upper frequency band i.e. 3.5 GHz. In the elevation (E plane), the antenna shows an Omni- directional pattern with major lobe along θ equal to 6 degrees and has a half power beam width of 116.2 degrees with a side lobe level of -2.1dB.



(a)	(b)

Figure 4.12: (a) E plane (Elevation) and 4.12 (b): H (Azimuthal) plane views of radiation pattern at 2.5GHz respectively.



(a)	(b)

Figure 4.13(a) and (b): E plane (Elevation) and H (Azimuthal) plane views of radiation pattern at 3.51GHz respectively

4.4. Parametric Analysis of the Antenna

CST MWSV.10 has certain features like parameter sweep, particle swarm optimizer & neural networks which help the user to optimize a certain parameter for getting a desired operation in terms of antenna characteristics like resonant frequency, VSWR and bandwidth. In this section the parametric analysis of the antenna's performance is done using the parameter sweep option in the software.

4.4.1. Parametric analysis of the width of smaller patch antenna (W2)

The width of the lower patch antenna affects the band operation from 3.39GHz to 3.76GHz.

Figure 4.14 (a) shows the frequency band at 3.5GHz gets shifted towards left as the width of the smaller metallic patch on the middle substrate layer is incremented. The band of operation with a centre frequency of 3.5GHz is curtailed as the width of the smaller patch antenna is decreased or increased from an optimum value. The lower band (2.39GHz - 2.64 GHz) remains unaffected with the change in width of the middle patch. This justifies the reasoning given for current distribution plots according to which the stacked rectangular patch antennas are responsible for showing the resonance at the upper frequency band from 3.39GHz to 3.76GHz. An optimized value of width of lower patch is chosen as 17.2mm (-8.6mm to 8.6mm) is chosen for covering the desired wireless applications.

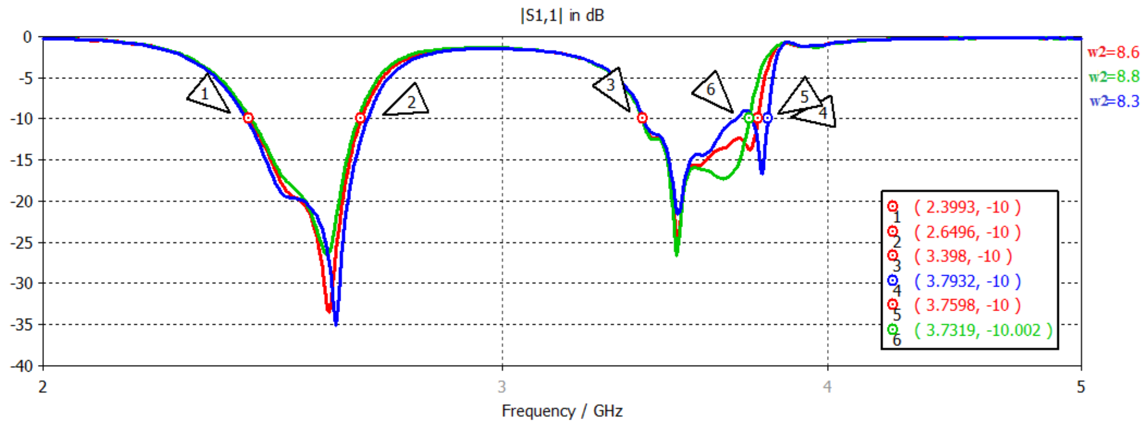


Figure 4.14 (a): Response of varying the Width of lower patch antenna

4.4.2. Parametric Analysis of Width (L3) of E slot in the DGS of the Antenna

The dimensions L3 of ‘E’ arm are varied to observe its effect on the impedance bandwidth of antenna. As observed from Figure 4.14(b), if the value of L3 in E arm is increased; the S_{11}(dB) at the lower band of 2.39GHz reduces and also the band frequencies start shifting towards right and the upper frequency band remains almost constant. This represents a lesser impedance matching so a dimension of L3 in ‘E’ arm is optimized at 9.1mm. This justifies the point that the E slot in the ground plane helps the antenna to exhibit a resonance from 2.39GHz - 2.64 GHz.

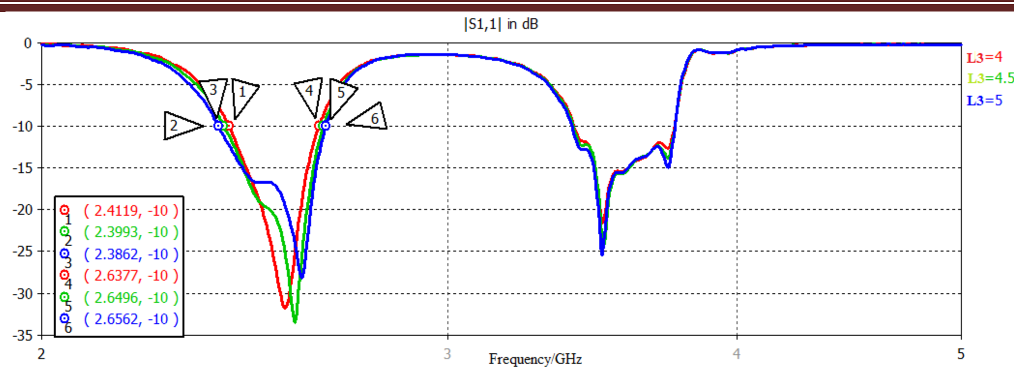


Figure 4.14(b): Response in terms of S_{11} (dB) by Varying L3 'E' Slot in Ground plane

4.4.3. Parametric Analysis of Variation of Longest 'E' arm (L9) in the Ground Plane

The effect of varying the longest 'E' arm (L9) in the ground layer is observed, from Figure 4.14(c). It is seen that the bandwidth of the resonant band reduces at the center frequency 2.51GHz as the length L9 is reduced. The resonant frequency also shifts by left with reduction in length L9. This supports the explanation given in the above sections about the slot in ground being responsible for showing resonance at 2.5GHz (i.e. the central frequency of lower resonant band).

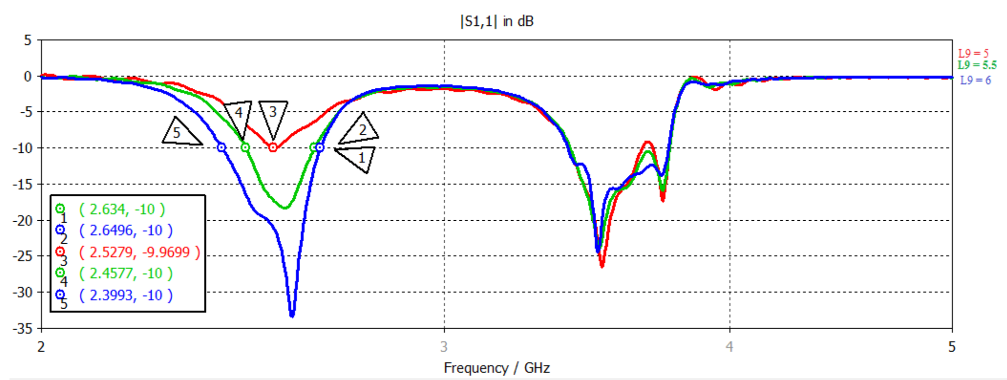


Figure 4.14(c): Effect of Variation in Longest E Arm (L9) on the Lower Resonant Band

4.5. Antenna Fabrication and Measurement of Results for Validation

The antenna was fabricated on a fiber glass Epoxy FR4 substrate with ε_r= 4.4, thickness 'h' equal to 1.57 mm and a dielectric loss tangent of 0.0024 using photolithography techniques. Three layers of FR4 were used with rectangular patches of height 0.035mm printed on the topmost two layers. The bottom layer has a reduced and defected ground structure (with an 'E' shaped slot) etched out from the ground layer on its top and a feed line with stub on the bottom of this layer. Figures 4.15(a), (b) and (c) show the view of the assembled antenna, the reduced ground layer with an 'E' shape defect etched out from it and a feed line with an orthogonal stub respectively.

Figure 4.15(a): Assembled Antenna.

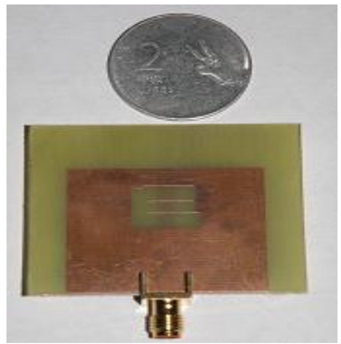


Figure 4.15 (b): Ground layer on the upper side of bottom substrate

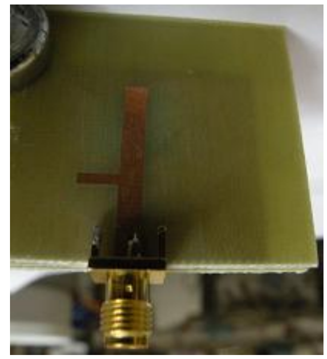


Figure 4.15(c): Feed line on the backside of bottom Substrate

The fabricated antenna was tested for S_{11} (dB) and gain measurements experimentally using the vector network analyzer working at a frequency range between 9 KHz to 8.5GHz. Gain measurements were made in a reflection free environment that is in an anechoic chamber that operates in a frequency range between 2 KHz to 20 GHz with a standard Horn antenna having a calibrated gain of 12dBi.

Figure 4.16 (a) shows the photograph of the VNA screen while testing the antenna using Agilent's E 5071C VNA. In order to find the correlation between the simulated and measured results of the antenna, a comparative plot of measured and simulated results is also plotted in MATLAB which is depicted in Figure 4.16(b). It shows a close proximity between the two results of the proposed antenna. A small variation in the impedance bandwidth at the two operational bands can be seen. The main justification bringing up this variation of results can be because of the inaccuracies incorporated while constructing the antenna using wet etching technique and also because of the alignment issues associated with the three printed substrate layers while connecting the antenna with a power supply using an SMA connector.

The measurement results using the VNA show that the antenna exhibits an impedance bandwidth of (S_{11}< -10dB) of 200MHz ranging from (2.43 - 2.64) GHz and 530 MHz from (3.4-

3.93) GHz, thus allowing the antenna to be appropriate for the suggested wireless systems. The antenna’s gain results obtained by placing the fabricated antenna in a reflection free environment in an anechoic chamber, (operating range from 8.5 KHz to 20MHz)are shown in figures 4.17(a & b) and Figures 4.18(a & b). The Figures show the comparative plots of simulated and tested radiation patterns of the antenna in E and H (elevation and azimuthal) planes (using MATLAB) at 2.51GHz and 3.51GHz respectively.

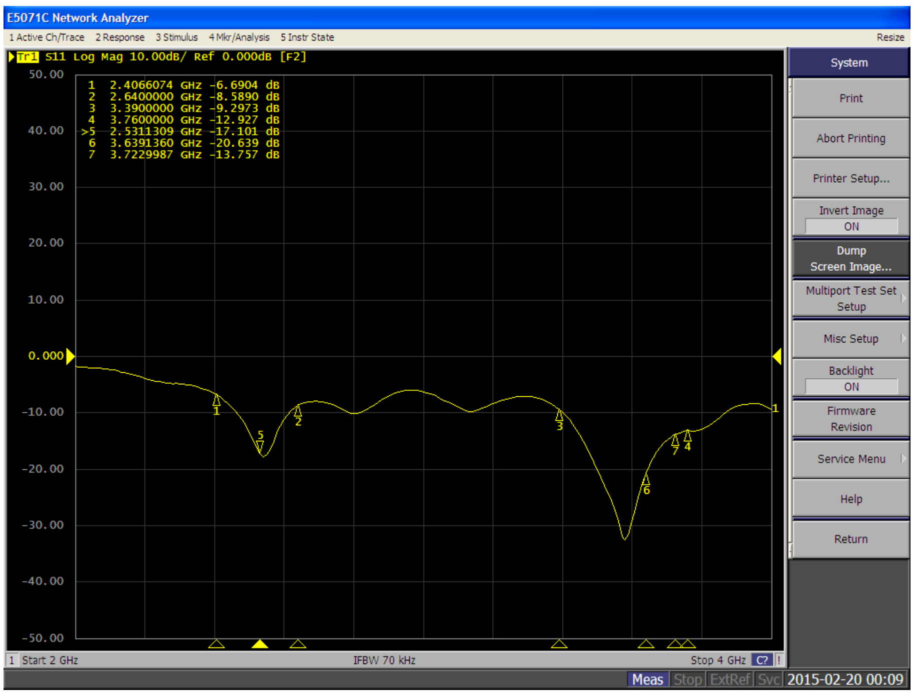


Figure 4.16(a): Snap Shot of VNA during antenna testing for S_{11} (dB)

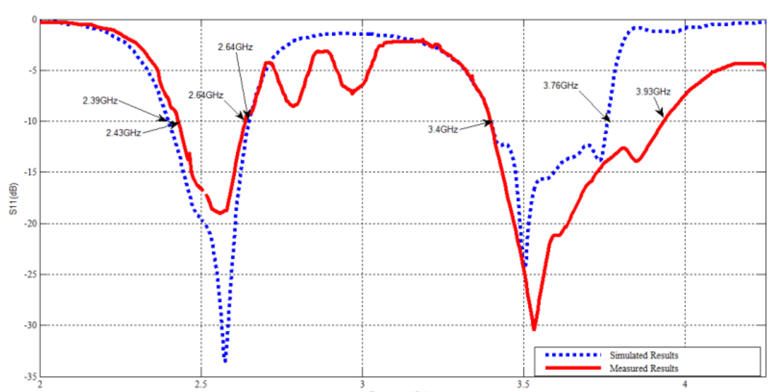
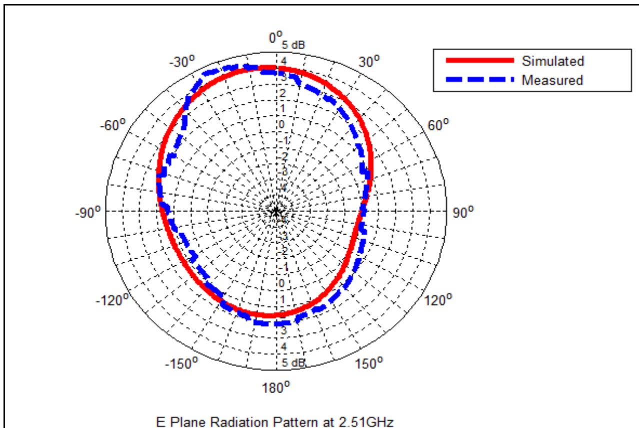
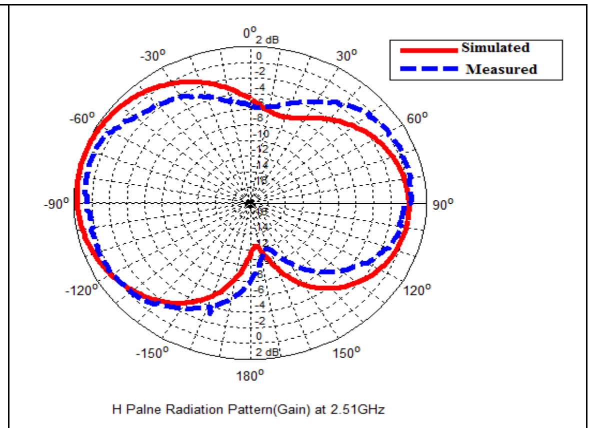


Figure 4.16(b): Relationship between the Simulated and Measured results for Impedance Bandwidth of the Antenna

The results of experimental measurements closely match the simulated ones but there is a small deviation seen in the measured results. A possible reason for this deviation of results comes from the fact that small valued noise signals are present in the environment, which make it difficult for the user to distinguish between those small magnitude gain values and noise and hence their measurement is a tough job. Also when the assembled antenna is placed in the chamber, there can be alignment problems between the transmitter and receiver that cause the pattern's output to get tilted by some angle.

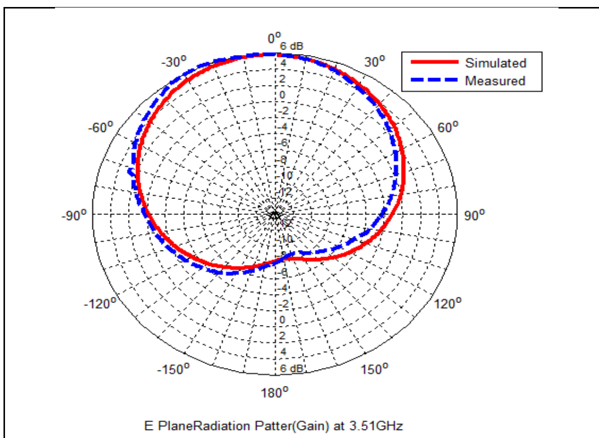


(a)

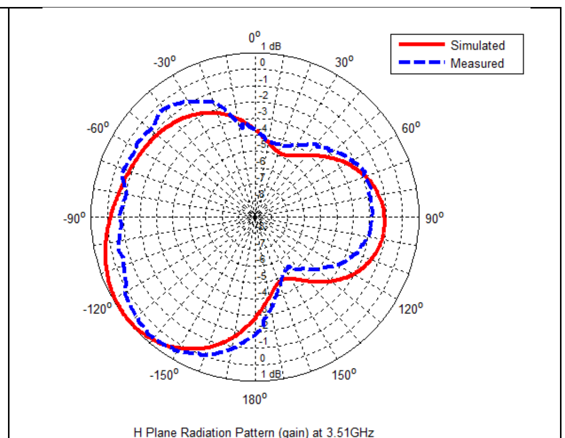


(b)

Figure 4.17: Simulated and Measured (a) Elevation- plane radiation pattern (b) Azimuthal-plane radiation pattern at 2.51 GHz



(a)



(b)

Figure.4.18: Simulated and Measured (a) (E plane) Elevation- plane radiation pattern (b) (H plane) Azimuthal-plane radiation pattern at 3.51 GHz

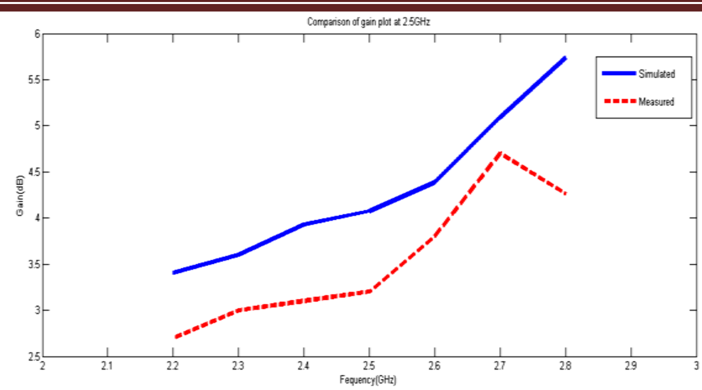


Figure 4.19(a): The comparison of gain plot for the lower frequency band

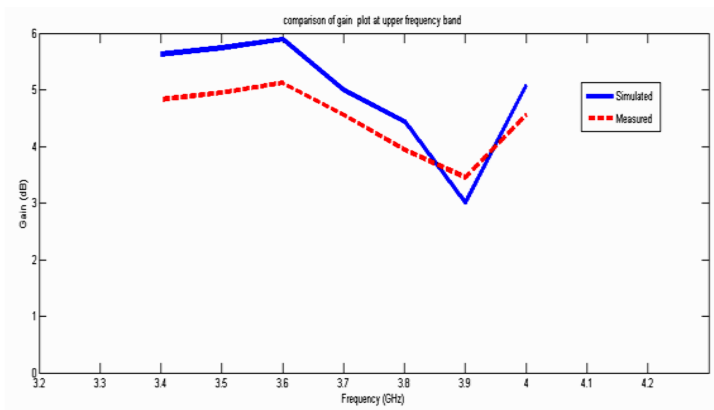


Figure 4.19(b): Comparison of gain plot at the upper frequency band

Figures 4.19(a) and (b) represent the relation between the simulated and measured gain of the antenna over the entire operation bands of (2.39-2.64) GHz and (3.39 to 3.76) GHz. There is a difference of around 1dB on an average between the simulated and measured gains values. This difference can be accounted for because of the fabrication and measurement faults in the system while performing the experimental testing of the antenna.

4.6.Conclusions

In the current research work, a multilayered circularly polarized rectangular patch antenna with two stacked patches and an aperture coupled feed is presented. The slot in the ground is modified to an 'E' shape thereby forming a DGS. The feed system of the antenna is responsible for it to show a circularly polarized behavior. The stacked antenna structure is small sized and is compact with dimensions of 4.85cm X 4.03cm X 5.01mm.

The proposed antenna is tested to suit the wireless applications of IEEE 802.11 or Wireless Local Area Networks operating at a band from 2.4GHz-2.485GHz, Bluetooth services from 2.4GHz-2.483GHz, ZigBee services from 2.4GHz -2.485GHz, IEEE 802.16 or Wi-MaX broad band services from 3.4GHz - 3.69GHz and IMT band from 3.4GHz to 3.6 GHz. This patch antenna has a measured gain of around 3.9 dB at 2.5GHz and 5 dB at 3.51GHz. Thus being a small sized antenna with a good gain makes it suitable for the above mentioned wireless applications with successful operation up to a few meters. The antenna has an input impedance of 50 ohms so as to match its impedance to that of an SMA (Subminiature) connector, thereby helping it to achieve a VSWR of 1.23 at 2.51 GHz and 1.38 at 3.51 GHz respectively.

In conclusion, in this chapter the effect of stacking two unequal patch antennas to obtain a wide bandwidth at a resonant band has been observed. In the current case the (3.39 - 3.76) GHz band (with a 10.27% bandwidth at the centre frequency) was exhibited due to the unequal rectangular patch antennas that are stacked. The effect of using DGS to obtain a second resonance in any antenna has also been observed. For the current case, the optimized ‘E’ shaped DGS gives a wideband operation from (2.39-2.64) GHz (with a 9.96% bandwidth at the centre frequency) which is justified by the current distribution results and the parametric study of the antenna too. The use of aperture coupled feeding method of the antenna for obtaining a wider bandwidth has also been realized. The validation of the mentioned antenna operation results is done by testing the antenna for gain and S_{11} (dB) measurements which allows the antenna to be practically usable for the mentioned wireless applications [138,139].

Chapter 5
Design and Analysis of an Elliptically Polarized Stacked Sierpinski Gasket Fractal Antenna with a Defected Ground Structure for UWB / WLAN/ Radio Astronomy and STM Link Applications

In this chapter a multilayer Sierpinski gasket fractal antenna with three layers of substrates of FR4 for a dual broadband operation at the frequency bands from 4.75GHz to 5.38GHz and 6.80GHz to 7.2GHz has been presented for applications in the Ultra Wideband, Wireless Local Area Networks, Radio Astronomy and STM (Synchronous Transport Module Level) bands. The antenna is fed using aperture coupled feeding method with the slot in the ground plane modified to a '┼' shape. The feed line that is used to couple power to the patch antennas has an orthogonal stub attached to it forming a '┼' shape and allows it to transmit circularly polarized waves.

The antenna has a compact structure because of its fractal geometry; the overall volumetric dimensions of the antenna are 6cm X 6cm X 0.483 cm (L X W X H). A Sierpinski gasket fractal is designed by applying the principle of a Sierpinski fractal to an equilateral triangle as the generator which allows the antenna to exhibit dual / multi-band characteristics. Stacking of two Sierpinski gasket fractal antennas of varying dimensions over each other helps to excite two operational bands with certain bandwidth. Further increase in the bandwidth of the antenna is gained by using a slotted ground structure of a cross shaped which allows it to be referred to as a defected ground structure. The stacked geometry also leads to an antenna of increased effective height and allows the fringing fields to be more loosely bound and allows the antenna to radiate more effectively. This enhances the bandwidth of the antenna thereby allowing the antenna to be suitable for the desired wireless applications.

The main aim of the current chapter is to show the effect of applying Sierpinski gasket fractal geometry to a triangular patch to obtain multiband characteristics. By piling up two fractal antennas over each other, two resonant frequencies of operation are excited and lead to enhancement in bandwidth of the antenna's operational bands. Secondly, to show that with judiciously chosen shaped and sized DGS, the bandwidth of the antenna can be increased. Thirdly, if an orthogonal stub of length not equal to feed line is connected to the feed line, the antenna transmits two orthogonal components of electric field which are almost equal in magnitude, resulting in circular polarization. The antenna design and simulations are carried out using CST MWS V.10. The proposed antenna is then fabricated and its prototype is tested for justification of the results.

The organization of this chapter is as follows; section 5.1 gives a general introduction to the need for such antennas and the related wok available in literature in this regard. Section 5.2 mentions the details of antenna design and its structure. Section 5.3 explains the parametric study of the antenna and the effect of adding DGS to the antenna's ground layer and section 5.4 mentions the antenna fabrication, measured results of antenna testing and the comparison of measured and simulated results for practical wireless applications.

5.1. General introduction

The MSA technology is gaining more and more importance day by day due to the inherent features offered by these antennas in terms of their cost effectiveness, smaller size, light weight, easy fabrication and mount ability on any type of surface [3], [6], [16].

With the introduction of more and more wireless technologies like WLAN, WiMAX, UWB, there is a need to cover multiple wireless applications using a single antenna. Otherwise one can imagine a multitude of antennas in a single device for covering multiple applications. Thus a need arises for multiband antennas that are capable of covering multiple frequency bands with adequate bandwidths for respective wireless applications. For small hand held RF devices, a MSA can easily be embedded inside the front end of the device because of its above mentioned properties [4], [6], [10]. The design and development of multiband antennas is one field that has been extensively researched by scientists, academicians and industry professionals as mentioned in [5], [13], and [31].

Fractal MSA are also a class of printed antennas that are capable of providing multiband behavior and they have an added advantage that they offer small sized antennas as compared to the conventional patch antennas at low frequencies of operation [32].These Fractal antennas are self-repeating structures that can be fabricated using two main techniques. As mentioned in chapter 2 using one method, a generator of a specific shape is chosen and it is added with the scaled versions of itself to occupy the given area. In the second method the generator shape is filled with scaled version of itself to form the final fractal antenna with multiband behavior [68].The second method in which a triangular generator is chosen and filled with scaled down versions of itself are used in this chapter to design the final Sierpinski gasket fractal antenna. A lot of researchers are working in the field of fractal MSA to design and develop multiband fractal antennas [140-144]. In order to further increase the bandwidth of these multiband fractal antennas, some researchers have combined the fractal designing with stacked antenna techniques to obtain a broadband behavior [55], [59]. The bandwidth of these stacked fractal antennas can further be increased by using a parasitic feeding methods like aperture coupling with these antennas. Further the aperture in ground plane can be modified to a specific shape so as to obtain a resonance touching the extremity of the existing band and the bandwidth of antennas can be increased accordingly [97]- [100].

Thus the present work therefore is focused on the design, development and analysis of Stacked Sierpinski gasket fractal antenna having a defected ground structure possessing circular polarization for the wireless applications of interest. The proposed antenna is also able to achieve elliptical polarization because of the cross shaped feed line that excites the antenna. In this work, the fractal geometry is formed by using triangular generator shape filled with scaled version of itself till the second iteration to form the final radiating antenna structure.

5.2. Antenna Geometry and Design

The presented stacked Sierpinski gasket fractal antenna consists of three layers of FR4 substrate each with dimensions of 6cm X 6cm, with a height of 1.57mm each. The electrical permittivity of FR4 used is 4.4 and has a dielectric loss tangent of 0.0024. The proposed antenna is capable of covering the wireless applications of UWB bands from 4.75GHz - 5.28GHz and 6.8GHz -7.2GHz, a radio astronomy band from 5.01GHz -5.03GHz and IEEE 802.11a/WLAN band from 5.15GHz - 5.35GHz.

Figure 5.1 shows the side view of the proposed antenna's layered structure, having a stacked antenna geometry with 'h_1' and 'h_2' representing the height of metal and substrate layers respectively. The top two substrate layers of the antenna have Sierpinski gasket fractals (applied to an equilateral triangular geometry) printed over them, the top layer has a larger size triangle and the middle layer has a smaller sized triangle. The bottom substrate layer has a ground plane of defected nature printed on its upper part with an aperture slot modified to a cross shape etched out from it. A feed line with stub printed on the lower part of the bottom substrate is used for activating the antenna as a radiator of EM waves. The metal thickness chosen for all the metallic layers is 0.035mm. The topmost and the middle patch antennas have a geometrical shape of an equilateral triangle whose dimensions of each side can be calculated using equation 5.1.

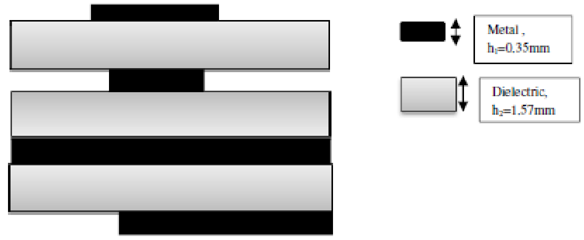


Figure 5.1: Side view of the antenna showing its layered structure

Fr = $|(0.15345 + 0.34px)\frac{c}{he\xi^n}, n = 0$

$and\ \frac{0.26c}{he}\xi^n\ for\ n > 0|$, ……………………………………………………………………..….(5.1)

where = h_n / h_{n+1} is the ratio of the height of the Sierpinski gasket in the n^{th} iteration to that in the $(n+1)^{th}$ iteration and $\delta = 1/\xi$ is the scale factor, $P = \xi - 0.230735$ and

x = 0; for n = 0 and

x = 1; n > 0

$$he = \frac{S_e\sqrt{3}}{2}\ and\ S_e = S + \frac{t}{\sqrt{\varepsilon}}$$

where 's' is the length of the side of the gasket and 'c' is the velocity of light and 'ε_r' is the thickness and 't' the dielectric constant of the substrate.

Using equation (5.1), the dimensions of the outer side of equilateral triangle (on top substrate layer) for the lower frequency band was found out as 34.4mm and that of the smaller triangle (on the middle substrate layer) for the upper frequency band was found out as 12.2mm. These equilateral triangles were considered as the generators for the proposed fractal antennas and both equilateral triangles are recasted with 2^{nd} iteration Sierpinski Gasket fractal to optimize the results. It is observed that as the order of iteration increases, the resonant frequency becomes lesser than that obtained from an antenna with $zero^{th}$ order of iteration, thereby allowing the antenna to cover lower frequencies without increase in the antenna dimensions. The parameter values for the dimensions of the side of an equilateral triangle for the two resonant frequencies of the proposed structure are also mentioned in Table 5.1.

Figure 5.2 shows the steps that are carried out to obtain the proposed Sierpinski gasket fractal of second order. This process is carried out for both the stacked patch antennas. The black part in the Figure 5.2 represents the metallic layer and the grey part represents the metal that is etched out so that FR4 substrate is visible in that region. The dimensions of the side of triangles after second iteration are 8.6 mm and 3.15 mm for the upper patch and the lower triangular patch antennas respectively. The radiating antenna structure is fed by aperture coupled method and the slot on the ground is modified to a cross shaped geometry, with dimensions as 6mm X 15mm (W_D X H_D) and 7mm X 11.5mm (L_D X W_{ds}). The detailed structure of the ground layer with feed line is depicted in Figure 5.3.

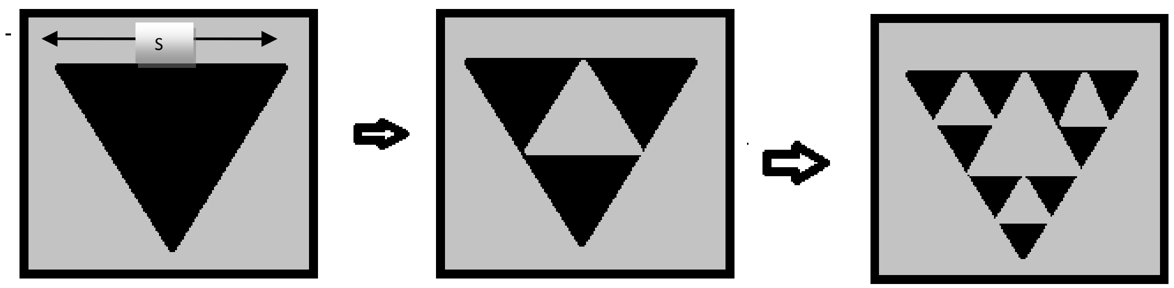


Figure 5.2: Intermediate Steps to get a Sierpinski Gasket Fractal of Second Order

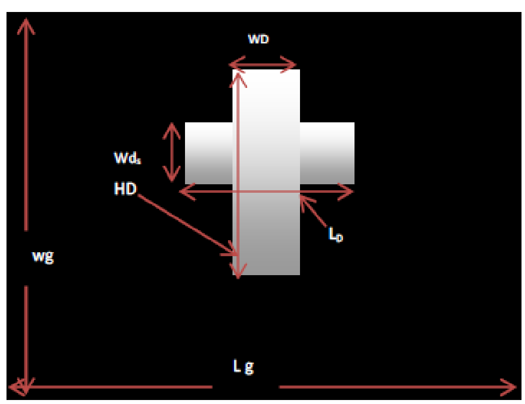


Figure 5.3: Defected Ground Structure of the Antenna

The dimensions of the ground plane are (Lg X Wg) 54mm X 58 mm. The feed line is shown as a metal patch on the bottom of lower substrate in Figure 5.4. It has an orthogonal stub attached to it forming a '┼' shaped geometry. The dimensions of the feed line are (H_f X W_f) as 23.25mm X 7.7mm and (L_f X W_{f1}) as 8.5mm X 3mm. The dimensions of the feed line are optimized so that it matches the impedance of the coaxial cable and the SMA connector of 50 ohms. The detailed dimensions of the antenna are mentioned in Table 5.1 also.

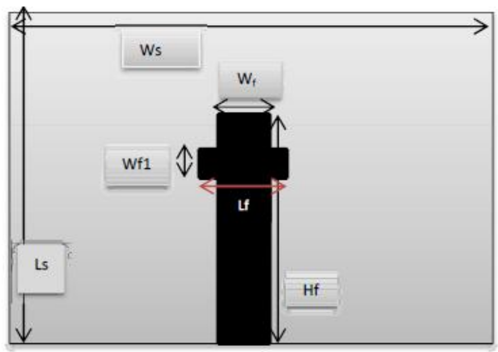


Figure 5.4: Feed line with a stub on the bottom of lower substrate

Table 5.1: Design Parameters of the Optimized Stacked fractal Antenna

Parameter	Dimensions(mm)
L_g	54
W_g	58
L_D	7
W_{ds}	11.5
W_D	6
H_D	15
Ls	60
W_s	60
H_f	23.25
W_f	7.7
L_f	8.5
W_{f1}	3
S	34.4
S1(side of smaller triangle)	12.2

5.3. Simulation Results

The presented antenna was designed as a three (substrate) layer structure with a DGS and aperture coupled feeding. This designed antenna was simulated using CST MWS V.10 and its output was analyzed in terms of impedance bandwidth, gain, radiation pattern, axial ratio bandwidth, VSWR and Current distribution in the succeeding sections.

5.3.1. Impedance Bandwidth

The set of frequencies for which the antenna is matched to the input impedance of the transmission line represents the antennas impedance bandwidth. Figure 5.5 shows the simulated return loss S_{11} (dB) plot of antenna plotted against frequency on X axis. The frequencies below the -10dB scale are the ones at which antenna is matched to the input impedance of 50 ohms. The antenna operates as a dual broad band antenna and covers two wide bands from 4.75 GHz - 5.38 GHz and 6.8 GHz - 7.2 GHz, thus allowing the antenna to be suitable for two UWB bands from 4.75 GHz - 5.28 GHz and 6.8 GHz -7.2 GHz, a radio astronomy band from 5.01GHz -5.03 GHz and IEEE 802.11a band from 5.15 GHz - 5.35 GHz, with peak return losses of -28dB and -21dB respectively at these two bands of operation. The antenna thus shows an impedance bandwidth of 12.6% at the lower resonant band and 6% at the upper resonant band.

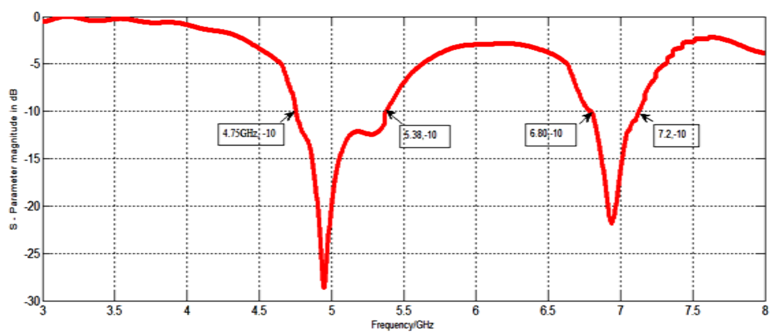


Figure 5.5: Simulated S_{11} (dB) Plot of the antenna

5.3.2. Axial Ratio bandwidth

The 1dB axial ratio bandwidth of the antenna is shown in Figure 5.6, which represents the range of frequencies at which the antenna maintains the major to minor axis ratio of the the ellipse as 1dB (for the two orthogonal components of the electric fields radiated by the antenna). The antenna possesses an elliptically polarized behavior,(with AR less than or equal to 1 dB) from 3.75 GHz to 4.25 GHz, an AR (≤1dB) bandwidth of 4.7 GHz to 5.2 GHz, AR (≤1dB) bandwidth of 5.21 GHz to 6.43 GHz.Thus the proposed antenna has a slightly elliptically polarized behavior at the bands at which antenna shows an impedance bandwidth too. This makes the antenna best for RF front end applications as the alignment of receiver (using the proposed antenna) with respect to the transmitter will not affect the communication system’s performance.

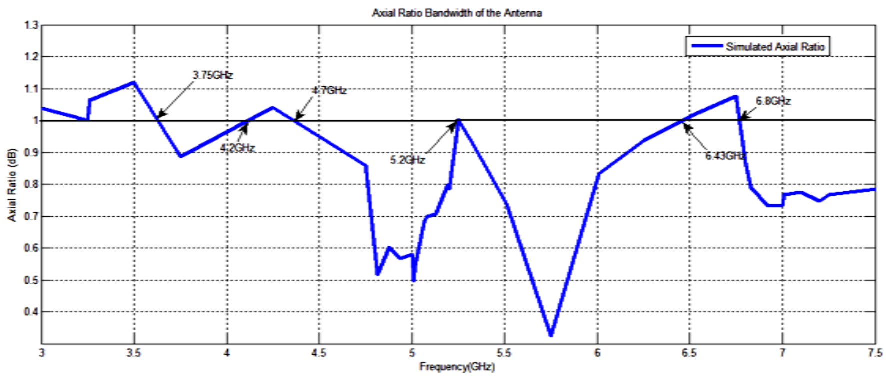


Figure 5.6: Simulated Axial Ratio Bandwidth of the Antenna

5.3.3. VSWR

Practically a VSWR of less than 2 is desirable for a good impedance matching. Figure 5.7 represents the VSWR plot of the antenna's operation with VSWR on Y axis plotted against frequency on X axis. It can be observed from the Figure 5.7 that the antenna shows a VSWR of 1.53 and 1.183 at the frequencies of 5.06GHz and 7 GHz respectively thereby representing a good impedance matching between source and antenna at the resonant bands of the antenna.

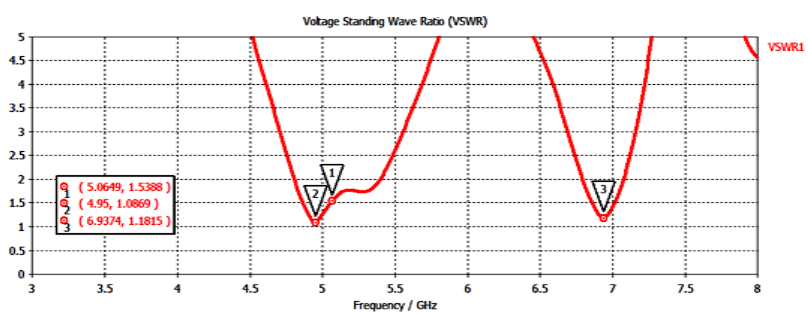
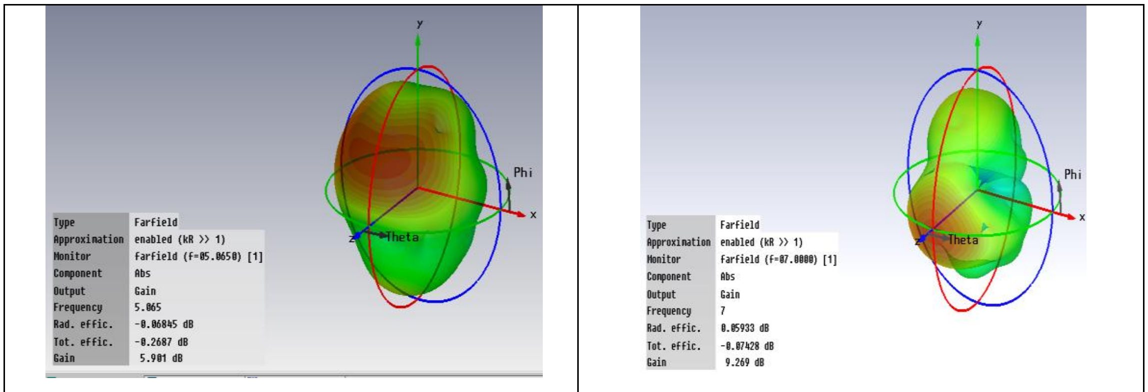


Figure 5.7: VSWR Plot of the Antenna at 5.06GHz and 6.9GHz

5.3.4. Gain

The proposed antenna shows a gain of 5.9dB at the center frequency of 5.06GHz at the lower frequency band ranging from 4.75GHz to 5.38 GHz and a gain of around 9.26dB at the center frequency of upper frequency band from 6.8GHz - 7.2GHz. The Figures 5.8(a) and (b) show the three dimensional radiation pattern plots of the antenna in terms of gain and show the peak gain measured along the major lobe (maxima) at the respective frequencies of antenna's operation.

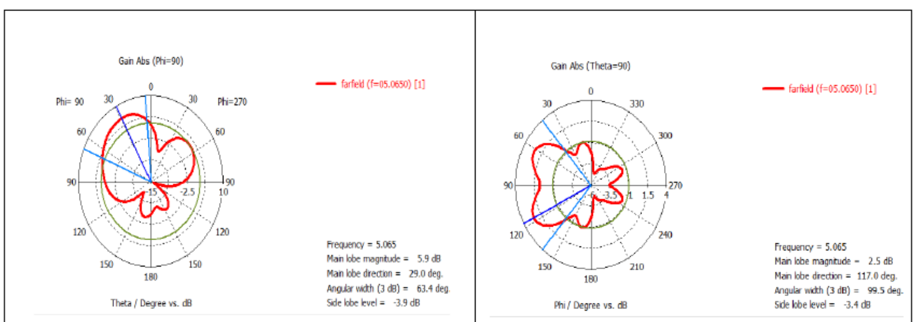


(a) (b)

Figure 5.8: 3D Gain Plot of antenna at (a) 5.06GHz and (b) Gain of antenna at 7GHz

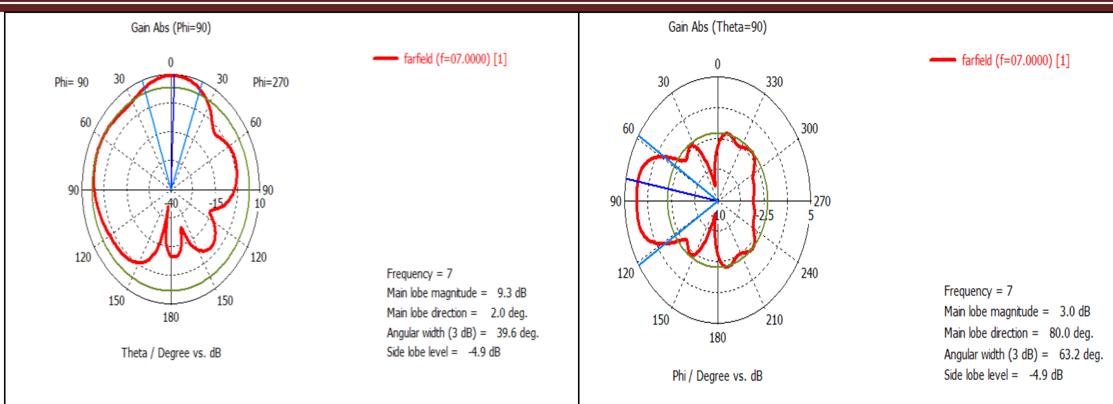
5.3.5. Radiation Pattern

Figure 5.9 (a) and (b) show the 2D radiation (gain) pattern plots of the antenna in the **E** plane (elevation) and the **H** plane (azimuthal plane respectively at the center frequency (5.06GHz) of lower resonant band. The antenna possesses a major lobe along 29 degrees in the elevation plane and has a half power beam width of 63.4 degrees with a side lobe level of -3.9dB. Figure 5.10(a) and (b) show the polar plots of **E** and **H** plane radiation patterns of the antenna at 7GHz. The antenna shows an approximately Omni-directional pattern in the E plane with major lobe along 2 degrees, a half power beam width of 39 degrees and a side lobe level of -4.9dB.



(a) (b)

Figure 5.9(a): Elevation plane pattern at 5.06GHz (b): Azimuthal plane pattern at 5.06 GHz



(a) (b)

Figure 5.10 (a): Elevation plane pattern at 7GHz (b): Azimuthal plane pattern at 7 GHz

5.3.6. Current Distribution

The antenna is energized to observe the distribution of current over its surface at the central frequencies of the two proposed resonant bands i.e. at 5.02GHz and 7 GHz resp. It is can be observed from the comparative study of Figures 5.11(a) and (b) that the distributed current on the surface of topmost patch antenna is of peak magnitude as 85.6A/m and on the lower patch antenna it is 66.6A/m. Since there is more concentration of current over the upper patch antenna at the center frequency of this band (i.e.at 5.02GHz), it is considered responsible for the operation at lower frequency band. Thus the upper patch antenna is mainly responsible for showing the resonance at center frequency of the band from (4.75-5.38) GHz. Figures 5.12 (a) and (b) show how the current is distributed over the antenna surface (at the lower and upper fractal patch antennas) respectively at 7 GHz. The lower patch antenna shows a peak current magnitude of 42.3A/m and the lower patch antenna shows a peak current magnitude of 82.8A/m at the central frequency of the upper band. Thus it is concluded that the lower patch antenna that is smaller in size is responsible for the resonant band from 6.8GHz to 7.2GHz.

Apart from the aperture coupled feeding method, the defected structure in the ground layer of the antenna further helps in improving the bandwidth of the antenna at the two resonant bands. Figures 5.13(a) and (b) show that the peak magnetic field strength/current distribution on the slot in the ground plane is almost same (i.e. 36A/m and 33A/m at the 5.06 and 7GHz resp.) at the central frequencies of both the bands. Thus it is concluded that the DGS helps in enhancing the antenna's bandwidth at both the operational bands.

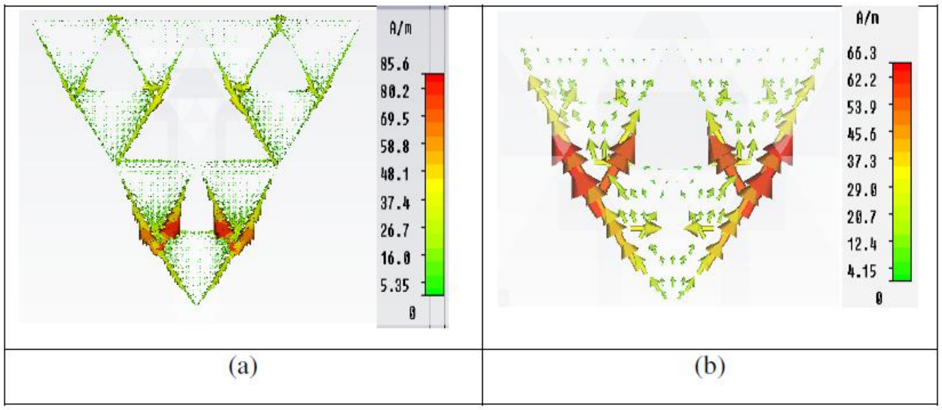


Figure 5.11Current distribution on the: (a) upper patch (b) lower patch at 5.02GHz

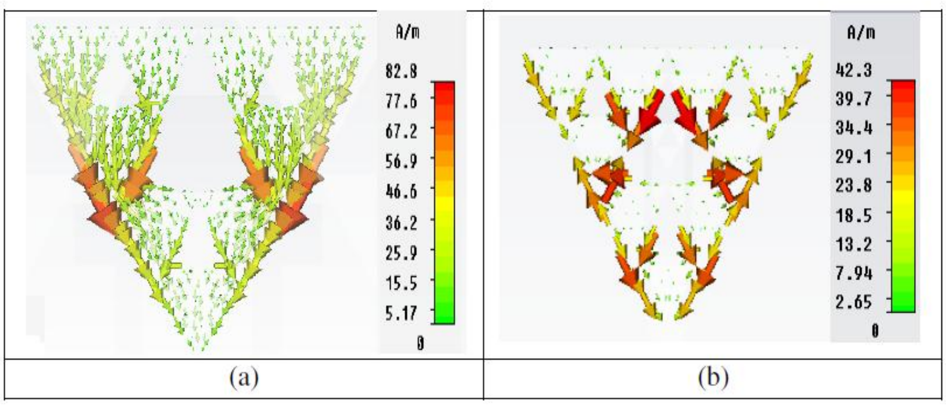


Figure 5.12 Current distribution on: (a) Lower patch and (b) Upper patch at 7GHz

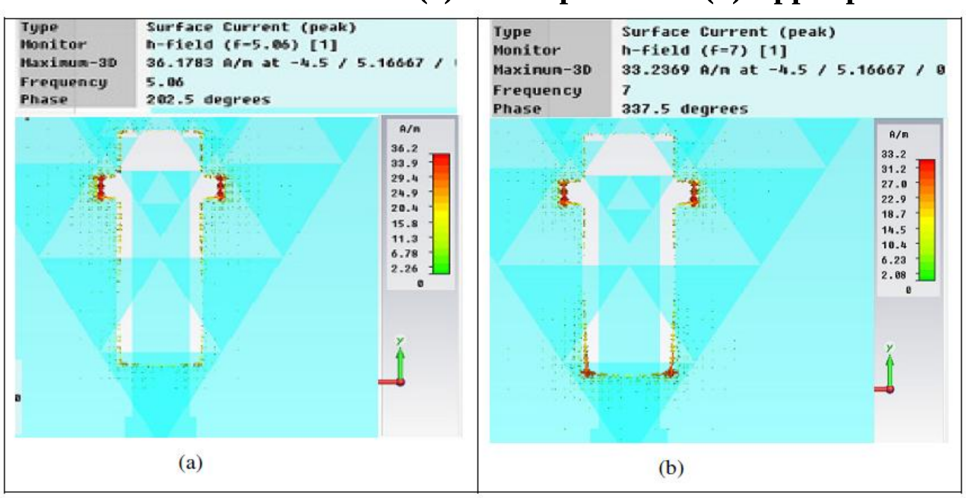


Figure 5.13: Current distribution on the ground plane at (a) 5 GHz and (b) 7 GHz

5.4. Parametric Analysis of the Antenna

The proposed MSA was analyzed for its operation at the two resonant bands by varying the dimensions of two fractal patch antennas. Figure 5.14 shows the parametric results of antenna in terms of the S_{11} (dB) plot. These results were obtained when the length of upper triangle's side(S) was varied. It can be verified from Figure 5.14 that the bandwidth of the antenna at the lower frequency band gets reduced with a little variation in the upper frequency band, when the side dimensions of the upper triangular patch were increased. The upper frequency band is not affected much for the values of side dimensions as 38.4mm and 36.4mm. But both the upper and lower resonant bands show an increase in the impedance bandwidth with side dimensions selected as 34.4mm. Thus it is concluded that the upper triangular patch dimensions of 34.4mm is optimum for getting the required bandwidths at both the bands.

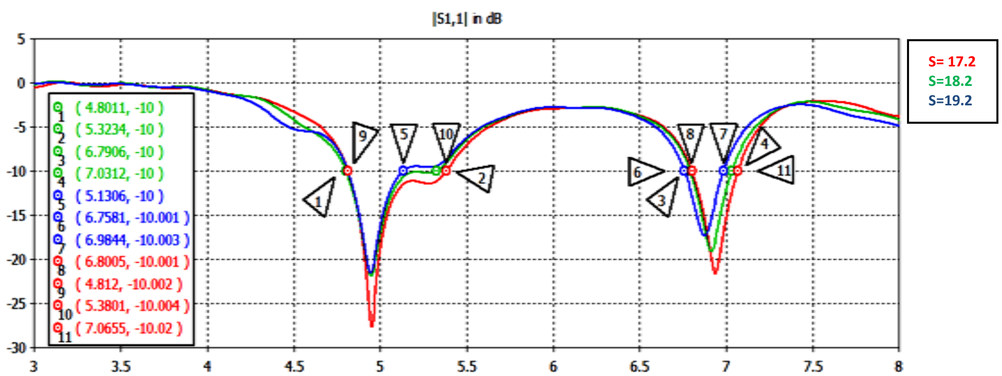


Figure 5.14: Results of parametric variation of side dimensions of the upper triangular patch

Figure 5.15 shows the effects of varying the side dimensions the lower triangular fractal patch antenna. The major effects of this change can be seen on the upper frequency band that causes its resonant frequency to shift either toward right or towards left on increasing or decreasing the smaller patch dimensions respectively. The impedance matching at the upper band also gets affected by varying the smaller triangular patch dimensions. The optimized side dimensions (S_1) for the lower triangular patch for the desired resonant band of operation were chosen to be 12.2mm (-6.1mm to 6.1mm). This also leads to a conclusion that the lower patch antenna is mainly responsible for the antenna to exhibit resonance at the upper frequency band.

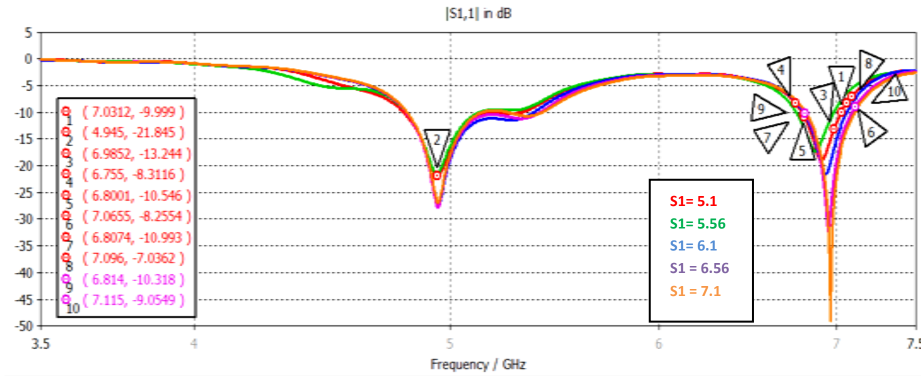


Figure 5.15: Results of parametric variation of the lower triangular patch antenna

The antenna's return loss results were also analyzed by eliminating the defected ground structure in the ground plane. Figure 5.16 shows the impedance bandwidth at the two resonant bands of antenna when the antenna was designed as a simple aperture coupled antenna without a cross shaped slot and the impedance bandwidth results when the antenna was designed with a cross shaped slot DGS. It can be examined from the Figure 5.16 that the antenna has a lower bandwidth at both the bands when the cross shaped slot is not used in the ground plane. The antenna resonates from 4.8GHz to 5.22GHz (BW of 420MHz) and 6.8GHz to 7 GHz (BW of 200MHz) without DGS as compared to a bandwidth of 450 MHz (from 4.75GHz to 5.38GHz) and 400MHz (from 6.8GHz to 7.125GHz) by using a DGS in the stacked antenna structure. This observation leads to the conclusion that a suitably chosen DGS can positively affect the antenna's performance and thus for the proposed antenna, the ground was chosen with an aperture slot modified to a cross shape.

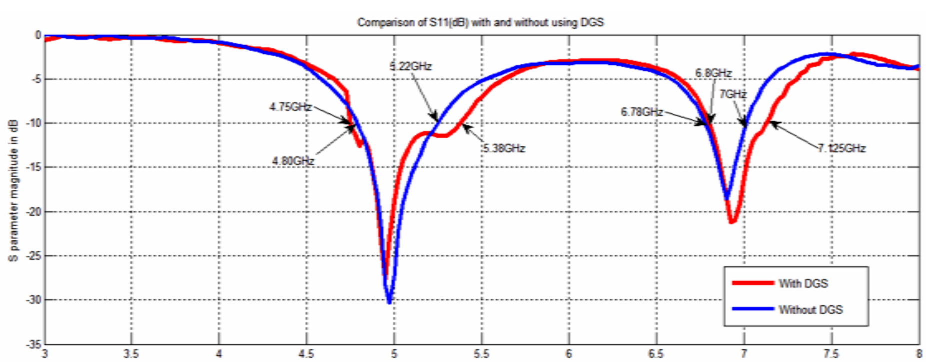


Figure 5.16: Comparison plot of Simulated S_{11} (dB) for the antenna with and without DGS

5.5. Antenna Fabrication and Testing

The presented antenna structure was constructed on FR4 substrate with a thickness of 1.57mm and a loss tangent of 0.0024 using the wet etching technique. The fabricated antenna structure with two fractal antennas on the top two layers of substrates and a the ground layer on lowermost dielectric substrate layer with feed network on its bottom is shown in Figures 5.17(a), (b) and (c). Figure 5.17(a) shows the three layered assembled antenna, Figure 5.17(b) shows the ground layer with a '┼' shaped defect and Figure 5.17(c) shows the feed network of the antenna on the lower side of its bottom most layer.

(a) (b) (c)

Figure 5.17(a) Assembled Antenna (b) Ground Defected Plane (c) Feed Network on bottom Substrate layer

The fabricated antenna was tested for measurements of S_{11} (dB) results using a vector network analyzer working at a frequency range between 9 KHz to 8 GHz and for measurement of gain in a reflection free environment using an anechoic chamber (with an operating range from 2 KHz to 20GHz to the center frequencies of the two bands at 5.02GHz and 7 GHz respectively. Figure 5.18(a) shows the snap shot of the VNA when the fabricated antenna was tested for S_{11} (dB) results and Figure 5.18(b) shows the comparison of the two results plotted using MATLAB.

It can be seen from the Figure 5.18(b) that the tested antenna shows an impedance bandwidth from 4.8GHz to 5.275GHz (475MHz) and 6.6GHz to 7.35 GHz (750MHZ).The comparative plot of the simulated and measured results in Figure 5.18(b) verifies that the measured results are in close agreement with the simulated ones. The measured impedance bandwidth of the antenna at the two bands is 475MHz (4.8-5.275) GHz and 750MHz (6.6-7.35) GHz which is good enough to cover the proposed applications from (5.8-5.275) GHz for UWB operation, (5.15-5.35) GHz for WLAN, (5.01-5.03) GHz for Radio Astronomy applications and (6.8-7.35) GHz for UWB operation. An extra band from (6-6.17) GHz is also observed in the measured results of the antenna which allows the antenna to be used for STM link applications.

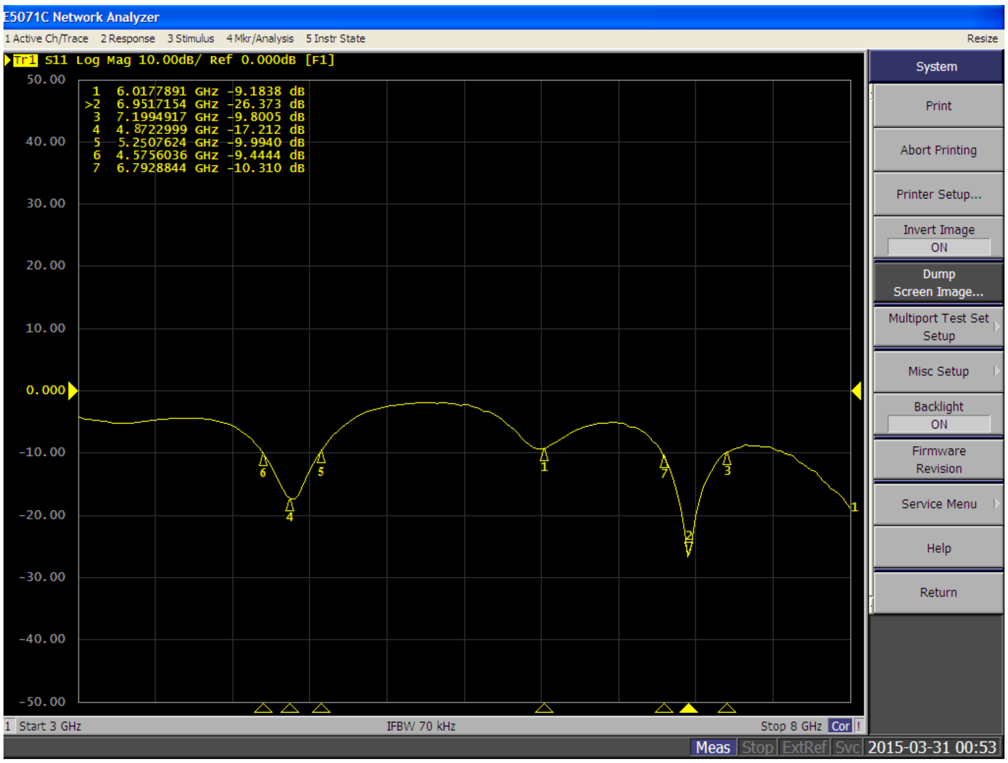


Figure 5.18(a): Snap shot of the antenna while testing of the antenna on a VNA

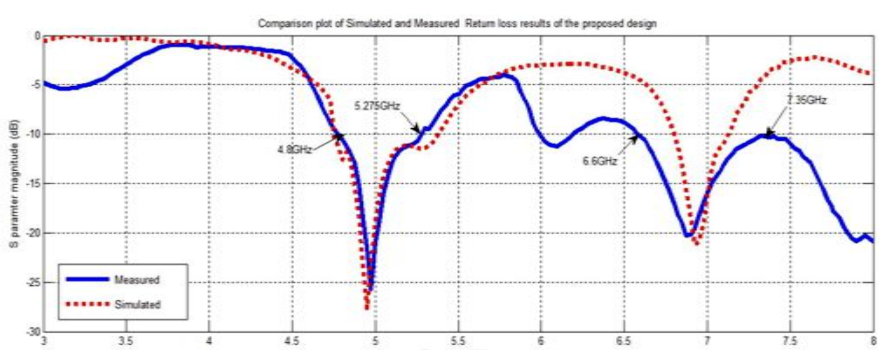


Figure 5.18(b): Comparison of simulated and measured results of the antenna using MATLAB.

A slight variation can be seen in the measured results from the simulated ones, the reason for this could be because of the inaccuracies introduced during the fabrication process, misalignment of the three stacked layers of the antenna and sometimes because of the misalignment of the feeding cable and the connector with the antenna. The errors in accurate modeling of the antenna, also lead to a slight variation between the simulated and measured results by some extent.

The fabricated antenna was placed in an anechoic chamber with a standard horn antenna having a calibrated gain of 12dBi was used for testing. The gain patterns of antenna in 2D polar plots along the elevation and azimuthal planes were plotted using MATLAB. Figures 5.19(a) and (b) show the comparison plots (between simulated and measured values of gain) of elevation plane and the azimuthal plane views of the antenna antenna's gain pattern at 5.02GHz respectively. From the measured radiation patters, the major lobe of the antenna is seen to extend from 210 degrees to 330 degrees which is a little shifted from the simulated radiation pattern that shows a major lobe from 230 degrees to 360 degrees. The reason for this shift can be because of the misalignment between the transmitter and receiver antennas when placed in an anechoic chamber.

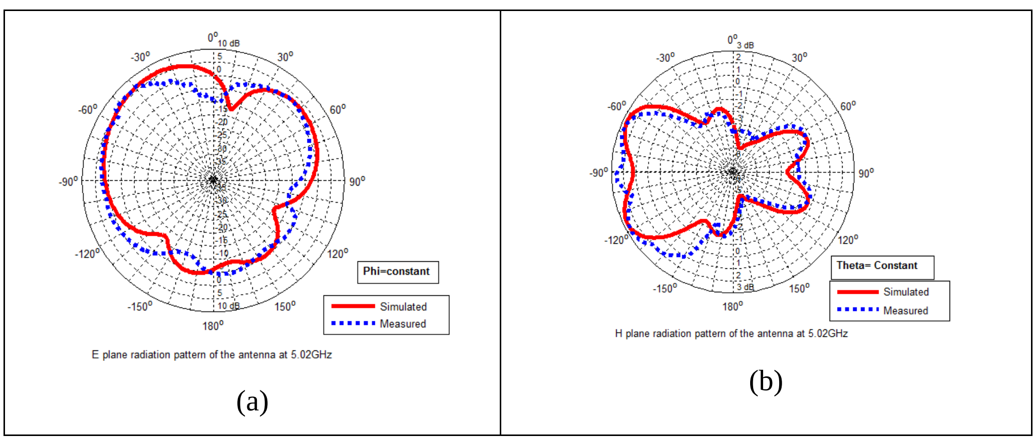
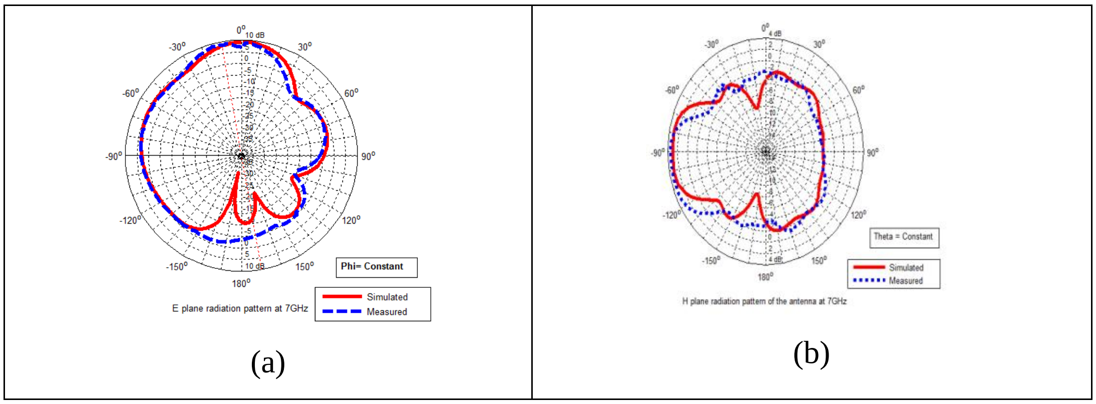


Figure 5.19 Comparison between the: (a) Simulated (b) Measured Elevation and Azimuthal gain plots of the antenna at 5.02GHz respectively

Figures 5.20(a) and (b) show the comparison between simulated and measured elevation and azimuthal gain plots of the antenna at 7GHz respectively (i.e. the central frequency of the upper band). The comparative plots indicate that the simulated and measured results of the radiation pattern plots at both the operation frequencies are almost identical with each other with slight variation also. These differences that can be attributed to the measurement errors that take place while testing the antenna. These could be in terms of alignment problems of the antenna itself, misalignment between transmitter and receiver and sometimes low noise signals that get mixed up with the low values of measured gain signals and are therefore difficult to measure.



(a) (b)

Figures 5.20 Comparison between the: (a) Simulated (b) Measured Elevation and Azimuthal gain plots of the antenna at 7GHz respectively.

Figure 5.21(a) shows a comparative plot of the measured and simulated gain over the entire operational lower frequency band. It is observed that there is a variation of around 1 to 2 dB in the values of simulated and measured gains in the frequency band from 4.75GHz to 5.3GHz. Figure 5.21(b) shows the variation between the simulated and tested values of gain at the frequency band from 6.8GHz to 7.2GHz. An average gain variation of around 0.6dB is seen between the simulated and the measured results at this band.

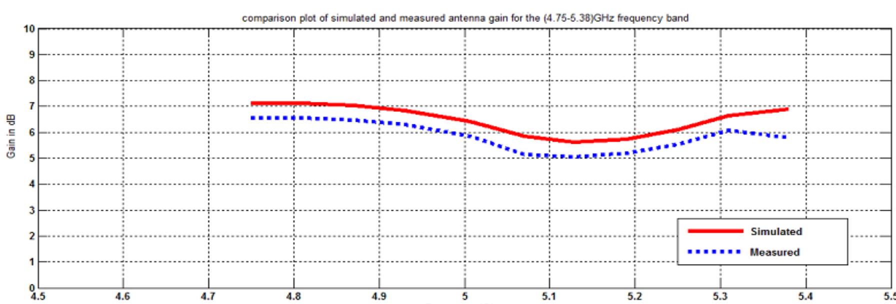


Figure 5.21(a): Variation between simulated and tested gain results for the 4.75 to 5.3GHz band

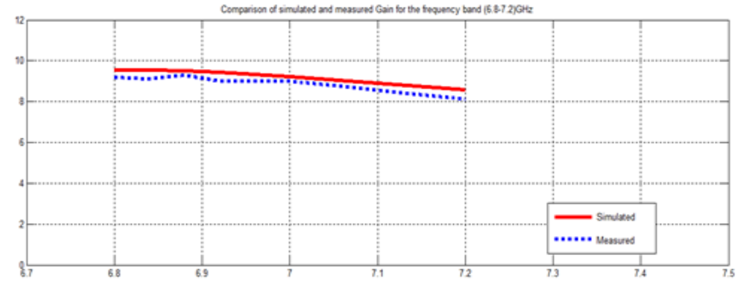


Figure 5.21(b): Comparison of simulated and measured gain for the 6.8 to 7.2GHz band

5.6. Conclusions

In the research work presented in this chapter a three layered stacked fractal microstrip patch antenna with an equilateral triangle geometry which is transformed to a Sierpinski gasket fractal geometry is presented for dual wide band wireless operations. The antenna is fed with an aperture coupled feeding method with the aperture in ground modified to a '┼' shape that is used to obtain an enhanced bandwidth from the antenna. The feed line of the antenna has a stub that is orthogonally attached to it to provide the impedance matching at 50 ohms and also helps in providing circular polarization to the fields emitted by the antenna. The antenna shows a VSWR of 1.53 and 1.18 at the centre frequencies of the two bands.

The presented antenna has a compact size of (6 X 6 X 0.483)cm^3 and its experimental measurement results show that it can be practically suitable for application in the radio frequency range from 5.275GHz - 5.8GHz for UWB operation, 5.15GHz - 5.35GHz for WLAN, 5.01GHz-5.03GHz for Radio Astronomy applications,6 GHz -6.17GHz for STM band applications and 6.8GHz -7.35GHz for UWB operation as it also shows a high gain of 5.9dB and 9.2dB at the central frequencies of the two bands. A high value of gain represents that the antenna is well suited for long range applications too.

In Conclusion, the research work presented in the current chapter antenna presents the use of stacked fractal antennas to obtain a multi frequency broadband behavior from 4.75GHz to 5.38GHz and 6.80GHz to 7.2GHz. It also illustrates the use of a Defected Ground Structure to enhance the bandwidth of the proposed antenna at the two resonant bands and the use of a feed line with stub to obtain circularly polarized waves for the proposed wireless bands. This makes the antenna suitable for the proposed practical wireless scenario [145], [146].

Chapter 6
Design and Analysis of a Stacked Complementary Microstrip antennas with a 'π' shaped Defected Ground Structure for UWB / WLAN/Wi-MAX and Radio Astronomy Wireless Applications

In this chapter, another three layer stacked microstrip patch antenna with an aperture coupled feeding mechanism is designed on a FR4 substrate for a broadband operation from 5.14GHz to 5.85GHz. The antenna has been proposed for Ultra Wideband, Wireless local area networks, Wi-MAX and radio astronomy wireless applications. This proposed aperture coupled antenna has a 'π' shaped slot in the ground plane, apart from the aperture slot, thereby making it a defected ground structure. The feed line that is used to couple power to the patch antennas has a stub attached at quadrature to it forming a 'T' shape; this allows it to transmit circularly polarized waves at the operational band.

The antenna has a compact structure having the overall volumetric dimensions as 4.7 X 3.82 X 0.483 cm^3 (L X W X H). The three layered structure has a square patch on the topmost substrate layer with a rectangular slot cut out from it. The middle substrate layer is of the same dimensions as the topmost layer. A patch is printed on the middle layer with the dimensions almost same as that of slot that is cut from the top layer, thereby giving these two layers a complementary geometry. The aperture coupled feeding used with the antenna gives an added advantage helps in increasing its bandwidth of operation as it allows more fringing of EM fields. The aperture in this case is a rectangular slot cut orthogonal to the feed line in the ground plane of the bottom layer. Apart from this, the top layer of the ground structure is made defected by etching out a 'π' shaped slot from it. The stacked antenna geometry leads to an increased effective height and this also allows the fringing EM fields to be more loosely bound and radiated out more, thereby increasing the operational bandwidth of the antenna. This allows the antenna to be suitable for the proposed wireless applications.

The main aim of the work presented in the current chapter is to show that by stacking two rectangular antennas (with a complementary geometry) one above the other can excite two nearby resonant bands. These close bands thus combine to give an enhanced bandwidth of operation. Secondly, by using a suitably shaped Defected Ground Structure, the bandwidth of the antenna can be further increased. If this antenna is fed with a feed line having a stub that is attached to it at quadrature, it can be allowed to transmit circularly / elliptically polarized EM (electromagnetic) waves. All the simulations for the proposed design are carried out using CSTMWS V.10 software. The proposed antenna is then fabricated and its prototype is tested for validation of the results.

The organization of this chapter is as follows; section 6.1 gives a general introduction to the need for such antennas and the related work available in literature in this regard. Section 6.2 mentions the details of antenna design and its structure which is done in CSTMWS V.10. Section 6.3 explains the parametric study of the antenna and the effect of adding DGS to the antenna's ground layer and section 6.4 mentions the antenna fabrication, measured results of antenna testing and the comparison of two results for practical wireless applications.

6.1. General introduction

Many researchers have been working in the field of microstrip antennas to introduce multiband and broadband antennas that are capable of covering multiple wireless technologies that are in demand like the WLAN, Wi-MAX and UWB etc. It is preferable to cover all these wireless applications with the help of single antenna otherwise one can imagine a myriad of antennas in a single device for covering multiple wireless applications. Thus a requirement arises for multiband/ broadband antennas that can cover multiple wireless frequency bands using a single antenna.

For small hand held RF devices, these MSAs can easily be embedded inside the front end of the device because of their properties of being compact, small sized and rugged [4], [6], [10]. Thus these MSAs have gained a lot of popularity among researchers working in the field of antennas for these wireless applications. Stacked microstrip antennas have been presented by various authors for multiband and broad band behavior. Several stacked antenna geometries have been proposed in this regard [122]-[142]. A simple and easy method to implement the stacked patch antenna for broadband behavior is the use of complementary patch antennas [147]-[148]. By using a larger patch on the top and a smaller patch below it such that the size of smaller patch is equal to the slot dimensions cut in the larger patch antenna; a broadband operation of around 700 MHz with a fractional bandwidth of 12.72% can be obtained.

The present work is therefore focused on the design, development and analysis of stacked complementary microstrip antenna having a 'π' shaped defected ground structure possessing circular polarization for the wireless applications of interest. The antenna is also able to achieve elliptical polarization because of the 'T' shaped feed line that is used for its excitation.

6.2. Antenna Structure and its Geometry

The presented stacked complementary microstrip antenna consists of three layers of Fr4 substrate each with dimensions of 4.7 cm X 3.55 cm, with a height of 1.57mm. The substrate used for all the layers of antenna is FR4 has an electrical permittivity of 4.4 and a dielectric loss tangent of 0.0024. On the top and middle layers of the substrate, metallic rectangular patch antennas are printed and on the bottom layer of substrate (double sided PCB), a ground layer is printed on its upper side and a feed line with an orthogonal stub on its lower side.

Figure 6.1 shows the side view of the antenna's layered structure. It shows the stacked antenna geometry with h_1 and h_2 representing the height of metal and substrate layers used respectively for the proposed antenna. The top two substrate layers of the antenna have rectangular patch antennas printed over them such that the lower patch is a complementary structure of the slot cut in the upper patch of height 0.035mm each. The bottom substrate layer has a ground plane printed on its upper part with rectangular aperture slot etched from it that is orthogonal to the feed line and a 'π' shaped slot also that makes the ground structure of a defected nature. The feed line with stub is printed on the lower part of this substrate for energizing the antenna for radiations. The metal thickness chosen for all the metallic layers is 0.035mm. Figure 6.2 shows the details of the layered structure of antenna. As can be observed from the figure, the top two layers have patches printed over them and the bottom layer has a ground plane on its upper side with a feed network on its lower side.

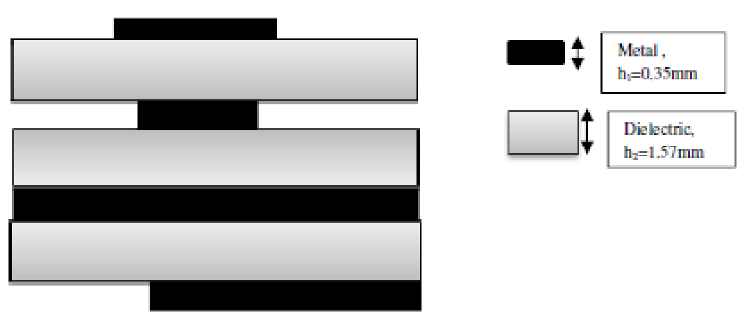


Figure 6.1: side view of the antenna showing its layered structure

The topmost and the middle patch antennas are rectangular shaped patches with a slot cut in the topmost patch antenna. The middle layer has a patch antenna that is optimized approximately to the same size as that of the dimensions of slot in the topmost patch antenna. The rectangular patch antennas are designed for the close by resonant frequencies in the (5 – 6) GHz band using the transmission line model, design equations mentioned in section 2.4 of chapter 2 of this thesis report.

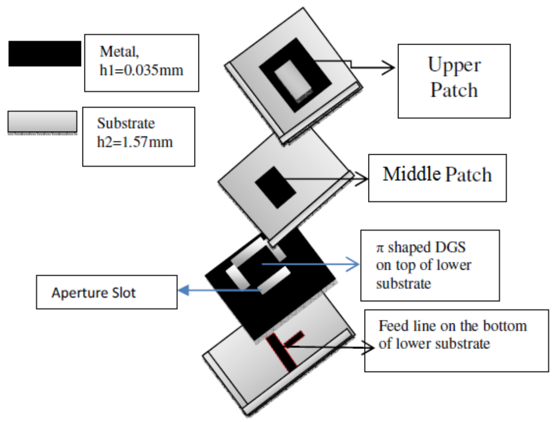
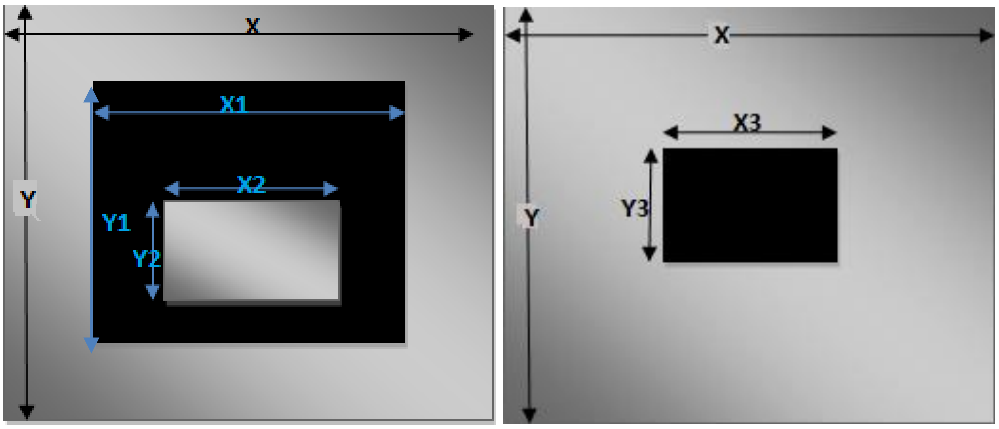


Figure 6.2: Perspective View of the Proposed Antenna

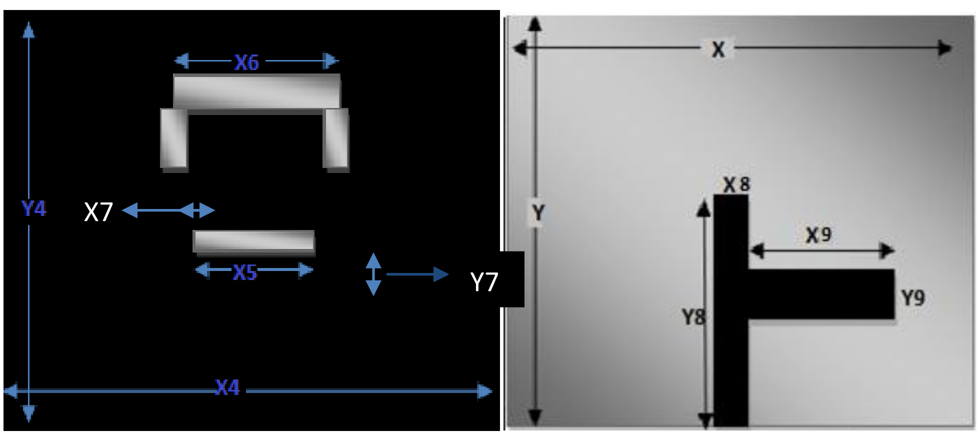
Using equations (2.1) to (2.15) mentioned in chapter 2 of the thesis work, the dimensions of the upper and lower patch antenna were found (X1 X Y1) as 27mm X 27.25mm and (X3 X Y3) as 13.8mm X 10mm respectively. The lower patch antenna is approximately of the same size as the slot dimensions in the upper patch antenna which is (X2 X Y2) as 13.9mm X 9.6mm; thereby making it a complementary stacked patch antenna. Figures 6.3(a),(b),(c) and (d) show the labeled parts of the top patch, lower patch, ground plane and the feed line and all the parametric values of these parts is mentioned in Table 6.1.

The dimensions of the ground plane are (X4 X W4) as 44 mm X 38.5 mm. The feed line is shown as a metal patch on the bottom of lower substrate in Figure 6.3(d) has an orthogonal stub attached to it and shows a 'T' shaped geometry. The dimensions of the feed line are (X8 X Y8) as 4.2mm X 9.3mm and the stub dimensions as (X9 X Y9) as 10 mm X 2.5 mm. The dimensions of the feed line are also optimized so that it matches the impedance of the coaxial cable and the SMA connector i.e. 50 ohms. This antenna is supplied power by energizing it through the feed line. Since it provides both the vertical and horizontal components of electric field radiated by the antenna; the polarization exhibited by this antenna is circular in nature.



(a) **(b)**

Figure 6.3: (a) Front view of Top patch and (b) lower Patch Antennas



(c) **(d)**

Figure 6.3: (c) ground plane of the antenna (d) the feed network of antenna

Table 6.1: Design Parameters of the Optimized Antenna

Parameter	Dimensions(mm)
X	47mm
Y	38.55mm
X1	27mm
Y1	27.25mm
X2	14mm

Parameter	Dimensions(mm)
Y2	9.5mm
X3	13.8mm
Y3	10 mm
X4	44mm
Y4	38.5mm
X5	10mm
Y5	0.5mm
X6	24mm
Y6	3mm
X7	3.5mm
Y7	7.5mm
X8	4.2mm
Y8	9.347mm
X9	10mm
Y9	2.6mm

6.3. Simulation Results

The simulation results of antenna's output that was designed using the CSTMWSV.10 software are presented in terms of impedance bandwidth, axial ratio bandwidth, gain, radiation pattern, current distribution and VSWR. The antenna was designed as a three (substrate) layered structure with a DGS and aperture coupled feeding and the results of simulations are presented in the following subsections.

6.3.1. Impedance Bandwidth

The range of frequencies for which the designed antenna's input impedance is matched to the impedance of the transmission line represents the impedance bandwidth of the antenna. Figure 6.4 shows the simulated S_{11} (dB) plot of antenna plotted against frequency on X axis. The frequencies below -10dB scale are the ones at which antenna is matched to the input impedance of 50 ohms with a reflection coefficient of less than or equal to 0.33. Figure 6.4 shows that the antenna covers a broad band from 5.14 GHz to 5.85 GHz with a peak S_{11}(dB) value of -28 dB, thus allowing the antenna to be suitable for one UWB bands from (5.28 – 5.85) GHz, IEEE802.11a/WLAN (5.15-5.35) GHz, a IEEE 802.11b/ WLAN band from (5.75-5.85)GHz and WiMAX band from (5.25- 5.85) GHz. Thus it shows an impedance bandwidth of 12.62% at the resonant frequency of the antenna's operation.

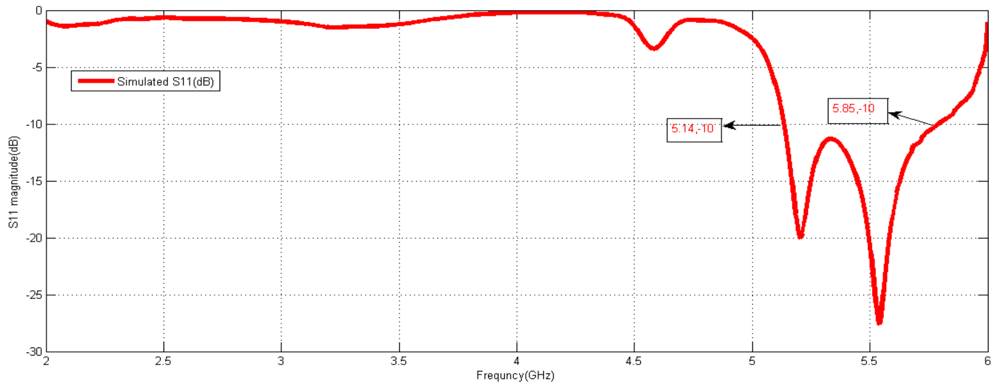


Figure 6.4: Simulated S_{11} (dB) Plot of the antenna

6.3.2. Axial Ratio Bandwidth

The 1dB axial ratio bandwidth of the antenna is shown in Figure 6.5. The range of frequencies at which the proposed antenna maintains the major to minor axis ratio of the ellipse/circle (that is traced by the extremity of the two orthogonal electric filed components radiated by the antenna) is equal to or below 1dB correspond to the 1dB axial ratio (AR) bandwidth of the antenna. The 1dB AR bandwidth measured in this case is 819 MHz as the antenna possesses circularly polarized behavior with a 1dB axial ratio from 5.16GHz to 5.98GHz at the operational band, thereby making it best for RF front end applications. In such devices, the orientation of receiver antenna will not affect the system's performance because of its ability to transmit and receive EM signals along both horizontal and vertical planes respectively.

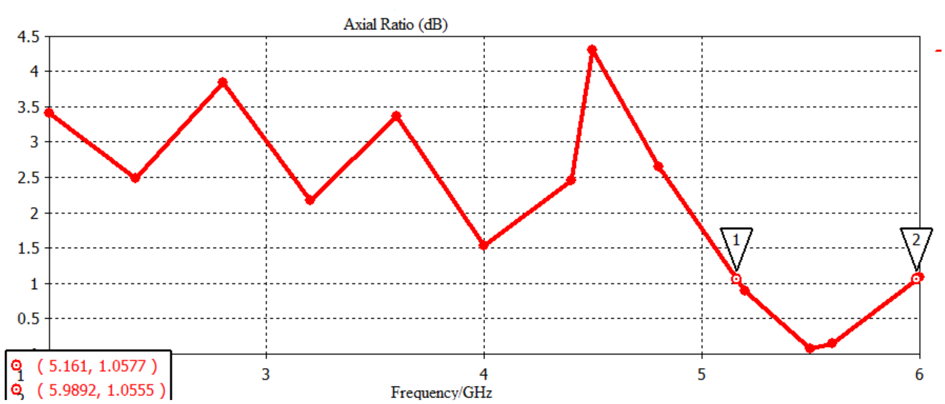


Figure 6.5: Simulated Axial Ratio Bandwidth of the Antenna

6.3.3. VSWR

The antenna can be fed with maximum input power if its impedance is matched to that of the transmission line and thus the antenna should represent a VSWR of less than 2 practically for optimized performance at those frequencies at which the antenna is matched to the transmission line. Figure 6.6 represents the VSWR plot of the antenna's operation with VSWR on Y axis plotted against frequency. It can be observed from the figure that the antenna shows a VSWR of 1.20 at the central frequencies of operation band i.e. at 5.5 GHz.

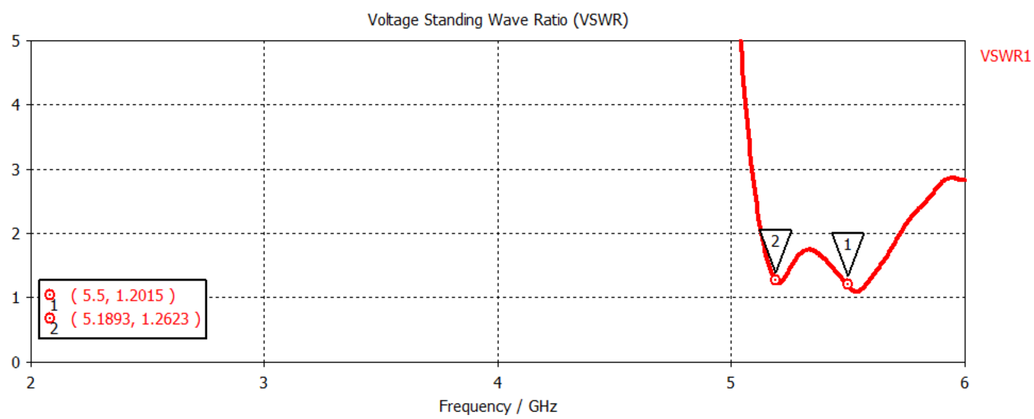


Figure 6.6: VSWR Plot of the Antenna at 5.5GHz and 5.18GHz

6.3.4. Gain

The proposed antenna shows a gain of 4.6dB at the central frequency 5.5GHz of the operational band. Figure 6.7 shows the three dimensional radiation pattern plot of the antenna in terms of gain that is measured along the major lobe (maxima) at the central frequency of antenna's operational band from 5.14GHz to 5.85GHz. The antenna possessing a good gain is suitable for indoor long range applications.

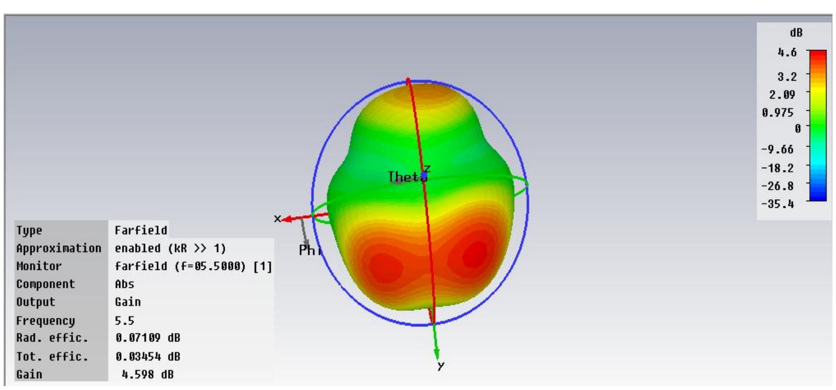


Figure 6.7 : Gain of antenna at 5.5GHz

6.3.5. Radiation Pattern

The polar plots of any antenna’s radiation pattern are the 2D representation of the antenna’s radiation characteristics in either elevation plane or in the azimuth plane. This can be plotted in terms of antenna characteristic like gain, radiation intensity and polarization. Figure 6.8 (a) and (b) show the 2D radiation (gain) pattern plots of the antenna in the **E** (elevation) and the **H** (azimuthal plane respectively at the center frequency (5.4GHz).The antenna has a major lobe along 300degrees with a Half power beam width of 268.2degrees in the elevation plane.

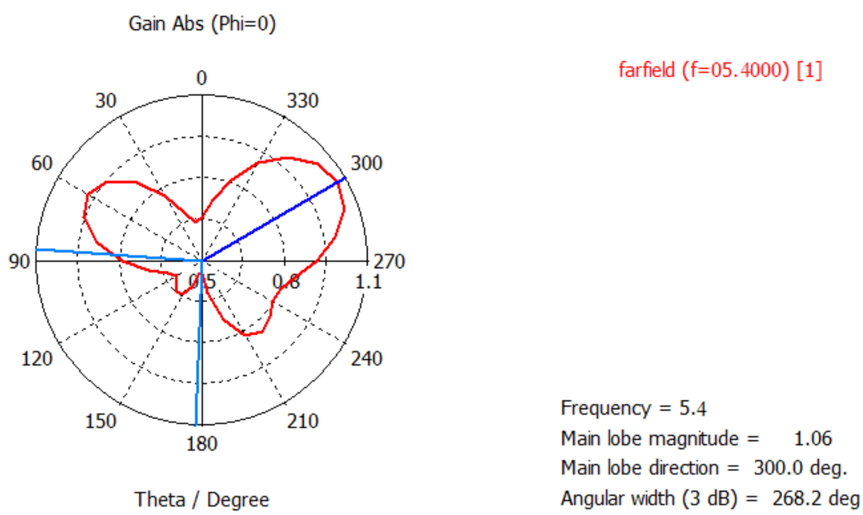


Figure 6.8(a): Elevation plane pattern of the antenna at 5.4GHz

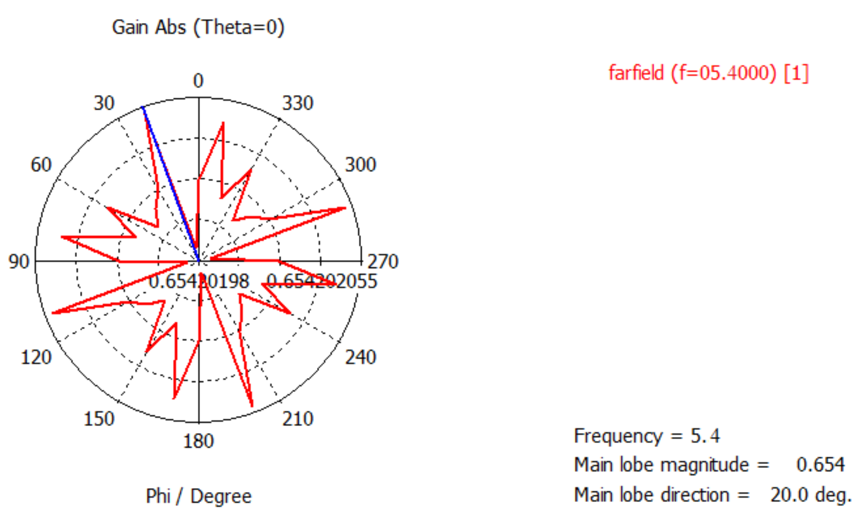
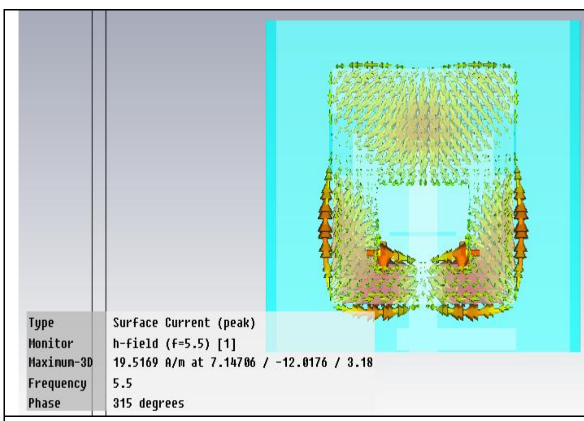


Figure 6.8(b): Azimuthal plane pattern of antenna at 5.4GHz

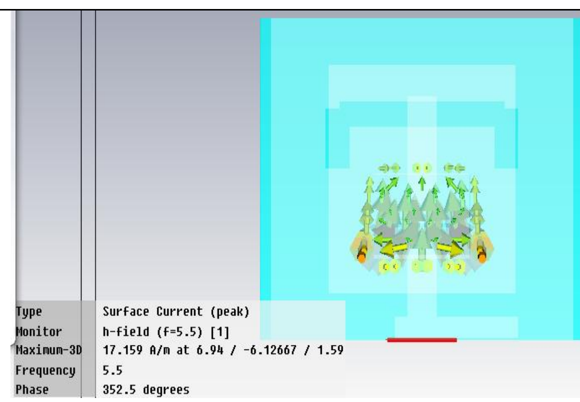
Figure 6.8(b) shows the top view of the radiation pattern plot of the antenna at 5.4GHz.The major lobe magnitude in this case is 0.654(on a normalized scale). From the radiation pattern plots it can be understood that the antenna gives a good coverage in a sector of 270 degrees approximately.

6.3.6. Current Distribution

In order to observe that which part of the antenna is mainly responsible for showing resonance at the central frequency of the band from 5.14GHz to 5.85GHz; the antenna is energized with an input of 1watt of power by the CST MWSV.10 software to observe the distribution of current over its surface at 5.5.GHz (center frequency). Figure 6.9 (a) and (b) show the distribution of current on the surface of top most and the middle patch antennas respectively. A peak magnitude of current on the top patch is 19.5 A/m and that on the lower patch antenna it is 17.15A/m. Figures 6.9 (c) and (d) show the distribution of current on the feed line and ground layers of the antenna respectively at 5.5 GHz. The ground layer of the antenna shows a peak current magnitude of 29.3 A/m and the feed line of the antenna shows a peak current magnitude of 30A/m at 5.5GHz. From the values of simulated current density on the four layers of the antenna, it is concluded that the two patch antennas are responsible for the resonance and the defected ground layer with an aperture slot help in enhancing the bandwidth at the operational band of the antenna from 5.14GHz to 5.85GHz.

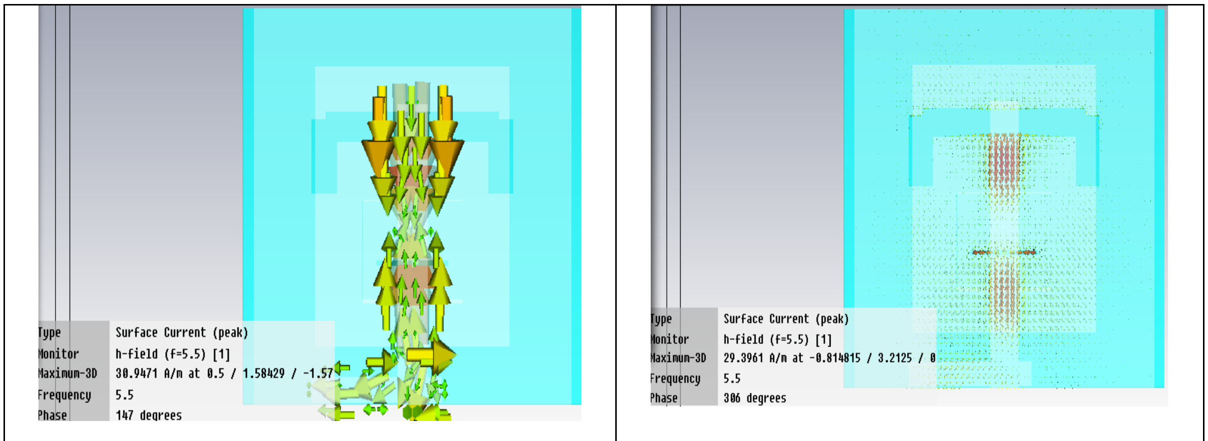


(a)



(b)

Figure 6.9 (a) and (b): Current distribution on the upper and lower patch antennas at 5.5GHz



(c) (d)

Figure 6.9 (c) and (d): Current distribution on the feed line and ground plane of the antenna

6.4. Parametric Analysis of the Antenna

The proposed MSA was analyzed for its operation at central frequency of the broad band by varying the dimensions of the patch antennas. Figure 6.10 shows the parametric results of antenna in terms of the S_{11}(dB) plot. These results were obtained when the length of patch was varied, it can be verified from Figure 6.10 that with variation in the upper patch length, the S_{11}(dB) values vary and since lower values of S_{11}(dB) are preferred for antennas with a better impedance matching, 27mm (-13.5mm to 13.5mm) was chosen as the length of upper patch antenna.

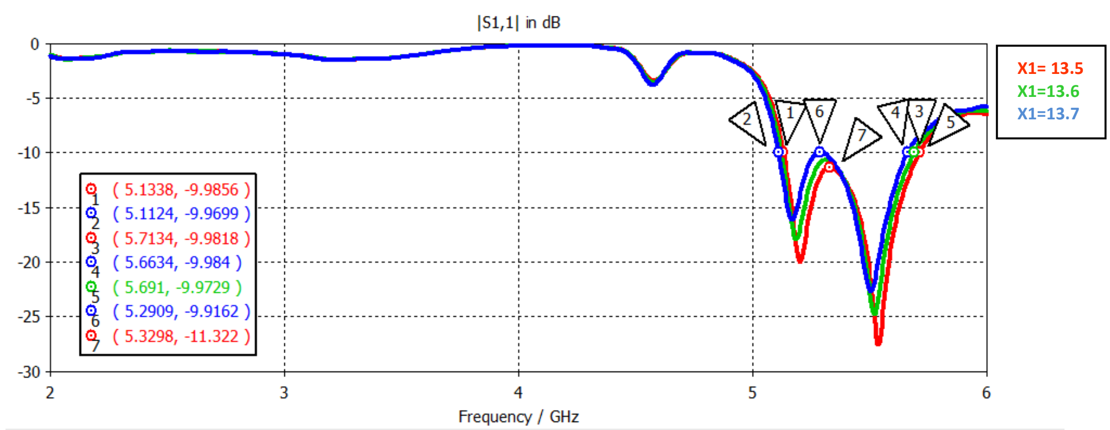


Figure 6.10: Results of parametric variation of the top patch antenna

Figure 6.11 shows the effects of varying the dimensions (Y3) of the lower patch antenna, the major effects of this change can be seen on the shift of the resonant frequency of the band towards left on increasing patch width. The impedance bandwidth at the respective frequencies also varies. Thus an optimized value of 0.62 is chosen as the other extremity of the lower patch width from -9.5 to 0.62mm.

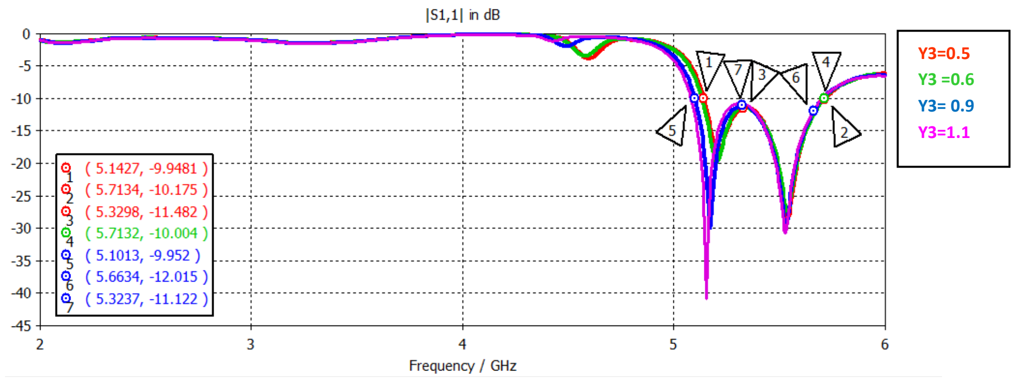


Figure 6.11: Results of parametric variation of the lower patch antenna

The Defected Ground structure that is designed according to the equations 2.18 mentioned in chapter 2 at the adjoining frequency of the existing band at 5.65GHz. This leads to the enhancement of the antenna bandwidth by 200 MHz and thereby making the antenna a broadband antenna with an impedance bandwidth of 701 MHz. The antenna's impedance bandwidth results were also analyzed by eliminating the defected ground structure in the ground plane. Figure 6.12 shows the comparison of impedance bandwidth results at the resonant band of operation for the case when antenna does not have a defected ground structure compared to the results with the antenna having a 'π' shaped defected ground structure .

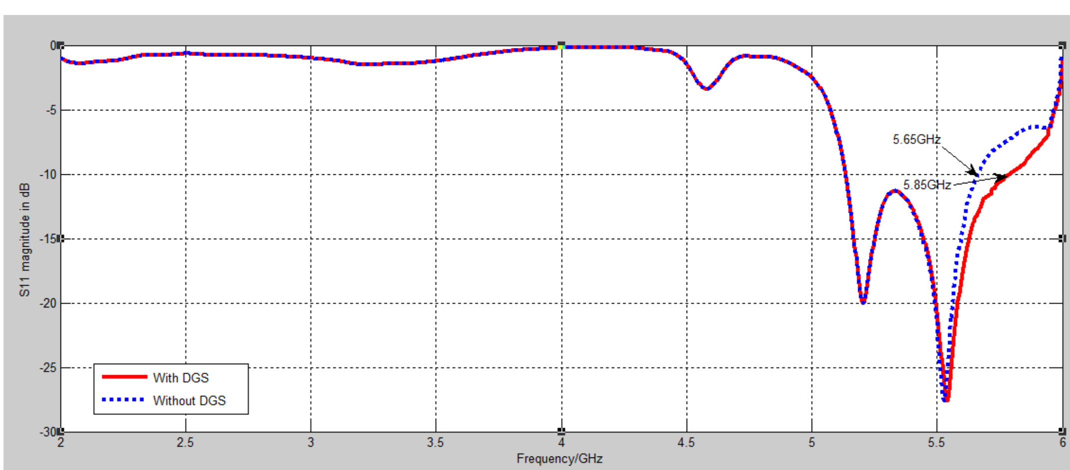


Figure 6.12: Comparison plot of Simulated S_{11}(dB) for the antenna with and without DGS

It can be examined from the Figure 6.12 that the antenna has a comparatively lower bandwidth at the proposed band when a 'π' shaped slot is not used in the ground plane. The antenna resonates from 5.14GHz to 5.66GHz (BW of 520MHz) , without a DGS as compared to a bandwidth of 701 MHz obtained from (5.14 to 5.85GHz) band of antenna's operation with a DGS. Therefore the antenna design in the current research work is considered with a defected ground structure for best results. The dimensions of the defected ground structure and the aperture in the ground plane were varied to optimize the operational bandwidth of the proposed antenna. Figure 6.13(a) shows the results of parametric variations of the antenna in terms of its impedance bandwidth of operation when the DGS dimensions X6 are varied. It is observed that the value of S_{11}(dB) as well as resonant frequency gets affected when the DGS dimensions are changed. The optimized value of Y7 is therefore chosen to be 7.5mm.

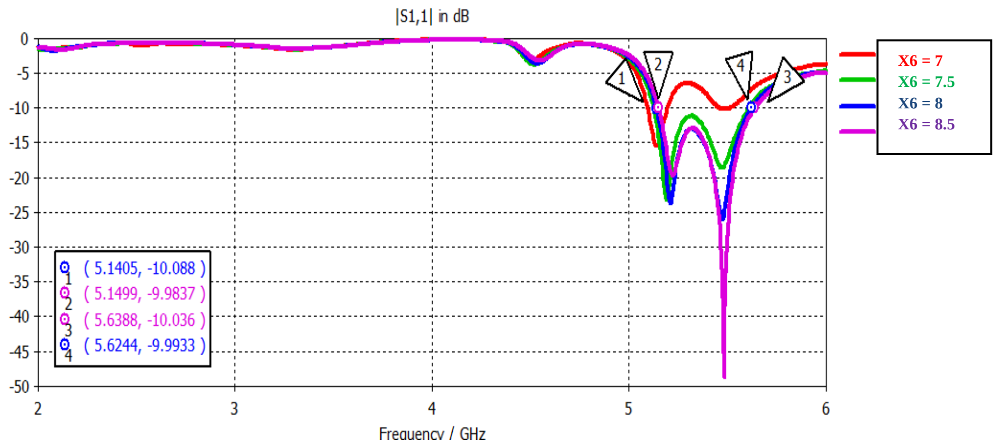


Figure 6.13(a): The variation in Impedance bandwidth of the antenna by changing The DGS width

Figure 6.13(b) shows the effect of variation of aperture slot width Y7 on the S_{11}(dB) results of the antenna, the variation in the height of the aperture slot leads to shift in the resonant frequency as the major portion of the energy gets coupled to the patch through this slot only. As the best results are obtained with a slot width equal to 0.5 mm i.e. from -5.25mm to -5.75mm, this is the selected height of the aperture slot.

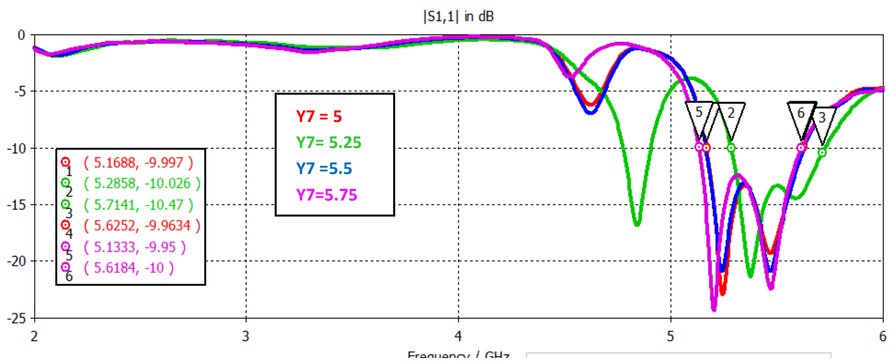


Figure 6.13(b): Effect of parametric variation of the aperture slot width

6.5. Antenna Fabrication and Testing

The presented antenna structure was constructed on Fr4 substrate with a thickness of 1.57mm and a loss tangent of 0.0024 using the wet etching technique. The fabricated antenna structure with a rectangular patch antenna on the top layer having a slot and a patch antenna roughly of the same dimensions as the slot in the middle patch is shown in Figures 6.14(a), (b) . Figure 6.14 (c) shows the ground layer with an aperture slot and a ‘π’ shaped defect and the Figure 6.14(d) shows the three layered assembled antenna.

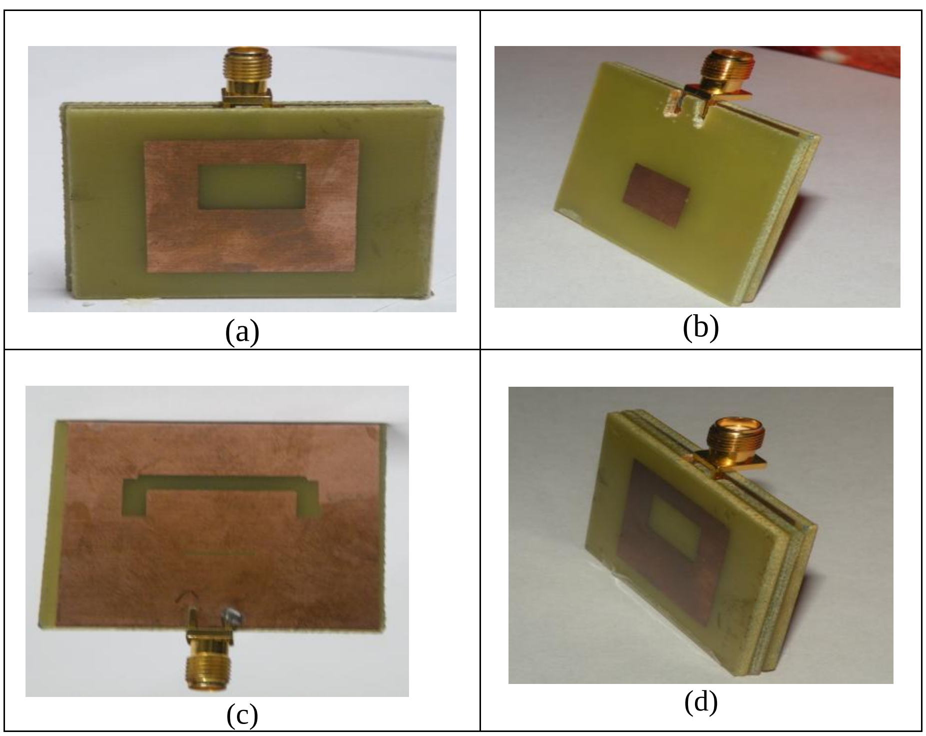


Figure 6.14(a) Top patch (b) Lower patch antenna (c) Ground Plane (d) Assembled Antenna

The fabricated antenna was tested for measurements of S_{11} (dB) results on vector network analyzer (model number E 5071C) working at a frequency range between 9 KHz to 8 GHz and for measurement of gain at in a reflection free environment using an anechoic chamber (with an operating range from 2 KHz to 20 GHz). The experimental results were measured around the center frequency of the band at 5.5 GHz. Figure 6.15 (a) shows the snap shot of the VNA when the fabricated antenna was tested for S_{11} results and Figure 6.15 (b) shows the comparison of the two results plotted using MATLAB.

It can be seen from the Figures 6.15(a) and (b) that the tested antenna shows an impedance bandwidth of 740 MHz from 5.16GHz to 5.90GHz .Thus the antenna is practically capable of covering UWB bands from (5.28-5.8) GHz and IEEE 802.11a/WLAN applications from (5.15 -5.35) GHz, Wi-MAX (5.25-5.85) GHz and IEEE 802.11b/WLAN band from (5.75-5.85) GHz, thereby allowing the antenna to be efficiently used for the proposed wireless applications.

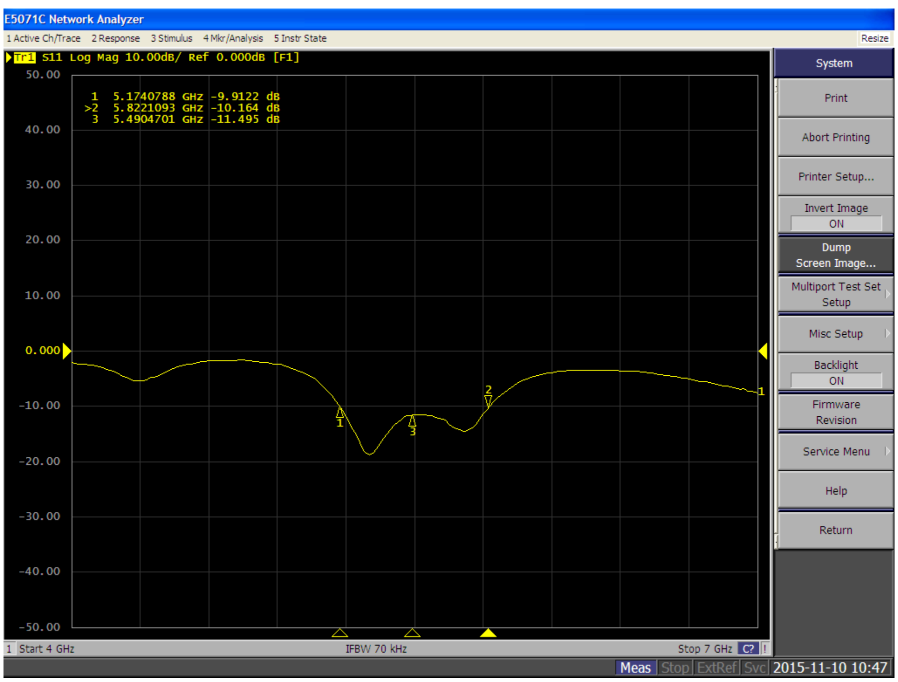


Figure 6.15 (a): Snap shot of the VNA screen while testing of the antenna on a VNA

In order to compare the results obtained from the experimental testing of the proposed antenna , a comparative plot of simulated versus measured return loss values is plotted using

MATLAB in the Figure 6.15(b). It can be observed that the simulated and measured results are in close approximation with each other. A slight variation in the measured S_{11}(dB) results show a little shift in the resonant band towards right of the frequency band. The reason for this could be attributed to the inaccuracies introduced during the antenna fabrication process, misalignment of the three stacked layers of the antenna and sometimes because of the misalignment of the feeding cable and the connector with the antenna causes the results to deviate from the simulated ones. The measured impedance bandwidth of the antenna is 740 MHz and is more than the simulated one (700MHz).The main reason behind this could be minor air gaps that are introduced while assembling the three antenna layers, as the effective height of antenna gets increased, the EM fields are more loosely bound and thus the antenna exhibits an increased bandwidth in the latter case.

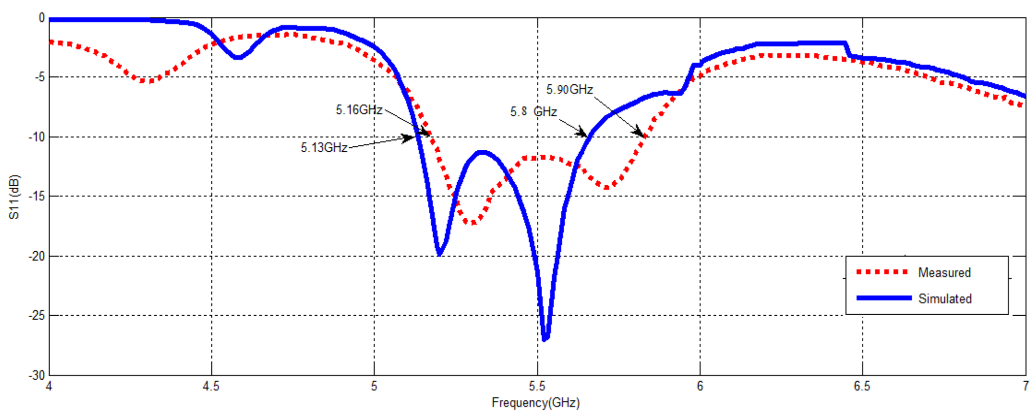
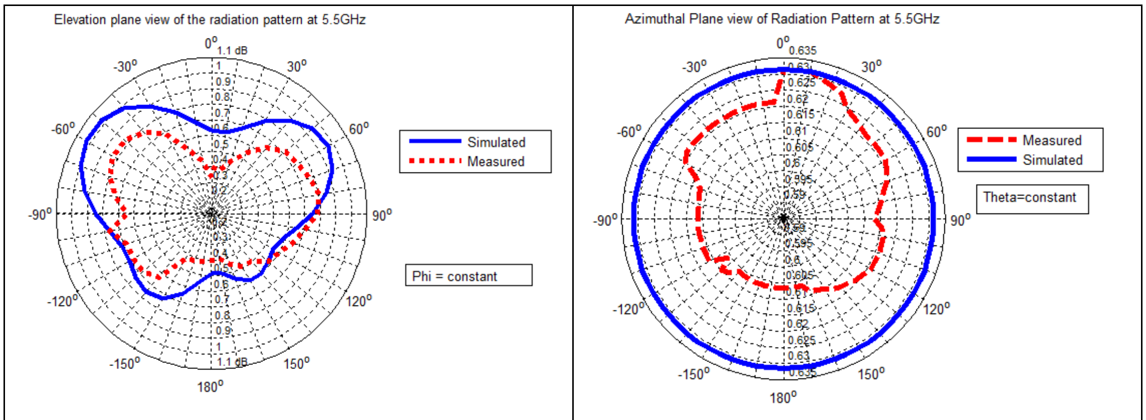


Figure 6.15 (b): Comparison of simulated and measured results of the antenna

The fabricated antenna was placed in an anechoic chamber with a standard horn antenna having a calibrated gain of 12dBi that was used for testing. The gain patterns of antenna in two dimensions along the elevation and azimuthal planes were plotted using MATLAB. Figures 6.16(a) and (b) show the comparison plots of elevation plane views of the antenna antenna’s gain pattern. It can be observed that antenna shows an omni-directional pattern in the azimuthal plane. The simulated and measured results of the radiation pattern plots at both the operation frequencies are quite identical but there are some differences that can be attributed to the measurement errors that take place while testing the antenna. The errors that mainly arise are because of the alignment problems of the antenna itself, misalignment between transmitter and receiver and sometimes low noise signals that get mixed up with the low values gain signals.

There is a variation of around 0.7 to 1 dB approximately seen in the values of simulated and measured gains at the central frequency of 5.5GHz as shown in the Figure 6.17. Apart from these minute variations, the measured impedance bandwidth and the radiation patterns are in good approximation with the simulated ones that allows the antenna to be practically suitable for the proposed wireless bands of interest.



(a) **(b)**

Figure 6.16(a) and (b): Radiation pattern plots of antenna at 5.5GHz

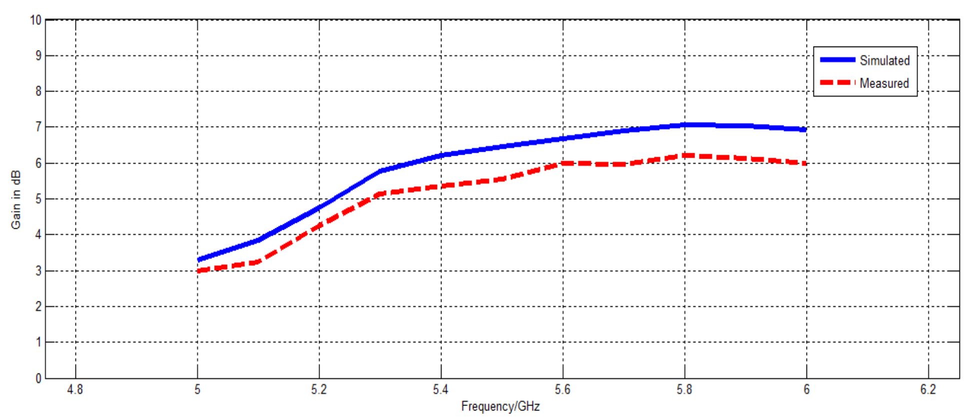


Figure 6.17: Comparison of Simulated and Measured gain of the antenna at 5.5 GHz

6.6. Conclusions

In the research work presented in this chapter, a three layered stacked microstrip patch antenna with rectangular shaped patches is presented for dual wide band wireless operations. The antenna is fed with an aperture coupled feeding method with a rectangular aperture in the ground and a 'π' shape defect in addition to the aperture slot is etched out from it that is used to obtain an enhanced bandwidth from the antenna. The feed line of the antenna has a stub that is orthogonally attached to it to provide the impedance matching at 50 ohms thereby showing a VSWR of 1.2 at the centre frequency of the band. The orthogonal stub helps in providing circular polarization to the fields emitted by the antenna

The presented antenna has a compact size of 4.7 X 3.82 X 0.483 $cm^3$and it was tested using a VNA and in an anechoic chamber so as to validate its applicability to wireless applications of interest. The proposed antenna is found to be well suited for the UWB band from (5.28-5.8) GHz and IEEE 802.11a/WLAN applications from (5.15 -5.35) GHz, Wi-MAX applications from (5.25-5.85) GHz and IEEE 802.11b/WLAN band from (5.75- 5.85) GHz. The antenna presents a high gain of around 5.5dB and circularly polarized behavior at all the mentioned bands and thereby allows it to be a good candidate for long range applications.

In Conclusion, the research work presented in the current chapter antenna presents the use of stacked slotted (complementary shaped) antennas to obtain a broadband behavior from 5.14 GHz to 5.90 GHz. It also illustrates the use of a DGS to enhance the bandwidth of the proposed antenna at the operational band and the use of a feed line with stub to obtain circularly/elliptically polarized waves for the proposed wireless bands. This makes the antenna suitable for use in handheld devices for the suggested wireless applications of interest.

Chapter 7
Conclusions and Future Scope of Work

7.1 Conclusions

The research work presented in this thesis has been initiated because of the need for small sized, compact, inexpensive, easy to manufacture and rugged multifrequency antennas typically for the unlicensed wireless frequency bands of operation like the WLAN, UWB and Wi-MAX. A lot of research work available in this context mainly focuses on the design and implementation of complex structured antennas that did not cover much wireless applications in a single device and were usually not circularly polarized (which is one of the main requirements of current wireless systems so as to have a liberty of orientation of the RF front end device).

This gives the initiative of the current research work presented in this thesis to mainly concentrate on the use of stacked microstrip antennas to achieve multi frequency and a wideband behavior from MSAs. The antennas were designed with aperture coupled feeding mechanism and the feed line was designed with a stub to achieve circular polarization. The use of judiciously chosen DGS for multiband and broadband behavior is also illustrated.

The antenna design and simulations are carried out using a software CST Microwave Studio version 2010 that is based on the Finite integration technique to carry out the full wave analysis of the antenna. This method is capable of evaluating the EM components for the entire EM and optical range of frequencies.

The main objective behind the research work is to carry investigations on the operation of a stacked microstrip antenna and study the effects of varying different antenna parameters on its performance in terms of multifrequency and impedance bandwidth. It is demonstrated that aperture coupled stacked microstrip antennas give an ample liberty of parametric variations for antenna optimization for different wireless and microwave applications to the researchers.

Four different types of stacked antennas have been designed, simulated and tested after fabrication as case studies for the current research work to be carried out successfully. The stacked antenna designs are proposed with a two layer of stacking, different designs like fractal structures, slotted complementary antennas simple stacked rectangular antennas with a specific shaped DGS have been presented. These antennas have a feed network in which the feed line that has an orthogonal stub attached to it, this helps in impedance matching as well as achieving circularly/ polarized waves transmitted by the antenna, thereby making the antennas as one of best choices for the proposed applications. On the whole, stacking of patch antennas has been illustrated to improve the operational bandwidth as well to obtain a multiband behavior. The use of defected ground structures for improving the bandwidth of the existing band as well as for obtaining a multifrequency behavior has also been illustrated in the research work presented here and a novel technique for making these MSAs circularly polarized in nature is by using an orthogonal stub with the feed line.

The major contributions of the thesis work categorized in chapters are as mentioned below.

- **Chapter 1** gives an impetus for the design and development of microstrip antennas for the latest wireless communication technologies in the unlicensed frequency bands namely the WLAN, UWB and WiMAX. The chapter defines the problem statement, research objectives, scope and entire methodology for conducting the current research work.
- **Chapter 2** presents an overview of the microstrip patch antennas, their feeding configurations with an example of research work carried out in each field respectively. Comparison of the feeding techniques to impress upon the use of aperture coupled method of feeding these microstrip antennas. The different parameters for analyzing the antenna's performance, the transmission line method to analyze the antenna's operation based on the design equations has been presented. An elaborated research work in the field of stacked microstrip antennas with different types of configurations has been done to study the operation of different configurations of a stacked antenna for various wireless applications. Thus the necessary literature survey required for carrying out the current research work that has been done is covered in this chapter.
- **Chapter 3** presents the design and development of a stacked broad band rectangular microstrip antenna for WLAN applications. Stacking up of two layers with no air gap between the substrates is done. The antenna is fed using aperture coupled method of feeding. Investigations on the parametric variations of the proposed antenna were carried out to see the effect of each variation on the antennas performance. The antenna possesses a gain of around 6dB. This was fabricated and tested for the validation of its applicability to the practical applications of interest. The antenna shows a measured impedance bandwidth

from 5.06GHz to 5.7GHz showing a bandwidth of 640 MHz and a measured gain of around 5.5dB. The conclusions from this chapter have been used as the basic benchmark tips for the design and study of different types of stacked microstrip antennas like fractal, complementary antennas and stacked rectangular antennas with DGS. The antenna can be successfully applied to IEEE 802.11a WLAN band (5.15-5.35GHz) U-NII-1 band (5.18-5.24 GHz) and the U-NII-2/2e band (5.26-5.70 GHz) applications.

- **Chapter 4** illustrates the use of stacked geometry with a DGS for dual band operation of MSA. The use of stacked geometery for enhanced bandwidth at one resonant band and use of defected Ground structure for the second resonant band of antenna's operation has been illustrated. This chapter presents the design and development of a Stacked Dual Wide Band Circularly Polarized microstrip antenna with DGS for WLAN, Bluetooth, Zigbee, Wi-Max and IMT Band applications as one of the case studies of current research work. This is a novel approach to design dual wideband MSA with a compact structure and circular polarization. The two stacked patches are responsible for one resonant band and the 'E' shaped DGS is responsible for the second resonant band. The antenna was fabricated and experimentally tested to suit the proposed wireless applications. The testing results show an impedance bandwidth of 200MHz from (2.43 -2.64) GHz and 530 MHz from (3.4-3.93) GHz, thereby allowing the antenna to be suitable for the proposed wireless applications for WLAN from 2.4GHz-2.485GHz, Bluetooth applications from 2.4GHz-2.483GHz, ZigBee applications from 2.4GHz - 2.485GHz, IEEE 802.16/ Wi-MaX applications from 3.4GHz - 3.69GHz and International Mobile Telecommunications band from 3.4GHz to 3.6 GHz. The tested antenna shows an average measured gain of 4.2 dB and 5dB at the two proposed wireless application bands respectively.
- **Chapter 5** illustrates the use of fractal antennas for multiband operation and the use of DGS to improve the bandwidth at the two bands. This chapter presents another case study to achieve the defined thesis objectives. It covers the design and analysis of a circularly polarized stacked Sierpinski Gasket fractal antenna with a defected ground structure for UWB, WLAN, Radio Astronomy & STM

link applications. The fractal structure is used to achieve a multiband operation and a size reduction at the proposed wireless frequency bands. The antenna is fed using aperture coupled feeding method with the slot in the ground plane modified to a '┼' shape. The slot in ground helps in enhancement of the operational bandwidth of the proposed antenna. The antenna testing results show a measured impedance bandwidth from 4.8GHz to 5.275GHz (475MHz) and 6.6GHz to 7.35 GHz (750MHZ) that is sufficient to cover the proposed applications from 5.275GHz -5.85GHz for UWB operation, (5.15-5.35) GHz for WLAN, (5.01-5.03) GHz for Radio Astronomy applications and (6.8-7.35) GHz for UWB operation thereby allowing the antenna to be practically feasible for the RF front end applications. An average measured gain of 6.7 dB and 8 dB at the two bands respectively have been reported for this antenna that allows it to be practically used for long range indoor wireless application bands.

- **Chapter 6** presents the fourth case study considered for the current research work. A Stacked Complementary microstrip antenna with a 'π' shaped Defected Ground Structure for UWB, WLAN, Wi-MAX and Radio Astronomy wireless Applications has been designed, fabricated and tested to suit the proposed practical wireless applications. The main aim of the research work done in this chapter has been to show the effect of stacking two rectangular antennas one above the other, the upper layer antenna being larger in size having a slot cut into its structure and the lower layer antenna being a complementary of the one that is on the top layer i.e. of the size of the slot in the upper layer approximately. This structure helps to excite two nearby resonant frequencies can be combined to give an enhanced bandwidth of operation (700MHz in this case). The use of a 'π' shaped DGS has been done to improve the operational bandwidth of the antenna. The testing results of the antenna show a measured impedance bandwidth of 5.16GHz to 5.90GHz i.e. a fractional bandwidth of around 13% at the centre frequency of the band. The proposed antenna is thus capable of covering the wireless applications of UWB band from (5.28-5.8)GHz and IEEE 802.11a/WLAN applications from (5.15 -5.35)GHz, WiMAX (5.25-5.85) GHz and IEEE 802.11b/WLAN band from (5.75- 5.85) GHz. A measured gain of approximately 5dB has been reported for this antenna that makes it a viable choice for indoor RF applications.

The table 7.1 below highlights the measured results achieved from the four antennas that were experimentally tested to show their practical applicability to the proposed wireless applications of interest.

Table 7.1: Experimentally Measured results of the proposed antennas and their applications

Antenna Structure	Measured Impedance bandwidth	Measured Gain	Applications
Simple Stacked Rectangular Patch Antenna with aperture coupled feeding	5.06GHz to 5.7GHz	5.5dB at 5.35GHz	IEEE 802.11a WLAN band (5.15-5.35GHz), U-NII-1 band (5.18-5.24 GHz) and the U-NII-2/2e band (5.26-5.70 GHz).
Stacked rectangular Patch antenna with a 'E' shaped Defect in the ground plane	200MHz from (2.43 - 2.64) GHz and 530 MHz from (3.4-3.93) GHz.	4.2 dB at 2.53dB and 5dB at 3.66 GHz	WLAN (2.4GHz-2.485 GHz), Bluetooth applications (2.4GHz-2.483GHz), ZigBee applications (2.4GHz - 2.485GHz), IEEE 802.16/Wi-MaX applications (3.4GHz - 3.69GHz) International Mobile Telecommunications band (3.4GHz to 3.6 GHz).

Stacked Sierpinski gasket fractal patch antenna with a cross shaped Defect in ground plane	4.8GHz to 5.275GHz (475MHz) and 6.6 to 7.35 GHz (750MHZ)	6.7 dB at 5.05GHz and 8 dB at 7 GHz	UWB operation (5.275-5.85GHz), WLAN (5.15-5.35) GHz,Radio Astronomy applications (5.01GHz -5.03 GHz) and (6.8GHz -7.35GHz) STM band applications.
Stacked complementary patch antenna with a 'π' shaped defect in the ground plane.	5.16GHz to 5.90GHz	5dB at 5.5 GHz	UWB band from (5.28-5.8) GHz and IEEE 802.11a/WLAN applications from (5.15 -5.35) GHz, WiMAX(5.25-5.85)GHz and IEEE802.11b/ WLAN band from (5.75- 5.85) GHz

7.2. Future Scope

The current research work presents a thorough study and analysis of stacked microstrip patch antennas. Various case studies have been incorporated in the research work to understand the working of stacked antennas with different configurations namely fractal, rectangular, complementary structures but some topics that have been left untouched in the research work and can be explored in future as mentioned.

- There is a lot of scope in this research field with different antenna geometries like circular, hexagonal, carpet and many more geometries for multiband and wideband operations.
- Antennas in this research work have been designed for generating circularly/elliptically polarized EM waves by using an orthogonal stub with the feed line. Many other methods like dual feeding the MSA using two feed lines, circular antenna geometry; edge feeding rectangular patches with truncated corners can also be used to generate circularly

polarized waves.

- The antennas that are designed and presented can be tested for the desired radiation pattern when enclosed in the handheld devices.
- The use of DGS shows tremendous potential for designing antennas for various applications with a wideband or multiband behavior. There are still a lot of DGS geometries whose hidden potential is yet to be discovered for obtaining desired antenna characteristics.
- Size reduction of the current antennas using defected ground structures can also be taken up as a research area for future.
- The antennas can be designed with Electromagnetic band gap structures (EBG) that can be used to design antennas with specific pass bands and stop bands.
- The MSA can also be used for biomedical applications like brain imaging and cancer detection; this can be taken up as a research objective for future.

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